The Society for Astronomical Sciences

Proceedings for the 41st Annual Symposium on Telescope Science

2022 June 2-4
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Alson Wong, Center for Solar System Studies

Back Cover:
SA-200 Grism spectrum of Wolf-Rayet star HD214419
Forrest Sims, Desert Celestial Observatory
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Welcome to the 41st annual Symposium of the Society for Astronomical Sciences. After two years of virtual meetings, we are excited to be back in-person in 2022. Thank you to those of you who stuck with us as we did our best. And welcome to first time participants who discovered a new hobby during the pandemic. We are grateful for your support and to be able to gather once again to share our interests and the fruits of our labor.

This year’s agenda reflects the broad diversity of interests among SAS members, with papers covering photometry, spectroscopy, interferometry and astrometry; instruments ranging from eyeballs to CCDs and spectrographs; and projects ranging from education to citizen-science to a variety of astronomical research activities.

It takes many people to have a successful conference. The SAS Program Committee members are:

Robert Gill          Robert D. Stephens          John C. Martin
Wayne Green          Jerry Foote
Robert Buchheim      John Menke

This year our veteran master of ceremonies, Jerry Foote, is passing his microphone to Rachel Freed. Please join us in thanking Jerry for his many years of service and giving Rachel a warm welcome.

SAS Membership dues and Registration fees do not fully cover the costs of the Society and the annual Symposium. We owe a great debt of gratitude to our corporate sponsors: DC-3 Dreams, Sky and Telescope, Software Bisque, and Woodland Hills Camera and Telescopes. Thank you!

We are grateful to the presenters, the attendees, and the community of practice in small-telescope research that is the heart of the SAS. We thank all of you for making the SAS Symposium one of the premiere events for professional-amateur collaboration in astronomy.

2022 May
Symposium Sponsors

The Society for Astronomical Sciences thanks the following companies for their participation and financial support. Without them, this conference would not by possible.

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The Essential Magazine of Astronomy
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<td>Joyce Anne Guzik</td>
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The Position Angle, Separation, and Additional Component of STF 1300

Sophia Risin  
Stanford Online High School  
Redwood City, CA  
sophia.risin@gmail.com

Josephine Stockton  
Stanford Online High School  
Redwood City, CA  
josephinesstockton@gmail.com

Keshav Narang  
Stanford Online High School  
Redwood City, CA  
keshavn@ohs.stanford.edu

Jack Durek  
Stanford Online High School  
Redwood City, CA  
jack.duerk.1@gmail.com

Scott Dixon  
Fairborn Institute  
Payson, AZ  
gscottdixon@hotmail.com

Kalee Tock  
Stanford Online High School  
Redwood City, CA  
kaleeg@stanford.edu

Abstract

Images of the double star system WDS 09013+1516 STF 1300 were taken using the robotic telescope at the Boyce Astro Robotic Observatory (BARO), the Dixon Astronomical Remote Observatory telescope (DARO), and Mount Wilson Observatory 60-inch telescope (MWO). Speckle Interferometry was used to derive the position angle and separation of the pair. Additionally, we detected evidence of an additional component, warranting further observations to assess for a third gravitationally bound star.

1. Introduction

In this paper, we use the technique of speckle interferometry to resolve a close binary system. Although we have access to the Las Cumbres Observatory (LCO) global telescope network, its 0.4-meter telescopes are unable to resolve stars with less than 5 arcseconds in separation. Therefore, we used speckle interferometry and data taken from the Boyce Astro Robotic Observatory (BARO) telescope, the Dixon Astronomical Remote Observatory (DARO) telescope, and the Mount Wilson Observatory (MWO) telescope to conduct astrometric measurements. The process of speckle interferometry involves taking the Fourier transform of each image. The result of each Fourier transform is a power spectrum in the Fourier domain for that image. Further analysis, in the form of bispectrum phase reconstruction, is then calculated to recover the single bispectrum image (Altunin et al, 2021).
2. Target Selection

Our target, STF 1300 was selected from a list of known binaries within 40 parsecs. This list was generated using the Gaia Double Star DataB and Access Tool (Risin, et al. in prep). The list was sorted to only include targets between 5 and 17 hours in right ascension, magnitude between 7 and 13, and a separation between 2 and 5 arc seconds. Because of this, the target was able to be observed by BARO, DARO and MWO from February through March 2022.

3. Results

STF 1300 was observed in February of 2022 on BARO and DARO, and observed again in March of 2022 on MWO. The elongation in figure 1 prompted further observations on MWO, leading to the discovery of a new component. This new component is visible in figure 2 and demarcated with a “C”. Numerical results for position angle and separation for each component are presented in table 1.

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<th>Telescope</th>
<th>PA (deg)</th>
<th>Sep (arcsec)</th>
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<tr>
<td>Gaia (a,b)</td>
<td>179.19</td>
<td>5.037</td>
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<tr>
<td>Ephemeris (a,b)</td>
<td>178.18</td>
<td>4.992</td>
</tr>
<tr>
<td>BARO (a,b)</td>
<td>177.57</td>
<td>4.989</td>
</tr>
<tr>
<td>DARO (a,b)</td>
<td>166.765</td>
<td>4.9485</td>
</tr>
<tr>
<td>MWO (a,b)</td>
<td>177.98</td>
<td>5.008</td>
</tr>
<tr>
<td>MWO (a,c)</td>
<td>194.65</td>
<td>5.808</td>
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<tr>
<td>MWO (b,c)</td>
<td>249.47</td>
<td>1.758</td>
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Table 1. Sep and PA values of STF 1300AB on Gaia (2015.5) Ephemeris, BARO, DARO, and MWO. Observations taken between February and March. C is a component not previously observed by Gaia and is reported as new.

4. Conclusions

In this study of STF 1300 we measured a position angle of 177.57 degrees and a separation of 4.989 arcseconds from BARO for the A and B. The measurement of STF 1300 from BARO is in line with the predictions from the calculated ephemeris. A position angle of 177.98 and separation of 5.008 were measured when using the Mount Wilson 60-inch telescope for the A and B component. We measured a position angle of 249.47 degrees and a separation of 1.758 arc seconds between the newly discovered component (C) and the secondary star.

The elongation of the secondary was able to successfully indicate a third component and shows the utility of small telescopes in the discovery space for new components. The new companion was not previously observed by Gaia, likely because it is so much dimmer than its companion stars. Further research can use the findings of this study to create new observation programs for large telescopes.

1. Acknowledgements

The assistance provided by Dr. Rachel Matson of the U.S. Naval Observatory was greatly appreciated. Dr. Matson provided the study with historical data on the systems being investigated. The past data came from the Washington Double Star Catalog, which is maintained by the U.S. Naval Observatory.
Specifically, the speckle interferometry used in this study was accomplished with the Speckle Toolbox written by David Rowe. In order to coordinate the observation of the targets and reference stars in our study, the SIMBAD Astronomical Database, and the Aladin Sky Atlas were used. The targets studied in this paper were chosen from the Gaia Double Stars Target List, created in December of 2021 by Rick Wasson. Astrometric measurements from the Gaia space telescope were also used in this study. Thank you to Rohan Satapathy, Liam Dugan, Dave Rowe, Rick Wasson, Reed Estrada, and Pat Boyce for help with programming, observing, and advising. Thank you to Tom Menegini for usage of the Mount Wilson Observatory telescope and for assistance with observations.

2. References


Investigation of the Variable Star CH CAM in the nebula NGC 1501

Adela Horsting  
Stanford Online High School  
415 Broadway Academy Hall, Floor 2, 8853, Redwood City, CA 94063  
adela.horsting@gmail.com

Carolina Noviello  
Stanford Online High School  
415 Broadway Academy Hall, Floor 2, 8853, Redwood City, CA 94063  
carolinagnoviello@gmail.com

Aisha Randhawa  
Stanford Online High School  
415 Broadway Academy Hall, Floor 2, 8853, Redwood City, CA 94063  
AishaPianissimo@gmail.com

Trent Mosher  
Stanford Online High School  
415 Broadway Academy Hall, Floor 2, 8853, Redwood City, CA 94063  
s.trentmosher@gmail.com

Kalée Tock  
Stanford Online High School  
415 Broadway Academy Hall, Floor 2, 8853, Redwood City, CA 94063  
kaleeg@stanford.edu

Abstract

Light curves of the central double-star variable pre-white dwarf of NGC 1501, CH Cam, were derived using multiple methods, including image stacking on AstroImageJ and a SExtractor code in Python. Because past research has suggested that CH Cam has 10 pulsation modes and that the variations are unstable, the data from the light curves were used with period folding software to identify the previously observed variations as well as any changes in variation. We found 10 prospective periods, ranging from 8 minutes to 94 minutes.

1. Data Collection

A total of 217 images of NGC 1501 were taken by the Las Cumbres Observatory (LCO) Global Telescope Network over seven different nights (Brown, 2013). Each image had a 2.5-minute exposure time and used a visible light filter. We constructed an RGB composite of the object, shown in Figure 1.

Three comparison stars were chosen using the AAVSO Variable Star Plotter (VSP). The chosen comparison stars were the closest in distance and in magnitude to the target. A few images were striated due to the telescope commencing imaging before being completely centered on the target, so these images were removed from the data sets.

Figure 1: RGB Composite Images of NGC 1501
2. Methods and Data

2.1 AstroImageJ Method

Two different methods were successful in creating light curves, the first of which was aperture photometry using the AstroImageJ software (Collins, 2017). We chose an aperture with a radius of 6 pixels by hand to ensure that all the light from the star was captured while minimizing light from the nebula within the aperture. After taking these measurements, differential photometry was performed. This involves measuring the flux of a target star relative to the combined flux of one or more comparison stars.

Measurements were conducted by performing single aperture photometry on the target and comparison stars. The target star’s relative flux was then calculated by dividing the target star’s net integrated counts by the sum of the net integrated counts of all of the comparison stars. Net integrated counts represent the sum of all ADU counts within the aperture, after subtracting the background flux near the aperture as measured between the inner and outer annulus. Initially, an aperture radius of 8 pixels was used, which enclosed some nebula light beyond the star. However, this resulted in an erroneous net integrated counts value. Therefore, we standardized the aperture radius to 6 pixels for all measurements that used this method.

Skynet’s period-folding tool, Skynet Plotting, was used to create periodograms (Reichart, 2021). Skynet periodograms use several algorithms, including Lomb-Scargle, to generate a power spectrum of potential periods (VanderPlas, 2018). A periodogram for the data from this method can be seen in Figure 2.

Two period folds for the AstroImageJ method can be seen in Figure 3.

![Figure 2: AstroImageJ Method Periodogram](image)

![Figure 3: Period Folds for AstroImageJ method at lengths of 84.38 and 89.84 minutes.](image)

2.2 Source Extractor Method

The second method that we used to perform photometry on the images was a SExtractor code that we accessed via Python (Bertin, 1996). With this method, the light-curves were found much less dependent on the aperture size after trying apertures of radius 6 and 8. An aperture of radius 6 was chosen to align with the method using AstroImageJ.

A periodogram from this method is shown in Figure 4, and a sample fold is shown in Figure 5, which shows the data folded at 24.665 (left) and 32.361 (right) minutes.

![Figure 4: Source Extractor Method Periodogram](image)

![Figure 5: Period Fold for Source Extractor Method at lengths of 24.665 and 32.361 minutes.](image)
3. Periods Found

Both AIJ and SExtractor photometry resulted in periodogram spikes near the periods found by Bond et al. (1996), with multiple spikes at half of those periods, results shown in Table 1. In the last column of Table 1, where applicable, the amplitudes are corrected to account for the muting of the pulse as a function of image exposure time relative to the pulsation period.

4. Acknowledgements

This research has made use of the International Variable Star Index (VSX) database, operated at AAVSO, Cambridge, Massachusetts, USA.

Credit is due to the developers of the principal software and databases used in this project: Our Solar Siblings (OSS) pipeline, Fabian Chereau; Stellarium Sky Atlas, Karen Collins and John Kielkopf; AstroImageJ Processing and Reduction Software, Las Cumbres Observatory Global Telescope Network, Guido van Rossum: Python Colab.

5. References


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<td>0.1</td>
<td>0.12</td>
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<td>9.1932</td>
<td>--</td>
<td>0.05</td>
<td>0.057</td>
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<td>9.8912</td>
<td>9.741*</td>
<td>0.075</td>
<td>0.084</td>
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<tr>
<td>13.877</td>
<td>--</td>
<td>0.075</td>
<td>0.080</td>
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Table 1: Periods found compared to Bond, 1996 periods, blue periods come from AstroImageJ method and black from Source Extractor. *These are half the value of the Bond period.


Abstract
Exoplanet HIP 65 A b is a gas giant of 3 Jupiter masses which orbits every 0.98 days close to its host star, near the Roche Lobe limit within a binary system. Images taken during transits were reduced with the Exoplanet Transit Interpretation Code (EXOTIC) and psx photometry. The depth of the transit was found to be about 2%, significantly smaller than the 8.2% transit depth reported in the NASA Exoplanet Archive. The radius of HIP 65 A b was found to be the same as previously reported, roughly 2 Jupiter radii, which can be explained by the extreme grazing nature of these transits.

1. Introduction
HIP 65 A b is a bright (Gmag 10.5) gas giant exoplanet of about 3 Jupiter masses. It transits in front of its host star, HIP 65 A, every 0.98 days. It initially became a target of interest due to the NASA Exoplanet Archive transit depth of 8.2%, which appeared too large a Hot Jupiter. The host has a dim (Gmag 15.4) companion separated by 3.8", which is close to the Roche Lobe Limit. The two stars have near-identical parallax and proper motion, and so are likely gravitationally bound.

2. Project Summary
Images of one transit of HIP 65A b were requested in Nov of 2021 from the Las Cumbres Observatory (LCO) Global Telescope network (Brown, 2013). The Exoplanet Transit Interpretation Code (EXOTIC) software was used to photometer the target along with the comparison star(s) shown in Figure 1. Using a nested sampling algorithm, EXOTIC fits the resulting light curve to determine transit depth, relative radius, transit midpoint, transit duration, semi-major axis over star radius, air mass coefficients, and scatter (Zellem, 2020).

In addition, 12 transits were obtained from the LCO Archives, and reduced via EXOTIC after external photometry was performed by the Our Solar Siblings pipeline (Fitzgerald, 2021). Finally, the host star’s companion was observed using speckle interferometry. Using Speckle Toolbox (STB), the position angle (PA) and the separation of the system were measured to compare with previously reported figures.

From this analysis, the posterior transit depth was lower than the NASA Exoplanet Archive value of 8.2%. Our reductions are shown in Figure 2.

When the prior relative radius was based on a transit depth of 0.8% as depicted as the depth, instead of the previous relative area shown as 8%, the output relative area was 13%, which is higher than the prior value of about 2 times the radius of Jupiter or 28% of...
the stars radius. The discrepancy may be due to the planet’s grazing transit, which has an impact parameter $b = 1.169$. Less than half of the disc covers the host star during transit (Nielson et al., 2020).

PSX photometry was used on 12 archival transits to measure the change in brightness of the host star over the images in each transit. Taking this preprocessed data, we ran EXOTIC to produce a light curve. Barring two outliers, the results showed an average depth of 2.7%.

As shown in Figure 3, changing the initial prior for the relative radius gave rise to different posterior values in EXOTIC’s fit, which underlines the importance of using accurate priors when fitting light curves.

To understand the effect of HIP 65 A’s dim companion star, which is separated by 3.8", we observed the system with speckle interferometry. We used STB to reduce the images taken by the PlaneWave 24-inch telescope in Chile (Harshaw et al. 2017). The reduction is shown in Figure 4.

The PA of the system was found to be 84.56° and its separation 1.059", which differs from the 2015 measurement of PA 322° and separation 3.8". This may be due to a calibration issue rather than a change at the stars, so the system should be re-observed. The 2015 measurement is the only prior measurement on the system in the Washington Double Star Catalogue.
3. Acknowledgements

We thank the Las Cumbres Observatory, Gianluca Sordiglioni, PlaneWave Instruments for use of the telescope and Leon Bewersdorff for taking the speckle observations, Astrometry.net, Karen Collins, John Kielkopf, Our Solar Siblings, and the NASA Exoplanet Archive.

This publication makes use of data products from Exoplanet Watch, a citizen science project managed by NASA’s Jet Propulsion Laboratory on behalf of NASA’s Universe of Learning. This work is supported by NASA under award number NNX16AC65A to the Space Telescope Science Institute.

4. References


MG1-688432: An Opportunity for Collaborative Pro-Am Observations

Eric R. Craine
Western Research Company, Inc./GNAT, Inc.
3275 W. Ina Rd., Tucson, AZ 85741
ercraine@wrc-inc.com

Christopher J. Corbally
Vatican Observatory Research Group, Steward Observatory
University of Arizona, Tucson, AZ 85721
corbally@as.arizona.edu

Brian L. Craine
Western Research Company, Inc./GNAT, Inc.
85 Bolinas Rd., Fairfax, CA 94930
blcraine@wrc-inc.com

Adam L. Kraus
Department of Astronomy
University of Texas, Austin, TX 78712
alk@astro.as.utexas.edu

Andrew S. Kulessa
Colin Gum Observatory, Greenhill, SA, Australia/GNAT, Inc., Tucson, AZ 85745
andskul@gmail.com

Roy A. Tucker
(deceased)

Abstract

MG1-688432 is an unusual optically variable, close binary star system (period ~ 6.65d) that exhibits frequent flickering and intermittent very high intensity optical outbursts of several hours duration. The star was discovered in the first MOTESS-GNAT (MG) sky survey and re-observed in the MG6 survey. During the past 20 years we have made and analyzed scan mode data, over 35,000 follow-up pointed photometric observations, and many nights of spectroscopic observation of MG1-688432. The primary star is spectral type K3 III-IV: (though the spectrum is unusual); we do not see spectroscopic signatures of the companion, which may be a white dwarf or an M-dwarf star. This is not an eclipsing system, with the inclination of the orbit precluding eclipse by the secondary. The system is at a distance of 1.5 kpc, and analysis of Gaia observations leads to the conclusion that the H-R diagram position of MG1-688432 is established by an intrinsic feature of the system. Two mechanisms (or combinations thereof) that might give rise to characteristics of the system are (1) magnetically induced chromospheric activity and (2) impacts with tidally disrupted planetary debris. We discuss properties of the star, indicate specific observations needed to interpret those properties, and offer a call for collaborative, coordinated observation by interested SAS members.

1. Introduction

An ongoing GNAT project is the follow-up analysis of interesting variable stars discovered and/or characterized as a part of the MOTESS-GNAT equatorial sky surveys [c.f. Kraus et al. 2007, Tucker 2007; Craine et al. 2021]. One intriguing such star is MG1-688432 which has been observed and analyzed by the GNAT team for over 20 years [Tucker et al. 2021]. Despite an intensive observing campaign, including both photometry and spectroscopy, there are still tantalizing un-resolved questions regarding the detailed nature of this unusual star.

Presented here is a brief summary of what is known about MG1-688432, a discussion of observations necessary to advance an understanding of
the star, and a call for partners to join in specific collaborative observations to achieve this goal.

2. Observations

Observations made to date are discussed in detail elsewhere [Tucker et al. 2021]. The content of that paper is briefly summarized in this section.

2.1 Discovery

MG1-688432 was recognized as a variable star in the MG1 Variable Star Catalog (MG1-VSC) with its first observations in that survey occurring in 2001-2003 [Kraus et al. 2007]. The basic data in MG1-VSC for this star are as follows: RA(2000) 12:23:10.16 DEC(2000) +03:12:37.4 [GAIA 2021], R = 13.968 mag, SD = 0.186 mag, Amplitude = 0.739 mag, skew = 0.59, and log period = 0.825d (≈ 6.6834d). The discovery light curve and the phased light curve for P = 6.68d are shown in Figure 1.

![Figure 1. This is the MG1-VSC graphical representation of the discovery data for MG1-688432. Upper panel is the phased curve (magnitude vs phase) with period, P = 6.68d; lower panel is the raw light curve.](image)

2.2 Photometry

In 2011, MG1-688432 became a frequent target for follow-up, pointed photometry at Goodricke-Pigott Observatory (GPO), in Tucson, Arizona. Over the next ten years more than 36,000 observations were made. A composite of ten years of observation is shown in Figure 2. Notable are the occasional, extremely high energy optical outbursts.

2.3 Spectroscopy

MG1-688432 was the subject of spectroscopic observation during three epochs. In 2011-2012 a small number of spectra were obtained at the Boller & Chivens spectrograph of the Bok 2.23m telescope of Steward Observatory at the Kitt Peak Observing Station in southern Arizona; in 2018 and 2020 multiple nights of spectroscopic observation were made at the VATT spectrograph of the 1.8m Vatican Advanced Technology Telescope of the Vatican Observatory and Steward Observatory at the Mount Graham International Observatory in southeast Arizona.

Representative red and blue spectra of MG1-688432 are shown in Figures 3 and 4.

3. Results

3.1 Key Features of Observations

A summary of the observational features of MG1-688432 reported by Tucker et al. (2021) is as follows:

- Periodic, quasi-sinusoidal light curve of period P ~ 6.65d.
- Exhibits occasional extremely high energy outbursts (~10^38 ergs).
- Outburst durations are typically several hours.
- Outbursts may be highly structured, indicative of discrete, sequential events.
- The light curve shows unusual amplitude, phase, and shape variations from year to year.
- It is a non-eclipsing binary.
- The primary star is of type K3 III-IV:e:, Te ~ 3950 K.
- The spectrum exhibits strong Hα emission with emission cores in absorption lines of Ca H and K.
- The spectra vary from night to night never matching MK standards particularly well.
- The secondary star is not seen and may be a white dwarf or an M-dwarf.
- The system radial velocity, as shown in Figure 5, would benefit from additional spectroscopic observations to further investigate the orbital mechanics.
3.2 Possible Models

Two possible “models” have been proposed to account for the high-energy flare events:

- The visible star exhibits magnetically induced chromospheric activity, and the periodic variations are caused by starspots. The optical outbursts are due to unprecedented flaring events.
- The high density, unseen companion star has shredded a free-floating planetary body and the distributed large pieces of planetary debris in the system periodically impact the stellar companion as it passes through the debris cloud, giving rise to the outbursts.

Both models give rise to questions that can only be resolved with further observation and analysis.

3.3 Open Questions

There are numerous questions germane to the understanding of the nature of MG1-688432, some of which can be addressed by a coordinated plan of follow-up time series photometric observations, including the following:

- How are the frequency, phase, and amplitude of optical outbursts evolving over time?
- Is there statistically significant coupling of outburst occurrence and optical phase of the primary star?
- Is the amplitude of high frequency brightness fluctuations a noticeable function of optical phase of the system? That is, is there low amplitude flickering of the system that is phase-locked to the optical light curve?
- Time series photopolarimetry could address the question: How does polarization of light from the primary star modulate as the star orbits the system barycenter and periodically encounters a debris plane or equatorial dust disk?

4. Collaboration

The primary goal of this paper is to offer an invitation for interested astronomical observers to join a collaborative team that is participating in the next phase of observation and analysis of this interesting and unusual star.

The ideal collaborator sought for this role is an experienced observer equipped with a 12 – 16in aperture telescope, and CCD camera capable of imaging a field of about 10-20 arcmin square. The telescope mount should enable good images with integration times on order about 5min. Ideal would be an auto-guiding system which could stay on the target field and automatically collect images unattended throughout the night. Most imaging will be open channel, but access to a filter holder for the camera would be useful.

The most helpful observing program would be continuous time series CCD imaging throughout the night for as many clear nights as possible. Observers who can provide at least periodic nights of data through an entire observing season are highly desirable; but even intermittent observation can be helpful.

Collaborators will have the opportunity to interact with the project team in several ways: 1) a monthly newsletter will record progress on the project, 2) all members of the team are invited to regular Zoom conferences to discuss the state of the project, and 3) periodic in-person meetings will be arranged, some coincident with other astronomical meetings.

All project team members will share in co-authorship of papers that are published using the proceeds of team member’s efforts. The next such paper is anticipated following the 2022 – 2023 observing season.
Prospective collaborators are encouraged to make contact with an author of this paper and arrange a time to discuss details of the program.

5. Acknowledgements

We appreciate the assistance of Elizabeth Green in the early Bok 2.23m telescope spectroscopy of MG1-688432. We also wish to acknowledge the generous assistance of the staff at the Vatican Advanced Technology Telescope which greatly facilitated key spectroscopic observations.

6. References


Figure 2. GPO follow-up phased light curves based on the 20-year mean period $P = 6.6491 \pm 0.0010d$ for MG1-688432.
Figure 3. A red spectrum of MG1-688432 obtained at the VATT in 2018. The inserts are of the Magnesium I triplet and Sodium D lines.

Figure 4. A blue spectrum of MG1-688432 obtained at the VATT in 2018. The inserts are of the Calcium II and Magnesium I lines. Note the emission cores in the H and K lines of Calcium.
Modeling Binary Stars Using Gaia Parallax Data

John E. Hoot
SSC observatories
1303 S. Ola Vista, San Clemente, CA 92672
jhoot@ssccorp.com

Abstract

Historically, binary stars systems were modeled by gathering photometric and spectroscopic observations to derive the masses and luminosities of the binary pair. These in turn were used to derive the distances of the system using the mass-luminosity relation and the distance luminosity laws. The release of highly precise parallax astrometry data from the European Space Agency’s Gaia satellite greatly reduces the importance of binary systems’ derived distances. However, the availability of high precision parallax measurements from Gaia enables the direct solution of binary star systems using only photometric data and high precision parallax to completely model binary star system without the need to acquire high precision radial velocity data. Once modeled, radial velocity data can be calculated from the simple application of Kepler’s laws. This paper presents a method for deriving full binary system models using this new method.

1. Introduction

Historically, one of the primary motivations for the study of binary stars was the ability to derive the distance to the binary systems from their light curves in multiple pass bands combined with radial velocities measured with high resolution spectroscopy. From the light curves, the relative masses, effective temperatures, orbital period and eccentricity of the stars were determined. From the spectroscopic data, the radial velocities of the stars orbits and the exact masses of the stars could be determined. Stellar models allowed the absolute luminosity of the stars to be found. Finally, by applying the distance luminosity law to the apparent and true luminosity, the distance to the stars could be found. This method helped measure the size of the Milky Way.

With the advent of the European Space Age Agency’s dedicated space astrometry missions, Hipparcos, ESA (1997) and Gaia, Gaia (2016), we have excellent unambiguous parallax measurements for more than 14.68 billion stars in the Milky Way. Measuring stellar distances in the Milky Way is no longer a significant motivation for modeling binary star systems. Nonetheless, a fair percentage of stars evolve as multiple star systems. The universe is rife with binary star systems. Binary star modeling still has great value in exploring binary systems with interesting members, merging systems, accretion phenomena, exposed cores, common envelope contact systems and other unique astrophysical environments.

Gaia is, however, a game changer in modeling binary systems. By using Gaia parallax derived distance and multiple pass band photometry, it is possible to completely model binary systems without needing access to high resolution spectroscopy! It is now possible to use the mass luminosity relation and binary star modeling derived from photometric light curves to completely characterize the physical properties of binary systems using small telescopes.

This paper demonstrates a numerical method for solving for the total mass of a galactic binary star system using only photometric light curves and Gaia data.

2. Theoretic Basis

The process begins, as in the traditional method, by photometrically measuring the light curves of the eclipsing binary system. Analyzing the time series data and determining the orbital period of the system. The light curve data is then used in conjunction with a binary star modeling software tool, to find a plausible synthetic light curves that match your observations. Some common examples of these tools include, Wilson-Devinney, Wilson(2020), PHOEBE Prsa(2008) and Nightfall, Wichmann(2003) along with many others.

All of these types of tools will provide you with a model of the stellar system that includes the apparent temperatures of the stars, the ratio of their masses, the inclination of their orbit relative to our line of sight, and how close the stars come to filling their Roche lobes. The pieces of the puzzle that are missing include, the actual mass of the stars, their distance from us, their absolute magnitudes, or luminosities and their radial velocities as a function of orbital phase.

We can generate all this missing values by getting the actual distances from the Gaia catalogs and
applying the Distance Luminosity Law and the Mass Luminosity Relation to what is already known.

3. The Solution Process

Having modeled a binary system, the next step is to find the distance to the binary system. This is done by querying the Gaia parallax catalog. Open a web browser and go to https://vizier.cds.unistra.fr/viz-bin/VizieR. Enter the name or location of your target binary and select one of the Gaia catalogs.

Select the Gaia EDR3 catalog by clicking the check box next to the entry and click on “Query selected Catalogs”. The following dialog will appear:

Click on the “Submit” button, and the results will be displayed in milli-arc seconds in the “Plx” column.

The next step is to convert the apparent magnitude of our binary system to an absolute magnitude. The absolute magnitude is defined as the magnitude you would measure if you were located exactly 10 parsecs from the stars. In the case of a binary system, the classical formula for converting apparent magnitude to absolute magnitude is:

$$M_{\text{abs}} = m_{\text{apparent}} + 5 \log_{10} \left( \frac{1}{\text{Parallax}_{\text{arcsec}}} \right) + 5$$

By plugging in the V band magnitude of the binary system into the equation above we can compute the absolute magnitude of the binary system. If we were looking at a single star, at this point we could convert the absolute magnitude to a luminosity using the formal definition for magnitude and expressing luminosity in units of solar luminosity.

The inverse function of which is:

$$\frac{L_\star}{L_\odot} = 10^{0.4(M_{\text{bol},\star} - M_{\text{bol},\odot})}$$

Where the absolute bolometric luminosity of the Sun is 4.74 magnitudes, and the V band absolute magnitude of the Sun is 4.85 magnitudes. Still assuming a single star as the source, the inverse mass luminosity relation should allow us to determine the true mass of the star.
The mass luminosity relation is not expressed as a single monotonic continuous function, but rather a piece wise continuous relation. Both it and its inverse are expressed in Figures 5 and 6.

Figure 5: MassToLuminosity(L) Relation, Duric, Nroboja (2004)

\[ M \approx \left( \frac{L}{0.23} \right)^{\frac{1}{33}} \quad (L \leq 0.033) \]
\[ M \approx L^{\frac{1}{4}} \quad (0.033 < L \leq 16.0) \]
\[ M \approx \left( \frac{L}{1.4} \right)^{\frac{1}{33}} \quad (16.0 < L \leq 1.76 \times 10^6) \]
\[ M \approx \frac{L}{32000} \quad (1.76 \times 10^6 < L) \]

Figure 6: LuminosityToMass(M) Relation

But in the case of a binary, we have \( L_\star \) is actually the sum of the luminosity of the primary and secondary stars vary as a function of time.

\[ L_{tot} = L_{pri} + L_{sec} \]

From our binary modeling software we do know the ratio of the masses:

\[ \text{MassRatio} = \frac{\text{Mass}_{sec}}{\text{Mass}_{pri}} = q \]

This allows us to compute the total mass from either the mass of the primary or the secondary star.

\[ \text{Mass}_{tot} = q \text{Mass}_{pri} + M_{pri} \]
\[ M_{tot} = \text{Mass}_{tot} + \left( \frac{1}{q} \right) \text{Mass}_{sec} \]

Figure 7: Computing Total mass from q and primary or secondary mass.

4. Numerical Solution Method

These relations allow for a numerical solution for the total system mass. Initially we calculate a total mass as though the peak luminosity, when both stars are most visible to us, arose from a single star. This will systematically underestimate the mass of the binary system.

Next, we begin our iteration cycle. In each cycle we then split this mass between the primary and secondary stars according mass ratio by applying the following formulas:

\[ \text{Mass}_{pri} = \frac{\text{Mass}_{tot}}{(1 + q)} \]
\[ \text{Mass}_{sec} = \frac{\text{Mass}_{tot}}{\left(1 + \frac{1}{q}\right)} \]

Next, we compute the luminosity of the primary and secondary using the formulas in Figure 5. We then generate a luminosity error:

\[ \text{Lum}_{err} = \text{Lum}_{tot} - \left( \text{Lum}_{pri} + \text{Lum}_{sec} \right) \]

If the absolute value of the luminosity error falls below our epsilon value of 0.01%, we accept the solution and display the calculated solution.

Otherwise, we generate mass new estimates in the following steps. First, we add the luminosity error to the brighter of the stars. Next, we compute new mass of that star using the revised luminosity and the formula in Figure 6.

Depending on whether the brighter star is labeled as primary or secondary, we compute the total system mass from the appropriate formula in Figure 7.

At this point we repeat the cycle until we converge on a solution.

This convergent algorithm is implemented in a python script contained in Appendix A of this paper. It is freely distributed under the GNU public license.

Once the total mass of the system has been established, it is then entered into your binary star
modeling software and a complete model of the system results.

5. Test Cases

Several test cases follow. The targets were selected from a series of binaries measured during a campaign vetting the accuracy of periods and types measured by sky surveys.

The first case is a detached EA type binary from the MOTES-GNAT catalog, (Kraus et al, 2000). MG1-15436 is a binary that has nearly complete coverage of the star in V and Rc Bands.

![Figure 6: MG1-15436 V and Rc light Curves.](image)

The light curves were entered into the Nightfall binary modeling program and parameters were adjusted and fitted with a as shown in Figures 7 & 8.

![Figure 7: A solution for MG1-15436 without mass](image)

![Figure 7: Light Curve Fit With Residuals](image)

The mass ratio, Gaia parallax and apparent magnitude were then passed to the python script titled BinaryMassCalc and the convergent solution is shown in Figure 8.

![Figure 8: Numerical solution generated for the system](image)

As shown in Figure 9, the mass total mass of the system is computed as 1.66 solar masses. This value was entered back into the Nightfall model and the system was recomputed.

![Figure 9: Solution with Mass and Radii Values](image)

Figure 10 shows a graphical presentation of the system as it might appear. On the right side of the figure, computed radial velocities are show as derived by the modeling software.
Is this a reasonable model of the system? To make a basic sanity test of the method, I have plotted the resulting mass, luminosity/absolute magnitude on the Herzsprung-Russell diagram as shown in Figure 11.

Figure 11 plots the stars on the H-R diagram. The result looks reasonable. It shows that the mass and luminosities for the system put both stars on the main sequence. This is exactly what should be expected for a detached system.

The next sample case is MG1-1353676 another star from the MOSTESS-GNAT study. This is an over contact binary with a light curve shown in Figure 12.

The curve fit generated with the Nightfall binary model for this system is shown in Figure 13.

The mass ratio, apparent brightness and parallax were fed to BinaryMassCalc and results are show in Figure 15. Indicating the two stars are both nearly Sun-like in contact with each other.
Plotting the stars on the H-R diagram as shown in Figure 18, again shows the stars lay comfortably on the main sequence. This result further supports the assertion the model is generating reasonable results.

The next test case is IT HER. Its light curve is shown in Figure 19. In this system the flat bottom of the second minima of the system indicates that the secondary is completely eclipsed from our viewing angle and assists in the determination of the effective temperature of the primary from the V-Rc color index.

The best fit model without mass in Figure 20 shows that the stars share a common envelop because both stars show the same surface temperature.

Figure 21: shows the quality of the light curve fit with residues 0.04 magnitude or less. These might be further reduced by making some small corrections to the epoch of minimum in the solution.
The mass and luminosity residuals from BinaryMassCalc are shown in Figure 22. They indicate a near solar mass primary with a sub dwarf secondary.

The complete model shown in Figures 23 is rendered in Figure 24 with radial velocities plotted on the right.

Plotting the system on the H-R diagram in Figure 25 provides some interesting results.

While the primary star lays on the edge of the main sequence, the secondary is displaced well to the warmer blue side of the diagram. Assuming the model is correct, it requires a plausible explanation. One explanation is that initially, the system started out as a detached system consisting of a main sequence dwarf with sub dwarf companion. Over time the dwarf primary has started to evolve off the main sequence. In doing so, its envelope has expanded to where the system has become an over contact binary with a common envelope. This has changed the apparent surface temperature of the secondary from its original deep red to match the primary’s effective temperature.
The other possibilities also include the Nightfall model fit is wrong and something else entirely is happening.
Ultimately, this is an example where some “More Data” is the answer. High resolution spectroscopy will confirm or refute the speculations above with regard to this system.

6. Refining the solutions.

To further improve the accuracy of this method we add a term to the absolute magnitude calculation to account for interstellar reddening. This extinction value can be specified as a fourth argument to the BinayMassCalc program. It is specified in units of magnitudes per kilo parsec. It compensates for the absorption of light by interstellar dust along the line of sight to the system. Literature suggests typical extinction correction coefficients values up to 2 magnitudes per kilo-parsecs depending how near the target is to the disk of the Milky Way.

Additionally, the expedient of using V magnitude as the basis of the current calculation of stellar absolute magnitude is a shortcut. The correct formal definition of bolometric magnitude is based on the total integrated radiation from DC to Gamma rays. The accuracy of the method could be improved several ways. A better approximation of absolute magnitude could be obtained by using unfiltered photometry. The challenge here is what to use as a reference standard. My answer is to again refer to Gaia. Its G magnitudes are essentially the unfiltered magnitude made with its silicon based CCD. That would, at least, integrate from NIR to UV. Using this approach, one should use the bolometric luminosity of the Sun (4.74 mag.) instead of the solar V magnitude. This practice should improve the accuracy, especially in the case of very blue and very red systems.

An even better solution would be to take low resolution spectra with a small scope. The spectra should then be calibrated to absolute luminance per wavelength using standard stars. At his point Wien’s law and Planck curves can develop more accurate bolometric magnitudes. This has the drawback that it does require significant apertures to work down below single digit apparent magnitude systems.

7. Conclusion

Binary stars, while less valued as distance standards, still proved insights into stellar evolution, atmospheres and formation. This method opens up new opportunities for smaller telescope to make valuable contributions in this area.

This technique is in its early stage of development. It offers a method for characterizing binary systems amenable to small telescope science. It needs further refinement and to be rigorously tested against systems already solved by traditional means.

8. Acknowledgements

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

9. References


Appendix A: Python Mass Solver

#!/usr/bin/python
#
# Binary Mass Solver
#
# Usage: BinaryMassCalc <q> <ApparentMag> <parallax> [extinction]
#
where:
q = binary max ratio defined as MASS(secondary)/Mass(primary)
ApparentMag = The apparent magnitude of the binary pair taken together
at system maximum.
Parallax = The parallax of the system expressed in milli-arc-seconds
Extinction = expressed as Magnitudes per kilo-Parsec

Outputs:
Absolute Magnitude of the System
Distance to system In Parsecs
Distance to system in Light Years
Total Mass of the binary pair
Mass of the primary star
Mass of the secondary star
Primary's Luminosity
Secondary's Luminosity
Primary's Absolute Magnitude
Secondary's Absolute Magnitude

by John E. Hoot
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observatory@ssccorp.com`

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Version 3, Dated 28 June 2007, a copy of which is
contained in the "../docs" directory distributed
with this program

import sys
import math

Usage = ''
Usage: BinaryMassCalc <q> <ApparentMag> <parallax> [extinction]

where:
q = binary max ratio defined as MASS(secondary)/Mass(primary)
ApparentMag = The apparent magnitude of the binary pair taken together
at system maximum.
Parallax = The parallax of the system expressed in milli-arc-seconds
Extinction = expressed as Magnitudes per kilo-Parsec

Outputs:
Absolute Magnitude of the System
Distance to system In Parsecs
Distance to system in Light Years
Total Mass of the binary pair
Mass of the primary star
Mass of the secondary star
```python
def error(msg):
    print(msg)
    print(Usage)
    quit()

def mass2lum(mass):
    if mass<0.43:
        return(0.23*(mass**2.3))
    elif mass<2.0:
        return(mass**4)
    elif mass<55.0:
        return(1.4*(mass**3.5))
    else:
        return(mass*32000.0)

# Constants
SOLAR_ABS_MAG = 4.85 # in V
LUM_SUB_DWARF = mass2lum(float(0.43))
LUM_DWARF = mass2lum(2.0)
LUM_MAIN_SEQ = mass2lum(55)

def lum2mass(lum):
    if lum<LUM_SUB_DWARF:
        return((lum/0.23)**(1/2.5))
    elif lum<LUM_DWARF:
        return(lum**0.25)
    elif lum<LUM_MAIN_SEQ:
        return((lum/1.4)**(1/3.5))
    else:
        return(lum/32000.0)

def lum2mag(lum):
    return(-2.5*math.log(lum,10)+SOLAR_ABS_MAG)

if len(sys.argv)<4:
    error('Error: Too few arguments.')
try:
    q=float(sys.argv[1])
except:
    error('Error: Invalid mass ratio entered.')
if q<=0.0:
    error('Error: Invalid mass ratio. ')
try:
    apparentMag=float(sys.argv[2])
except:
    error('Error: invalid magnitude value. ')
try:
    parallax=float(sys.argv[3])*1e-3
except:
    error('Error: Invalid parallax value. ')

extinction=0.0
if len(sys.argv)>4:
    try:
        extinction = float(sys.argv[4])
    except:
        error('Error: Invalid extinction coefficient.')

parsecs=1/(parallax)
lightYrs = parsecs*3.26
absMag = apparentMag-5.0*math.log(parsecs,10)+5-(parsecs/1000.0)*extinction
#absMag = apparentMag+5.0*(math.log(parallax,10)+1)-(parsecs/1000.0)*extinction  #Alternate formulation

# Total System Luminosity (Lum_pri+Lum_sec)
lumTot = 10**((absMag-SOLAR_ABS_MAG)/-2.5)
```
# Initial Guesses
sysMass = lum2mass(lumTot)
complete = False
epsilon = 0.0001

while not complete:
    massPrimary = sysMass / (1.0 + q)
    massSecondary = sysMass / (1.0 + 1.0 / q)
    lumPrimary = mass2lum(massPrimary)
    lumSecondary = mass2lum(massSecondary)
    sysLum = lumPrimary + lumSecondary
    sysLumError = lumTot - sysLum
    # debug convergence
    print('sysMass=%.3f PriMass=%.3f SecMass=%.3f sysLum=%.3f slumTot=%.3f
    sysLumError=%.3f'%(sysMass, massPrimary, massSecondary, sysLum, lumTot, sysLumError/lumTot))
    if abs(sysLumError/lumTot) >= epsilon:
        # recompute mas based on new new lu
        if massSecondary > massPrimary:
            lumSecondary += sysLumError
            massSecondary = lum2mass(lumSecondary)
            sysMass = massSecondary * (1.0 + 1.0 / q)
        else:
            lumPrimary += sysLumError
            massPrimary = lum2mass(lumPrimary)
            sysMass = massPrimary * (1.0 + q)
    else:
        complete = True

print(' System Solution:)
print(' Absolute Magnitude: %.3f' % (absMag))
print(' Distance (psec): %.2f' % (parsecs))
print(' Distance (lyr): %.2f' % (lightYrs))
print(' TotalSystemMass(solar masses) %.2f' % (sysMass))
print(' Primary's Mass(solar Masses) %.2f' % (massPrimary))
print(' Primary's Luminosity %.2f' % (lumPrimary))
print(' Secondary's Luminosity %.2f' % (lumSecondary))
print(' Primary's Abs. Magnitude %.3f' % (lum2mag(lumPrimary)))
print(' Secondary's Abs. Magnitude %.3f' % (lum2mag(lumSecondary)))
print(' Total Model Absolute Luminity %.2f' % (lumPrimary + lumSecondary))
print(' Total Model Abs. Magnitude %.4f' % (lum2mag(lumPrimary + lumSecondary)))
Abstract

Prime Solutions Group, Inc. (PSG) in partnerships with the Southwest Research Institute (SwRI), Northern Arizona University (NAU), and the Astronomy Association of Arizona (AAA) are proposing the development, launch and operation of a CubeSat mission for lunar exploration of water-ice detections. This mission will greatly expand the use of CubeSats for space exploration with demonstrating mission capability at the Technology Readiness Levels (TRLs) 8 and 9.

This lunar mission is flying a mini–Synthetic Aperture Radar (SAR) on a 27U CubeSat into lunar orbit to image the permanently shadowed regions near the poles. Primary targets include the Shackleton/Shoemaker crater region near the lunar south pole, which is an area of interest for potential near-future human exploration and directly supports NASA Strategic Plan 2018, Science Plan 2020-2024, and Strategic Technology Investment Plan 2017. This CubeSat, designated as Lunar SAR (LSAR), will join a growing list of CubeSats currently targeted for the Moon. These include the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) CubeSat which is scheduled to launch on a Rocket Lab Electron rocket. The Space Launch System, Artemis 1, is carrying several 6U CubeSats devoted to lunar studies, including LunaH-Map (Arizona State University), Lunar Flashlight (Jet Propulsion Laboratory (JPL)), Lunar IceCube (Morehead State University) and LunIR (Lockheed Martin). The key focus for these lunar CubeSats is to look for additional evidence of water-ice on the Moon. LSAR is designed to complement the data collected from these missions and will further support the search for lunar resources and potential landing sites.

What makes this mission unique is the emphasis on the public and educational outreach activities provided by the AAA. The AAA will provide STEM opportunities for local and statewide high school, community college and university level students. Opportunities for advanced amateurs and the general public will be made available for involvement in all stages of the project which will bring a greater awareness and appreciation for science, engineering and astronomy in specific. We present the proposed high-level mission concepts and designs for the CubeSat and describe the mission goals. The primary science objectives will be discussed as well as the unique role they play in this ambitious project.

1. Introduction

CubeSats are a class of small spacecraft called nanosatellites. CubeSats are built to standard dimensions (Units or “U”) of 10 cm x 10 cm x 10 cm. They are built in multiples of 1U, 2U, 3U, or 6U in size, and typically weigh less than 1.33 kg (3 lbs.) per U. Loff (2018). The maturity of CubeSat technology continues to expand as is indicated by the growth in the number of missions, mission complexity, and the expansion of subsystem capability. The introduction of the CubeSat satellite technology has incentivized the general space industry to achieve science for less cost. The introduction of utilizing CubeSats systems beyond Earth orbit is now starting to take place.
CubeSats originated as an educational tool for teaching students about spacecraft hardware, electronics, programming, and operations. Initially most CubeSats were designed by students and faculty with educational levels down to middle and high schools building and flying elementary type systems, NASA news (2018). Commercially designed and operated CubeSats are now in the majority, such as the many downward pointing 3U telescopes. This paper is focused on the development of a CubeSat designed to image the permanent shallowed craters on the moon’s south polar region. Previous missions have indicated that these areas contain water-ice making them prime areas for a sustained operations and a possible lunar base. Detailed topologic maps of these craters are needed to carry out successful landing operations.

2. Background

It has been 50 years since the Apollo lunar flights ended in December 1972, but the moon has remained of great interest to NASA and scientists around the world. “Apollo” is near the top of all search queries on NASA’s public website. NASA has sent numerous Apollo lunar samples to scientists around the world for ongoing analysis with each year a handful of new scientific papers are published offering insights and updates to what we’ve learned about the moon from these samples.

As the primary focus of NASA’s mission of returning to the moon, it is implementing the Trump’s Administration Space Policy Directive-1 to “lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system.” NASA stands on the verge of commercializing low-Earth orbit and these experiences and partnerships will enable NASA to go back to the Moon in 2024 – this time to stay -- with the U.S. leading a coalition of nations and industry, Dunbar (2022).

2.1 NASA Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. It is the name of NASA’s efforts to return astronauts to the moon and establish a new wave of science payloads and technology demonstrations to the lunar surface. The program is organized around a series of Space Launch System (SLS) missions. Each SLS mission centers on the launch of an SLS booster carrying an associated Orion spacecraft.

Artemis I (as of this date for article submission, currently planned for May 2022) will be an uncrewed test of the SLS and Orion spacecraft and is the first test flight for both craft. The mission will place Orion into a lunar orbit and then return it to Earth. The SLS will use the second stage to perform the Trans-Lunar Injection (TLI) burn to send Orion to lunar space. Orion will enter a retrograde lunar orbit and remain for about six days before initiating a Trans-Earth Injection (TEI) burn and returning to Earth. The Orion capsule will separate from its service module, re-enter the atmosphere for aerobraking, and splash down under parachutes, Clark (2020).

Artemis II (2024) will be the first crewed test flight of SLS and the Orion spacecraft. The four crew members will perform extensive testing in Earth orbit and Orion will then be boosted into a free-return trajectory around the moon, which will return Orion back to Earth for re-entry and splashdown, Sloss (2021).

Figure 1. NASA’s Space Launch System (SLS) rocket with the Orion spacecraft will launch from Launch Complex 39B, May 2022 timeframe.

Figure 2. The lunar portion of Artemis system consist of the Gateway where astronauts will transfer between Orion and the lander, the Human Landing system will take astronauts from lunar orbit to the surface and back to orbit and the Base Camp which give astronauts a place to live and work on the moon.

Artemis III (2025) will be a crewed lunar landing. The mission depends on a support mission to place the Human Landing System (HLS) in place in a near-rectilinear halo orbit (NRHO) of the moon prior to the launch of the SLS/Orion system. After HLS reaches NRHO, SLS/Orion will send the Orion spacecraft with
a crew of four to rendezvous and dock with HLS. Two astronauts will transfer to HLS, which will descend to the lunar surface and spend approximately 6.5 days on the surface. The astronauts will perform at least two EVAs on the surface before the HLS ascends to return them to a rendezvous with Orion. Orion, Foust (2019).

3. The Need for Detailed Maps

NASA briefed its Artemis III Science Definition Report in January 2021. Recommendation 8.3-1b from that report states that additional levels of accuracy and precision are needed for landing and surface operations, Weber (2021).

![Figure 3. Lunar surface at 100-meter resolution](image)

Recommendation 8.3-1c states that more detailed geologic mapping of candidate landing sites are to be accomplished at a scale similar to what was done in preparation for the Apollo landings. A location for the Artemis III landing site and the subsequent Artemis Base Camp selections are focused on the Moon’s south polar region which provide access to persistently illuminated areas of the Moon and surface-accessible volatile deposits that can be leveraged for large-scale resource utilization. These volatile deposits are located in the permanently shadowed crater regions near the poles, Sangha (2018).

To obtain the detail needed for cartographic products describing the nature and composition of these crater regions, we must look at either low light cameras or Synthetic Aperture Radar (SAR).

3.1 What is SAR

SAR is a type of data collection where a sensor records the amount of energy reflected back after interacting with the target either actively or bistatically. While optical imagery is similar to interpreting a photograph, SAR data requires a different way of thinking in that the signal is instead responsive to surface characteristics like structure and moisture.

The spatial resolution of radar data is directly related to the ratio of the sensor wavelength to the length of the sensor's antenna. For a given wavelength, the longer the antenna, the higher the spatial resolution. Using a satellite in space operating in the C-band frequency (around 5 cm wavelength) in order to be able to get a spatial resolution of 10 m, a radar antenna of approximately 4,250 m long is required. An antenna of this size is not practical for satellite sensors in space or anywhere for that matter. For SAR, a sequence of data collections from a shorter antenna are combined to simulate a much larger antenna, thus providing higher resolution data. Synthetic Aperture Radar, NASA Earth Data (2022).

![Figure 4. Permanently shadowed crater.](image)

The uniqueness of SAR is that it can image without illumination, through clouds and dust. This capability is needed to image the lunar craters which are in permanent shadows which are the target regions

![Figure 5. Synthetic Aperture Generation (credit: NASA)](image)
for manned landings. The best available imagery of these crater regions is 75 meters per pixel provided by the Mini-SAR on Chandrayaan-1, Spudis et al. (2009).

### 3.2 Previous Lunar SAR Missions

Several SAR satellite missions have been successfully executed mapping the moon. While these missions were successful in imaging the dark regions of the moon and providing the first indications of lunar water-ice, the image data is coarse at 75 m/pixel and only one system is still in operation.

**Figure 6.** Chandrayaan-1 was the first spacecraft to detect widespread presence of water molecules in lunar soil.

#### 3.2.1. Chandrayaan-1

The Chandrayaan-1 mission performed high-resolution remote sensing of the moon in visible, near infrared (NIR), low energy X-rays and high-energy X-ray regions. One of the primarily objectives was to prepare a three-dimensional atlas (with high spatial and altitude resolution) of both the near and far side of the moon. It conducted chemical and mineralogical mappings of the entire lunar surface for distribution of mineral and chemical elements such as Magnesium, Aluminum, Silicon, Calcium, Iron and Titanium as well as high atomic number elements such as Radon, Uranium & Thorium with high spatial resolution, Indian Space Research Organization (2022).

#### 3.2.2. Lunar Reconnaissance Orbiter

The Lunar Reconnaissance Orbiter (LRO) is a NASA spacecraft currently orbiting the Moon in an eccentric polar mapping orbit, Petro and Keller (2014). Its detailed mapping program is identifying safe landing sites, locating potential resources on the Moon, characterizing the radiation environment, and demonstrating new technologies.

Launched on June 18, 2009, in conjunction with the Lunar Crater Observation and Sensing Satellite (LCROSS), LRO was the first United States mission to the Moon in over ten years. LRO and LCROSS were launched as part of the United States’ Vision for Space Exploration program. The Mini-RF SAR was included on LRO as a technology demonstration. It is a cheap, lightweight (6 lbs.) SAR system providing a 150 m x 150 m azimuth x range resolution. Two operating frequencies: ~ 2.4 GHz and 7.1 GHz provide circular polarized transmission, V or H receive.

**Figure 7.** LRO is currently orbiting the moon in an eccentric polar orbit.

**Figure 8.** CAPSTONE is designed to follow a trajectory to the moon which minimizes required propellant.

### 3.3 Current Lunar CubeSat Missions

In contrast to the large expensive missions described above, a series of CubeSat projects are underway to support the Artemis program.

#### 3.3.1. CAPSTONE

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) spacecraft is a CubeSat mission that
will test operations in the near-rectilinear halo orbit (NRHO) around the moon that will be used by Artemis missions. The spacecraft is built by Tyvak Nano-Satellite Systems and is a 12U CubeSat with a radio tower on top. It will launch on a Rocket Lab Electron rocket using a version of that company’s Photon satellite bus, Foust (2022).

CAPSTONE will not go directly to the moon but instead will follow a “ballistic lunar transfer” that will take it out as far as 1.5 million kilometers before returning into lunar orbit. The transfer is designed to save propellant and make the mission feasible using a CubeSat launched on a small rocket.

3.3.2. Lunar Flashlight

Roughly the size of a briefcase, Lunar Flashlight is a very small satellite being developed and managed by NASA’s Jet Propulsion Laboratory that will use near-infrared lasers and an onboard spectrometer to map ice in permanently shadowed regions near the Moon’s south pole, World News (2020).

3.3.3. Lunar Ice Cube

As we return to the Moon and work to establish a sustained lunar presence, finding and utilizing water on the lunar surface becomes increasingly important. Lunar water is largely in the form of, but not necessarily limited to, water ice. This water-ice could be used for various crew needs, potentially including fuel. The Lunar IceCube mission, led by Morehead State University in Morehead, Kentucky, will study water distribution and interaction on the Moon. The mission will carry a NASA instrument called Broadband InfraRed Compact High-Resolution Exploration Spectrometer (BIRCHES) to investigate the distribution of water and other organic volatiles, Harbaugh (2018).

3.3.4. LunaH-map

LunaH-Map is a new type of NASA planetary science mission. LunaH-Map is a miniaturized, fully functional spacecraft the size of a shoebox that will map hydrogen enrichments within permanently shadowed regions of the lunar south pole. The spacecraft will use a miniaturized propulsion system, attitude control, power and communications systems to maneuver into orbit around the Moon. LunaH-Map will enter a low altitude, elliptical polar orbit and will measure the abundance of hydrogen using a compact neutron spectrometer. Neutron measurements made at low altitude over the lunar south pole will allow LunaH-Map to constrain the hydrogen within permanently shadowed regions at high spatial resolution, Arizona State University (2022)

3.3.5. A Proposed Lunar CubeSat Project

As described above, recommendation 8.3-1c from the Artemis Science Definition report state that
detailed geologic maps of candidate landing sites need to be developed at an Apollo mission scales to carrying out the proposed missions. In addition, before plan habitats can be established at the Moon’s polar regions, more knowledge about the nature of water ice in these regions and how to access it given their terrain must be obtained.

Following on the footsteps of the above lunar CubeSat projects, a CubeSat carrying a SAR instrumentation package to the lunar south polar regions is being proposed. We have designated this project as LSAR. The primary initial targets will include the Shackleton/Shoemaker crater region near the lunar south pole, which is an area of interest for potential near-future human exploration and directly supports NASA Strategic Plan 2018, Science Plan 2020-2024, and Strategic Technology Investment Plan 2017. The two objectives for this mission are the imaging of lunar south pole permanent shallowed craters to produce high resolution imagery of potential landing sites and the confirmation of water-ice in these crater regions.

3.4 High Resolution Imagery

The objective of LSAR is to provide high resolution imagery on the order of 0.5 to 1 meter per pixel resolution of the target craters. Accurate mapping of topography in permanent shallowed craters is essential for successful mission landing operations. An example of how the terrain can be hidden in the shadows is shown by comparing the crater West near the Apollo 11 landing site in Figures 12 and 13.

Figure 12. LRO image of crater West near Apollo 11 landing site.

Figure 13. Crater West sun lit.

Figure 14. The Sliding Spotlight imaging mode increases the image length of high-resolution spotlight acquisitions to achieve a 5km x 10km image footprint on the ground (Resolution is 1 meter/pixel).

Figure 15. Image property of Sandia National Laboratories.
Figure 16. Map of potential water on the Moon which exists in the form of ice caps around the lunar poles. Moon’s south pole (left) and north pole (right). (Image: NASA)

Figure 17. Standard CubeSat subsystems

SAR processing has matured to where 1 m pixel accuracy is now a common product on commercial Earth orbiting SAR systems. Special techniques such as spotlight can be used to scan large footprints at high resolution. See Figure 14.

Another example of high-resolution SAR imagery is shown in Figure 15.

3.5 Confirmation of Water-ice

A secondary objective of LSAR is to confirm the existence of water-ice in the south polar region. At the southern pole, most of the ice is concentrated at lunar craters, while the northern pole’s ice is more widely, but sparsely spread. Data from NASA’s Moon Mineralogy Mapper (M3) instrument identified three specific signatures that definitively prove there is water ice at the surface of the Moon. Most of the newfound water ice lies in the shadows of craters near the poles, where the warmest temperatures never reach above -250 degrees Fahrenheit. Because of the very small tilt of the Moon’s rotation axis, sunlight never reaches these regions.

4. CubeSat Design

The CubeSat will be a 27U system consisting of a standard bus and SAR instrumentation package. The standard components for a CubeSat bus are shown in Figure 17.

In addition to the subsystems shown in Figure 17, a CubeSat SAR system contains a SAR antenna. To create the SAR image, successive pulses are transmitted to “illuminate” the target scene, and the echo of each pulse is received. The pulses are transmitted, and the reflections received using a single beam-forming antenna, with wavelengths of a meter down to several millimeters. As the SAR device on board the spacecraft moves, the antenna location relative to the target changes with time. The signal processing of the successive recorded radar reflections allows the combining of the recordings from these multiple antenna positions.

4.1 Approaches to CubeSat Development

There are two approaches to developing the LSAR system: 1. modification of a current commercial SAR spacecraft for lunar operations and 2. The integration of a mini-SAR system into a custom CubeSat bus and support system.

4.1.1. Modification of Current Commercial SAR System

A whole set of commercial vendors have established themselves in the ever-competitive SAR market. These include commercial companies of:

- ICEYE
- Synspective
- Capella Space
- UMBRA
- PredaSAR

Each of these companies has plans for expanded SAR constellations operating in Earth orbit. As they vie to build and operate some the world’s most advanced commercial SAR satellite constellations, whether in terms of size, tasking speed, revisit rate, or image resolution, there’s an atmosphere of healthy competition that will lead to improved capabilities at reduced cost.

The modification of a current SAR system would be the cleanest engineering approach however most of these systems are beyond the size of the standard 3U and 6U CubeSat sizes. It is anticipated that the SAR system will need to be at least 27U.
Figure 18. Capella-2, a 107kg microsatellite. When launched into orbit it is the size of a small washing machine. Once Capella-2 is deployed on orbit it deploys a boom the length of a minivan and unfurls a high gain antenna the size of a small bedroom.

Figure 19. PredaSAR looks to corner SAR data market with purpose-built constellation.

4.1.2. Custom Development of SAR System

A secondary approach is to integrate a mini-SAR sensor onto a CubeSat satellite bus, essentially building a custom SAR system. Sandia National Laboratories has been developing it MiniSAR and has successfully flown its systems on multiple platforms. For two decades Sandia has been shrinking SAR size and increasing performance. Sandia systems are best known for their fine resolution (4-inch), high quality imagery (<-20dB multiplicative noise ratio), and real-time image formation. MiniSAR is a revolutionary step forward in this long tradition. Some of the unique features of this system are:

- Reconnaissance from small UAVs vehicles
- Cost affordability
- Potential for use as an all-weather precision guidance sensor
- Basic Modes: Spotlight SAR, Stripmap SAR, and CCD

(Fine resolution stripmap and CCD imagery is ground processed)
- Future Modes: GMTI, stereo SAR, videoSAR
- MiniSAR prototype basic modes were flight tested on Lockheed Martin’s Sky Spirit FCS Class 3 UAV in 2006

Figure 20. Sandia’s Synthetic Aperture Radars remains unequaled. MiniSAR fills a void in current remote sensing technology by providing unprecedented image quality and resolution while achieving a 4 to 5x reduction in size, weight, and cost.

Table 1 – Sandia SAR Specifics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Notes/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>27 – 50 lbs (configuration dependent)</td>
<td>Factors influencing weight include number of programmed data storage and baseline configuration.</td>
</tr>
<tr>
<td>Frequency</td>
<td>16.7 GHz (center frequency)</td>
<td>Have demonstrated x-bands, also available for Ka-band.</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 – 50m (configurable)</td>
<td>Range is variable, depending on several factors, including frequency band of operation, antenna aperture size, resolution, etc.</td>
</tr>
<tr>
<td>Maximum Range</td>
<td>2 – 23 km</td>
<td></td>
</tr>
<tr>
<td>Tx Power</td>
<td>60V</td>
<td></td>
</tr>
<tr>
<td>Antenna Type</td>
<td>Widespread patch arrays (polarized)</td>
<td></td>
</tr>
<tr>
<td>Modes</td>
<td>Spotlight, Stripmap</td>
<td>GMTI and real-time fine-resolution stripmap and CCD modes are in development. Future modes include videoSAR and stereoSAR.</td>
</tr>
</tbody>
</table>

5. Getting to the Moon

Designing, building, and testing a lunar CubeSat SAR satellite is only part of the mission. Once the CubeSat have been developed, the task of delivering the satellite into lunar orbit and commencing imagery operations is worked.

5.1 NASA Rideshare

The inaugural flight of NASA’s Space Launch Systems (SLS) rocket with the uncrewed Artemis-1 mission around the moon will carry the LunaH CubeSat. The CAPSTONE mission will launch on a Rocket Lab Electron rocket. Scheduled for summer 2022, Astrobotics, and Intuitive Machines will begin private rideshare missions to the lunar surface, both under NASA’s CLPS (Commercial Lunar Payload Services) program, PhysOrg (2022).
The difficulty with this approach is that even with the Artemis planned missions, trips to the moon are rare.

5.2 Individual Path

A secondary approach is to develop the CubeSat bus to contain the propulsion system to perform TLI capability. This scenario would be the launch of the CubeSat into Earth orbit and then perform a TLI burn to inject the satellite onto a lunar intersection trajectory. This would alleviate the need to sync the development and construction schedule to planned lunar mission timelines.

6. Project Development Timeline

If a rideshare approach is selected, a possible development timeline is depended on the Artemis schedule launch schedules.

6.1 Artemis II Rideshare

For catching a rideshare on the Artemis II mission, the development timeline is around 22 months as shown in Figure 22. While this schedule is achievable for a simple CubeSat development using a standardize bus, for the modification of even a commercial SAR system for lunar operations is extremely tight. The advantage of being able to achieve the Artemis II timeline is that high resolution imagery would be available prior to attempting lunar landings.

6.2 Artemis III Rideshare

Relaxing the development schedule into a 36-month timeline allows a possible Artemis III launch schedule as shown in Figure 23.

While the 22-month development schedule is desirable in terms of supplying high resolution imagery to support lunar landing missions, the 36-month development schedule is more realistic.

7. Project Team Organization

7.1 Partnerships

To execute this program, a series of partnerships have been established with a select set of engineering and science organizations. This mix of expertise ensures that the probability of mission development and execution is maximized. This partnership organization includes the following profession organizations.

7.1.1. Primes Solutions Group, Inc.

Prime Solutions Group (PSG) is a professional engineering services company with a legacy in Intelligence, Surveillance & Reconnaissance (ISR) technology. Leveraging deep experience and expertise in synthetic aperture radar (SAR) processing, core skills in complex system-of-systems engineering, and cutting-edge applied research and development in image-based machine learning, PSG helps solve the 21st century challenges faced by both private industry and government organizations. PSG will provide the program office and system integrator functions for the project. PSG will lead a MBSE approach to development of system requirements. PSG will develop the SAR processing chain necessary to produce the SAR imagery.
The Department of Astronomy and Planetary Science at Northern Arizona University will be involved in the project from the science perspective of analysis of surface features and geology of interested regions. NAU offers various bachelor’s degrees, and a doctoral degree in planetary science. The department has a small, family feeling.

7.1.2. Southwest Research Institute

Southwest Research Institute (SwRI), headquartered in San Antonio, Texas, is an independent and nonprofit applied research and development (R&D) organization. Founded in 1947 by oil businessman Tom Slick it provides contract research and development services to government and industrial clients. Southwest Research Institute’s Planetary Science Directorate is in downtown Boulder, Colorado. Areas of research and development include:

- Space Studies
- Planetary Physics
- Planetary Atmospheres and Surfaces
- Lunar Origin and Evolution
- Solar Physics
- Solar System Dynamics
- Astronomy
- Computer Systems
- Space Operations
- Space Technologies
- Mission Operations

SwRI’s space research experience and expertise are a critical element of this program. SwRI will lead the development of the CubeSat bus, integration of the SAR sensor (if appropriate) and develop and execute all the mission flight profiles and operations.

7.1.3. Northern Arizona University

The Department of Astronomy and Planetary Science at Northern Arizona University will be involved in the project from the science perspective of analysis of surface features and geology of interested regions. NAU offers various bachelor’s degrees, and a doctoral degree in planetary science. The department has a small, family feeling.

7.1.4. Astronomy Association of Arizona

The Astronomy Association of Arizona is a nonprofit 501(c)3 organization. The vision is to create an environment where anyone, regardless of ethnic origin, cultural belief, or socioeconomic status, succeeds in meeting their personal astronomical and education goals through state-of-the-art learning activities and unsurpassed membership benefits. Mission statements include the following:

- Our mission is to engage and educate those of all interest levels and to provide the highest quality of astronomical science to our community and beyond.
- Provide formal and informal education programs for both beginners and experienced astronomers.
- Encourage member participation regardless of their level of interest.
- Create and support programs to increase skills, broaden knowledge and focus on studies and research in specialized astronomical sciences.
8. Project Funding

The NASA Research Opportunities in Space and Earth Sciences (ROSES) - 2022 was released February 14, 2022. The Development and Advancement of Lunar Instrumentation (DALI) Program under ROSES supports the advanced development of instruments in support of future lunar missions including expected commercial ventures and NASA’s Artemis Program, NASA NSPIRES (2022). The goal of the DALI program is to develop and demonstrate science instruments for lunar missions to the point where they may be proposed in response to future announcements of flight opportunities without additional extensive technology development (approximately technology readiness level TRL 6). The DALI Program is intended to enable technology infusion into NASA lunar science missions to take place in a timely and efficient manner. As such, the technology readiness levels (TRLs) that DALI supports are an entry TRL of approximately 4 and an exit TRL of approximately 6.

The DALI funding mechanism is being targeted to support the research, systems engineering and development of the LSAR and associated satellite bus. Launch preparations, flight operations and SAR imagery processing will be proposed under a separate NASA area.

9. Conclusion

A Synthetic Aperture Radar CubeSat to image the permanent shadow craters on the moon’s polar region is being proposed. The science objectives of the mission are to image the permanent shadowed craters on the moon’s south pole to a resolution of 0.5 to 1m per pixel with the second objective of confirming the presence of water-ice in these craters to support the Artemis program of returning humans to the moon. The education objectives are to bring public awareness to the importance of man exploration of space.

10. Acknowledgements

I would like thank Joe Marvin, president of Prime Solutions Group, for allowing me to pursue the area of CubeSat research and development, an area currently outside of PSG’s area of expertise. I would also like to thank the executive committee of the AAA for supporting me in developing the aspects of the project and the involvement.

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What Has Epsilon Auriga Been Up To?

J. C. Martin
University of Illinois Springfield
Henry R. Barber Research Observatory
One University Plaza, MS HSB 314
Springfield, IL 62730
jmart5@uis.edu

Jim O’Brien
University of Illinois Springfield

Abstract
The long period eclipsing variable Epsilon Aurigae was the subject of a popular AAVSO citizen science project in the 2009 International Year of Astronomy. Following intensive coverage during its last eclipse (2009-2011), we continued to record its spectrum several times each year using an SE200 Echellette Spectrograph on the Barber Observatory 20-inch Telescope. The spectra cover from 970 – 320 nm at R = 20,000. In this paper we give a summary of what the spectra have recorded for H-alpha since the end of the last eclipse.

1. Introduction
Epsilon Aurigae is an eclipsing variable with an exceptionally long period of 27.1 years. The primary is F0 spectral class, most likely a giant or supergiant. The latest analysis of its GAIA DR2 distance implies that it is a post-ABG star (Parthasarathy & Muneer, 2019). The secondary is not directly observed. It is enshrouded in a large opaque disk of material which eclipses the primary for more than two years (Kloppenborg et al., 2015). The 2009-2011 eclipse was the focus of an extensive observing campaign including The Citizen Sky Project (Stencel, 2012 and others in AAVSO journal volume 80, https://app.aavso.org/jaavso/volume/80/).

To correctly interpret the eclipse data, it must be disentangled from variability driven by semi-regular pulsation in the primary star with a periodicity of ~67 days (Kim 2008). Most spectroscopic monitoring has concentrated on eclipses and the years immediately preceding or following them (Lambert & Sawyer (1986), Mauclaire et al. (2012), Leadbeater et al. (2012), Gorodenski (2012), Portavnov & Grinin (2013), Sadakane et al (2013), Gibson et al. (2018)). A few have considered longer term monitoring (Struve et al. (1958) and Griffin & Stencel (2013)) with Griffin & Stencel (2013) showing that the influence of the disk in the spectrum extends well outside of the primary photometric eclipse.

2. Spectroscopic Observations
The University of Illinois Springfield, Henry R. Barber Observatory has continued to monitor Epsilon Auriga with moderate resolution spectroscopy (R=20,000) at optical wavelengths. The observations are made with a 20-inch telescope and a SE200 Echellette Spectrograph designed by Optomechanics Research Inc. Spectra are taken using the “high resolution” dispersing element with a resolution of R ~ 20,000 over a wavelength range from 316. – 1063. nm. The exposures are recorded using a Kodak KAF-3200E/ME CCD and processed using custom software.

The Barber Observatory have been recording spectra of Epsilon Auriga from July 20, 2009 through the present with only one interruption (in the 2021 observing season). During the interruption, we observed selected wavelength ranges of the spectrum at a resolution R=10,000 using a 10-C spectrograph (model 0 built by Optomechanics Research) on the same 20-inch telescope.

Preliminary wavelength calibration was performed using a mercury lamp spectrum exposed immediately before or after the star spectrum. Fine adjustment of the scale was made using the prominent 615.6 nm telluric H2O absorption (same spectral order as the H-alpha feature). The wavelength scale for the spectra reported here is in the rest frame of the telescope/spectrograph and is not corrected for annual or diurnal motion of the Earth.

3. Measuring H-alpha
The focus of this work is to report the behavior of the H-alpha feature in the hydrogen Balmer series over the ten years following the most recent eclipse. Mauclaire et al. (2012) provide an extensive report of variation of this feature during the 2009-2011 eclipse. The spectra we gathered during and immediately
following the eclipse were previously summarized by Jarrett et al. (2014).

The continuum for the H-alpha feature was set by interpolating linearly between the average spectral flux over +/- 0.1 nm at 655.45 nm and 657.28 nm. The signal-to-noise (SNR) of each spectrum was measured from the continuum corrected flux between 656.78 – 657.46 nm. The SNR of the spectra vary between 50 – 150.

The H-alpha feature in Epsilon Auriga’s spectrum is a complicated mix of absorption and emission components (see Figure 1). To track its post-eclipse variation, we have chosen to measure:

- Total equivalent width between 655.6 – 657.1 nm measured with net emission as positive equivalent width and net absorption as negative equivalent width. (Figure 2 at end of paper)
- The depth relative to the continuum at maximum absorption. (Figure 3 at end of paper)
- The ratio of the peak emission intensity on the blue/violet side of the feature and the red side of the feature (V/R) (Figure 4 at end of paper)
- The wavelength separation between the blue/violet and red emission (V-R) (Figure 5 at end of paper)

The estimated uncertainty in each measurement is calculated using the SNR for the spectrum in a manner which also accounts for the estimated uncertainty in the continuum and the relative flux.

4. Discussion

Hopkins (2012) measured the fourth contact conclusion of the photometric eclipse on 2011 August 26 (MJD 55800). Spectroscopic fourth contact, determined from Na I absorption by the eclipsing disk, was many months later around 2012 January 25 (MJD 55950). Our spectra show the H-alpha feature continued the trend established during egress well past those dates. This coincides with the extensive optically thin outer layer of the disk identified in Ca II, Mg II, and Fe I absorption by Griffin & Stencel (2013). Jarrett et al. (2014) also noted a prolonged egress from the eclipse by H-alpha. The V-R separation continued to decrease steadily through April 2012 before leveling off (Figure 5). The maximum absorption and total equivalent width of H-alpha also showed no change in trend or notable end to the eclipse through at least 2015 (Figure 2 and 3).

Griffin & Stencel (2013) showed some correlation between brightness fluctuations and changes in spectral features. Since 2015 there has been significant variation in the H-alpha feature. Figure 6 (at the end of this paper) shows this in detail for the total equivalent width and the ratio of blue/red emission intensity (V/R). The maximum absorption depth (Figure 3) shows similar fluctuations. The separation of the blue/violet and red emission peaks (V-R, Figure 4) also show some variation, but it is not as significant due to the size of the measurement errors.
A cursory inspection of the data implies the changes in H-alpha over the last several years may be driven by two factors: variability and decrease in the absorption component and fluctuations in the emission components. The blue/violet and red emission components appear to undergo periodic “reversals” as demonstrated in Figure 7. The “reversals” appear in the V/R plot (Figure 4) as the spectrum changing from V/R > 1 (blue/violet emission stronger) to V/R < 1 (red emission stronger) and back again. Further analysis is required to clearly quantify and characterize the variability.

5. Acknowledgements

First, we thank Larry Gorski for bringing Epsilon Auriga to our attention and suggesting it as a long-term target of interest for the Barber Research Observatory. We also thank Shelby Jarrett and Cybil Foster who, as students, began the measurement and analysis of these spectra. And we thank the observer volunteers who contributed their time and talent to recording the spectra, including Kevin Cranford, Jennifer Thomas, and John Lord.

6. References


Figure 2. Total equivalent width of the H-alpha feature measured between 655.6 – 657.1 nm

Figure 3. Maximum absorption depth of H-alpha feature measured relative to the continuum = 1.0.
Figure 4. Ratio of the intensity of the blue/violet emission peak to the red emission peak.

Figure 5. Wavelength separation of the blue/violet emission peak from the red emission peak (V-R).
Figure 6. Fluctuation in total equivalent width and the blue/red emission intensity ratio (V/R) since 2015.
Revisiting the δ Scuti Star FG Virginis

Joyce Ann Guzik
Los Alamos National Laboratory, MS T-082, Los Alamos, NM 87545
joy@lanl.gov

Jason Jackiewicz
Department of Astronomy, New Mexico State University, Las Cruces, NM 88003

Anne M. Hedlund
Department of Astronomy, New Mexico State University, Las Cruces, NM 88003

Abstract

FG Virginis is a δ Scuti variable star that was the target of several ground-based multi-site photometric campaigns from 1992 to 2004. Over 75 pulsation frequencies were detected (Breger et al. 2005), more than for any other δ Sct star before the era of space photometry. FG Vir was observed for 52 days in 30-minute cadence photometry by the NASA Kepler spacecraft K2 mission in 2016, and for 23 days in 2-minute cadence photometry by the NASA TESS spacecraft in 2021. We present light curves and amplitude spectra obtained from these space missions. We find around 40 significant frequencies in the K2 data, including some low frequencies (<5 cycles/day) that were not detected using the ground-based data. If low frequency pulsations are confirmed, FG Vir would be classified as a γ Dor/δ Sct hybrid variable star. We find more than 100 significant frequencies in a preliminary look at the TESS data. There is good correspondence between the top 10 or so highest-amplitude modes found in the K2 and TESS data and those found from the ground-based multisite campaigns, although the amplitude order is slightly different, indicating some stability in mode frequencies and amplitudes spanning 20 years. However, the 9th highest-amplitude mode of Breger et al. has moved down considerably in amplitude rank, while the 35th highest-amplitude mode has moved up to near the top 10 as seen in both the K2 and TESS data. We also review stellar model results and some of the many challenges for asteroseismology for this well-studied δ Sct star.

1. Introduction

The δ Scuti variables are main-sequence or slightly post-main sequence stars with mass around 2 M⊙, which pulsate in one or more radial or non-radial modes (Aerts et al. 2010). These stars are of interest for asteroseismology, i.e., using the pulsation properties in conjunction with modeling to derive stellar interior structure and to test theories of stellar evolution and pulsation driving.

FG Virginis (HD 106384) is a well-studied bright (V = 6.558) δ Scuti star of spectral type A8. FG Vir was the object of ground-based single-site (1982; see Lopez de Coca et al. 1984) and multi-site (1992-2004; see Breger et al. 1995, 1996, 1998, 2004, 2005, Breger and Lenz 2019) photometric campaigns. These campaigns resulted in detection of 75+ pulsation frequencies (Breger et al. 2005), more than for any other δ Sct star before the era of long time-series space photometric missions such as CoRoT (Poretti et al. 2009), Kepler (Baricki et al. 2010, Gilliland et al. 2010, Koch et al. 2010), and TESS (Ricker et al. 2015). See also Guzik (2021) and Daszynska-Daszkiewicz et al. (2005, 2021) for more information about δ Sct stars and results from space missions.

FG Vir was observed for 52.5 days in 30-minute cadence photometry by the NASA Kepler spacecraft during Campaign 10 (6 July – 20 Sept. 2016) of the extended Kepler mission (K2, Howell et al. 2014) as part of our Guest Observer program (see Guzik et al. 2019). We present the results of analysis of these data and comparisons with the amplitude spectra obtained using the ground-based multi-site data. We also review some of the findings from asteroseismology and unanswered questions for this interesting δ Sct star.

2. Kepler Data Analysis and Results

FG Vir is EPIC 201132898 in the K2 Ecliptic Plane Input Catalog (Huber et al. 2016). We retrieved the data from the Mikulski Archive for Space Telescopes (MAST, https://archive.stsci.edu/). Figure 1 shows the K2 light curve, and Fig. 2 shows a 3-day zoom-in on a portion of the light curve. Figure 3 shows the amplitude spectrum resulting from a Fourier analysis of the light curve, and Fig. 4 shows a zoom-in on the lower-amplitude frequencies. To determine the significant frequencies, the highest-amplitude modes were removed from the light curve successively until only noise remained, a process called pre-
whitening. For evenly spaced 30-min cadence data, the Nyquist frequency limit is 24.4695 c/d, so the amplitude spectrum is truncated at this frequency.

Table 1 lists the 46 frequencies obtained from the pre-whitening analysis in order of signal-to-noise ratio (S/N), down to S/N ~ 3. Table 1 also notes associations of these frequencies with those from Breger et al. (2005) obtained from the multi-site observations. Considering the first 11 modes, apart from two modes with very close frequency to the highest-amplitude mode, all of them are found among the 10 highest-amplitude modes of Breger et al., although the amplitude ordering is slightly different. Breger et al.’s 9th highest-amplitude mode (frequency 19.228 c/d) is only the 19th highest-amplitude using the K2 data. Some of the remaining modes found from the K2 data can be associated with the Breger et al. frequencies. It is interesting that the 35th highest-amplitude mode in the Breger et al. list (frequency 20.511 c/d) corresponds to the 13th highest in the K2 data.

Table 2 lists the 46 modes found in the K2 data in order of frequency. Breger et al.’s lowest frequency is 5.7491 c/d; it may be difficult to measure low-amplitude frequencies around 1 c/d from the ground, even using a global multi-site network. However, low frequencies may be more easily detectable in the K2 data with a continuous multi-day time series.

The three lowest-frequency K2 modes can be associated with multiples of close frequency differences between high-amplitude modes f1, f2, and f9. To compensate for the loss of a second reaction wheel, the K2 mission used solar radiation pressure to keep the spacecraft pointed in the same direction, and in addition fired thrusters every 5.8849 hours (K2 Handbook, Migliel and Van Cleve 2020). The thruster-firing frequency of 4.0782 c/d and its 2nd harmonic at 8.1564 c/d appear in the K2 frequency list. Two other low-frequency modes at 0.47434 and 0.49454 c/d are combinations of the f2 and f9 modes minus 3x the thruster-firing frequency.

Apart from these combinations, there are still several modes remaining with frequencies 0.3 to ~3 c/d, in the right frequency range to be γ Dor gravity modes. Some of these have S/N < 3.5 so might be spurious. However, if any are real, FG Vir could be considered a hybrid δ Sct-γ Dor variable-star candidate.

We truncate the K2 frequency search at the Nyquist limit of 24.4691 c/d for evenly spaced 30-min cadence data, but the multi-site data is not evenly spaced, and the detected frequencies extend up to 44.2591 c/d. One K2 frequency at 14.36915 c/d may be a Nyquist-reflected frequency, associated with the 34.5737 f23 mode of the Breger et al. list.
Figure 4. Zoom-in on low-amplitude region of FG Vir K2 amplitude spectrum.

3. Preliminary Look at TESS Data

The Kepler spacecraft was retired in November 2018; fortunately, the TESS spacecraft was launched in April 2018 into a 13.7-day elliptical orbit around Earth, maintained by a 2:1 lunar resonance. TESS data for FG Vir is now available at MAST, taken during the 27.4 observing days of sector 46 (Dec. 2-30, 2021). Moreover, data were taken at 2-minute cadence, so the S/N is much larger and Nyquist frequency limit much higher than for the 30-min cadence K2 data.

FG Vir is TIC 277227048 in the TESS Input Catalog (Stassun et al. 2019). Figure 5 shows the TESS FG Vir light curve, including data from 22.84 days, excluding the gap. Figure 6 shows a 1-day zoom-in on the light curve; small features are resolved in the TESS 2-min cadence light curve that were not resolvable in K2 30-min cadence light curve.

Figure 7 shows the FG Vir amplitude spectrum for TESS data, truncated at 50 c/d. Figure 8 shows a zoom-in at lower amplitudes. We performed preliminary pre-whitening analysis for the first 100 modes with highest S/N ratio. The S/N of the 100th peak is 27, so it is likely that many more significant frequencies remain in the residual.

Table 3 lists these 100 frequencies in frequency order. No significant frequencies were apparent at frequencies > 50 c/d. The 9 highest-amplitude TESS frequencies are found among the 10 highest-amplitude Breger et al. (2005) frequencies, although the amplitude order is slightly different. The 9th highest-amplitude frequency in the Breger et al. list is 29th in the TESS data, while f35 in the Breger et al. list is 10th highest in the TESS data, confirming the significant amplitude changes in these modes found using the K2 data.

Figure 9 overlays the FG Vir K2 and TESS amplitude spectra, showing some common frequencies as well as many differences. Differences in amplitude for the same mode are expected because of the different photometric passband of Kepler vs. TESS. The TESS data shows fewer modes with frequencies < 5 c/d, in the γ Dor frequency range, and the TESS low frequencies do not coincide with the K2 low frequencies. Perhaps continued pre-whitening will reveal more low-frequency modes.

Figure 5. FG Vir TESS 2-min cadence light curve from sector 46, showing 22.84 days of data, excluding the gap. Time is measured after barycentric Julian day 2457000.

Figure 6. 1-day zoom-in on FG Vir TESS 2-min cadence data. Small features from lower-amplitude frequencies are resolved that were not resolved using K2 30-min cadence data.
4. Unresolved Questions for Asteroseismology

As discussed by, e.g., Guzik (2021), there are many inter-related unresolved problems for δ Sct stars that make asteroseismology challenging.

First, there is a mode visibility problem for non-radial oscillations as seen in δ Sct stars. Temperature variations described by spherical harmonic patterns average out over the unresolved stellar disk, making higher degree ℓ modes more difficult to see in photometry. Usually, it is expected to detect modes of degree 0 (radial), 1 (dipole), and 2 (quadrupole). Is it possible to measure modes of degree 3 or higher, particularly with the higher precision and longer continuous time series possible with space-based photometry? Daszynska-Daszkiewicz et al. (2006) conclude that modes of ℓ = 3 and even much larger should be detectable, even using the FG Vir ground-based data, and that most of the modes discovered for FG Vir below 30 c/d must have ℓ > 2!

Second is the rotational splitting problem. Stellar rotation splits modes into 2ℓ + 1 separate multiplets, and rotation can shift frequencies even for radial (ℓ=0) modes. FG Vir’s equatorial rotation velocity is 30-80 km/sec (Mantegazza and Poretti 2002, Zima et al. 2006), so we should expect a rotational splitting frequency of around 0.5 c/d for FG Vir stellar radius ~2.2 R☉. We don’t see obvious rotationally split modes in the FG Vir amplitude spectrum.

Third is the mode selection problem. Not all of the modes expected from stellar models for δ Sct stars are seen in the amplitude spectrum. And there are modes observed that are not expected from the best-fit pulsation models.

Then there is the mystery of amplitude and frequency variations. Amplitudes and frequencies of individual δ Sct stars can be relatively stable over time. It was possible to associate many of the highest-amplitude modes in the K2 (2021) and TESS (2016) data sets with modes in the Breger et al. (2005) list. However, the order of the mode amplitudes is somewhat different for the first dozen or more modes; some modes appear in the K2 and TESS data that aren’t in the Breger et al. list, and vice versa; and the Breger et al. f9 mode has moved down in amplitude rank, while the f35 mode increased in rank. Nonlinear mode-coupling effects are suspected as the cause of these variations.

Breger and Pamyatnykh (2006) investigate the problem of closely spaced modes in FG Vir, with separations less than 0.1 c/d, too small to be the result of rotational splitting. Are these separate modes, or are they the result of amplitude variability of a single frequency? Breger and Pamyatnykh (2006) were able to rule out amplitude variability for several of the FG Vir closely spaced modes.

These many complications lead to a mode identification problem. We can’t identify modes by patterns in the amplitude spectrum and match them directly with modes expected from theoretical models. However, methods have been developed to identify the angular degree (ℓ) and azimuthal order (m) of the highest-amplitude modes using color photometry, phase information, line profile variations and radial velocities from spectroscopy (see, e.g., Breger et al. 1999, Mantegazza and Poretti 2002, Daszynska-Daszkiewicz et al. 2005, Zima et al. 2006, Viskum et al. 2008). Some FG Vir modes have been identified using these methods, but mode identification has been somewhat uncertain. For example, Daszynska-
Daszkiewicz et al. (2005) identifies the angular degrees for 12 FG Vir modes to 80% probability, but there are ambiguities for 6 of these modes. In early studies of FG Vir, the highest-amplitude mode at 12.7162 c/d was thought to be the radial fundamental mode (e.g., Mantegazza et al. 1994, Breger et al. 1995), but later studies (e.g., Viskum et al. 1998, Mantegazza and Poretti 2002) showed that this mode is most likely an $\ell=1$ dipole mode, and the radial fundamental mode is the 2nd highest-amplitude mode at 12.1541 c/d.

Attempts have been successful to find patterns of frequency spacings (e.g., Breger, et al. 2009). The spacings could correspond to the large separations between modes of successive $\ell$ values, or a rotational splitting spacing, or a combination of these two spacings (see also Paparo et al. 2016a,b, Suarez et al. 2014, Bedding et al. 2020). Patterns of mode spacings can therefore be useful to identify modes of common $\ell$ value, determine the stellar mean density, or even to measure the stellar interior rotation rate.

5. FG Vir Models

The goal of asteroseismology of FG Vir is to use the observed frequency properties to determine the stellar interior structure and evolution state. Evolution and pulsation models of FG Vir have been calculated over the years to attempt to make use of the observed frequencies. It is helpful to have additional constraints from multicolor photometry, spectroscopy, and stellar model grids to provide a starting point for detailed model explorations. The TESS Input Catalog (TIC, Stassun et al. 2019) lists FG Vir properties collected from several sources: effective temperature $T_{\text{eff}} = 7361 \pm 131$ K, log surface gravity (log g) = 3.974 $\pm$ 0.086, radius R = 2.205 $\pm$ 0.082 $R_{\odot}$, mass M = 1.6 $\pm$ 0.282 $M_{\odot}$, luminosity L = 12.86 $\pm$ 0.44 $L_{\odot}$, and distance 83.02 $\pm$ 0.37 pc.

Viskum et al. (1998) use FG Vir frequencies to derive a mean stellar density ($\rho$) = 0.1645 $\pm$ 0.005 $\rho_{\odot}$. Assuming $T_{\text{eff}} = 7500$ K and metallicity Z = 0.02, they find M = 1.82 $\pm$ 0.03 $M_{\odot}$, L = 14.1 $\pm$ 0.9 $L_{\odot}$, R = 2.227 $\pm$ 0.012 $R_{\odot}$, and log g = 4.002 $\pm$ 0.003. Their derived luminosity places FG Vir at a distance of 82 $\pm$ 3 pc.

Breger et al. (1999) find a best-fit model to the FG Vir frequencies with M = 1.95 $M_{\odot}$, $T_{\text{eff}} = 7492$ K, L = 14.92 $L_{\odot}$, R = 2.301 $R_{\odot}$, and log g = 4.002. This model has metallicity Z = 0.02, initial helium mass fraction Y = 0.28, and mean density 0.1597 $\rho_{\odot}$. The model uses artificially modified opacities, and core convective overshooting.

Templeton et al. (2001) find a best-fit model for FG Vir with M = 1.9 $M_{\odot}$, $T_{\text{eff}} = 7413$ K, L = 14.16 $L_{\odot}$, and age 0.93 Gyr. This model has Z = 0.03 and hydrogen mass fraction Y = 0.28, and it includes core convective overshooting.

Table 4 lists the $\ell$ = 0, 1, and 2 pulsationally unstable frequencies for an FG Vir model calculated by Guzik. These model frequencies were used by Paparo et al. (2016a,b) to illustrate how frequency spacings could be used to help identify modes in $\delta$ Scuti stars. The physics of the models is the same as used in the Guzik et al. (2000) FG Vir models. The model $T_{\text{eff}}$, 7419 K, was chosen to match the 12.1541 c/d mode identified as the radial fundamental. For this model, L = 13.92 $L_{\odot}$, R = 2.26 $R_{\odot}$, and log g = 3.9896. These values are within the uncertainties of the values in the TIC catalog. The model has Z = 0.02 and Y = 0.28, and mean density 0.1577 $\rho_{\odot}$. The model does not include core convective overshooting. The model age is 0.867 Gyr, and core helium mass fraction is 0.708, indicating that about 2/3 of the core hydrogen has been converted to helium.

The calculated model frequencies in Table 4 do not include rotational splittings, which will divide non-radial modes into $\ell + 1$ multiplets, with spacings of around 0.5 c/d, depending on the rotational velocity adopted. A total of 98 $\ell$ = 0, 1, and 2 modes are predicted, taking into account rotational splitting. However, even including rotational splitting, not all of the observed frequencies of Breger et al. (2005) can be matched for FG Vir.

6. Conclusions

We compare the FG Vir frequencies detected using 52.4 days of 30-min cadence Kepler K2 photometry with those detected using at least 363 nights (Breger and Lenz 2019) of multi-site ground-based network data. More than 75 significant frequencies were measured in the ground-based data (Breger et al. 2005), compared to around 40, depending on S/N limit adopted, using the K2 data. It was possible to extend detections to higher frequencies, using ground-based data, and frequencies as high as 44.25 c/d were identified. The K2 frequency detections were limited to frequencies below the Nyquist frequency limit of ~24.5 c/d for 30-min equally spaced data. The ground-based multi-site data included color photometry, which turned out to be extremely useful for mode identifications of the highest-amplitude modes.

On the other hand, the continuity of the K2 data and, possibly, the elimination of day/night aliases enabled detection of low-frequency modes, including modes between 0.3 and 5 c/d that may be high-order $\gamma$ Dor gravity-mode pulsations. If these modes are confirmed, FG Vir would be a hybrid $\delta$ Sct/$\gamma$ Dor star.
The TESS data appear more promising for further FG Vir discoveries. The time-series length of the TESS data was 22.84 days, shorter than for the K2 series, but the shorter 2-minute cadence increased greatly the S/N, allowing the detection of over 100 modes with S/N > 27. The 2-minute cadence also increased the Nyquist frequency limit, so that modes up to 45 c/d, as found in the ground-based data, could be detected. The TESS data should reveal many more modes of even lower amplitude than found in the ground-based data, requiring consideration of modes of angular degree > 3 for asteroseismic models. The increased number of detected modes will make mode identification even more challenging!

There was general agreement between the frequencies of the 10 highest-amplitude modes between the ground-based, K2, and TESS data. Two modes of interest were the f9 mode of Breger et al. (2005), which moved down in amplitude rank, and the f35 mode of Breger et al., which moved up in amplitude rank in both the K2 and TESS data.

7. Acknowledgements

We are grateful for data from the NASA Kepler and TESS spacecraft. We acknowledge a Los Alamos National Laboratory Center for Space and Earth Sciences grant CSES XX8P. J.G. acknowledges support from LANL, managed by Triad National Security, LLC for the U.S. DOE’s NNSA, Contract #89233218CNA000001. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and the Mikulski Archive for Space Telescopes (MAST). J.G. thanks the Society for Astronomical Sciences for the opportunity to present these results.

8. References


Figure 9. FG Vir K2 (blue) vs. TESS (orange) amplitude spectra.
Table 1. FG Vir K2 frequencies in order of S/N compared with Breger et al. (2005) frequencies.

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Abstract

As a condensable gas, the distribution of ammonia vapor is an important tracer of Jovian tropospheric meteorology. Current understanding of this distribution and its relationship to aerosol opacity, cloud height, and circulation is provided by atmospheric retrieval models using observations from major ground-based facilities or from spacecraft such as Juno. As a potential pro-am complement to these efforts, optical filter ratios have been used to investigate 645 nm ammonia absorption using a small telescope. The technique and associated analysis software have been refined over two apparitions. The work has shown latitudinal, longitudinal, and time-varying structure in Jovian ammonia absorption. However, this technique is limited in its ability to retrieve environmental conditions such as ammonia abundance, aerosol characteristics, and cloud height. It is also limited currently by coverage only from a single observatory. If low-cost techniques providing real, physical measurements, could be demonstrated, extended, and promulgated among the amateur community, then routine atmospheric monitoring of Jupiter would reach a new level of sophistication and would further complement professional observations. This paper presents a review of filter-based techniques demonstrated during the 2020 and 2021 apparitions along with highlights of results. Next steps toward use of a simple reflecting layer model, using additional filter bands, are discussed for first order retrieval physical values in the Jovian atmosphere. Finally, best practices and lessons learned are presented along with how to share resulting observations.

1. Introduction/Background

Ammonia condensate clouds are responsible for most of the cloud and band structure seen in visible light. The distribution of ammonia gas is dependent on vertical and horizontal motions along with sources (chemical production, evaporating condensates) and sinks (condensation, photochemical destruction). In essence, it is a proxy for active weather in the upper troposphere.

![Figure 1: Average map of ammonia abundance in Jupiter retrieved by the Juno MWR during PJ1 to PJ8 as a function of latitude and pressure [Figure 1 of Guillot et al., 2020].](image)

New microwave and MIR observations, along with models, reveal much about Jupiter’s NH₃ cycle at depth. For example, Guillot et al. (2020) show in Figure 1 the average NH₃ abundance retrieved by the Juno MWR instrument to a depth of 100 bar. Additional recent work has used mid-IR observations to probe to depths of several bars (c.f. Fletcher et al. 2016; Fletcher et al., 2020; Fletcher et al., 2021). Similarly, there have been efforts at global retrievals using hyperspectral imaging in the optical and near-IR (c.f. Braude et al., 2017; Braude et al., 2020; Dahl et al., 2021). Complementing these efforts have been notable improvements in the understanding of the ammonia optical and NIR absorption bands (Irwin et al., 2018; Irwin et al., 2019). Finally, long baselines of slit spectrometry data continue to be pursued (Teifel et al., 2018; Vdovichenko et al., 2021).

Ammonia, like methane, has molecular absorption bands accessible in the visible and near infrared (NIR) regions of the spectrum. Ammonia observations region [Teifel et al., 2018; Tejfel et al., 2017] have been less extensive than methane observations in large part because the absorption by NH₃ is weak compared to CH₄. However, recent work has shown the efficacy of imaging Jovian features in the 645 nm ammonia absorption band (Hill, 2021). Retrievals of environmental parameters are the bread and butter of atmospheric physics, and the potential contribution of NH₃ observations in the optical needs to be fully assessed.

While work to incorporate the NH₃ optical absorption band into retrieval models is pending, refining this technique and acquiring more data will strengthen the case for its utility. This is especially true if the observations can be easily duplicated, and a
variety of Jovian atmospheric conditions can be observed. The interest, breadth of techniques, and importance of the study of Jovian ammonia prompt this investigation, which asks the question: Can observations of NH$_3$ in the top ~1 bar of the atmosphere be used to infer deeper processes?

The remainder of the paper is organized as follows: The next section summarizes the technique along with the observations made during the 2020 and 2021 apparitions. Sections three and four describe observational highlights and the initial potential of simple model retrievals respectively. Section five provides best practices for other amateurs who may wish to make ammonia observations. The sixth section summarizes this work and its findings.

2. Technique and Observations

The NH$_3$ absorption imaging technique assessed in this work is straightforward (Hill, 2021). It rests on the premises that one can establish the ammonia absorption on a pixel-by-pixel basis by dividing an in-band image by the average of adjacent continuum images. The resulting products of the process include disk-integrated absorption, meridional absorption profiles, and resolved absorption images (Figure 2). Assuming a canonical disk-integrated NH$_3$ equivalent width, the equivalent width can be computed for each pixel.

The processing pipeline is shown in more detail in Figure 3. FITS images, typically from a CCD camera, or AVI/video files, typically from a CMOS camera can be used. Standard calibrations are applied, and initial stacking is carried out. Disk-integrated photometry doesn’t require image navigation, so it can be performed at this point in the pipeline. Once navigated, images are again stacked, compensating for planetary rotation. The image ratio computation is carried out on mapped images that have been rotationally aligned. But before the ratio is computed, the images are brightness equalized in order to simplify accounting for differences in filter throughput. For detailed study, the images are converted into cylindrical projection maps and only the central 45 degrees to the central meridian and equator are analyzed. This avoids more severe limb darkening effects on the data.

Forty observing sessions were carried out from the author’s observatory in Denver, Colorado. Of those, one was discarded as unusable, leaving 39 sessions for analysis. Two imaging configurations were used, both with a 0.28 m aperture Celestron 11 catadioptric telescope. The first configuration used lucky imaging with a CMOS camera at a long focal length to attempt to detect discrete ammonia abundance features, but in a non-quantitative manner. The second configuration captured images with a CCD camera for which quantitative photometric analysis could be performed.

Figure 4 shows observations contributing to NH$_3$ absorption measurements during 2020 and 2021 versus System I longitude. It also overlays Juno perijove data. Note that during July 2020, CMOS observations overlap with the longitudes observed by Juno (PJ28) and those facing Earth at that time. Similarly in September 2020, CMOS and CCD observations are obtained adjacent to Juno PJ29. The best adjacent observations in 2021 occurred in October (PJ37). Also, while somewhat coincident with a Juno perijove (PJ36), the System I longitude range of 140-180 degrees was observed multiple times, with close consecutive observations in September and October. This allows for observing the evolution of features in the Equatorial Zone (EZ).

It’s important to note that the 2021 observations were of higher quality than the 2020 observations. The 2020 observations were not consistently flat-field calibrated and only used a single continuum reference image. The 2021 observations were fully calibrated and used both blue-side and red-side continuum reference images.
3. Highlights

Observations in the ammonia absorption band showed numerous features of interest. Examples are shown in the mapped observations in Figures 5-7. Figure 5 shows large-scale features including the NEB depletion (reduced absorption), the EZ enhancement, and depletion around the GRS. In these plots the overlayed contours show the estimated 645 nm equivalent width. Note both the correlations and lack of correlation with certain visible features, e.g., depletion correlated with the GRS, but the dark northern EZ and NEB region in the NUV image overlaps both the ammonia-enhanced EZ and ammonia-depleted NEB areas.

Figure 6 shows detail in the EZ and NEB, including ammonia absorption enhancements in proximity to plumes and dark features. These are areas of noted upwelling and downdraft most likely associated with a global Rossby wave. Typically, ammonia abundances have been seen to be depleted in the dark features and enhanced in the bright plumes. Note that dark features are seeing deeper into the atmosphere and the bright plumes represent high clouds. Thus, the NH$_3$ absorption can’t tell the story of actual abundance without better knowledge of the scattering path length. Nevertheless, improved spatial resolution would be helpful to understanding the dynamics of this atmospheric region.
Figure 7: Reduced ammonia absorption at and near (southeast) the Great Red Spot at three epochs in 2021.

Ammonia absorption in and around the GRS is shown from July through September 2021 in Figure 7. It shows depletion over the GRS but is shifted to the southeast. This depletion is mostly due to the high altitude of the scattering layer and has been noted by Teifel et al. (2018). A gradient from an enhanced to a depleted ammonia mole fraction (440 mb) from north to south across the GRS has been seen in MIR data (Fletcher et al., 2016).

Figure 8 shows the meridional variation of NH$_3$ absorption from 45S to 45N planetographic latitude. The average NH$_3$ mole fraction at 440mb measured by Fletcher et al (2016) is also presented, along with the standard deviation from their data. The contrasts are higher than those observed EW observations. In addition, the depletion seen in the SEB is not seen in the optical observations either of this work or that of Teifel et al., (2018). These differences suggest significant deviations due to cloud-top heights and scattering properties as mentioned above.

4. Modeling

In terms of what discriminating factors exist between different visible features, Figure 9 shows a scatter plot of brightness in the 889 nm methane band versus the equivalent width in the 645 nm ammonia band. High brightness in the methane band indicates higher cloud tops, which lead to less absorption. Thus, one sees that the GRS (high brightness red ‘tail’ in the 15-30S band) indicates a high reflecting layer. Not surprisingly, the ammonia equivalent width is relatively low there, due to the smaller scattering length to the reflecting layer. The EZ (green and purple) exhibits high brightness in CH$_4$, but also a wide range of NH$_3$ EWs suggesting a range of features related to ammonia abundance or cloud height. The NEB shows uniformly low CH$_4$ brightness, indicating deeper cloud tops, but also shows the lowest NH$_3$ absorption. This would support an actual depletion in ammonia abundance since the scattering distance to the reflecting layer is large.

Atmospheric modeling and retrieval of environmental parameters such as ammonia abundance is essential to understanding convection and circulation. While sophisticated multiple-scattering models for retrieval are available, they are beyond the scope of this work. However, simple Reflecting Layer Models (RLMs) are straightforward to implement and can provide first order insight into parameters of interest (Mendikoa, 2012; Antuñano et al., 2020). The goal is to retrieve reflectivity, cloud top pressure, and NH$_3$ abundance by extending the Mendikoa (2012) model.

The model as originally implemented uses broadband NUV, red, green, blue, and 889CH$_4$ filtered images to retrieve reflectivity and cloud-top pressure. Adjustments under consideration would be to narrow the scope to wavelength bands in the red region of the spectrum that provide red continuum, continuum slope, methane absorption, and ammonia absorption. This can be accomplished with filters placed at roughly 620, 632, 647, and 656 nm.

The simplest proof of concept is to estimate the cloud height using CH$_4$ with two channels that were used in the 2022 apparition: an in-band channel (889 nm) and a nearby ‘continuum’ channel (940 nm). The 940 nm channel is less than perfect as a continuum reference but does have greatly reduced absorption. As
for the NH$_3$ analysis, we can compute an EW for methane at 889 nm. But then, since the methane abundance is spatially constant, we can estimate the cloud-top pressure height (the effective reflecting layer height) using the radiative transfer equations. This was tested with raw images from 2021-09-05 UT. The resulting cloud heights (~250 mb) are roughly consistent with prior literature and models, as well as with the results of Mendikoa (2012) using a full RLM retrieval model and different filter bands. The line-of-sight to the cloud-top reflecting layer can then be used to estimate the ammonia abundance. In this test case the ammonia abundance retrieved (0.6×10$^{-3}$ to 1.1×10$^{-3}$) appears to be higher than expected by a factor of >10 at the 0.2 to 1.0 bar level.

During the 2022 apparition, these initial retrieval tests will be refined and adopted for images that are calibrated in terms of absolute reflectivity. Error sources will be determined and mitigated as much as possible. And finally, an integrated retrieval will be performed using a version of the Mendikoa (2012) model extended for NH$_3$ abundance.

### 5. Best Practices

With experience over two Jovian apparitions, the observational technique for NH$_3$ absorption has been assessed and refined. Noise sources and biases have been identified and their level of impact evaluated. Several of those that have been determined to be significantly impactful have been addressed or will be addressed in 2022. This section provides an outline of “best practices” based on these experiences. First, the “standard” rules apply for high quality planetary imaging:

- Maximize signal to noise (big aperture, longer exposures/stacking, pixel binning)
- Apply bias, dark, and flat-field corrections, and
- If the elapsed time during an imaging session exceeds two minutes, correct for rotation before stacking images.

Ignoring any of these items will degrade the direct images as well as the computed NH$_3$ absorption image. However, in addition to these best practices, there are additional key guidelines:

- Ensure that camera settings for gain and gamma are linear,
- Do not apply any sharpening techniques such as wavelets or unsharp masking,
- A session to produce an NH$_3$ image shouldn’t be longer than about 20 minutes,
- The centers of the in-band and continuum reference observations should be within five minutes of each other,
- It is necessary to have a continuum reference on both the red and blue sides of the 645 nm NH$_3$ band, and
- Continuum references must avoid other absorption bands as much as possible such as the CH$_4$ band at 619 nm.

Nonlinear camera settings will yield results that cannot be quantitatively analyzed. Any sharpening applied will magnify noise, and that noise is further amplified in computing the image ratios necessary to produce the ammonia image. In addition, sharpening techniques often introduce artifacts and/or are ‘non-conservative’ – meaning that they don’t preserve the true relative flux. Thus, NH$_3$ images in this work necessarily appear less sharp than could be achieved with a ‘normal’ image pipeline that includes sharpening.

If imaging sessions run longer than about 20 minutes (~12 degrees of rotation), limb darkening effects may become noticeable sources of systematic error. The same goes for the time-centers of each of the filter observations – if they are offset by more than about five minutes, relative limb darkening effects between the images to be ratioed may become noticeable sources of systematic error.

Having continuum images on both the red and blue sides of the in-band image is key. Globally, Jupiter has a shallow but non-zero color slope around 645 nm. However, individual features can have significant color slopes that can contaminate the NH$_3$ features or even mimic them. Having a continuum measurement on either side of the absorption band produces an average continuum at or about 645 nm. And with Jupiter’s rich molecular absorption

![Figure 9: Scatter plot 889 nm CH$_4$ relative signal versus 645 nm ammonia equivalent width for different meridional bands (2021-07-08, CM2 354 deg).](image)
spectrum, one must take care to avoid other nearby bands.

The processing of the images is sensitive to certain kinds of errors. Some of those sensitivities are discussed in (Hill, 2021) and they include:

- Linear alignment offset,
- Rotational alignment (timing) offset,
- Differential sharpness, and
- Different background levels.

All of these issues can result in artifacts that can confuse the interpretation of the actual ammonia absorption signal. Even after regular image navigation by limb-fitting (and perhaps using moons to achieve a better fit), there may be residual errors in alignment.

To create an ammonia absorption image, the first step is to rotationally align in-band and continuum images. This can be done by creating a rotationally corrected RGB image in WinJUPOS as follows:

- Red = Red-side continuum (656 nm, 658 nm, or less preferably 672 nm),
- Green = In-band image, 647 nm filter, and
- Blue = Blue-side continuum (632 nm).

The camera and filter bands will have different responses giving different total signal levels. However, within the relatively narrow band of interest (~35 nm wide), the disk-integrated reflectivity of Jupiter is nearly constant. The bigger difference is in the filter and camera response. Thus, taking the RGB image and white balancing it (in an image processing program like MaximDL) normalizes the three channels to the same global brightness.

At this point the image planes can be split into monochromatic images and the division arithmetic done. But, before the ratio is computed, this is an excellent time to re-verify the alignment of the image planes and iterate if necessary. The actual computation performed on the images is:

\[
I_{NH_3} = \frac{1}{2} \left( \frac{I_{647}}{I_{632}} + \frac{I_{647}}{I_{656}} \right)
\]

where \(I_{NH_3}\) is the ammonia absorption ratio image, \(I_{647}\) is the in-band image, \(I_{632}\) is the blue continuum image, and \(I_{656}\) is the red continuum image. Scaling the resulting image from 0.9 to 1.1 provides good contrast without saturation and can saved in a 16-bit PNG file.

Once the scaled image is established, canonical global averages of absorption can be used to estimate the local variations in equivalent width, e.g., Figures 5-7.

The continuum wavelengths are different offsets from the in-band filter, so a more accurate approach might be to compute:

\[
I_{NH_3} = \frac{15}{24} I_{647} + 9 \frac{I_{647}}{24} I_{656}
\]

As can be seen in Figure 5 the color slope between the two continuum filters is much less than the net ammonia ratio signal (both map panels are scaled from 0.9 to 1.1). The revised computation will be applied in 2022.

The color slope image is computed as:

\[
I_{ColSlo} = \frac{I_{632}}{I_{656}}
\]

so that regions tending to be redder are darker and bluer regions are brighter.

It’s crucial to obtain and share more observations in the ammonia band to provide better temporal coverage and potentially improved spatial resolution. Together, this will permit the better understanding of the evolution of \(NH_3\) absorption features on various temporal and spatial scales, and it will enable validation of retrieval models. Obtaining observations coincident with Juno perijoves will complement Juno and accompanying ground-based observations.

Figure 10: Example image array for upload to a data sharing site. Ammonia absorption image is at bottom center. Ideally the source images should not be sharpened.

Data can be uploaded at several websites for amateur collaboration, for example: Planetary Virtual Observatory and Laboratory (PVOL) (http://pvol2.ehu.eus/pvol2/) and Association of Lunar and Planetary Observers in Japan (ALPO-Japan) (http://alpo-i.sakura.ne.jp/indexE.htm). When uploading ammonia band observations, upload the ammonia absorption image itself (and identify the scaling if it is other than 0.9 to 1.1) and the source in-band image and reference continuum images. This will provide opportunities for independent confirmation of the ammonia absorption image as well as allowing others to attempt other processing approaches.
Additional context images taken with the same instrument in other filters will be helpful to interpretation. An example image array for sharing is shown in Figure 10.

Minimum meta-data to be included should be central time of observation, filter bands (including center wavelength and width). Additionally, the instrument, focal length, airmass and derived values like central meridian can be provided.

Finally, if you want to try this yourself, standard astronomical filters for Hα and NII can easily be obtained for the red-side continuum reference. For the in-band image, Edmund Optics 647nm CWL, 25mm Dia., Hard Coated OD 4.0 10nm Bandpass Filter (Stock #65169) will work. For the blue-side continuum reference the 632nm CWL, 25mm Dia., Hard Coated OD 4.0 10nm Bandpass Filter (Stock #65166) will work. It also has the side benefit of capturing the faint OI signal in emission nebulae. Each of these cost $230 at the time of writing. Each requires an empty 1.25” filter cell for mounting. Depending on the brand of filter cell, slight ‘padding’ around the edge may be needed.

6. Summary and Conclusion

This paper has reviewed two years’ experience applying a new filter ratio technique for retrieving qualitative and quantitative ammonia abundances and distributions in Jupiter’s atmosphere. The method is demonstrated to show detail inaccessible with other standard imaging techniques and that may have utility for atmospheric retrieval models, circulation, and convection. Best practices are outlined as well as the equipment needed to replicate this work.

7. References


Abstract

AZ Cas is a 9.3 year eclipsing binary having a Red (mag 9.3) and a Blue component (mag 11), thus the spectrum is dominated by the Red star down to about 4000A. An earlier home-built spectrometer (f3.5, R=3000) has worked well (see SAS 2011), but can only observe one end of the spectrum at a time. Following the original design, I built a new Double Grating Spectrometer (DGS) by adding a dichroic filter to reflect light shorter than 5000A onto a second (“Blu”) grating so both ends of the spectrum could be imaged simultaneously with one camera. This paper will outline its operation, and some of the challenges of the new design. I include early AZ Cas spectroscopic and photometric results.

1. Introduction

The Binary Blues. No, binaries don’t necessarily convey sadness. But if you have a binary like AZ Cas, combining a red giant and a blue giant, the red star will dominate the spectrum. And the blue star is likely to be so faint that obtaining a spectrum of it is very difficult. So, then the Binary Blues are upon you as my ever-loving wife Meg assured me, even as she found music to go along with it: Cue up the “Binary Blues” by Joseph Fiddes.

The basic data on AZ Cas were determined in 1977 by Anne Cowley et al, but little work on AZ Cas has been done since then. The current project involves long term monitoring of the photometry (B, V, R, I) and spectroscopy of AZ Cas. By observing every available night over several years, limits can be placed on “normal” variations of the spectra when the stars are far apart, as well as developing a detailed observation of the events during and after periastron.

AZ Cas is a 9.3-year eclipsing binary having giant red (M0) and blue (B0) stars of masses 18 and 13 solar masses respectively. The red star diameter is about 600 solar diameters (larger than the orbit of Mars), while the blue star is about 36. The red star dominates the light, giving AZ Cas a mag V=9.3, with a blue mag B>=11. Blue spectroscopy of this star at R=3000, even with an 18inch telescope, is challenging due to low light levels.

The orbit is a very eccentric 0.55. The geometry is such that the primary eclipse (blue passing behind red) occurs at phase=0, while periastron (when the two stars are closest and interacting) occurs at about phase=0.1 (~1 year later), and then the secondary eclipse (blue in front of red) is at about phase=0.17. See the schematic in Figure 1.
This report discusses the mix of activities needed to investigate AZ Cas. The goal is to accumulate photo- and spectrometric data that will enable a better model of the AZ Cas system. Four filter photometry is needed to cover both the red and blue starlight. Spectroscopy on the brighter red star is important, but so is coverage of the blue end of the spectrum where there is a lower level of light from the red star, giving at least some ability to observe the blue star more or less directly. Both ends of the spectrum require at least a few hours of observing to get useful spectra. Thus, in an area where the weather allows only about 1:4 nights of even adequate sky condition, it is desirable that the spectrometer be able simultaneously to measure both red and blue ends of the spectrum: Thus, the Double Grating Spectrometer (DGS) concept was born. This report covers both instrumental issues (especially re the DGS), and also a summary of AZ Cas data to date.

2. AZ Cas Photometry Setup and Results

The photometry has its own setup in an observatory about 400 ft from my house, all remote operated, with a C11 on an AP900 mount. The camera is an Atik839, with a modified SBIG CFW8 filter wheel holding B, V, R, and I filters, controlled by MaximDL5. A wider field is provided by using a Reducer (Celestron x3). During the program, earlier colored glass filters have all been replaced with sharp interference filters, which have the great virtue that they do not degrade from humid Maryland weather nearly as fast as the glass filters. After imaging each filter cycle, a simple custom program measures the pixel location of a chosen reference star on the image and moves the telescope to restore any pointing shift. During the night, this system keeps nearly all stars within about 1 pixel of their original location.

An observing session involves taking about 80 sets of images. These are downloaded the next morning to an office computer, where the data are analyzed (taking about 20 min) using MaximDL5 and a custom Excel spreadsheet.

The purpose of this observing program is to record the basic photometric data, especially around the eclipse. The primary eclipse is relatively easy to observe, especially in the Blue. The secondary eclipse has evidently not been observed because the smaller blue star in front of the red star would appear to block at most only about 0.1% of the red star light. 1 milli-mag photometry to distinguish the eclipse of an intrinsically variable red star would appear to be a substantial challenge.

Roughly predicted dates of interest include:

- Primary eclipse: Mar. 2022-June 2022
- Periastron: April 2023
- Secondary eclipse: Feb. 2024

There are few AZ Cas data in AAVSO. In this observing program, the observed field is about 14x25 a-m, and includes the target and eight other reference stars identified in the AAVSO database. Due to the wide range of star brightness in the field, exposures for each filter vary from 12 to 80s. Thus, each night, given 40-80 images, the total duration on each filter was rather short, leading to some scintillation errors.

On March 15, 2022, the primary eclipse (blue star behind red) began in B and V filters, as shown in Figure 2. The prior work by Cowley had shown that the entry and exits of the primary eclipse each last about 10 days, while the eclipse lasts about 100 days. Photometric observations are on-going.

3. AZ Cas Spectroscopy Setup (including the DGS)

The spectroscopic observing system is also in its own observatory, also about 400 feet from the house, and remote operated. The telescope is a homebuilt f3.5 18-inch Newtonian, mounted on an AP1200 mount (see Menke 2012 and 2013).

The AZ Cas light is dominated by the brighter red star (about 9.3 mag), with the smaller blue star at about mag 11-12. The spectrum is virtually all due to the red star, down to about 4000A where the blue star spectrum begins to dominate. AZ Cas is classed as a Be star, having emission in the Ha and other regions of the spectrum. This emission in AZ Cas can be highly variable, with huge changes in only a few hours.
(as shown by serendipitous measurements by Menke 2019).

In general, as a spectrograph resolution is increased, the bandwidth (the range of recorded wavelengths) shortens. Thus, most spectrographs that cover the visual range (roughly 4000-7000Å) have a rather limited resolution of less than R=1000, with a wavelength resolution of around 5Å. One method for avoiding this limit is to use an echelle optical system which converts the single trace spectrum into multiple traces on the same image. This system has its own issues, including that it is not very suitable for amateur construction.

To resolve the spectral lines reasonably well requires a spectrograph resolving of at least 3000. In 2011 I built a fast f3.5 R=3000 spectrometer (f3.5 to match the 18-inch telescope) which I have used for many observations, including my long-term observing program of AZ Cas beginning in 2019. This spectrometer has the name Fast Spectrometer #1, or FS1. Sporadic observations of AZ Cas started in 2012, but since 2019, I have observed AZ Cas on *every* available night (about 1:4 in Maryland), generally observing the 6100-6700Å region. Because the spectrometer showed itself to be highly stable, I have even been able to measure variations in the Doppler shift of the red star using a nearby (in the sky) comp star as wavelength reference. With this method, I have been able to measure the Doppler shift of the red orbiting star to a precision of about 0.2Å (10km/s), a precision about 10-20x the resolution. These data may be able to improve the binary orbit solution.

At least 3 hours of observations are desirable. Each hour comprises roughly 9x5 min on AZ Cas, 1x5 min on SAO11931 (a nearby B star), and 1x5min on SAO11927 (a nearby K2 star, similar to the red component of AZ Cas). The narrow Ha region absorption and other lines in the K2 star provide an excellent wavelength reference for the Doppler measurement.

In other tests with FS1, attempting to observe the blue star by shifting the grating to the blue end of the spectrum failed due to insufficient signal level. However, as I continued to work the star, given the limited number of observing nights, it became clear that if I wished to measure the blue signal and still keep track of the red signal, it would be necessary to have a spectrometer that would measure both the red and blue ends of the spectrum simultaneously to make best use of limited observing time.

4. Development of the Double Grating Spectrometer (DGS)

Starting with the basic spectrometer design as proved in the earlier spectrometer, I developed a design that would incorporate a second grating. Using a dichroic filter, I could reflect the blue portion of the spectrum into a new “Blu” grating, while allowing the red portion to pass through to the “Red” grating (both are 1200 l/mm). By tilting the gratings slightly, I would then see the two spectral traces, one above the other on a new, more blue sensitive camera.

The spectrometer would still be a Littrow design, in which the light enters the slit, passes through the collimator/camera lens where it is made parallel. The light then passes to the gratings, where it is diffracted back as diverging rays. The light reenters the collimator lens, now used as the camera lens, and is then focused onto the camera sensor. With a fast f3.5 design to match to the f3.5 18 in. telescope, this design is susceptible to astigmatism and other distortions, especially if only a simple achromat is used for the collimating lens, as is the case here. The earlier spectrometer had shown that these errors were acceptable in this application.

That was the theory: but in practice, things are never simple! Indeed, three different versions of the DGS were built as the design became more refined. The f3.5 design leaves little space for adjustments.

As with the FS1, the DGS was built in a 3x3inch aluminum box channel. The gratings were each held in fairly simple mountings allowing for manual (knob) rotation providing the wavelength setting. The same input design as in the previous spectrometer was used, including a pellicle (thin) partial 8% reflection to an off axis guiding camera, with the remainder of the light traveling to the 50u slit. The slit is 3mm tall, allowing for easy sky background subtraction.

As before, the guiding system, once aligned, allows the star image to be placed easily on the 50u slit, with guiding maintained to a precision of about 3u. A major benefit is that the guide camera provides a field of view of about 6x8a-m, so it is usually easy to locate the target star and move the scope to put the star on the field pixel corresponding to the slit location.

Initially, to reduce the optical path lengths, the gratings were angled slightly toward one another. However, the resulting ghost images were so pervasive that the spectrometer was rebuilt so that the gratings faced away from each other.

The dichroic required a special order (from Chroma, Inc). It is 50x75mm, 2mm thick, anti-reflection coated on the rear (red) side, and roughly 1/4 wavelength flat, with a wavelength transition at about 5100Å. After construction, experimentation was also
required to learn how to mount the dichoric without applying bending forces that would distort the blue (reflected) spectral trace.

The camera was a major issue. The FS1 spectrometer used an SBIG STF8300 camera. Although more blue sensitive than previous cameras, it was still limited, and most really sensitive cameras were extremely expensive. However, the ZWO 2600MM (monochrome) became available at this time, at an introductory price of $2000. It had a bigger sensor (allowing a wider bandwidth by providing a wider span spectrum) and was very sensitive (approaching 80%) in blue. With Covid delaying shipments, it took a while to arrive, and when received, the camera window had a defect that ZWO replaced some months later. The camera uses ASCOM control software, which works reasonably well with MaximDLV5 program (under XP). This camera has a very small pixel of 3.5u. Because the spectrometer design assumed a 9u pixel, I normally run at Bin=2. While the larger ZWO sensor allows a broader spectral length, it also requires increased the angular acceptance of the optical system, increasing effect of aberrations and requiring even tighter alignment.

Once assembled and working, I found a series of faults, the most serious being resolutions of around 5-15A vs the ~2A I had seen in the previous spectrometer! Most of the faults were traced to inadequate alignment of the instrument. Measurements and rough calculations showed that at f3.5 the collimator must focus the slit to very high precision: the light leaving the collimator must be parallel to about 0.01deg, implying a collimator focus precision of about 0.1mm (about 0.004inch, 1:1000). If the light is not parallel, the resolution is also degraded, and the diverging light to and from the Blu grating will expand the blue spectral trace. The alignment method, and more discussion of alignment issues, is provided in the appendix to this paper.

A second fault was in the use of a standard inexpensive telescope elliptical for the inlet reflector. This led to major distortions of the spectrum and was resolved by using a 1/8 wave elliptical mirror.

The weight of the DGS is about 8.5lb. This is mounted on an 18-inch Newtonian, which itself is mounted on an AP1200 telescope mount. The focuser used is a modified Clement, 2-inch focuser, a model no longer in production that easily handles this load (other focusers may not). The focuser is driven by a RoboFocus digital system, and allows precise, very low backlash focusing to the needed 0.1mm precision.

When this project began, I assumed that it would take 3-4 months to complete (similar to the earlier, similar spectrometer). However, the presence of a reflected beam, and the need for both the red and blue light to be in exact focus at the same camera position drove the more complex alignment and demanded higher quality components. Nevertheless, early on, there were encouraging signs of successful blue (star) spectrum detection, so it appeared worthwhile to continue the project, and it finally did result in success.

Overall, this spectrometer design has met the objectives. It is relatively easy to build (after the learning curve)—only basic machine tools (lathe and mill) and skills are needed. The cost is about $3000 plus camera. A schematic for the DGS is in Figure 3 (at the end of the paper).

5. AZ Cas Spectroscopic Observations

My own spectroscopic data for AZ Cas goes back to 2012. As part of trying out the new FS1 spectrometer (single grating), I began observing various Be (hot Class B stars showing at least some Hydrogen line emission lines). In 2012 I had stumbled on AZ Cas, where, by chance, I observed an immense change in the Ha line (6563A) in a few hours, at that time, at about phase=0.04. Although I made several more observations in the following years, I never again saw such “wow” behavior. Upon learning more about AZ Cas in later years (mostly via Cowley), I decided to pursue a more systematic investigation in an attempt to gain improved data on the system than was available in 1977.

As those observations progressed, mostly using the FS1 spectrometer, it became clear that AZ Cas showed rather wild swings in its spectrum during the time from phase=0 even to about phase=0.6, which is when I started my more intense observations (ie, all feasible nights). After phase=0.6, most of my data have been “boring”, with only minor, but very definite spectroscopic variations occurring. One conclusion of this is that the spectroscopic disturbances are clearly not simply related to the distance between the two stars, but also to how recently the periastron had occurred. That is, periastron apparently leads to a series of changes in the system that cause fairly violent spectrum changes for up to five years (half the orbit) before dying out. During the next five years, relatively weak (but so far unexplained) changes continue to occur.

Figure 4 shows a typical FS1 Ha red region spectrum, this from Jan 21, 2021showing a broad Ha emission structure that has an offset (blueward) absorption feature. The general very broad emission feature is hand drawn in dotted red, superimposed on the actual AZ Cas spectrum data. These features, including the amplitude of the general emission feature, the depth of the absorption line at 6562A, and especially the “wiggles” on the red side of the emission feature all wax and wane in apparently random times of hours to weeks. The green curve data
and absorption line is Hα from K2 star SAO11927 used as a reference (offsets are due to Doppler effects). The black line is the broad Hα absorption from SAO11931, presumably from rotational broadening, and is used only for rough verification of system operation.

The first and most obvious question was “does this AZ Cas emission/absorption feature originate in the red or the blue star? With various theories from various astronomers echoing in my ears, the question was answered in March 2022 as the blue star was blocked at the beginning of the primary eclipse: the Hα spectroscopic features remained unchanged, proving that the Hα feature is generated by the red star. Of course, the presence of the blue star is presumably essential in providing the energy or the gasses in the surrounding space to cause at least some of these spectral effects.

![Figure 4. AZ Cas H-alpha Region](image)

Switching to the DGS, although not fully completed, I did obtain preliminary blue spectral data during the first several months of 2022 to serve as a reference. For example, Figure 5 (at end of the paper) shows the blue spectrum from Feb 21, 2022, a month before the eclipse. The stars light intensity decreases rapidly as the wavelength shortens, but it is obvious that there is still usable signal down to perhaps 3900A. The data from the three sources were normalized to “1” at about 4000A. The AZ Cas data have been averaged over +/- 4 pixels to counter high noise levels due to very small signals.

On average, the AZ Cas wavelength intensity tracks the K2 reference star SAO11927 rather closely (normalized at 4000A), but below 4100 begins to exceed the K2 ref. star as the contribution from the blue star becomes relatively brighter. This is shown in Figure 6 (at end of the paper) that shows an expanded view of the data below about 4000A. Here the difference between the two spectra is obvious, as are some of the spectral features (as well as the noise component of this very limited data).

It should be noted that at this time (mid 2022), AZ Cas is very low in the sky during observing hours. More photometric and spectroscopic observations are needed throughout the next 3-4 years as the interaction events unfold.

6. Conclusion

The Double Grating Spectrometer has proved to be a useful tool for observing both red and blue parts of the spectrum simultaneously. Because the resulting blue and red spectra are standard, linear, and well behaved (unlike many echelles) the observer can use standard methods to analyze the spectra.

The observations of AZ Cas are ongoing. As of this date, the eclipse/periastron events of 2022-4 have begun. The primary eclipse should end by about June 2022. As the stars continue to approach periastron in mid-2023, the stellar interactions are expected to occur. In the past, these have been seen to vary widely even within a few hours, so continuing observations will be useful.

Unfortunately, at this time there is no central location that is compiling AZ observations other than limited data within AAVSO. Hopefully, individuals will take care to preserve their observations and to provide access to them on the internet so they can be found by later researchers. The author of this paper would also be glad to receive notification of the availability of photometric or spectroscopic data sets for AZ Cas.

7. References


Appendix 1 – DGS Alignment

The first step in aligning the DGS is rather simple. Install a small laser in the inlet, mounted on the centerline. Check that the laser beam strikes the elliptical in the center, then that it strikes the Collimating Lens (CL) to the left of center and then on to the center of the red grating. This assures maximum light reaching the gratings.

The f3.5 DGS has two gratings and it is highly desirable that the spectra from each grating both be in focus at the camera. Because there are small differences in path length between the Blu and Red gratings (including that the red grating has two passes of the thickness (at 45deg) of the dichroic), when the diffracted light leaves the gratings one will diverge/converge more than the other, leading to different vertical heights and dispersion of the spectra. This can be avoided if the light from the collimating lens (CL) is precisely parallel, i.e., that the CL focus relative to the slit is accurately set to infinity. The precision needed is quite high—approximately 0.02 deg of divergence, equivalent to about 0.1mm (.004inch, 1:1000) of CL positioning with respect to the slit. Because light in the Blu channel is reflected twice, this makes the collimation particularly important for the Blu channel even though, as in our case, it is the red channel that is getting data of the most significance. Note that the fast f3.5 makes all the settings even more critical.

This is one reason for precise CL alignment. The second is that slight divergence of the beams will also degrade the resolution, again, especially with respect to the Blu grating. The precision required to avoid this problem is slightly more relaxed than the above requirement but is of the same order.

One of the challenging issues is also to assure that the slit is the plane of the source light for the CL when it is being measured for focus. This is not a given: if the telescope focuses light inside or outside the slit plane, then that focus position, albeit bounded by the slit, will be the incorrect but effective source for the CL. Therefore, the CL focus position must be set relative to the physical slit, and the telescope must also be focused there.

Thus, the critical issue of alignment (in addition to getting maximum light through the instrument) is to set the collimation of the collimation lens as accurately as possible: Just getting collimation “close” is not good enough. Given the need to make very small adjustments in the CL position, and to avoid jostling the instrument whenever an adjustment needs to be made, I installed a small stepping motor/screw adjustment remote operating mechanism.

After working with several different alignment schemes, the chosen one has only two steps (neither requiring an artificial star):

- Adjust the CL focus to infinity
- Adjust the camera focus

Remove the red grating. Install a neon lamp (NE2) shining into the back of the pellicle, with a diffuser between the lamp and pellicle. This will provide a diffuse light onto the slit. Attach a lens (in this case, a 50mm diameter f3.5) to the camera and adjust it to focus on infinity (very distant trees, etc) to make a telescope. Aim the telescope into the red grating (grating removed) end of the DGS and image the illuminated slit via the collimator lens. Adjust the collimator lens for sharpest slit image in the camera. If the “telescope” lens is equal to the collimator lens, the magnification of the slit is “1”, so the slit width in the camera should equal the physical slit, but this is not a requirement. The CL is now set to infinity.

Now replace the red grating and camera in their proper places and observe the neon spectrum. Adjust the camera focus for best image.

The system is now aligned. The camera and CL focus should not be touched again. When the telescope image is placed on the slit, adjust the focus of the telescope for sharpest image.

Note. Thanks to Steve Conard for his great help in developing this alignment recipe. Also note that a variety of different alignment methods can be used, but the method described here appears as good as any, and much simpler than most.
Figure 3. Double Grating Spectrometer (DGS) Schematic

Figure 5. AZ Cas blue spectrum.
Figure 6. AZ Cas detail of blue spectrum.
Speckle Interferometry of 53 Aqr AB solar-like candidate binary star system projected to be close to Periastron

Mark Harris  
Oorsprong Science  
300 Colonial Center Parkway  
Suite 100N  
Roswell, GA, 30076  
mark@oorsprong.science

Robert Baker  
Wildwood School, Los Angeles, CA  
2453 30th St.  
Santa Monica, CA 90405  
rbaker314@gmail.com

Kelcey Davis  
Brown University  
69 Brown St Box 1822  
Providence, RI 02912  
kelcey_davis33@gmail.com

Pat Boyce  
Boyce Astro Research Initiatives and Education Foundation (BRIEF)  
San Diego, CA  
pat@boyce-astro.org

Grady Boyce  
Boyce Astro Research Initiatives and Education Foundation (BRIEF)  
San Diego, CA  
grady@boyce-astro.org

Abstract

53 Aqr AB is a solar-like G2 and G3 double star projected to be a gravitationally bound binary system with a possible periastron in 2023 (Hale, 1994). Alternative more recent ephemerides from Izmailov and Tokovinin (Anton R., 2021) project an earlier 2021 periastron. 10,000 short exposure high magnification image sequences of 53 Aqr AB were taken during October to November 2021, and new separation distance (Rho) and position angle (Theta) measurements were calculated, using accurate bispectrum speckle interferometry analysis software (Rowe D., 2020). The new 2021.8 Rho was measured to be 1.3 +/- 0.1 arc seconds and Theta = 97.6 +/- 0.6 degrees. These measurements combined with historical data from the Washington Double Star catalog (WDS, 1961), more recent measurements by Rainer, Tokovinin (Anton R., 2021) and others, continue to support the double star being a true binary system (Hale A., 1994), with an ephemeris close to the Hale projection, and even closer to the Tokovinin ephemeris. Periastron was projected to have occurred at 2021.3 +/- 0.6.

1. Introduction

53 Aqr AB (22266-1645, SHJ 345AB) should reach periastron in this decade, and in 2023, according to the projected ephemeris calculated in Dr Alan Hale’s dissertation published in 1994 (Hale, 1994). We took short exposure images and processed them using bispectrum speckle interferometry techniques (Labeyrie, 1970). We determined the current separation distance (Rho) between the double star A and B components and the position angle (theta) of B to A. Historical data was obtained from the Washington Double Star catalog (WDS, 1961). Additional data was obtained from the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf et al., 2001) using the Stelle Doppie Double Star Database tool (Sordiglioni, 2009).
53Aqr (Figure 1) is a potential 4-star gravitationally bound system (WDS, 1961). 53 Aqr AB are solar-like G2V and G3V bright nearby yellow stars of Magnitude 6-7 with key parameters shown in Figure 2. The 53 Aqr AB double star system was discovered in 1800 by South & Herschel (WDS, 1961).

53 Aqr AB also met the selection criteria in Figure 3, which define the ideal parameter ranges for the telescope and camera configuration that was used for spectral interferometry images, as described in Section 2.

53 Aqr was also observable in October to November 2021 from the Boyce Astro Remote Observatory (BARO) in San Diego, CA, USA.

<table>
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<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>Discoverer Code</td>
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</tr>
<tr>
<td>First Observed</td>
<td>1800</td>
</tr>
<tr>
<td>Last Observed</td>
<td>2019</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>270</td>
</tr>
<tr>
<td>First</td>
<td></td>
</tr>
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<tr>
<td>Separation</td>
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<tr>
<td>Epoch</td>
<td>1800</td>
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<tr>
<td>Last</td>
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<tr>
<td>Separation</td>
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</tr>
<tr>
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<td>G3V C</td>
</tr>
<tr>
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<tr>
<td></td>
<td>(B) 6.83</td>
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<td>Magnitude - Secondary</td>
<td>(V) 6.32</td>
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<tr>
<td></td>
<td>(B) 6.96</td>
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</table>

Figure 1: 22266-1645, SHJ 345AB, 53Aqr. Credit: Aladin 11

Figure 2: 53 Aqr Stellar Parameters

<table>
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<th>Criteria</th>
<th>Unit</th>
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<td>AB Stars</td>
<td>Mag</td>
<td>Brighter or equal to 12</td>
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<td>Separation ρ</td>
<td>arc second (as)</td>
<td>1″-3″</td>
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<tr>
<td>Observations</td>
<td>Count</td>
<td>&gt;= 20</td>
</tr>
</tbody>
</table>

Figure 3: Selection Criteria

2. Equipment and Methods

2.1 Equipment

The Boyce Astro Research Observatory (BARO) was used for the Speckle Interferometry images. 5000 images were taken for the double star system using the Planewave Corrected Dahl-Kirkham (CDK) 17 telescope (Figure 4) with focal length of 2939mm and aperture of 432mm, on the Planewave L-500 mount (Figure 5). The mount was re-calibrated using plate solving prior to taking the images.

It is located at the San Diego Astronomy Association’s observing site near Tierra Del Sol, California (32° 36’ 48” N; 116° 19’ 55” W; 3710 feet elevation or 1131m altitude).

Figure 4: BARO’s Planewave CDK-17 Telescope at sunset

Figure 5: Equatorial Planewave L-500 Mount
BARO was remotely operated with a roll-off roof design (Figure 7). The roof rolls to the west, limiting the western observable altitude to ~35°. The north and south limiting altitudes are ~0°. A flap folds down to the east which enables ~28° limiting altitude.

2.2 Speckle Interferometry

Speckle Interferometry images used the BARO Observatory equipment and camera settings exactly as defined in Section 2.1. Observing sessions started with focuser calibration. Continuous test images were taken prior to starting the speckle imaging, to visually optimize the contrast of the Speckle, by setting the exposure time. Depending upon seeing conditions and airmass the optimum exposure times varied between 5-15 ms during these observations. Sequences of 5,000 short exposures for the 53 Aqr system were taken with the ZWO camera with a gain setting of 250.

Identical sequences of images with the exact same settings were also taken for a reference star located within a few degrees of the target system. 50 Aqr was chosen as the reference single star, as it is close by, has a visual magnitude of 5.75, compared to the Target A and B components of 6.2 and 6.3 magnitudes respectively, and is also of a similar color to the target system, being a G7 star.

Figure 8 shows an example of the short exposure high magnification images obtained. Figure 11 in Section 3.1 shows the observing log information for the 53 Aqr system images.
Image processing used the Speckle ToolBox 1.15 Version 4.0 (Rowe D., 2020) software application. Firstly, FITS data cubes were created for each 53 Aqr image set and the reference star, on each observation night, using the exact same number of speckle images for each FITS data cube. Bispectrum processing of each of the two FITS data cubes was then selected using the software, to produce the triple correlation data cube for the reference. Finally, bispectrum phase reconstruction processing was selected using both the target and reference bispectrum cubes. This created the final diffraction-limited image of the double star system. Having reference star data allowed the deconvolution to remove optical aberrations from both the double star and reference star images. Figure 9 shows an example of the final image of a double star system using the Speckle ToolBox software.

![Figure 9: 03073-0824 final processed image using the Speckle ToolBox software. A is the primary star and B is the secondary. m, n and Airy rings around B were artifacts created by the bispectrum speckle interferometry processing that were ignored.](image)

The photometry tools in the Speckle ToolBox were then used to make Rho and Theta measurements using the final images. First, an aperture was placed in a useful background area of the image. A second aperture circle sized to enclose the standard deviation edge of the Secondary star B was then applied manually using the software, followed by a third aperture circle around the Primary star A. Figure 10 shows another example of the measurement apertures added to a final reconstructed image. m and n image features as well as the Airy rings around B were just artifacts produced by the mathematical processing of the final image and were ignored.

After entering the mount calibration degree offset and camera arcsec per pixel numbers for the telescope and camera configuration used, the Speckle ToolBox calculated the new Rho separation in arcsecs and Theta position angle in degrees.

Speckle interferometry final images with Rho separation and Theta position angle measurement results for 53 Aqr, are shown in Section 3, with measurements stated in Figures 14 and 15.

![Figure 10: Speckle interferometry image after processing 03073+0824. Primary star A, Secondary star B and background reference Z.](image)

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<td>2459514.583</td>
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<tr>
<td>Julian Date 2</td>
<td>2459522.583</td>
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</tbody>
</table>

Figure 11: Observation Log

3. Data

3.1 Speckle Interferometry Images

Speckle images of 53 Aqr AB were produced using the telescope and equipment at BARO as laid out in the Observation Log (Figure 11).

Short exposure high magnification speckle images were taken during the observing sessions and processed using the Speckle Toolbox. Both final images from the two observing sessions are shown in Figures 12 and 13. These final images include 5000 Speckle images taken each observing night with a camera gain of 250, and exposure times varying between 5ms and 15 ms.
Figure 12: Speckle interferometry image of 53 Aqr AB from Observation Night 1. Primary star aperture is circled central star image, Secondary star aperture is circled right-hand star image, and background reference is circle in top right-hand side. Left-hand apparent star image is just a mathematical artifact from the speckle processing.

Figure 13: Speckle interferometry image of 53 Aqr AB from Observation Night 2. Primary star aperture is circled central star image, Secondary star aperture is circled right-hand star image, and background reference is circle in bottom right-hand side. Left-hand apparent star image is just a mathematical artifact from the speckle processing.

Figure 14: Final Rho (Separation) Results

<table>
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<th>Measurement</th>
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<tbody>
<tr>
<td>Mean Rho $\rho$</td>
<td>1.25 as</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.071 as</td>
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<tr>
<td>Standard Deviation of the Mean</td>
<td>0.050 as</td>
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</table>

Figure 15: Final Theta (Position Angle) Results

<table>
<thead>
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<th>Parameter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mean Theta $\theta$</td>
<td>97.55°</td>
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<tr>
<td>Standard Deviation</td>
<td>0.778&quot;</td>
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<td>Standard Deviation of the Mean</td>
<td>0.550°</td>
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</table>

Figure 16: 53 Aqr Historical Data Plot from WDS

Averages across all Rho (Separation) and Theta (Position Angle) measurements for each batch of images were taken to calculate the results. Our Speckle Results are shown below in Figures 14 and 15.

3.2 Historical Data

The Washington Double Star Catalog (WDS, 1961) provided the full historical set of observation data for 53 Aqr AB (Figure 16).

3.3 Ephemerides and Specific Measurements

3.3.1. Hale Ephemeris

Dr Hale’s dissertation (Hale, 1994) proposes that most solar-like double stars are likely to be co-planar (implying matching inclinations of the star pairs) and gravitationally bound binary systems. We call this the Hale Ephemeris in this paper. 53 Aqr was one of the key solar-like double star systems that Hale calculated a projected ephemeris, based on orbital elements arising from various characteristics of solar-like stellar profiles. Figure 17 shows some of the calculated orbital elements. In particular, the Period is projected to be ~3,500 years and the Periastron is expected to occur in 2023. The eccentricity of the system is projected to be a high 0.90 as demonstrated in the ellipses image produced in the ephemeris work (Figure 18). Also, the inclination angle is high at ~44 degrees, which means that the apparent shortest separation distance will occur just before the true actual periastron.
3.3.2. Izmailov Ephemeris

Izmailov (Anton R., 2021 & Izmailov 2019), has performed his own orbital element projections and speckle observations for 53 Aqr based on WDS historical data and newer observations spanning several years, projecting a different ephemeris. Izmailov projected the periastron to have occurred in 2021, the ephemeris differing greatly from Hale’s ephemeris, with a projected Period of only ~600 years (Anton R., 2021). Figure 20 at the end of the paper shows Rho and Theta variations by Epoch, between the various Ephemerides.

3.3.3. Tokovinin Ephemeris

Another very recent ephemeris (Anton R., 2021) is very close to Hale’s ephemeris, with a similar 0.90 eccentricity and a little lower 37.1 degrees inclination angle compared to Hale’s 44.1. Also, the orbital period is estimated to be ~2000 years, much closer to Hale’s 3500 years than Izmailov’s 600 years. Figure 20 has the comparison graph, and Figure 21 shows a subset of the Tokovinin ephemeris data alongside the Hale numbers.
4. Discussion

The WDS historical data in Section 3.2, Figure 16 shows a strong elliptical arc that implies 53 Aqr AB could be a binary system pair. The sharper theta curve in the recent WDS measurements, with ~4 degrees increase per year measured in recent epochs (see Figure 21 data), also supports Hale’s projected high eccentricity and a possible periastron around this part of the century.

Hale’s high inclination i of 44.1 degrees and Tokovinin’s i=37.1 degrees are supported by the shortest apparent Rho separations being observed before the projected periastron (see Figure 21 below for Rho minimum: in 2014 for Hale, and 2016-2017 for Tokovinin. These Rho minimums are highlighted by the dashed rectangles in the table).

Figure 20 shows the Izmailov ephemeris moving sharply away from Hale and Tokovinin ephemerides as well as the recent professional speckle measurements, starting around 2018. This must imply that the short 600-year period is incorrect. By contrast the close correlation and close parallel path of the Hale, Tokovinin and recent professional speckle measurements all support a longer orbit period of 53 Aqr, somewhere closer to ~2000 and up to ~3500 years (referencing Tokovinin and Hale projected periods respectively).

Our Harris et al measurements late in 2021, reported in this paper, and highlighted in Figure 20, added recent new accurate measurement extensions using the same best practice Speckle interferometry. The average Harris et al Theta measurement of 97.6 +/- 0.6 degrees for the 2021.8 epoch closely correlates with and extends the professional speckle interferometry measurements of this double star system, since the 2000 millennium epoch. The Harris et al results also closely match the Tokovinin ephemeris.

The Tokovinin ephemeris projected the periastron of 53 Aqr AB to be 2021.21. Using our new actual measurement at epoch 2021.8, we used this extension of measurements to re-calculate the periastron epoch, by adding our more recent data point to the Tokovinin ephemeris data of Figure 21. This calculation is shown in Figure 22.

According to Tokovinin (Tok), Theta increased by ~4.737 degrees between the 2021.0 and 2022.0 epochs (see equation (1) in Table 22.) The Tokovinin theta angle at the Tok periastron epoch is calculated by equations (2), (3) and (4). The Theta angle at the Tok projected periastron was calculated to be ~94.60 degrees.

Given our Harris et al measurement of Theta was 97.6 +/-0.6 degrees at epoch 2021.8, this means that the periastron must have already happened, shortly before we made our measurements in 2021.8. In fact, Theta had increased by ~2.95 degrees between just the time of the Tok projected periastron and the Harris et al. 2021.8 epoch (equation (5) in Table 22).

The actual later measurement of Theta = 97.55 degrees at epoch 2021.8 was then used to update the projected periastron epoch. This was started by taking an average of Theta rate change per Epoch between 2021 and 2021.8 (equation 6). The already estimated 2.950 degrees Theta increase from periastron to the measured 2021.8 epoch value was then divided by the average of Theta change per Epoch (Equation (7)). This gave the proportion of an Epoch earlier when the Periastron had occurred. By subtracting the Equation (7) result from Epoch 2021.8, we have the updated Periastron Epoch as 2021.3 +/- 0.6 (Equation (8)). This has hardly changed the 2021.21 Tokovinin ephemeris projection of the periastron epoch.

5. Conclusion

The speckle interferometry results from Harris et al and other recent professional speckle interferometry measurements of the 53 Aqr AB system, certainly support an ephemeris close to the Hale projection and an ephemeris even closer to the Tokovinin projection. These results certainly imply that 53 Aqr AB is a gravitationally bound binary system that recently underwent periastron around 2021. Based on the highly correlating Tokovinin ephemeris, we estimate that Periastron T occurred at 2021.3 +/- 0.6.

The Period P of the 53 Aqr AB system is projected to be less than 3,500 years estimated by Hale, and close to 2,000 years as projected by Tokovinin, given the closer correlation of recent speckle measurements by Harris et al and others. Given the high eccentricity of the system this is a challenging calculation to build with high accuracy at this time, but the period is likely
to be several times larger than the Izmailov 600-year projection, based on the Harris et al and recent professional speckle interferometry measurements this century.

The high inclination of the system to our apparent view is also likely to be close to the ~37 degrees of Tokovinin, a little lower than the Hale ~44.1 degrees.

The closeness of the Hale ephemeris to the Tokovinin one across eccentricity, inclination, and periastron orbital elements, certainly continues to provide support of the co-planar orbit projection that the Hale ephemeris is constructed upon.

Our plan is to continue making several annual speckle interferometry measurements of the 53 Aqr AB system for the next 3-5 years, so that a much more accurate calculation of the orbit can be achieved, planning more comprehensive orbital element analysis, along with utilizing additional Gaia data as that becomes available.

6. Acknowledgements

This paper was supported by the Boyce Research Initiatives and Education Foundation (BRIEF), San Diego, California, USA.

A special thanks to Dr Alan Hale for his suggestion to consider new Speckle Interferometry images of 53 Aqr, to see if his projected ephemeris is accurate, and for additional recent Speckle observation data from other sources.

A special thanks to Dr Rainer Anton for further recent Speckle observation data of his own and for ephemeris information.

Thanks to Dave Rowe, CTO of Planewave Instruments, Adrian, MI, USA for the creation and use of the powerful Speckle Toolbox.

A special thanks to Richard Harshaw of Brilliant Sky Observatory, AZ, USA for his direct advice and guidance in speckle interferometry during this research.

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Finally, a very special thanks to Pat and Grady Boyce of BRIEF for their amazing training and direction, without which this research would not have been possible, and to Keelsey Davis for extended review and mentor support.

This material is based upon work supported in part by the National Science Foundation under Award 2040433.

This research has made use of the Washington Double Star Catalog (WDS, 1961), maintained at the U.S. Naval Observatory, the World's principal database of astrometric double and multiple star information.

This work has made use of data from the European Space Agency (ESA) mission Gaia. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

This research has made use of "Aladin sky atlas" developed at CDS, Strasbourg Observatory, France

7. References


Washington Double Star Catalog (WDS), maintained by the United States Naval Observatory (USNO). (1961).


Sordiglioni, G., Stelle Doppie is a Double Star Database using the Washington Double Star Catalog. (2009).


Figure 20: 53 Aqr AB system Theta angle in degrees versus Epoch: for Hale, Izmailov and Tokovinin ephemerides, and Harris et al and other recent speckle measurements.
Variable Blue Straggler Stars in Open Cluster NGC 6819
Observed in the Kepler ‘Superstamp’ Field

Joyce Ann Guzik
Los Alamos National Laboratory, MS T-082, Los Alamos, NM 87545
joy@lanl.gov

Andrzej S. Baran
ARDASTELLA Research Group, Pedagogical University of Cracow, Poland
Embry-Riddle Aeronautical University, Department of Physical Sciences, Daytona Beach, FL 32114

Sachu Sanjayan
ARDASTELLA Research Group, Pedagogical University of Cracow, Poland
Centrum Astronomiczne im. Mikołaja Kopernika, Warsaw, Poland

Peter Nemeth
Astronomical Institute of the Czech Academy of Sciences, Czech Republic
astroserver.org, Fő tér 1, 8533 Malomsok, Hungary

Anne M. Hedlund
Department of Astronomy, New Mexico State University, Las Cruces, NM 88003

Jason Jackiewicz
Department of Astronomy, New Mexico State University, Las Cruces, NM 88003

Abstract

NGC 6819 is an open cluster of age 2.4 Gyr that was in the NASA Kepler spacecraft continuous field of view from 2009 to 2013. The central part of the cluster was observed in a 200 x 200 pixel ‘superstamp’ during these four years in 30-minute cadence photometry, providing a unique long time-series high-precision data set for asteroseismology. NGC 6819 is of interest because stars near the main-sequence turnoff are somewhat more massive than the Sun, near the expected mass range for γ Doradus-type variables, which pulsate in non-radial gravity modes with periods of around 1 day. The cluster also contains blue straggler stars, i.e., stars on the main sequence above the cluster turnoff that should have left the main sequence to become red giants. The NGC 6819 blue stragglers have the right temperatures to show δ Scuti-type pulsations, i.e., acoustic-mode pulsations with periods of around 2 hours. We present light curves and pulsation frequency analyses derived from custom photometric reductions for five confirmed cluster members—four blue stragglers and one star near the main-sequence turnoff. Two of these stars show a rich spectrum of δ Scuti pulsation modes, with 236 and 124 significant frequencies identified, respectively, while two stars show mainly low-frequency modes characteristic of either γ Doradus pulsations or global Rossby modes. The common age and element abundance for the cluster members, considered along with the frequencies extracted from the light curves, will provide valuable constraints for asteroseismic analyses, and may shed light on the origin of the blue stragglers. The fifth star has an unusual spectrum, showing only several harmonics of two main frequencies. This star is a known active x-ray binary, and it may be an RS CVn variable.

1. Introduction

NGC 6819 is an open star cluster in the constellation Cygnus (Fig. 1a) discovered by Caroline Herschel in 1784.¹ NGC 6819 is about 2.4 billion years old (half the age of the Sun) and around 8000 light-years away (Basu et al. 2011, Balona et al. 2013, Brewer et al. 2016). This cluster was in the NASA Kepler spacecraft (Borucki et al. 2010; Gilliland et al. 2010) continuous field of view from 2009-2013 (Fig. 1b). The central part of the cluster (Fig. 1c) was observed during these four years in 30-minute cadence

¹ https://en.wikipedia.org/wiki/NGC_6819
photometry, providing a unique long-time-series high precision data set for asteroseismology (Kuehn et al. 2013). Studying clusters is advantageous for asteroseismology because the cluster members formed together, providing additional modeling constraints such as a common age and element abundances.

Since the cluster is younger than the Sun, the stars at the cluster main-sequence turnoff are somewhat more massive than the Sun, near the expected mass range for γ Doradus-type pulsating variables which pulsate with gravity-mode periods of around 1 day (Aerts et al. 2010). This cluster also contains “blue stragglers” stars, i.e., stars on the main sequence above the cluster turnoff that should have already left the main sequence to become red giants (Fig. 1d). Blue stragglers are believed to have formed either via stellar mergers or mass transfer from a companion sometime in the star’s past (Rain et al. 2021). The NGC 6819 blue stragglers have the right temperatures to show δ Scuti-type pulsations, i.e., acoustic-mode pulsations with periods of around 2 hours (Aerts et al. 2010). If pulsations are found, stellar modeling and asteroseismic analysis may help to better understand the origins of these blue stragglers.

We discuss light curves derived from *Kepler* NGC 6819 superstamp data and pulsation frequency analyses for five confirmed cluster members. Four stars are blue stragglers, and one is near the cluster turnoff.

![Figure 1a. NGC 6819 image from Wikipedia (source Stellarium, photo credit Roberto Mura). The image is approximately 42 x 32 arc minutes. The north celestial pole is toward the top; increasing right ascension (east) is to the left.](https://commons.wikimedia.org/wiki/File:Kepler_FOV_hiRes.jpg)

![Figure 1b. Zoom-in on *Kepler* original mission field of view showing location of NGC 6819 in lower center CCD. (https://commons.wikimedia.org/wiki/File:Kepler_FOV_hiRes.jpg, NASA/Ames/JPL-Caltech, Image credit: Software Bisque, Public Domain).](https://commons.wikimedia.org/wiki/File:Kepler_FOV_hiRes.jpg)

![Figure 1c. 200 x 200 pixel *Kepler* superstamp image of the center of NGC 6819 (Kuehn et al. 2013). *Kepler* pixel sizes are 3.98 arcsec/pixel.](https://commons.wikimedia.org/wiki/File:Kepler_FOV_hiRes.jpg)

2. *Kepler* Data Analysis and Results

The superstamp field centered on NGC 6819 was viewed nearly continuously for the four years of the original *Kepler* mission. These data span barycentric Julian Days 131.5 to 1591.0 after Julian Date 2454833.0. Gaps in data of around 90 days for Quarters 6, 10, and 14 arise because *Kepler* CCD module #3 and later #7 (out of the total of 21) failed during the mission.
We used simple aperture photometry (SAP) for the light curves and prepared final light curves using our custom scripts and PyKE software (Kinemuchi et al. 2012). We searched for variations in each superstamp pixel showing variability in the right range to be δ Scuti or γ Doradus candidates. This search resulted in five cluster members and eight non-members (not discussed here) for follow-up.

Cluster membership probabilities were derived using astrometry data from Gaia Early Data Release 3 (Gaia Collaboration 2021). All members that we identified have 96% or larger membership probability. We use a 5-D approach, i.e., accounting for proper motion (2x), coordinates (2x), and parallax. Radial velocities are available that could be used but they need to be taken with the same instrument to avoid instrumental shifts, so it was judged more reliable not to use them.

Note that two of the five member stars have *Kepler* 30-min or 2-min cadence light curves that can be found in the Mikulski Archive for Space Telescopes (MAST, https://archive.stsci.edu), and some also have been observed by the *TESS* spacecraft (Riker et al. 2015). This paper only makes use of superstamp pixel data with our customized reduction. The *Kepler* pixels are 4 arcsec, considerably smaller than the 21 arcsec pixels of *TESS*, reducing the risk and consequences of contamination of the light curves by nearby stars in the crowded field in the cluster center.

To determine significant frequencies, the light curves were processed by Fourier analysis, and the successive highest-amplitude peaks removed from the light curve by pre-whitening until only noise remained. We used a detection threshold signal-to-noise ratio (S/N) around 5 as discussed by Baran et al. (2015). This level is the average over the entire *Kepler* frequency spectrum from 0 c/d to the Nyquist frequency limit of 24.4695 c/d for 30-min cadence data. Generally, the noise level is greater for low frequencies than for higher frequencies in this range.

For *Kepler* time series greater than about one year, frequencies higher than the Nyquist limit can be found by taking advantage of the shift in arrival time of the signal caused by the light travel time to the spacecraft in orbit around the Sun (Baran et al. 2012, Murphy et al. 2013). The true frequencies have a higher amplitude than their Nyquist-reflected frequencies in the amplitude spectrum (see examples in sub-sections 2.1 and 2.4).

Table 1 summarizes properties of the 5 cluster member stars we discuss in the remainder of this Section. The effective temperature, log surface gravity, radius, mass, luminosity, and distance were taken from the *TESS* Input Catalog (TIC) version 8.01 (Stassun et al. 2019) available on MAST. The stellar quantities are approximate as many are derived from color photometry and stellar model grids. Spectroscopy and asteroseismic modeling making use of the stellar pulsation frequencies should improve the accuracy of these quantities.

**Figure 2.1a.** 5-day zoom-in on portion of KIC 5024468.

### 2.1 KIC 5024468

KIC 5024468 was known pre-*Kepler* as a δ Scuti variable in the blue straggler region of the NGC 6819 color-magnitude diagram (Talamantes et al. 2010).
The *Kepler* light curve for this star is contaminated by light from a nearby eclipsing binary, KIC 5024450, with a period of 3.05 days.

Figure 2.1a shows a 5-day zoom-in on the KIC 5024468 light curve; Figure 2.1b shows the amplitude spectrum, revealing many modes in the $\delta$ Sct frequency range; the highest amplitude modes have frequencies around 12 c/d. Pre-whitening analysis reveals 236 significant frequencies with S/N > 6, including 7 real frequencies above the Nyquist limit. Figure 2.1c zooms in on the low-amplitude portion of the spectrum, showing several frequencies in the $\gamma$ Dor frequency range, with frequencies < 5 c/d. We therefore categorize this star as a $\delta$ Sct/$\gamma$ Dor hybrid candidate.

Figures 2.1d and 2.1e show the light curve and amplitude spectrum of the eclipsing binary KIC 5024450. The $\delta$ Sct oscillations of KIC 5024468 around 12 c/d contaminate the KIC 5024450 spectrum; the binary frequency and its harmonics were removed when determining the KIC 5024468 frequencies.

**Figure 2.1b.** Amplitude spectrum for KIC 5024468 showing $\delta$ Scuti modes. The Nyquist frequency for 30-min *Kepler* cadence data is 24.4695 c/d, but here we extend the spectrum to 28 cycles/day as there are real Super-Nyquist frequencies that have higher amplitudes than their reflections.

**Figure 2.1d.** 5-day zoom-in on light curve of eclipsing binary KIC 5024450 showing eclipses with period 3.05 d.

**Figure 2.1c.** Zoom-in on low-amplitude portion of KIC 5024468 spectrum showing many significant low-amplitude modes in both the $\gamma$ Dor and $\delta$ Sct frequency range.

**Figure 2.1e.** Amplitude spectrum of KIC 5024450. The $\delta$ Sct oscillations of KIC 5024468 around 12 c/d also contaminate the KIC 5024450 spectrum.
2.2 KIC 5024084

KIC 5024084 is listed as a blue straggler in the SIMBAD database. The Kepler light curve available via MAST for this star was studied by Balona et al. (2013), who write “KIC 5024084 shows very clear variations with irregular amplitudes but a distinct period of 2.07 d which is probably the rotation period of the star with spots.”

Figure 2.2a. 50-day zoom-in on light curve of KIC 5024084.

Figure 2.2b. Low-frequency portion of KIC 5024084 amplitude spectrum showing many low-frequency modes.

Figure 2.2c. KIC 5024084 amplitude spectrum extended to 12 c/d showing single 11.2 c/d mode in δ Sct frequency range.

Figure 2.2a shows a 50-day zoom in of the KIC 5024084 light curve extracted from the superstamp pixels. Figure 2.2b shows the amplitude spectrum, revealing many low-frequency modes, including the two highest-amplitude modes with periods 2.038 and 2.058 days that may correspond to the period identified as a probable rotation period by Balona et al. (2013).

It is not straightforward to determine the origin of low-frequency peaks in the amplitude spectrum. Saio et al. (2018) offer an alternative explanation for ‘hump and spike’ features in amplitude spectra seen in some γ Dor stars as a rotation frequency (spike) accompanied by a lower-frequency cluster of global Rossby modes (hump). Other groupings of modes, e.g., some higher than the rotation frequency, may be γ Dor gravity modes. For KIC 5024084, there may also be harmonics of the largest amplitude modes (around 0.5 c/d) at around 1 c/d and 1.5 c/d. Pre-whitening analysis revealed 50 modes with S/N < 25. This S/N cutoff was chosen to be larger than for stars showing mainly high frequency δ Sct modes because the noise level is determined from the entire frequency range, and is highest at low frequency. Figure 2.2c shows the amplitude spectrum extended to 12 c/d; the single mode in the δ Sct frequency range at 11.2 c/d has S/N = 25. We categorize this star as a γ Dor/δ Sct hybrid candidate. The δ Sct classification is very tentative given that only one δ Sct frequency is seen.
2.3 KIC 5024455

KIC 5024455 is also listed as a blue straggler in SIMBAD. This star’s Kepler light curve data were studied using early data releases by Uytterhoeven et al. (2011), who categorize it as a γ Dor star, and later by Balona et al. (2013), who categorize it as a suspected γ Dor star. Milliman et al. (2014) list KIC 502445 (also known as WOCS 014012) as a single-line spectroscopic binary with a 762-day orbital period.

Figure 2.3a. 20-day zoom-in on light curve of KIC 5024455.

![Figure 2.3a](image)

Figure 2.3b. KIC 5024455 amplitude spectrum.

Figure 2.3a shows a 20-day zoom-in on a portion of the light curve. The amplitude spectrum (Fig. 2.3b) shows only modes with frequencies < 5 c/d, in the γ Dor frequency range. Pre-whitening analysis reveals 84 frequencies with S/N > 8.4. There may be additional significant frequencies, but it is difficult to be sure they are real because of higher noise levels at low frequencies. While some of these low frequency groupings may be gravity modes, some may also be global Rossby modes, and more analysis will be needed in conjunction with stellar models to understand and identify the mode patterns. Pulsation modes cannot be distinguished from signatures of rotation and star spots using the light curve alone. We categorize this star as a γ Dor candidate.

2.4 KIC 5113357

KIC 5113357 does not have Kepler data available in MAST, and it is not categorized as a variable star in SIMBAD. Its temperature and luminosity do put it in the blue straggler region for the NGC 6819 cluster.

Figure 2.4a shows a 10-day zoom in on the KIC 5113357 light curve derived from the superstamp pixel data. There is an overall modulation at 0.24755 c/d (period around 4 days) that is the 2nd highest peak in the amplitude spectrum (Fig. 2.4c). This peak may be a rotational modulation. Figure 2.4b shows a 2-day zoom-in on the light curve, revealing higher frequency oscillations in the δ Sct frequency range.

Figure 2.4a. Zoom-in on 10-day portion of KIC 5113357 light curve.

![Figure 2.4a](image)
Figure 2.4b. Zoom-in on 2-day portion of KIC 5113357 light curve.

Figure 2.4c shows the amplitude spectrum out to 50 c/d. It is evident that most frequencies are reflected about the Nyquist frequency limit of 24.4695 c/d. However, some super-Nyquist frequencies have larger amplitudes than their reflected counterparts and are the real frequencies. Pre-whitening of the spectrum shows 124 modes with S/N > 5.3, most in the \( \delta Sct \) frequency range. 36 of the 124 frequencies are above the Nyquist limit, with the highest of these at 36.496 c/d, still in the \( \delta Sct \) range. Figure 2.4d shows a zoom-in on the low-amplitude and low-frequency portion of the amplitude spectrum. There are a few modes in the \( \gamma Dor \) frequency range. We therefore categorize this star as a \( \delta Sct/\gamma Dor \) hybrid candidate.

Figure 2.4d. Zoom-in on low-amplitude and low-frequency portion of KIC 5113357 amplitude spectrum. A few low-amplitude frequencies are present in the \( \gamma Dor \) frequency range.

2.5 KIC 5112843

We conclude with another interesting and mysterious star, KIC 5112843. This star does not have processed Kepler data available in MAST. It can be found in SIMBAD under its TIC catalog number, and it is listed as an eclipsing binary. Talamantes et al. (2010) discuss the ground-based light curve of this star from pre-Kepler data, and they note that sometimes the light curve shows one shallow, almost nonexistent, dip that makes it resemble a detached eclipsing binary, and, at other times, a contact binary. Concerning these latter phases, Talamantes et al. write, “the system showed some of its deepest eclipses and showed variations identifying it as an EW [W UMa contact binary] system with gravitationally distorted stars of nearly equal temperature.”

The Kepler light curve derived from the superstamp pixel data shows the signal of two close frequencies beating against each other, combining constructively or destructively to create the pattern seen in Fig. 2.5a. The amplitude spectrum shows the two largest-amplitude modes that are close in frequency at 5.2071 and 5.7357 c/d, but also two lower-amplitude frequencies at half these values, 2.6036 and 2.8678 c/d. Pre-whitening analysis of the light curve reveals only harmonics of these two frequencies, six of them from the 2.6036 c/d mode (f2-f8, but missing odd harmonics f5, f7, and f9) and nine harmonics f2-f10 of the 2.8678 c/d mode. Talamantes et al. identify the binary period as 0.348687 d (frequency 2.8679 c/d), corresponding to one of the lower-amplitude frequencies in the amplitude spectrum. It is not known why there are pairs of frequencies, and why the amplitudes of the parent frequencies are smaller than their first harmonic.
KIC 5112843 was also the target of x-ray observations by the XMM-Newton space telescope (Gosnell et al. 2012). They find that this star is an x-ray source, and list it as an active binary. Figure 2.5c from Gosnell et al. shows the location of NGC 6819 x-ray sources on the color-magnitude diagram, including KIC 5112843 labeled as X9, superimposed on photometry from Kalirai et al. (2001b). They speculate that it is a possible sub-subgiant binary system, similar to RS CVn binary systems, which are defined as close but detached binaries with active chromospheres that can cause large star spots (Eaton and Hall 1979).

3. Conclusions

Our search for variable stars using pixel data from the Kepler NGC 6819 superstamp field resulted in identification of five stars that were determined to be cluster members, showing multimode variability in the frequency ranges characteristic of $\gamma$ Dor (< 5 c/d) and/or $\delta$ Sct (> 5 to ~40 c/d) stars. Two of these stars, KIC 5024468 and KIC 511335, show a rich spectrum of $\delta$ Scuti pulsation modes, with 236 and 124 significant frequencies identified, respectively, while two stars show mainly low-frequency modes characteristic of either $\gamma$ Dor gravity-mode pulsations or global Rossby modes. Low-frequency variability caused by rotation and star spots cannot be ruled out. The fifth star has an unusual spectrum with several harmonics of two main frequencies. This star shows x-ray activity and may be an RS CVn variable.

These results from long time-series Kepler photometry will provide excellent constraints for stellar modeling, combined with the common age and element abundances of the cluster members. These data should be useful for determining the origins of the four blue straggler stars. Tables of significant frequencies will be published in a forthcoming paper.

In the future, it would be worthwhile to look for frequency-spacing patterns for the $\delta$ Sct modes, which can be used to determine stellar mean density and
perhaps enable mode identification. It would also be useful to examine period spacings for the \( \gamma \) Dor candidate stars, as these patterns in conjunction with stellar models can help to distinguish gravity-mode and Rossby-mode groupings, and to determine the stellar rotational period.

It would also be useful to derive accurate effective temperatures, surface gravities, and element abundances using existing and new stellar spectra to provide further constraints on stellar models. Time-series spectra could be examined for radial velocity variations and used to characterize binary orbits for KIC 5024455 and KIC 5112843, possibly providing additional stellar modeling constraints.

4. Acknowledgements

We are grateful for data from the NASA Kepler spacecraft. J.G. acknowledges a Los Alamos National Laboratory Center for Space and Earth Sciences grant CSES XX8P and support from LANL, managed by Triad National Security, LLC for the U.S. DOE’s NN5A, Contract #89233218CNA000001. Funding from the Polish National Science Centre No. UMO-2017/26/E/ST9/00703 and UMO-2017/25/B/ST9/02218 is acknowledged.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and the Mikulski Archive for Space Telescopes (MAST). J.G. thanks the Society for Astronomical Sciences for the opportunity to publish this paper.

5. References


Table 1. Summary of properties of five NGC 6819 stars observed in Kepler superstamp field.

<table>
<thead>
<tr>
<th>KIC ID</th>
<th>5024468</th>
<th>5024084</th>
<th>5024455</th>
<th>5113557</th>
<th>5112843</th>
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<tr>
<td>RA</td>
<td>295.3227668</td>
<td>295.2647409</td>
<td>295.3210065</td>
<td>295.4430993</td>
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<td>DEC</td>
<td>40.18431117</td>
<td>40.14515408</td>
<td>40.10131114</td>
<td>40.27555384</td>
<td>40.20623482</td>
</tr>
<tr>
<td>TIC ID</td>
<td>1880383370</td>
<td>139109448</td>
<td>139109202</td>
<td>184010448</td>
<td>139154029</td>
</tr>
<tr>
<td>V mag</td>
<td>12.98 ± 0.046</td>
<td>14.87 ± 0.15</td>
<td>14.943 ± 0.046</td>
<td>14.971 ± 0.183</td>
<td>15.772 ± 0.126</td>
</tr>
<tr>
<td>T eff (K)</td>
<td>7059 ± 130</td>
<td>6501 ± 123</td>
<td>6701 ± 122</td>
<td>7328 ± 122</td>
<td>5493 ± 126</td>
</tr>
<tr>
<td>log g</td>
<td>3.442 ± 0.945</td>
<td>3.80161</td>
<td>4.24602</td>
<td>4.14243</td>
<td>3.77708</td>
</tr>
<tr>
<td>Radius (R⊙)</td>
<td>3.93 ± 0.25</td>
<td>2.3997</td>
<td>1.48651</td>
<td>1.81081</td>
<td>2.09715</td>
</tr>
<tr>
<td>Mass (M⊙)</td>
<td>1.56 ± 0.25</td>
<td>1.33</td>
<td>1.42</td>
<td>1.66</td>
<td>0.96</td>
</tr>
<tr>
<td>Luminosity (L⊙)</td>
<td>34.57 ± 4.03</td>
<td>9.266777</td>
<td>4.014114</td>
<td>8.518837</td>
<td>3.607382</td>
</tr>
<tr>
<td>Distance (pc)</td>
<td>2359 ± 129</td>
<td>2718 ± 137</td>
<td>1870 ± 142</td>
<td>2445 ± 125</td>
<td>2399 ± 164</td>
</tr>
</tbody>
</table>

Notes: Blue straggler, Light curve contaminated by KIC 5024450, Blue straggler, Blue straggler, Blue straggler, Near main-sequence turnoff

Literature notes:
- SIMBAD: δ Sct variable
- Talamantes et al. 2013: s Sct star

Classification based on light curve analysis:
- δ Sct/γ Dor hybrid candidate
- γ Dor/δ Sct hybrid candidate (Only 1 δ Sct mode)
- γ Dor candidate
- δ Sct/γ Dor hybrid candidate

Number of frequencies: 236, 50, 84, 124, 17
Seeing Measurements at Two Lowell Observatory Sites
Using Differential Image Motion Monitors

Tom Polakis
Command Module Observatory
121 W. Alameda Dr., Tempe, AZ 85282
tpolakis@cox.net

Abstract
Lowell Observatory is planning to install a new telescope in one of two existing domes at its Anderson Mesa site near Flagstaff. Since local terrain induces turbulence, it was desired to concurrently measure seeing conditions at both locations before making the site selection. Differential image motion monitors (DIMM) were employed at both sites, using 14-inch telescopes equipped with masks that split the light from a single star into two closely spaced images. Seeing is computed by measuring the variance in relative positions of the two star images during video captures. After completing the Anderson Mesa observations, the equipment was moved to the Lowell Discovery Telescope site, where the ambient seeing could be compared to that at the focus of the 4.3-meter telescope. Details regarding hardware, image acquisition, data reduction, and results are described in this paper.

1. Introduction
The world’s best astronomical observing sites share three characteristics: a high percentage of clear nights, a low level of sky brightness, and stable air. For most types of observations, good seeing is of paramount importance. Seeing is influenced by local terrain, so it can be quite different over distances of only several hundred feet. A portable telescope with a differential image motion monitor (DIMM) system is useful for comparing seeing conditions at multiple sites.

Lowell Observatory plans to install a 1-meter-class telescope at its Anderson Mesa site, 9 miles southeast of Flagstaff, Arizona. Two existing domes are available for this installation, separated by roughly a quarter mile. Simultaneous observations with 14-inch telescopes equipped with DIMM systems were conducted on 28 nights during a 2-month period with the intent of choosing the better site. Weather stations were installed at both locations to better understand the effects of meteorological conditions on local turbulence.

The Lowell Discovery Telescope (LDT) is a 4.3-meter instrument located 33 miles south-southeast of Flagstaff. It is known to typically have sub-arcsecond seeing at its focus. DIMM systems were moved to the site, where data is being gathered since January 2022.

The purposes of the LDT site observations have been manifold. The first is to compare seeing in the open air to that at the focus of the large telescope. Secondly, this enables comparisons between a legacy method involving a CCD camera employed in 2002 to the current system that uses a modern video camera. Finally, by measuring seeing at varying shutter speeds, a determination of the frequency of the seeing variations can be made. This will become important if adaptive optics are pursued for the LDT.

2. DIMM general concepts and historical examples
A DIMM system is comprised of simple hardware. A mask with two widely spaced circular holes is placed over the front aperture. In one of the holes is an optical wedge, which displaces one of the star images relative to the one coming in from the open hole. At the focus of the telescope is a planetary video camera, which periodically takes recordings of hundreds or thousands of frames.

In the absence of any atmosphere, the two star images would maintain exactly the same distance from each other throughout a video recording. Atmospheric turbulence changes the direction of the wavefront between the two holes, causing the distance between the two star image centroids to vary over short timescales. A statistical calculation based on the variance between the star images during the recording provides the FWHM seeing value. A far more detailed description of DIMM theory and application appears in Sarazin & Roddier (1990).

The concept of DIMM dates back at least 60 years (Stock & Keller, 1960), and has been used frequently in site surveys since the early 1980’s. Pederson et al. (1988) describe the use of DIMM to determine the best site for the European Southern Observatory’s Very Large Telescope in Chile. Determination of seeing was part of the site survey by Tsay et al. (1990) for the
Navy Precision Optical Interferometer on Anderson Mesa. Before the LDT was sited at its current location, a portable DIMM was employed at several candidate hilltops. At the selected LDT site, observations on 117 nights during a 16-month period revealed median seeing of 0.84 arcseconds (Bida et al. 2004).

In addition to the obvious advantage of portability, a DIMM system is mostly immune to a poorly mounted telescope: both star images deflecting by the same amount do not impact the distance between their centroids.

3. Anderson Mesa seeing measurements

3.1 Mesa Sites and equipment

Lowell Observatory’s Anderson Mesa site is a rise of roughly 400 feet above Lower Lake Mary to its southwest. The site is only 9 miles from the center of metropolitan Flagstaff (population 140,000), but strict lighting ordinances result in a sky brightness that is only several tenths of a magnitude above the natural level. More than half of nights are useful for astronomical observations.

On the Mesa are two available domes, pictured in Figure 1. Near the entrance at the north end is the 31-inch telescope dome, whose construction with cinder blocks is notorious for releasing stored heat during the night, which is deleterious to seeing. At the south end of the property is the LONEOS telescope dome, whose sheet metal construction is more favorable for minimizing dome seeing.

At both locations, 14-inch f/11 Celestron telescopes were set up. The DIMM masks have two 3 ½-inch diameter holes separated by 8 inches, as shown in Figure 2. Cameras are ZWO model ASI174MM, whose 5.86-micron pixels yield a prime focus image scale of 0.3 arcseconds per pixel. Laptop computers were wired to the mount, camera, and focuser, and were operated remotely from nearby control rooms. A photo of the equipment outside the 31-inch dome appears in Figure 3.

3.2 Data acquisition and reduction

At the telescope, focus was first achieved on a bright star using a Bhatinov mask. Since these telescopes have aluminum tubes, refocusing was required several times between dusk and dawn. The DIMM mask was indexed such that installation would result in the two star images being oriented horizontally.

Program stars with a declination similar to the site’s latitude were selected to begin a couple hours east of the meridian, with a zenith distance of less than
30° (1.15 airmasses). This would typically enable three hours of continuous observation before moving to the next star. All the selected program stars are brighter than magnitude 2, which enabled good signal with the 20-millisecond shutter speed that was used for all recordings.

Video capture was obtained using FireCapture software. A total of 1000 frames were gathered in 16-bit SER format, with a cadence of 5 minutes. To avoid excessively large files, a subframe of 400 pixels square was typically used. Names of the observed stars as well as UT dates and times were inserted into the filenames by using FireCapture’s “Profile” feature. Figure 4 is a screen grab showing the software setup. In the frame, the program star images are separated by roughly 25 arcseconds.

A scheduled data dump from the laptop to a Lowell server occurred just after sunrise each morning. Lowell astronomer Stephen Levine wrote a pipeline which grabbed the video files as input, and output seeing data tables and time-series plots for each night. A review of the equations that go into the data reduction may be found at references cited earlier in this paper.

Figure 4. FireCapture window

3.3 Results at two mesa sites

Between September 9 and October 31, 2021, simultaneous observations at the two sites were made on 28 nights. At the LONEOS and 31-inch locations, observing time totaled 184 and 204 hours, respectively.

A typical time series plot comparing the two sites for a single night appears in Figure 5. The horizontal scale runs from 5:00 p.m. to 7:24 a.m. local time. Figure 6 is a histogram plot comparing seeing results for the 28 nights in which concurrent observations were made.

Figure 5. FWHM on one night at two mesa sites

Figure 6. Binned seeing results for the two sites

During the nearly two months of measurements, the two potential telescope sites exhibited seeing conditions that are very similar, with a median value of about 1.1 arcseconds FWHM. While this observing interval does not consider seasonal effects, those would consist mostly of turbulence thousands of feet aloft that is insensitive to local terrain.

A rigorous analysis comparing seeing conditions to weather station data has not yet been done. However, it is well established from many decades of observations at Anderson Mesa telescopes that wind direction is the most important parameter. The prevailing southwest breeze creates seeing that is substantially better than the less common winds from the north and east. Seeing is largely insensitive to wind velocity and air temperature, although sites with a lower dusk-to-dawn temperature drop have more stable air.

The favorable results at Anderson Mesa dispel an incorrect notion that Arizona has poor seeing. Being only a couple hundred feet above the surroundings, preferably near a steep drop facing the prevailing wind makes for an excellent observing site. Basins below the mesa have poor seeing due to cold air drainage. By
simply observing a car thermometer during commutes down the hill at dawn, it became apparent that the nighttime lows are fully 10 to 15°F lower in the meadows.

3.4 Impact of airmass

On September 20, 2021, the LONEOS DIMM telescope was unattended. Rather than following the usual program at the 31-inch, recordings of a group of stars at various zenith distances ranging from 0 to 80° were rapidly taken to determine the effect of altitude on seeing. This was done eight times, with a cadence of one hour. A typical group of stars and their altitudes is shown in Table 1.

Classical Kolmogorov turbulence theory predicts that seeing is related to zenith distance, z, by this equation.

\[
\text{FWHM}(z) = \text{FWHM}(z=0) \times \cos(z)^{-3/5}
\]

In Figure 7, the eight datasets were plotted against airmass enabling a comparison with the model. Recall that a good approximation of airmass is simply: secant (zenith distance). The model matches the data closely at large zenith distances but underestimates the change between 1 and 2 airmasses.

4. LDT seeing measurements

Observations at the LDT site began on January 24, 2022, with the same equipment that was used near the 31-inch at Anderson Mesa. This summary covers the period through March 27. During that period, 157 hours were covered in 25 nights. There is interest not only in comparing seeing outside the dome and at the focus of the 4.3-meter telescope, but also in assessing the effect of varying shutter speed, and repeating observations using the same CCD camera that was used in 2002.

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<th>Star</th>
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<td>9.0</td>
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<td>54.7</td>
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<td>18.2</td>
<td>79.1</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 1. Stars selected for one airmass series

Figure 7. Sensitivity of seeing to airmass

Figure 8. Roll-off shed location at LDT site

Figure 9. Both DIMM telescopes near LDT

4.1 Site and equipment at LDT site

The roll-off shed that was used at the 31-inch was moved to the LDT site, where a location was carefully selected. The shed is placed along the fence near the abrupt drop-off to the south and west, maximizing the prevailing wind and minimizing the obstruction from the LDT enclosure. Figure 8 is an aerial photo of the site looking southwest, with the shed highlighted.
Toward the end of March, the second telescope that had been inside the LONEOS dome at Anderson Mesa was moved to a location near the shed, shown in Figure 9. Rather than using a modern video camera, a CCD camera and a strip scan method was employed to gather frames. The system is up and running, but a discussion of those results is outside the scope of this paper.

4.2 Data acquisition and results

Other than the addition of a finder scope and auto guider, the equipment was unchanged from what was used at Anderson Mesa in 2021. Data was again acquired remotely from inside an LDT control room. Periodically, the LDT telescope operator was asked to report seeing at its camera. Future work will involve comparing seeing data inferred from images to DIMM values.

Video was recorded as before, with the significant change being that the shutter speed was varied between recordings on many of the nights. Recall that 20 milliseconds was used for all Anderson Mesa recordings. In this case, speeds of 2, 10, 20, 100, and 200 milliseconds were used.

Figure 10 is a time-series plot of a single night of reduced data, showing the effect of varying shutter speed. When seeing is sub arcsecond as in this case, recording at 2 ms shutter speed produces a result that is a factor of 2 worse than 200 ms. On one night after the passage of a trough in which seeing was worse than 3 arcseconds, this factor was as high as 4. A histogram for the 25 nights with a summary table can be found in Figure 11. Noting that previous strip scan measurements were made with a 10ms exposure time, FWHM results for 10 and 20ms are shown. Median seeing for those two exposure times are 0.91 and 0.82 arcseconds, respectively.

![Figure 10. FWHM results for a single night](image1)

It is possible that Lowell Observatory will be pursuing adaptive optics for the 4.3-meter LDT, which would greatly improve its resolving power. If this is the case, a permanent DIMM system may be employed in order to better characterize the frequency of the local turbulence.

5. Conclusions

A portable DIMM system using an off-the-shelf video camera is a valid method to measure local seeing conditions. When used at the Anderson Mesa site, both locations showed comparably good seeing of roughly 1.1 arcseconds. LDT site seeing compared favorably with values reported by the Telescope Operator, but further analysis is required. Shorter exposure times than 20 milliseconds better capture turbulence, and 10 milliseconds is consistent with prior methods.

6. Acknowledgements

The author would like to thank Jason Sanborn and Amanda Bosh, who tirelessly guided this effort. Stephen Levine created the pipeline for data reduction. Mike Collins generously provided a temporary donation of his modern mount, which is a large improvement over the existing tuning fork mount. Len Bright and Solvay Blomquist produced observations at both telescopes. Adam Blake was helpful with writing a clear manuscript.

7. References


Astronomical all sky background light pollution database and modelling analysis at MHAONB UK, from distant conversions to LEDs and climate change

Chris Baddiley
Ferney Cottage, Mathon, WR13 5PP, UK. Tel. +44 1886880047, cj.baddiley@physics.org

Abstract
In 2012, a geographic dark sky survey of the Malvern Hills Area of Outstanding Natural Beauty (MHAONB) was carried out, commissioned by Malvern Hills Conservators. The sky brightness has been measured continually ever since then at the author’s Mathon based rural Observatory, in the last few years at 2-minute intervals in all weathers. On the darkest of nights, a fisheye lensed all-sky camera is also being used at 30 second interval horizon to horizon exposures. The equipment is in addition to two computer-controlled and auto guided camera carrying telescopes of 30 and 37 cm aperture class used for other projects. This paper with presentation is a summary of the light pollution monitoring analysis and results.

Separately, the author had previously done modelling of the effects of LED changes from different types of light sources and their directionality using ray tracing from industry luminaire profiles from semi-rural scenario ground reflection and scatter through the atmosphere and down across the sky as a function of colour spectrum.

This paper covers a number of projects using the data base, some are covered in a previous paper published in JQSRT, all reassessed using alternative processing, and others are new. Parametric curve fits to the sky background across the whole sky were found to be consistent on the clearest of nights. The skewness of the curve fitting is an indication of the proportion of distant and local lighting and can be evaluated by subtracting on linear scale the mirror image of the sky from itself from the asymmetry of the curve fitting. It can also be evaluated from isophote plots and again emphasized by subtracting on linear scale the mirror image about the Zenith. The clear dark sky always gets steadily darker during the night, before dawn by about 0.3 magnitudes per square arc second on the background at 21. Histograms of frequency of light levels are also plotted for individual nights or the clearest nights for each year over eight years. Polarization measurements were done in the same way. Brightness and colour variations are very much dependent on the weather conditions locally compared with distant near dew point from scattering or blocking by water droplets.

There is a trend in brightness distribution and colour changes on the sky, especially towards the horizon, typically six times brighter than the zenith, with clearly separated bright white sky domes. The sky quality meter (SQM) photometry data near zenith does not show any great change but it is becoming very much whiter on the clearest nights. The data can be correlated with the weather station.

The white sky domes on the horizon are due to lighting LEDs in all directions and identifiable from cities up to 150 kilometers away. The all-sky camera is calibrated against the SQM and corrected for vignetting and geometric distortion. The SQM at 52° nor is tilted 20° N so does not see the milky way.

Backscatter ratio was determined using a known luminance flat panel calibration LED source pointing upwards in the observatory, not visible to the SQM, and turning it on and off repeatedly hundreds of times taking the SQM near zenith readings when on and off and subtracting the natural variation in background during the period. The backscatter was found to be consistent at about 2 x 10^-7 m2/sr. +/- 8%. And applied to an intended lighting development with no direct upward lighting only reflection to determine the expected sky brightness from ground reflection on the effect of an observatory. This is not available in any commercial lighting plan program. The paper draws a number of conclusions on the impact in rural areas.

1. Introduction

This paper covers a range of light pollution projects by the author over many years. The continuing research from the accumulating archive has been presented at a number of international conferences. It was brought together in two papers published in JQSRT in recent years, which are referred to [1], [2], so the results are just summarized here. They are available but the author did not have any
finances to pay page charges, so they are not free. This work here described in detail is also taken from the ever-accumulating database but uses new methods of analysis applied to archive data and new projects that are related.

2. Modelling angular distribution and colour

Continuous records of the sky brightness together with the all-sky imaging on the best of nights were started in 2012. This was after a geographic photometric survey at the request of Malvern hills conservators. Early measurements were used to confirm a modelling program, developed to compare the effects of different types of luminaires on sky, and then a study of the change of lighting to blue rich LEDs in towns and roads adjacent to the Malvern Hills AONB, again at the request of the Malvern Hills Conservators in 2015. The modelling was based on ray tracing from the angular distribution photometry of various luminaire optical designs, with spectral integration, including reflectivity off the ground and atmospheric scattering into the line of sight, for various viewing angles on the sky in good atmospheric conditions (here atmospheric visibility 23 km).

The modelling program is simple by modern day standards but was sufficient to illustrate differences between different types of luminaires and their effect on the sky. For details see references [1] and [2], it is just summarized here.

For modelling, industry published polar diagrams for brightness as a function of azimuth and gamma angle for various luminaires were used as the starting point. Ray traces were taken at angles the sky and downwards reflecting and scattering off surfaces back into the sky. Principal rays were traced, with a combination of Lambertian scatter and specular reflectivity according to surface roughness. The scenario was usually suburban, single sided illumination of an asphalt road with grass borders, but with a range of possibilities. These were stepped through the visible spectrum accounting for spectral response of the luminaires, that of the scattering surfaces, that of the atmosphere according to view path, and that of the human eye response at appropriate scotopic levels. Selected points were taken along the view slant path from the observer to the sky crosses from towards the luminaire to zenith, and opposite horizon. The angle at each point of the intersection with the scene direction was used to find the atmospheric scattering phase function at that altitude into the view path for the altitude and visibility. This was a combination of Rayleigh scattering from atmospheric symmetric molecules, which varies as one over the wavelength to the power 4, and is equally backwards and forwards, less sideways, together with Mie scattering which is not spectrally dependent, but on the size of the dust and water molecules and is mostly beamed forwards. The former is why the sky is blue overhead in daylight due to the spectral bias, and the latter white towards the horizon. Scattering into and out of the view path was calculated. This gave the sum of the direct and scattered light in any direction up into the sky.

The results were plotted as a function of azimuth and elevation angle away from the source, or distance from the source, together with spectrally integrated content. The sky profiles across the sky were not totally dissimilar from the curve fitting to data here. They illustrated the major differences on the sky from different designs of traditional road lighting luminaires and spectral luminaire sources.

3. All-sky imaging and photometry

This section discusses the observed effect of streetlight angular cutoff and colour temperature changes on UK rural dark skies and Milky Way visibility, for which the contrast to background is now critical. The examples here are from the Mathon Observatory in the Malvern Hills Area of Outstanding Natural Beauty, (MHAONB). The observatory is on the Herefordshire - Worcestershire Borders. Key historic references are found in the previous research papers by the author [1] and [2] and listed at the end of this paper.

3.1 Severn Valley light pollution and changes

Fig.1 shows Dark sky areas of Worcestershire and Herefordshire, showing the Malvern Hills area and the cities of Worcester, Cheltenham, Gloucester, and Hereford. Birmingham is N.E. (P. Cinzano / F Falchi ISTIL- Dipartimento di Astronomia Padova, Italy) Philips – Maps publication for CfDS, 2006. The towns are lit but the roads between are not.

Fig.2 and Fig.3 show the view of the Severn Valley from a high point on the Malvern Hills, the Wyche cutting, in 2012 and 2018 respectively. The colour changes on the ground and in the sky from relighting trend to LEDs can be seen. These exceed that due to the change of cameras.

Many lights show significant upwards components. In Fig.5 the Moon is just rising (red disc, on the right horizon). The motorway M5 runs across the horizon, now with LED relighting, but is only lit near junctions. The red lights of the Droitwich long wave transmitter (mid left horizon)
are common to both images. The blue-white luminaire dominance is changing the sky colour compared to 2012. There are fewer upward components in 2018, but still, many remain even from some of the replacements, both in Malvern and across the Worcestershire Severn Valley. These can be seen by the camera in its elevated location near the ridge of the hills, so they are polluting the sky of on the far side of the Malvern Hills, in more rural Herefordshire.

3.2 2012 MHAONB Geographic photometry Dark Sky Survey

In the autumn and winter of 2012, a near-zenith photometry and sky camera image survey were conducted on behalf of the Malvern Hills Conservators over the MHAONB (approx. 25 km x 10 km) on the darkest nights. Fig.15(a) shows the map of the Malvern Hills area and Fig.15(b) shows the 2012 Dark Sky Survey site locations and SQM photometry values, consistent to +/- 0.1 mag. arcsec$^{-2}$, on successive dark of the moon periods in the winter of 2012. Fig.15(b) shows the 1 km grid square locations and values on dark of the moon nights. F.C.Mathon Observatory this is a summary of the work described in JQSRT [2]. The observatory site is W. of the Hills, Malvern town is E. of the Hills, Castle Morton to the SE., Wellington Heath S., and Alfrick Pound to the N. There was a trend to more darkness periods in the late winter early spring due to increased wind and rainfall, clearing the air.

For a significant part of the survey, the Milky Way was near overhead and had to be avoided when taking photometry. The uplift of the Milky Way was removed corrected the in the curve fitting of the camera zenith angle profiles.

Fig.4 is a Map of the Malvern Hills area and 2012 Dark Sky Survey site locations. (Google Maps) Fig.5 shows a grid at 1 km squares of Dark Sky Survey measurements, mag.arcsec$^{-2}$ covering 25 km x 10 km of the Malvern Hills AONB. The character codes are for the place names, Ferney Cottage Mathon observatory, (FCM) for continuous SQM Data and regular all-sky imaging. Monthly SQM readings were taken at all others shown. On one date, a set of all-sky camera images were taken for photometry at good horizon view locations: Malvern Link Common (MLC), Poolbrook Common Malvern (PBC), Castle Morton Common (CMC), Wellington Heath View (WHV), Alfrick Pound Langley (APL), and Ham Green Mathon (HGM). The towns (pink areas) are Malvern, NE., and Ledbury, SW.

From 2013-2015, Herefordshire road lighting was replaced with blue-rich LEDs, while in the Severn Valley including Malvern, only a few had been converted at that time. Since then, many towns and cities have had more conversions.
This work has already been published [2], so is only summarized here.

Analysis of the images of figure 6 below and the SQM Data show that sky brightness in central Malvern for the horizon in September 2012 clear nights was the same as at the observatory location, the far side of the hill 5 km away. Readings corrected to be effectively overhead on the Malvern Town commons and at the observatory, entirely rural, were brighter by between 0.25 and 0.35 mag.arcsec$^{-2}$. Depending on location. The profiles have not changed greatly since, now with a truly all sky camera, just from the observatory mast SQM and camera. Individual light sources were seen in different orientations according to the observer position. That enabled identification of their locations. From the Mathon observatory, Monmouth and Cardiff and Birmingham are obvious as is Cheltenham and Gloucester etc. Hereford relighting is obvious as well.

All images have N. at the top and E. on the left. and are not corrected for lens vignetting, which would make the sky near the horizon 30% brighter; no processing has been done. The Canon 20Da camera used from 2012 to 2014 and the Canon 400D from 2015 to 2016 with the 8 mm sigma lens N. S. field of view did not reach the horizon. The Canon 5D from 2017 onwards covers the entire horizon. The plots are corrected for lens vignetting and geometric distortion. The SQM was tilted N. of zenith to avoid the Milky Way. In subsequent years an SQM was attached to the observatory mast tilted at approximately 20° N. The sky colour was all similar, slightly orange, well before most LED lighting conversions.
The measurements were repeated monthly in clear dark of the moon periods during that winter. The whole AONB had the same zenith luminance readings within a few percent, except in the two towns of Malvern and Ledbury. There are no major towns in Herefordshire on W. side of the hills except of Hereford and Ross on Wye well to the S. Outside the towns, the zenith sky brightness showed little variation geographically across the whole area. The brightness increases to the horizon by 1 mag.arcsec\(^{-2}\), depending on weather conditions. For calculation purposes the logarithmic scale magnitudes values are converted to a linear scale milli-Candelas.m\(^{-2}\); when requiring subtraction.

The night sky from Malvern Link Common and Poolbrook Common Malvern are away from direct lighting but surrounded by housing estates and built up areas; so the sky is brighter than the surrounding rural areas. Castle Morton common is well S. of Malvern and is entirely rural. Alfrick Pound Langley side is to the N. but still suffers from light pollution. Ham Green is in the Western shadow of the Malvern Hills, as is the F.C.Mathon, several km further. These were all taken on the same night.

For the different locations it was possible to identify distant sources due to them appearing in different azimuth according to location. The sky glow in the direction of the red arrow is common to many, because it is Birmingham about 60 kilometers away.

Locally, sky glow is dominated by Malvern and Worcester. The zenith sky brightness at Poolbrook common in Malvern was about 0.5 magnitudes per square arc second brighter than at the rural location of castle Morton common or Mathon observatory five kilometers south and west of the hills.

### 3.3 Photometry calibration

The observatory is shown in figures 7 and 8, there are continuous photometry records from 2013 in all weathers to date, in recent years at 2-minute intervals. There are also all-sky camera image sequences using a Sigma fisheye 8mm focal length lens on the canon camera, but that is only when I am running the telescopes on dark moonless nights at the same time, so same sampling for the darkest clear nights, about 24 a year. Several cameras were used over the period, most recently, with a full 36mm frame Canon 5D. The photometry is from a Unihedron lensed sky quality meter (SQM) with 20° field of view, it has high blue sensitivity, but at longer wavelengths than 500nm, the profile is close to a Johnson V band astronomical filter. This is now the networked version, in a temperature controlled weatherproof housing. It is mast mounted with the camera but tilted approximately 20° N. of the zenith to avoid seasonal intrusion from the Milky Way, which has been measured separately. The SQM has been checked with other handheld SQMs not in weatherproof housings to be within +/- 0.1 mag.arcsec\(^{-2}\) for consistency. The all-sky camera images from the Mathon observatory sky were calibrated at the near zenith with the SQM.

Fig.9 shows an empirical representative function used to compensate for the spherical to flat detector plane projection, (see equation box 1 below). With the camera pointing at the zenith, the projection is 1 to 1 on axis, progressing to a radial compression of \((2/\pi)\) at the horizon. This ratio was expected and measured. The projection correction was applied to all the plot pixel position data to determine zenith angle on the camera.

Fig.10 shows the angular profile of foggy day sky and curve fit with Canon 5D camera used in recent years, together with optimum parametric curve fit, which was applied as the vignetting correction in the dark sky photometry vs. zenith angle profile plots. It only becomes significant towards the edge of the field of view. This was not done for the images; those are not processed and are straight off the camera.

Figure 7.

Figure 8.
3.4 Colour balance between the different cameras used

Fig 11 shows the normalized spectral profile of the Unihedron SQM, (re-digitized from images and re-plotted, Cinzano) together with the relative quantum efficiency of the photodiode without filter. The spectral response of the detector is the quantum efficiency per photon times the photon energy (i.e., scales as the photon energy, Planck’s constant times frequency, varying as reciprocal of the wavelength). This is multiplied by the spectral response of the filter. Fig. 12 shows the Spectral normalized response of SQM and Johnson-Cousins B&V band filters. (re-digitized from images and re-plotted) shows the Johnson -Cousins standard B and V band filters with the SQM for comparison. The SQM power spectral curve follows the Johnson B filter at short wavelengths and the V filter at longer wavelengths giving it an enhanced blue.

The cameras used for all sky imaging since 2012, were the Canon 20Da, 400D, and the full frame 5Dii, all with the same Sigma fisheye lens. See figures 13 and 14 show the red sensitivity filter enhancement form the 20D and 60D to the 20D, 20DA and 60 DA. The 400D is similar to the 20 D and the 5D is similar to the 60D but being a full-sized camera chip gave complete all sky horizons. Before and after each camera change over the years, imaging was compared and no visual overall colour difference was noticed attributed to the cameras.
This section is a summary of the curve fit functions described in ref. [2] which are used extensively in the continuing data analysis.

The function generator for lens vignetting is a simple parametric curve and was also adapted for curve fitting to all sky profiles. It requires a minimal number of parameters, and was found to be accurate across the whole sky in clear conditions to better than +/- 0.05 mag.arcsec\(^{-2}\) an example of this is the dotted curve fit in figure xx. The function generator parameter set is shown in the equation box 1 below. The basic function is a modified Gaussian, allowing any power above 1, rather than just 2. To avoid negative values the absolute of the argument is taken. It is a bell-shaped curve between zero and peak of 1. To allow for asymmetry about the peak, the parameters supplied are set separately either side. For the use against the night-sky, it is transformed by inversion to arrange from one to infinity than one or subtracted to give a range from zero to infinity for the purpose is scaling, then a base value added for the zenith. For curve fitting, close to zenith value is one reference fixed point, and the other two are points along the profile data set either side and can be any zenith angle well apart but here mostly set at 60°. The power controls the gradient about the fixed points for extrapolation to the horizon. It has less influence between the fixed points and the base point. The minimum is 1. At gradient powers less than 1.5 close to the midpoint the curve needs to be gradually approaching zero gradient centrally over a reasonable range either side, so a modification is applied only between there, and the side fix points. This is a linear scaling of the gradient from 2 at the base point (a Gaussian) to the set value at the side set point. The function is purely empirical, and as described, requires a total of only five parameters of which three are fixed points on the data profile curve.

3.6 Natural sky background

The background night-sky brightness in the absence of any artificial lighting is from airglow, principally caused by electron recombination of oxygen atoms in the Earth’s upper atmosphere at night, previously photo-ionized by daytime sunlight. At all times, there is luminescence by cosmic rays striking the upper atmosphere and also chemical luminescence, mostly by oxygen and nitrogen reacting with hydroxyl ions at hundreds of km altitude. It peaks at 20° above the horizon where there is maximum molecular clear atmospheric depth, (22.0 mag.arcsec\(^{-2}\) ); and is rarely seen in the UK due to the dominance of artificial lighting. In the absence of artificial lighting, the Milky Way would be 175% contrast above background.
4. **Image processing and curve fitting showing Milky Way contrast to background**

Figures 15, 16 and 17 are examples of processing from the database archive. The isophote processing plots are original to this publication.

The all-sky image 2018-07-15 figure 16 from which the others are derived, has the Milky Way overhead. E. to W. = red and S.to N.= blue. The isophote plot Fig. 13, shows the Milky Way overhead but with a bias showing the darkest part of the sky is some 20° degrees west and north of zenith, due to the absence of towns over the northwest horizon compared with other directions. The north south and east west profiles and the curve fits are shown in figure 14, they are corrected for vignetting.

The spikes in the profiles from the camera are from stars and pixel and sensitivity variation fixed pattern noise. These can be moving average reduced to determine the zenith value photometry calibration, though stars dominate, and the curve fitting is best done manually. The near central overhead uplift from the Milky Way from the curve fit can be seen at -0.35 mag.arcsec⁻². When overhead at the MHAONB, it is about 20% contrast above the moonless typical dark background of 21.2 mag.arcsec⁻², (0.36 mCdm⁻²). Just a 30% increase in road lighting overall illuminance to increase uniformity throughout Europe, would render
it invisible in most rural areas in the UK and the continent.

4.1 The relative contribution of local and distant sources from skewness

Fig.18, 2021-06-28, shows a typical all-sky camera image from the observatory rural location at the Malvern hills AONB of urban light-domes from identified cities and towns beyond the horizon. The image from the Canon 5D camera has not been contrast enhanced. N. is top, E. is left. To the E. shows the light-polluted skies from the Severn Valley. Malvern town E. over the Malvern Hills is 5 km, Ledbury WSW., 11 km, Worcester NE., 18 km, Birmingham NE. 67 km. Light pollution from the E. is usually dominant. Hereford WSW, 27 km showing more blue-white light pollution. Other identifiable sources are Cheltenham SE., 55 km & Gloucester 55 km, Monmouth SW. 45 km & Cardiff 105 km, and Birmingham NE. 65 km. There is now clearer separation between the towns brighter sky domes. The image shows Ursa Major overhead. The usual maximum extended source of light pollution is from Malvern town E. of the hills 5km, but partially obstructed by them. When mist is on the hills, they are obscured. The brightness and colour distribution vary greatly, so not dominant at times. All show much whitening over recent years and increased directional affect with the lighting been better directed essentially for reflection from the ground being illuminated.

The isophote plot inset Fig 19, shows the milky way but also a skewness in the direction northwest due to the absence of over the horizon towns, darkening the sky more in that direction. This also shows that distant towns make a significant contribution to the sky background, even at small zenith angles, but this is dependent on observing site and also distant town site weather conditions, as in the example, which are very variable.

In much of the UK, one is never far from a town or city. The darkest areas are close to the open sea, with no light sources, or well away from towns and blocked by geological features, hills, etc. Light pollution does not confine itself to zones; it stretches continuously right across the English Channel. Even in the darkest rural areas, the zenith sky brightness is controlled by cities and towns beyond the horizon, up to hundreds of km away.
Most towns and villages in the UK tend to be equally distributed beyond the local horizon except in very remote rural areas. Moving away from one town brings one closer to another which even out the sky brightness towards zenith. The sky background is the combination of all of them. There was much weather dependence from humidity variations and clouds on the horizon, reflecting the light of distant towns and cities beyond.

The contribution of individual sources, both local and distant, can be determined from curve fitting to the data. The units given here are in magnitudes of sec$^2$, but to separate source contributions individually, a linear scale must be used. The plotting program can also use units of milliCandels.m$^2$, not shown here.

Fig 18 with 19 is another example but with the milky way overhead; it is compared in fig. 20, a simulation taken from a publicly available simulator using Suomi remote sensing satellite imaging spectrometer VIIRS DNB together with Johnson band V Gaia star and Milky Way brightness data.[1] https://gambons.fqa.ub.edu/#top

The relative contribution of over the horizon to local lighting affecting the zenith sky, can be determined by scaling of the horizon-to-horizon profile from a mirror image of itself on the magnitude scale or a subtraction on a linear scale. That shows the scaling or difference from one side to the sky to the other for the corresponding opposite side horizon elevations. An example of this using the dotted line curve fit comparisons is shown in figure 21 east-west and north-south compared to zenith and then purple dotted curve those compared with each other all derived from parametric curve fits in figure 20. The case was chosen because of the significant uplift one side from the milky way

4.2 Skewness from isophote analysis, showing relative contributions with distance and atmospheric conditions affecting colour

This processing method using archive data is new to this paper.

The skewness can also be illustrated from taking the image scaling from its mirror image and on the magnitude scale or subtracting on the linear subtracting. This is shown in figure 24 from image 22, also another case figure 27 from image figure 25. Also, another set figure 30 from image 28. The three original images show the colour variation from date to another which is due to changing atmospheric condition. The local fruit farm, less than one kilometer away just over a local ridge, is likely responsible for the orange colour at 3.00 in figures 25 and 28, compared with the white led lighting from sources beyond the horizon.

This illustrates how local atmospheric conditions and suppress or enhance local lighting contributions with respect to distant and change the colour of the sky completely temporarily.

Isophote plots of the mirror image subtraction and shows the relative contribution of distant sources on the horizon to that of the zenith. An example is the darkness towards the horizon west northwest where there are no significant towns in the direction of Wales. In this case, the contribution of towns and cities beyond the horizon was about 10% of the zenith compared with local sources, but it is critical of the atmospheric conditions at the time.
Two different cameras have been used before the Canon 5D in 2017 with no significant difference in Bayer matrix spectral profiles between them, as was shown in the earlier spectral section. The white balances were kept the same.

Since 2013 to 2020 there has been an increase in sky brightness on the horizon concentrating more on towns and cities together with colour increasingly blue white. There is still a great mix and the colour of the sky is dependent on what is dominant at any one time in the way of clouds above the distant towns reflecting the light. The sky brightness in not perfect conditions can vary greatly according to distant and local cloud scattering and humidity where near dew point, water droplets are forming at various distances in the atmosphere, either absorbing all scattering the light locally and beyond. Much of the light shown in the figures 31 to 34 is from lighting illuminating the ground which is reflected back into the sky and scatter back down again. It becomes dominant when this is towards the horizontal.
4.3 Brightness reduction through the night

2020-03-27 figures time plot 35 and histograms figures 36 and 37 dusk to dawn of clear night. Sky brightness decreases by about 0.3 mag.arcsec\(^{-2}\), with time, to before dawn.

The reduction in sky brightness during the night is always the case for a clear night and may be due to a combination of distant lighting being turned off and reduction in traffic, but cases during 2020 lockdown show this not to be so. It is most likely largely due to air cooling during the night towards the dew point, when water droplets condense out, and obscuring distant lighting. Such trends are most obvious on clear long dark nights of winter, for which there were several in the winter of 2017 to 2018, but very few in 2019. The darkening trend during the night has been seen by researchers across Europe. Time plots and histograms figures 36, and 37 are more examples. This is a summary of the relevant section of [2].
4.4 Brightness reduction through the night

2020-03-27 figures time plot 35 and histograms figures 37 and 36 dusk to dawn of clear night. Sky brightness decreases by about 0.3 mag.arcsec^{-2}, with time, to before dawn.

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The author has correlated data with the weather station to determine what atmospheric parameters make any difference. When the sky darkness level goes beyond 21.1, it is usually to lack of visibility of stars through increasing humidity. But in conditions of slight wind this is not the case.

4.5 Lockdown 2020 and comparison 2018

There is no obvious correlation with the inactivity caused by lockdown and the brightness of the sky during this period from this rural area and histogram shows the sky on clear nights during the lockdown to one or similar meteorological conditions two years. This is shown in figure 39 in 2020-03-23 and histogram figure 40 compared with similar clarity conditions in 2018, histogram figure 41.

4.6 Yearly histograms, changing in brightness frequency over the years with change of lighting and climate change

Only clearest nights and partially clear nights are stored in the database, which is done manually. This is a summary of the findings [2].

The figures 42 to 46 for years 2016 to 2020 show the histograms for the darkest of nights, the axes are the number the number of minutes at any particular near zenith light level in bins of 0.1 magnitudes per square arc second. The dark bars meet the criteria of international dark sky association for dark sky status.
There is no obvious trend, but this is just near-zenith; the horizon is a different matter and that is very much changing with increasing light levels. The horizon is typically six times brighter than near zenith.

There will be natural background effect from the solar cycle as well. Degradation of the all-weather enclosure window is less than 0.10 mag.arcsec$^2$.

Figure 42.

Figure 43.

Figure 44.

5. Polarization of the sky

5.1 semi cylinder horizontal polarization filter

The first experiment used to Semi-cylinder horizontal polarization filter that could be rotated to any azimuth shown in fig. 47. The isophote illustrations figures 48 and 49 show the orientation of the polarization changes during the night, with the azimuth of the Moon and the Sun below the horizon. One can see the polarization increasing towards dawn. Artificial light is mostly from lower atmosphere scatter rather than dipole Rayleigh scattering resonances in the upper atmosphere scatter and so is not polarized. If there was a polarized component it would not change azimuth with time of night.

Figure 45.

Figure 46.

Figure 47.
5.2 cylindrical horizontal and vertical polarization cylinder filters

The second experiment used separate cylindrical horizontal and vertical polarization cylinder filters, one of which is shown in figure 50. So azimuth rotation does not apply.

Isophote time dependent orientation examples during the night and towards dawn are shown in figures 51 to 52. The latter also illustrates polarised all sky images approaching dawn.

The conclusion was sky polarization is determined by celestial sources and not a lot of usual ones. Even with the Moon below the horizon it has an effect on the sky polarization and so changes at the time of night just like that of the sun during the night dependent on the elevation below the horizon. This is consistent with many researcher’s results so work on this has been discontinued.
6. Determination of the local atmospheric back scatter ratio from the upwards luminance flux to downwards luminosity

6.1 measurement and derivation of backscatter ratio at the Malvern hills AONB.

The observatory mast SQM is sufficiently sensitive to respond to scatter from local upward lighting, even on a clear night with good visibility. Fig.53 shows local air scatter luminance change from switching lights on and off.

The observatory has two LED flat panels mounted vertically on a side wall under the mast, facing the telescopes in parked positions, for calibration purposes. One of these was deliberately mounted horizontally temporarily below the level of the observatory wall so the mast mounted SQM pointing 20° north of zenith with a 20-degree field of view would not see any luminance from the panel except that scatter down within its field of view from the sky. The panel was of a known brightness.

![Figure 54: 2020-07-12, Sky luminance: horizontal flat panel lights on/off mag. arcsec^-2](image)

![Figure 55: 2021-05-07, Sky luminance for flat panel set horizontal, on/off mag. arcsec^-2](image)

The all sky camera and also the SQM tilted 20° north of zenith and the flat panel luminaires, repositioned below the observatory wall pointing upwards for the experiment. These are normally used for calibration of the two 300 MM aperture telescope systems with autoguiding that can be just seen in the pictures. The SQM readings were manually taken as a series with the LED switched panel on and off many times for about 1 minute at a time, during the darkest and most stable part of the night. This is enough time for the SQM to settle to give reliable readings. This was limited by the rate at of change of the luminosity of the sky, which was changing continuously, especially on the very short nights of summer. Up to 170 readings were taken and averaged, for interpolating for the ones when off and vice versa, see the plots below. This was done on the clearest of nights for about one year. For good quality nights are shown for the light panel on and off repeatedly, figures 54 to 57. The differences are shown in figures 58 to 62. Examples from different times of the year.
In analysis, for readings of lights on while there were no readings of lights off at the same time, and vice versa, the last previous values were used, so they were always in pairs. The combined sources were 6,500 Lumens and with the average reflectivity a figure was obtained for the total luminance upward.
flux into $\pi$ steradians. The luminance ratio between on and off for the better of the two nights was determined to be $-0.036 \text{ mag.arcsec}^{-2}$. The calculation was done by converting the sample data to a linear scale of milliCandels.m$^{-2}$; the difference was found to be 0.022 mCd.m$^{-2}$ with 8% standard deviation, 6% above dark sky background. This gives an estimate of the downwards luminance to upwards luminous flux ratio, as approximately $3.2 \times 10^{-8}$ m$^{-2}$sr$^{-2}$ in units of optical throughput. This is shown in table 2, again selecting the best of nights.

The backscatter ratio was found to be $2 \times 10^{-7}$ m$^{-2}$sr$^{-2}$ in units of optical throughput $\pm 8\%$.

In figures 63 to 65 the plots show the backscatter figures as a function of humidity; wind speed and outside temperature. There is some correlation with humidity i.e., water droplet content, as to be expected. Not for other parameters as only the very clear nights were used.
6.2 Expected sky brightness based on Non-intrusive lighting plans for housing estate surrounding observatory Reepham Norfolk, using backscatter figures from the above.

The example used was for a proposed new housing estate figure 66, adjacent to a school observatory site see figure 66, where the developer’s lighting designer report claimed no light would reach the observatory directly, so not an issue. But it did allow determination of the luminous flux of the lighting. Using this, the estimate of the effect of the housing estate on the night sky at the observatory. Using an example typical curve fit to measured data of the sky, it was possible to model the sky luminance vs. zenith, see figure 67.

No commercial lighting layout programs consider atmospheric scattering.

The angle profile expected from this lighting scheme in figure 65 is above normal rural background. From the intended estate lighting compared with a clear night natural background (grey), as a function of zenith angle seen from the observatory. Here a difference of 0.5 mag.arcsec^-2 for medium back scatter, humidity >85% (orange), and 0.1 and for low back scatter (violet), according to local weather and time dependent conditions.
Satellite crossings of camera images from increasing numbers of starlink satellites.

Satellite crossings are increasingly from mega constellations for global Internet coverage; now 1 or 2 in every 30 minutes, for 2 deg. Fov, for many parts of the sky away from local midnight. It is becoming impossible to image the sky away from midnight without satellite crossings every few frames and this is just a fraction of what is to come.

Here is just a small sample from the author’s increasing collection. Figure 67; Satellite crossings of Pinwheel galaxy 120 sec exposure.600mm FL lens F/5.6, ISO 16002; figure 67 NGC 4565 galaxy 120 sec exposure.

General Conclusion

For the AONB dark sky survey in 2012 carried out on the darkest nights every month through autumn and winter, showed little variation in the sky brightness over the whole area except in the towns, by about 0.7 mag.arcsec-2. The air clarity and general darkness improved up to April that year due to rising temperatures, so less saturated humidity, and more rainfall.

Since 2012 to 2019, the change in sky brightness and colour towards the horizon was visually obvious, mostly confined to sky domes adding colour according to local lighting over the towns. It is becoming increasingly blue-white due to conversions to LEDs, and can change colour and direction over minutes to hours according to cloud changes over each town and mist on the local hills obscuring the Severn Valley lighting by as much as 0.3 mag.arcsec-2. The darkest nights are those with slight mist or fog with little stellar visibility, or clear locally but with mist or low cloud on the horizon obscuring the primary sources, which can vary rapidly.

For the Mathon observatory, there are no very local light sources. The amount of rural sky brightness near zenith is mostly determined by the adjacent town and accumulation from towns and cities beyond the local horizon. As one gets further away from one town, one gets nearer another. It doesn't comply with single town source dark rural location measurements, where a steady falloff with distance is described in many papers and has been modeled by the author. It is not an inverse square law relationship.

Any blue light to the sky is scattered to great extent, so the sky brightness trend over recent years is towards increasingly blue white; this is most obvious towards the horizon from distant town and city light sources. The changes vary from the zenith to the horizon and are critically dependent on weather conditions. In some areas, the sky brightness measures much the same as before, while in others it can increase due to particular sources and changes in lighting. The most commonly installed LED lighting has a blue-white colour, because of the high efficiency blue type phosphors in the LEDs, which also match the peak dark-adapted eye response, where colour vision is absent. At full day light levels, the human eye has little sensitivity in the blue.

The International Dark-Sky Association and after a major study on brightness and colour changes from blue rich LEDs, strongly advises low CCT, see [19],[20]. The lower CCT LED lighting (<3000K) produces far less scattering for the same ground brightness; it also causes a lot less glare. This is a requirement near sites of international observatories.

The material for the research was based on a number of authors, referred to in [2], that is [4] to [20]. The results for SQM readings agree reasonably with atmospheric modelling and some satellite data sets [21],[22],[23]. Satellite based photometry such as the Suomi VIIRS imaging spectrometer data, is often used in studies, has no blue response, while ground based camera imaging does, so in a better position to see colour changes. It has limited spatial resolution, but it is calibrated and has large world coverage, see [24],[25],[26]. For recent papers are measuring sky brightness in light-polluted areas including spectrally, see [27], [28], [29], and remote dark areas [30].

There are many other issues concerning night-time pollinating insects and other creatures being attracted by blue lighting for more than yellow, also many other environmental consequences and human health issues, which are not the subject of this paper.

Expansion of UK towns is often associated with brightly blue-white LED illuminated peripheral retail parks and new roads, as in Hereford. Commercial and private uncontrolled non-directional LED lighting is increasing, negating the improvements in road lighting. The trend to increase brightness of road
lighting and adding luminaires to increase uniformity across Europe could double the light getting to the sky, making the Milky Way contrast in rural areas from 20% down to 10% in which case it would be hardly ever visible. This trend can be reversed with more thoughtful control and restrictions. The European lighting industry is becoming aware of this. The loss of visibility of starry skies and the Milky Way, our heritage, legacy and inspiration, is at stake. The impact on the environment and fauna habitation is already very significant and are part of humanities responsibility of climate change. There is now the UK all party parliament group that has made recommendations to the government on controlling light pollution and rationalizing between different departments centralizing control and responsibility. The ideal model would be government regulation like there is now in France. Sky above is the natural ultimate area of scientific interest and yet it has no protection in law. Only in darkness can you see the stars. Martin Luther King Jr.

9. Acknowledgements

The British Astronomical Association Commission for Dark Skies has made occasional small financial assistance.

The author acknowledges two commissions from Worcestershire Council through the Malvern Hills Conservators: for the 2012 MHAONB dark sky survey, covering some equipment costs, and the 2015 environmental impact of the Herefordshire LED rollout, for the initial modelling only.

Besides this, the author has not had any access to funding for the work or requirement used over the years.

The author’s previous work was published in JQSRT and throughout this paper has been referred to and only presented as summaries. The re-analysis and new techniques and related projects are original in this publication

10. References


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Lessons Learned from the FlexSpec-1 Spectrograph

Authors: Jerrold L. Foote, Wayne Green, Greg Jones, Frank Parks, Anthony Rodda, Forrest Sims, Thomas C. Smith, Clarke Yeager
Small Telescope Science Initiative
7131 Oriole Lane, Boulder Colorado, USA 80503
SMTSci.net

Abstract
This final paper of the FlexSpec-1 series presents lessons as applied to 3D-Printed/Hybrid material spectrographs for small telescope science. We present a detailed analysis of the photon-path from source to sensor and identify the places within the spectrograph to mitigate instrumentation issues. We present the calibration unit, the "Kzin" ring, as a stand-alone aspect of the project suited to all spectrographs. A full implementation is in the public domain via Github. Public documentation is available via ReadTheDocs.io (Rtd).

1. Introduction

This paper addresses issues with thermal expansion, torsion, and flexure; difficulties with achieving and maintaining focus/resolution; off-axis issues with calibration lamps. We identify optical noise sources, light contamination, and external environmental issues found in Small Telescope Science (STS) spectrographs along the lines of the LowSpec 3D models used in the authors' previous work (Foote, J. et al [2021]). FlexSpec-1 (FS-1) extends our previous designs with an automation architecture to allow ease of focus on starting with the bench through remote operation of the spectrograph.

Complete design and documentation, design files and automation source code is available via FlexSpec1.ReadTheDocs.io. We use RtD through this paper to refer to relevant sections.

2. Overview

The FS-1 (Figures 8 and 9) is a small conventional spectrograph that follows the LowSpec (folded classical) layout. This design uses a hybrid construction approach. To address thermal expansion and flexure, we used a rectangular aluminum extrusion roughly 4x6x3 inches for the walls to provide the mechanical support of the nosepiece/dovetail, guide camera, and basic science camera supports. We used a 12-Gauge steel plate as the base support plate. 3D printing allowed accurate design of sub-assemblies used throughout the spectrograph.

The application of the grating equation is the critical aspect of spectrograph design. The critical lesson from the grating equation was the need to maintain a precise angle of incidence. We followed the light path and noted impacts come from several places: 1) if the collimating lens is out of focus the output beam produces a variation in the ‘angle of incidence’ for the grating, and 2) higher Fraunhofer lobes carry about 4% of total energy and have their own angles of incidence that cannot be fixed with a collimating lens.

We added two types of baffles to mitigate stray and reflected light.

Automation allows for local and remote control of the FS-1 to provide wavelength selection, collimator focus, calibration lamps and flats. (Foote, J. et al [2022]).

3. FS-1 Structure

The roughly 2.3 kg weight of the FS-1, including the science and guide cameras, affects the centers of mass and introduces flexure as the telescope is pointed to various targets. Repositioning the telescope changes the parallactic angle. This requires rotation of the spectrograph with respect to the optical axis for equatorial mounts.

A thick aluminum extrusion provides a rigid structure but carries a coefficient of thermal expansion (CTE) double that of steel. To counteract this expansion, the optical components of the FS-1 are all mounted on a steel plate backbone which has about ½ the CTE of aluminum. In the FS-1 design the two structural components are firmly coupled together only along the front edge of the spectrograph at the nose piece.

The entire optical path is referenced to a steel plate backbone to minimize individual component movement with temperature.
3.1 Design Tools

The FS-1 was designed using SolidWorks and Fusion 360. These parametric design tools allow both intra- and extra-parametric part design. With over 40 individual components, it was imperative that each part interfaced properly with the entire system. It is hard to mix and match CAD files between CAD packages. Parametric design allowed fast, easy precise development of components. The components were assembled with little or no alignment issues. This produces repeatable and predictable results.

3.2 3D Components

FS-1 has 44 printed parts. We used PETG with Carbon and took care to fine-tune the printer and part orientation when printing. (See RtD section Printer).

The parts were printed with a 0.4mm hardened steel nozzle and a layer height of 0.1mm. Wall thickness was set to 1.2mm and line width at 0.4mm. Infill density was set at 10%. These are good starting parameters when printing the FS-1 components and should be adjusted to suit your printer.

3.3 Calibration Module (Kzin Ring)

To add calibration lines, locator markers, and flat lamp illumination, we designed the ‘Kzin Ring’ module. We integrated the ring into the FS-1. The Kzin ring was broken out as an independent module to reside inside the nosepiece for use with existing spectrographs. This design does not consume valuable back focus space.

Placing the lamps on a ring roughly symmetrical with the optical axis better matched the science and reference images. See Figure 5 and 7. Results were more in line with dome flats common in photometry (Traspsteen, Walker [2017]). See Figure 6.

We added a shutter mechanism to provide better flat image characteristics. We use UV LEDs to extend the blue range of the flats. (See RtD section Kzin Ring).

3.4 Guider

Past guiders suffered from restricted field of view, distortion, difficulty achieving focus, and orientation. We adopted a two-lens relay system modeled with a spreadsheet. (See RtD section Guider).

We typically get a FOV of over 20 arcminutes and sample 4.5mm of a 6mm slit with a small camera.

3.5 OVIO Slit Holder

The slit holder utilizes a similar holder to the original LowSpec spectrograph and incorporates the 1.5 mm thick OVIO glass slit disk. We blocked the 500-µm slit to use as a dark position or shutter.

Orienting the slit’s shiny side towards the sky removed double/triple star images. The issue is the glass thickness, and the angled orientation of the slit produces an optical caustic. Shiny side to the spectrograph exacerbates parallactic angle problems, in turn requiring a wide slit leading to lower resolution at the sensor. (See RtD section OVIO).

During a Young’s single slit experiment with the OVIO slit, we noticed output rays produce severe Fraunhofer diffraction patterns. We analyzed the pattern and devised a slit baffle, located immediately behind the slit with a few mm exit pupil to mitigate the additional lobes. See figure 2 and 3. The energy in the additional lobes arrive at the grating with a different angle of incidence adding a ‘fog’ to inappropriate areas of the spectral range.
3.6 Collimator

Focusing the collimator lens is critical.

After considerable testing we have found that collimating lens focus is a forgotten area that leads to lower resolution. To improve this, we incorporated a collimating lens focus mechanism such that the collimated light coming from the lens strikes the diffraction grating at the same angle across the entire illuminated portion of the grating. Consider an out of collimation beam: the edge rays on one side of the grating strike the grating at an angle not parallel to the central ray. Thus, the diffraction angle is different between the edge rays and the central rays, resulting in a decrease in resolution.

As this focus is very critical, we have designed a two-stage focus lens holder with the first stage a rough focus that accounts for lens focal length tolerance while a second motorized stage provides a very fine focus adjustment.

3.7 Grating

We found the traditional lever-arm/micrometer head grating rotator to be temperature sensitive. We substituted an automated, motorized, gear driven, magnetic drag anti-backlash grating mechanism replete with home sensor.

3.8 Stray Light Baffles

Any stray light bouncing around in the spectrograph will decrease the signal to noise ratio, degrading the resolution. Figure 4 shows the before/after results. The baffles prevent fogging of critical areas. We found the Culturehustle™ BLK3.0 acrylic paint to be the darkest/flattest of those we tested.

3.9 Camera Lens

Light leaving the grating has each wavelength focused at infinity provided the collimator is properly focused. Since the angle varies with wavelength, a properly focused camera lens forms the sharp image of each spectral feature. Fishtail effects arise with short-focus lenses. Commercial camera lenses are designed for color photography with special optics to provide a flat field. This is exacerbated by the mechanical tilt often found between the camera faceplate and sensor surface. While we settled on Pentax f/1.8 55mm Super-Takumar lenses, any reasonable lens will suffice.
4. Results and Data

We obtained data on several reference targets. Here we present testing and scientific images. Figure 7 is a target and reference star.

4.1 Mechanical Performance

The FS-1 has proven to be very stable. Kzin calibration frames were taken across several positions. Figure 6 shows an exaggerated test whereby a first calibration frame was taken with the telescope in the parked, horizontal position at the beginning of the session. The telescope was slewed through a meridian flip, to the opposite sky quadrant. Target acquisition and calibration frames were taken. Over the course of the observing session, the telescope was then slewed multiple times for similar target and calibration frames. This was repeated back through the meridian flip, until it was again parked horizontally.

During the return journey the grating was deliberately moved 1000Å blue-ward and back again with the motor.
This operation that would not be attempted during a normal observing session without full recalibration.

The ‘before’ and ‘final’ calibration spectra differ by about 3 pixels, with software reporting less than a 3.6Å shift.

5. Conclusion

It is amazing what you see when you look. We placed emphasis on following the noise, not the signal. The first conclusion reached was the importance of maintaining focus of the collimating lens across temperature extremes of one evening’s observing run.
Key noise sources we found, underreported in the literature, result from stray light and the Fraunhofer diffraction pattern of rays exiting the slit. These are easily mitigated with simple baffles.

The critical mechanical aspects of flexure and thermal stability exacerbate calibration shifts and inaccuracies for line centroids on the sensor. We designed a calibration source along the optical path to better mimic the light cone from the main OTA with no mechanical movement. This allows spectral calibration lines to be easily and frequently obtained throughout the night. We used a commercial camera lens where the optics are designed to produce a flat projection onto a planar sensor surface.

The redesign of the guider lens system provides the widest FOV with small guide camera sensors to improve tracking and target acquisition. The design permits easy lens substitution to adapt the guider for the 30cm-1m telescopes becoming common in the small telescope science community.

We realized automating the FlexSpec-1 makes setup, maintenance, and operation easy and extendable from the local bench to distant locations. See (Foote, J. et al, [2022])

We applied a flexible train of thought to the complex interwoven aspects of spectrograph design. Our team of engineers, scientists, and software engineers pull from the varied life-experiences of all members of this team. We are, in essence and deed, modern instrument and telescope makers.

6. Acknowledgements

We express our appreciation to numerous websites, web-videos etc. that help deepen our understanding and appreciation for the science and optics needed to refine this design.

7. References


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Figure 5 Relco NeAr lamps, from Kzin ring, captured with FS-1. The grating is a 600 l/mm grating, blazed in blue. This is an example of a finder image for that specific instrument. Lamp intensities vary.

Figure 6 This figure has three uncalibrated calibration images (pixel coordinates) showing the stability of the calibration lines. Taken at different positions on the sky, from three different nights taken in New Castle upon Tyne US. There was a 3o C change across all images.
Figure 7. Alignment of the target HD 1266601 (Blue) and a reference star (red).

Figure 8. CAD Rendering of the Device.

Figure 9. The final assembled Device with guide and science cameras.
Using IRAF/PyRAF with Small Telescope Spectroscopy
Wayne Green
Small Telescope Science Initiative
7131 Oriole Lane, Longmont Colorado, USA 80503

Abstract
This paper introduces a new IRAF/PyRAF Package designed for the FlexSpec-1. The package encapsulates the parameters tuned to the architecture of small spectrographs in general and the FlexSpec-1 instrument in particular. While the IRAF/PyRAF analysis aspects are very dated, they still work well for very low-resolution spectrographs. The core of this package is a "cmosproc" procedure for use in lieu of the standard ccdproc approach. The package is available on GitHub. We offer a suite of tools to augment PyRAF scripting. The documentation is publicly available on ReadTheDocs.io.

1. Introduction

IRAF is the Image Reduction and Analysis Facility (Tody [1986]). The IRAF project started at Kitt Peak (pre NOAO) in 1981, adopted by STSci in 1983, and saw its first release outside of NOAO in 1984. In 2001, PyRAF was announced as the next ‘extended cl’ (de La Peña et al. [2001]). It was dropped from STSci/NSF support in 2018 and continues with community support as a Github repository under the direction of Ole Streicher (Streicher [2017-2022]). Its main competitor was the Interactive Data Language (L3Harris Geospatial Solutions, Inc. [2020]), and more recently Astropy (Robitaille et al. [2013], Price-Whelan et al. [2018]). Popular packages in the Small Telescope Science (STS) community include RSPEC (Field [2011, 2021]), VSPEC (Desnoux [2022]), ISIS (Buil,Christian [2022]), BASS (Paraskeva [2022]), Demetra (Cochard [2022]), and other custom projects.

The critical decision about data reduction is one of software capability. One chooses the software, then the computer. Most Small Telescope Scientists (SMTs) own Microsoft computers. There is a small Apple’s Mac/OS environment community. Linux runs a distant third. Most professional environments are centered on Unix/Linux or leverage the Unix features of Mac/OS.

The processing environments fall into categories: 1) closed source / commercial GUI programs like BASS, ISIS, Demetra, Maxim/DL, PRiSM etc.; 2) open-source GUI programs like AstroImageJ, Exotic; 3) closed script environments like IDL, Python/Astropy; and 4) open script environments IRAF/PyRAF, bash etc. Closed source packages give little indication about how they handle new sensors. In general, many packages treat sCMOS and smaller cameras as though they are well behaved CCD sensors.

Spectrographic image processing is divided into two basic areas: 1) camera corrections for bias, zeros, flats, instrumentation, and response corrections and 2) extracting, analyzing and publishing data. The real issue is with the corrections. Once an acceptably reduced image has been achieved, the analysis portion proceeds as with any other spectra. Advanced spectrographic analysis (temden package) is a bit long in the tooth, using outdated astrophysical constants. This is easily compensated by internal/external Python scripts.

This paper is a case study about developing an IRAF/PyRAF workflow using all the capabilities and tricks with sCMOS sensors. The short answer is a carefully crafted suite of cl and PyRAF scripts together with a few hardcoded support programs.

For this paper, IRAF from the Anaconda repository (Anaconda [2022]) was used on an Intel I7 processor together with the Anaconda Python environment. Anaconda ‘lags’ the very latest releases to be as consistent as possible across all the included modules and packages. It is possible to write Python 3.x code that is compatible with Python 2.7 to be generally available across users and platforms.

2. CMOSPROC

The current ccdproc task for IRAF assumes that each pixel in an image array is essentially the same as all others. This is the case with ‘old-think’ sensors and more modern, albeit expensive, CCD sensors. The variance of each pixel remains steady across a set of exposures (where one pixel may be high – it is consistently high).

2.1 Noise Models

Built-in noise mitigation for newer CCD sensors with Sony HAD and On Semi TrueSense technology brings its own set of issues. The average counts for a
bias frame will differ only slightly from dark exposures. However, the variance of the dark exposure grows with time. The variance of any one pixel across the night is high. Developing master correction images takes on aspects that ccdproc was not developed to handle. This problem is exacerbated by the difficulty that less expensive cameras have attaining -20C (253 K) absolute temperature. Vendors often state cooling for the camera as ‘below ambient’, difficult for people who live in hot climates to achieve and maintain.

2.2 Well Depth and GAIN Issues

Traditional cameras have large well depth, for example the E2V 231 has a well depth of 350,000, with 8 readout amplifiers. The additional readout amplifiers require processing not found in ccdproc. The sCMOS cameras have readout electronics for each column, a case that ccdproc will never handle correctly. New sCMOS sensors have technology to limit dark counts and read noise on the order of 1 to 2 photo-electrons per read.

Very early cameras had a current-mirroring diode assembly that added between 99 and 101 electrons to the electrical current from a shift register before the ADC stage. This was to stabilize early ADCs. This was usually called the BIAS image. The resulting BIAS image carries Poisson white noise statistics. BIAS is the origin of the PEDESTAL keyword. A ZERO image was a readout of the entire array, together with bias diodes. This image carries a large Gaussian component – based on the process characteristics of the chip together with the small BIAS Poisson pedestal level. DARK images are a combination of the BIAS/ZERO image together with a Poisson dark current model.

Lessor cameras use a 10, 12 or 14-bit Analog-to-Digital-Converter (ADC), converting accumulated photo-electron charge into Data Numbers (DN) or Analog Data Units (ADU). Images often have the 2 or 4 least significant bits (LSBs) fixed to zero. The saturation still reports as 65535 which is impossible with a well depth of only 20,000. The simplistic GAIN value should at least read 4 for 14-bit ADCs and 16 for 12-bit ADCs. This requires research and special pre-processing of bias and dark images. The number of bits needed for a well depth is easily computed as \( \ln(\text{well})/\ln(2) \). For 20,000 this will be 14.29 bits. The limit for 14 bits is \( 2^{14} = 16, 383 < 20,000 \).

2.3 Camera Modes

The newer cameras have several ways to convey accumulated photo-electrons to the FITS file. High ADU counts offered in sales literature are the result of binning 2x2. In general terms, small pixels are not able to support high well depths. This requires careful modeling of the input flux to meet Signal to Noise Ratio (SNR) requirements. Small pixel geometries are extremely sensitive to slight process variations, leading to noisy pixels overall. Binning raw images at the camera level is not recommended. Best practices include using post-exposure trimming, noise correction like that of LACosmic (van Dokkum et al. [2012]) and normalization with localized PSFs to preserve all information needed to fully inform data reductions.

With low read noise per pixel, it is possible to spread a signal over many more pixels than the ‘old-think’ CCD exposure logic. More pixel samples lead to more refined PSFs and lend the ability to correct the numerous pixels. The ability to identify and correct noise may be lost using a 2x2 binned samples. Gaussian fitting of spectral lines requires a minimum of 3-pixel widths, 5 or 7 being better. Many reads may take place for long exposures. For image sequences where cosmic ray damage may occur, the images with damage to the science features may be omitted during stacking results. Determining resolution values to support these decisions is easily accomplished with the IRAF/PyRAF task imexam in combination with accurate calibration lamp images. Quick access to the values can be obtained with ds9’s statistics tasks accessible with regions.

3. CMOSPROC

IRAF is essentially programmed in FORTRAN/C. The coding process starts with writing a `.x` extension file using the Subset Preprocessor Language (SPP) program xp, written in C using lex as the token parser. The special SPP syntax is closely related to both cl and FORTRAN. This preprocessor translates code into either C or FORTRAN, then uses the GNU compiler to make the executable `.e` program. Users modify/write their code and produce a `.e` executable file suitable for use within the IRAF/PyRAF environment.

As an example, in the case of the ASI294 camera, the data section of a bias may contain 16-bit byte sequences like ‘0x0b70’ and ‘0x0c30’. The byte order is BIGENDIAN per the FITS specification (Chiappetti [2016]). Each pixel, like 0x0b70, is 12-bits of data left-shifted by 4 and padded with zeros. The data is compressed into 3 nybbles, 2^12 bits, with a range of [0..4095]. The camera literature offers a well-depth value of 66,000 electrons. Very small pixels are incapable of supporting that charge. Careful examination of a graph within the literature shows this camera has features that use 2x2 binning, corresponding with a color Bayer mask for color
4. Spectrographic Reduction

In general, the reduction of photometry and spectra proceeds the same as it always has after images are cleaned with post-processing, creation of masters, and the handful of steps with the cleaned data. One slight difference is the order of spectral reductions and the need to trim spectral ranges to eliminate noisy areas.

4.1 Basic Observations and Reduction

This paper refers to ‘bias’ images as ‘zero’ images. The zero designation is traditional across IRAF and accurately states the type of file – a ‘zero second exposure’. Complete headers, trimming away useless information for large chips, mitigating large variances, producing accurate calibration and flat images are necessary for spectroscopy.

Updating headers is important. Two new FITS keywords are introduced here: CMOSMODE and CMOSGAIN. The mode and gain are keywords to record the instrumentation settings employed by camera firmware and software to render the photoelectron counts. It is important to record the clear aperture of the telescope, its effective focal length, camera type and a locally assigned serial number, and any other site-specific instrumentation information.

The header is the only record and allows for auditing errors in the future.

The sCMOS chip-sizes are daunting. Never bin. Binning does two destructive things to the data: 1) it drags spectral information from adjacent wavelengths into the neighboring data and 2) the noise is dramatically increased by merging widely varying pixels. The massive images should be trimmed at the point of observation to preserve the trace of the spectra, guard bands, and skyline areas. The X axis data should be trimmed to remove any part of the spectral aperture containing missing or unacceptably noisy data. The blue range is often quite noisy. Removing the X values to begin with helps fit the data using linear polynomials. Trimming operations should add a physical-to-image WCS to headers to retain information about where pixels were on the sensor.

Bias and dark images may carry their own patterned noise. IRAF usually creates master zero and dark files by median combining a set of images. Median combining needs to work with an odd number of images, otherwise the value is taken as the average of two middle values. When the median combine approach is used, it returns the middle value for each pixel across the stack of images. To be clear, the returned value, at pixel (1,1) may take the 17th frame’s value, but at (1,2) may take the 12th frame’s value. For chips with little variance, this is a great approach.

For FlexSpec-1 using lessor sensors, the masters are median combined and then a surface is fit to the data. This smooths down the variance to bring the entire surface to within a few ADU values overall for zero and dark images.

Most STS spectra are produced with the ‘trace’ of the star along the chip’s rows (across its columns). Ideally each column has the same wavelength. Many software packages rectify the image first by re-sampling across columns to remove the ‘tilt’, ‘slant’ and ‘smile’ artifacts of the optics and instrument setup. This immediately introduces additional error. The rectification is a step common to long-slit spectroscopy and is part of IRAF’s twodspec package. In the onedspec package, during the ‘aperture extraction’ IRAF follows the trace, fits a polynomial to the trace, defines a guard gap and infers the trace to be used to gather skyline noise for subtraction. The polynomial may include a 9th order Chebyshev polynomial or other order of a non-linear polynomial.

To mitigate the effects of uneven slit illumination, the FlexSpec-1 Kzin ring boosts blue data. The cmosproc package has code that creates a master flat by sampling only along one column to generate the profile. This is normalized to the location of the aperture’s trace from the apextract task.
requirement is a one-d spectra interpretation of creating a flat image.

Creation of the response curve also follows the extracted trace’s path.

At this point the master bias, darks (if used), and flat images have been created using logic related to the sCMOS sensor behavior. Extraction of the data proceeds along the usual onedspec reduction technique.

5. Augmenting Analysis with Python

IRAF/PyRAF is a hack of the Python 2.7 readline command altering Python’s native syntax to be very similar (often exact) with the original cl syntax. The open nature of the PyRAF shell environment makes mixing and matching of internal tasks and external programs very easy.

6. Summary

IRAF/PyRAF is under open-source community support. The environment allows users wide latitude for reducing data. It is still possible to write a suite of ‘tasks’ (Python scripts) and mix them together using a Unix bash script to achieve the same flexibility. Writing a PyRAF script is just as easy and brings the power of IRAF’s tried and true algorithms to bear on data reduction.

Each night’s data is unique. There will never be a one-size-fits-all pipeline – only pipeline kits. The IRAF/PyRAF facility is the most flexible package available and carries the power needed to perform successful data reduction of the myriad of new sensors we see on the market today.

Details and examples are available at this paper’s Github repository: https://github.com/The-SMTSci/STS_IRAF.git and documentation available at http://flexspec1.rtfd.io/ and the Github project’s wiki pages.

7. Acknowledgements

The author expresses his sincere thanks to the greater open-source community for providing numerous tools free of charge for non-commercial and educational work. He especially thanks the IRAF community and the Anaconda Team at Continuum.io for their dedication and efforts.

8. References


Figure 10. Left: SAOImage/ds9 histogram of the variance across 5 KPNO tk05 zero frames. Right: Histogram of variance across 5 ASI296 bias frames. The red (left in image) and green (right) lines are set to the same value. XAxis is in variance terms computed using the make2dstats Python script.
Automation of the FlexSpec-1 Spectrograph

Authors: Jerrold L. Foote, Wayne Green, Greg Jones, Frank Parks, Anthony Rodda, Forrest Sims, Thomas C. Smith, Clarke Yeager
Small Telescope Science Initiative
7131 Oriole Lane, Longmont Colorado, USA 80503
SMTSci.net

Abstract

This paper presents the platform agnostic and extensible control architecture developed for working with remote instrumentation. We cover issues and benefits of a web-based distributed system at the local and international level. We discuss the edge conditions we found with the technology and tool-chain management. The code is available on Github. The documentation is publicly available on ReadTheDocs.io.

1. Introduction

Using an Arduino Nano 33 BLE Sense or IoT processor to assist with focusing and operating the FlexSpec-1 (FS-1) spectrograph requires both hardware and software control layers to assist with the operations. The architecture is designed and built from the instrument towards an observer/controller. The key control aspects include 1) calibration sources (NeAr lamps, marker LEDS and flat lamps), 2) focusing the main telescope, 3) a sensor and rotator to compensate for parallactic angle, 4) a way to select the slit on the fly (vary resolution several times during one run), 5) finding the slit, 6) focusing the collimator (on bench and during the night), 7) selecting the grating, 8) selecting the central wavelength (high resolution mode, grating blaze angle), 9) focusing the “camera” lens, and 10) interacting with the sensor/cameras during the run.

We chose to develop a web-app software control layer to allow any human or computer – anywhere on the network/Internet – to take data. One goal was to sidestep software installation of WIMP GUIs and all the platform and IT issues that follow that approach. The essence of control is sending a message to perform simple or complex operations and receiving feedback/data from that process. A Single Board Computer (SBC) is placed on the Optical Tube Assembly (OTA) together with 1 power cable and 1 Ethernet cable. This meets design goals to remove the rat’s nest of cables and to solve long-haul USB issues. The addition of a power block and switch allows for more than one package per OTA. This allows piggy-back photometry without increasing the number of cables.

The software uses a Bokeh server to communicate with a dispatch-server to manage 3.3V serial communications with the Arduino processor controlling FS-1 and other instruments like the piggy-back OTA.

2. Overview

The subsystems include an EEPROM for storing unit specific parameters, a 6-DOF IMU for parallactic angle, focusable collimator, rotatable grating with home sensor, Kzin lamps and a servo-controlled shutter mechanism. Future plans include slit selector for low/high resolution science during one observing run, slit back-illuminator, temperature sensors, interoperability with auxiliary controls via I2C and SPI ports, guide camera focus, and more.

The overall architecture is based on the idea of having one power cable and one Ethernet cable from the outside world onto the OTA. This makes each instrument payload independent and easily remotely managed. The heart of the FS-1 architecture is a SBC running Linux and operating in a distributed peer-to-peer system.

Each sub-system of the FS-1 is implemented by an Arduino C++ class mirrored by a Bokeh Python class. The communications loop consists of the user-interface sending its values to its mated C++ class. The C++ class alters the state of the FS-1 to conform the values. Values are stated in units familiar to the user, like Angstroms for central wavelength, angles, intensities in percentages, etc. The model is one of a Navy Captain telling the engine room to make revolutions for 23 knots (Captain’s user units on the Python side), and the engine room performing the necessary actions (C++ Arduino side) for the result. The Arduino will come close to the requested Angstrom setting and return the achieved position back to the user.

We implemented a simplistic routing protocol using a pure ASCII JSON string. We require the
Python side to do all error checking to save limited space within the Arduino. We use a peer-to-peer Bokeh server within the RPi to host our code in the same machine as KStars/LibINDI/Ekos for control of cameras. One or more Bokeh servers running on the OTA communicate with a Socket-based dispatch-server (also on the RPi) to dispatch messages to one or more devices over the simple 3.3v Serial Rx/Tx interface. This requirement avoids issues we found with USB communication to Arduino devices.

3. Calibration Module (Kzin Ring)

The Kzin ring, see Figure 4, is named after the cat-like creature with "unusually colored eyes" from Larry Niven's "Ring World" (Niven, Ellis [1970]). It is a multi-lamp concept that provides calibration, flat, and marker lamps for the FS-1 (and other) spectrographs. Initial spectral coverage is from the about 3600Å to NIR. The Kzin is as much a concept as a device.

The concept of the Kzin is fairly simple. For a slit spectrograph one wants both calibration and flat illumination that is uniform in the spatial direction and smooth in the dispersion direction. To achieve this, we've attempted to emulate the converging "beam" from the telescope, geometrically, with an eye to uniformity along the slit. Three additional user selectable "marker" LEDs with narrow known wavelengths were added for use in setup and remote diagnostics.

A selection of emitters are paired symmetrically on each side of the slit. The emissions are reflected from an annular ring around the telescope's converging light cone. To help reduce spurious reflections and further shape the Kzin emissions a circular baffle is placed behind the ring between the ring and the slit. While the Kzin emissions through the slit are likely broader than those from the converging cone from the telescope, they should centroid to the same location. Testing to date confirms this.

Current emitters include a pair of calibration bulbs (Neon or "Relco"); grain of wheat incandescent bulbs, broadband mid wavelength "white" LED and a selection of NUV LEDs to extend the flat capabilities. Multiple LEDs have been used for spectroscopic flat images by the EXPRES Spectrograph and as a commercial spectrographic source by Gamma-sci.com.

3.1 Electronics

The electronics package consists of two control boards and the Kzin ring. We decided early on that all boards needed to be able to store their configurations and support an internal serial communication link. Both boards carry an EEPROM and have the one wire 3.3v serial capability.

The primary board for the FS-1 is based on Arduino Nano BLE33 IOT (or Sense). The BLE and IOT have IMUs (6 or 9 DOF integrated multi-axis accelerometer) that can give the spectrograph's orientation for an optional ADC or rotator. The board also drives the Kzin, up to four 2BYJ-48 motors, slit illuminator, Hall sensor inputs, and a number of additional I/O options. Designed to run on 8-12 volts, two switching regulators drop the supply voltage for use by the processors. A separate regulator for the High Voltage inverter used to drive the calibration lamps.

A second much smaller board hosts a small Seeed's XIAO processor to support a standalone Kzin assembly for existing spectrographs.

All boards for the project were developed using KiCAD EDA software (free). Boards were initially fabricated then later fabricated and “stuffed” by JLCPCB (China). We used SMT parts with through-hole connectors throughout. The full set of design files and documentation are on the Github with documentation found in the ReadtheDocs.io.

4. Implementation

We decided to use free or inexpensive tools to develop this project so students may find the entire project approachable and useful.

At the start of the project, we were presented with a decision between developing a Python/GUI vs MQTT/Panel/Plotly vs a WEB-app Bokeh combined with more traditional Unix peer-to-peer architectures.

Bokeh uses HTML5/CSS5/NodeJS and template environments like Django or Flash to craft user interfaces that do not require software installation, updates or maintenance on the user-side. We chose Bokeh by virtue of its prominent role with data-informatics.

A second goal is to simplify wiring from the pier to the devices of payloads mounted on the OTA. We developed 'piggy-back' photometry for simultaneous filtered observation of spectrographic fields. This involves mounting a reasonable refractor and its own control system own same mount.

SBCs like the Raspberry Pi running Astroberry – its own Raspbian OS image loaded with Kstar/libINDI/Ekos and a rich suite of other tools – were a perfect match to host our Bokeh/Python server to allow communications with our instruments based on Arduino ARM processors.

Arduino ARM processors support the mBED or SAMD C++ environments. This is a full C++-11
standard GNU compiler with exception handling disabled. This allows developing a suite of C++ classes that inherit necessary attributes of a system for communicating commands and meeting hardware interface aspects for this processor family.

We use the Arduino Nano 33 BLE Sense and IoT processors with built in Internal Measurement Unit (IMU) to report data for mitigating the impact of parallactic angle effects. The Seeed Xiao ARM devices are the perfect small chip format for control of the Kzin ring.

During the design we realized the need for a multi-drop serial capacity to support many small Arduino class programmable System on a Chip (pSOC) devices. This has been accomplished with the software architecture and I2C/SPI short haul interfaces.

Since we had to host high-power for the NeAr lamps, shift registers, and sensors of various kinds we designed our own Printed Circuit Boards (PCBs). We leveraged popular commercial board production services. We were able to email PCB designs to China and have boards in hand in just over a week. This feature allowed our British team member to do the same and receive boards faster than we could ship them with US carriers. We did two turns of the boards.

4.1 The Core JSON Message

We use a pure ASCII JSON (JavaScript Object Notation) string for information transfer to avoid mixing string and binary data values. The JSON string carries a key:value with the delivery address (a unique name), and the ‘Process’ string. The server process is the RPi Postmaster to send the string together with the return address via a connection. The receiving Postmaster either owns the device, or may know how to forward the message via an I2C or other means to the intended delivery point. This requires fine tuning of each instrument. This is a DIY project after all.

Each message starts with a STX character, the body of the message is guaranteed. The receiving Postmaster creates a C++ string and queues that string for processing. A dispatcher, sensing a new string, sends the JSON value to a mapped device.

We implemented task control with a weighted round-robin non-preemptive scheduler. Each task is disciplined to use only a small amount of time. Tasks requiring sequences of long running steps return a ‘wait request’ to the dispatcher – freeing the dispatcher to visit other queued tasks. We call this a ‘ThinkFast’ process. Examples: 1) a request for the current angle of the spectrograph’s slit (parallactic angle) is a very fast read and report of IMU registers; 2) a request to move a motor requires a sequence of step commands where each step incurs a rather lengthy wait for the motor to actually move. A request of 30 steps would result in 30 ThinkFast requests.

In another example, a message to enable calibration lamps would appear as:

```json
{"Tony's Kzin Ring": {"Default":
"wheat": -1, "callamp": 92, "hbeta": "0", "oiii": "0",
"halpha": "0", "uvboost": "0",
"flat": "0", "state": 1}, "Receipt": 1}}
```

The message requesting flat lamps would appear as:

```json
{"Tony's Kzin Ring": {"Default":
"wheat": -1, "callamp": 92, "hbeta": "0", "oiii": "0",
"halpha": "0", "uvboost": "0",
"flat": "0", "state": 1}, "Receipt": 1}}
```

4.2 System Software Components

TCP/IP running in a Windows Icon Menu Pointer (WIMP) GUI interface is a ubiquitous feature for laptop and desktop systems. Because writing platform agnostic code is a daunting task, we chose a browser-based connection to a Bokeh server residing in a SBC on each OTA. See Figure 3 for the general control tabs and for examples of Kzin lamp operation. In order to route commands between devices we adopted a Postmaster/Delivery paradigm.

Each JSON device serves as a Postmaster, a peer among equals. A Python dispatch-server routes messages locally. This sidesteps implementation and message delivery issues found with MQTT systems.

4.3 Arduino Code Overview

The Arduino OS calls a setup() and loop() routine in that order. The loop() essentially calls two subroutines. 1) If the Serial1 device (the hardware Rx/Tx 3.3V serial interface) has a character, it shoves that into a state machine. This in turn queues messages properly addressed to the processor (a named FS-1 or Kzin in our case). 2) regardless of the state machine, a dispatcher is called.

A mirrored class hierarchy uses proper Object-Oriented Design concepts for maximum flexibility with system maintenance. Code is developed and tested on a Linux machine (or a Docker container), then deployed to the Arduino. This allows ease of basic debugging. The Docker container provides an excellent way to manage the toolchain.
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Figure 11: A browser serves as the main user interface, with buttons and sliders to frame and send commands via the Internet to 2) a Bokeh/server running on a raspberry Pi. The server passes JSON strings to 3) the various classes within the Arduino. Postmaster routes lamp/shutter info to Kzin ring.

4.4 Code Maintenance

We chose to use a private Github development repository, pushing release to a public facing FlexSpec-1 repository. The private repository permits experimenting without public visibility into the project. The freedom to make mistakes was a powerful motivator for this team. Git repositories are far more powerful than a Zip/Email environment. A developed (CAD/EDA/Code) pushes updates and issues a simple email as a ‘pull-request’. The rest of the team may then pull results and pick up new features. We chose not to wade too deeply into the Git world.

4.5 Documentation

We chose a Sphinx approach to documentation supported by ReadTheDocs.io. The web url address, FlexSpec1.readthedocs.io takes anyone to the documentation. We write documentation in reStructuredText (.rst) format. Sphinx makes HTML, latex/pdfs and ebooks for users to access and download. Sphinx provides a powerful documentation production environment. Local testing of this process was managed using a Docker container.

5. Conclusions

The software architecture is a stretch for most of the team. We are all retired professionals with strong technical backgrounds in science, software and hardware engineering. The tendency to ‘just do it’ taking an easy way was leveraged for low-level test cases. Python and C++ are portable languages. The GNU/Clang tool-suites support very small to very large processors. WEB-app browser-based deployment means, well, no deployment for user’s machines. One can just as easily access any instrument (with proper permissions) from their cellphone in an emergency. FlexSpec-1 automation is both flexible for our immediate needs and suited to future instruments to come.

This paper describes the very basics of the FlexSpec-1 design. The Python dispatch-server task can be extended to route messages onto Astroberry tasks. Those tasks, like our file notifier, allow asynchronous operation with other network programs, like SAOImage/ds9 or a remote PostgreSQL database. Ease of use, extensibility and, above all, interoperability is necessary for operating equipment on the bench, in the backyard or across the world.

The code is available for download at: github.com/The-SMTSci/FlexSpec1. The documentation is available at flexspec1.rtfd.io/.

6. Acknowledgements

We express our appreciation to numerous websites, web-videos etc. that help deepen our understanding and appreciation for the science and optics needed to refine this design.
7. References


Figure 13: The Browser Interface. Left: The main panel: All JSON messages carry this device name. The slit is chosen (*); a grating is specified together with the central wavelength for the next operation; the guider is focusable (*); the collimator may be focused; and the parallactic angle may be requested. Right: The Kzin ring control panel. Top: slider controls a PWM chip to allow brightness control for NeAr lamps (on/off in FS1). Bottom: sliders change PWM ports for various lamp’s brightness. The On message for flats will activate the KZin shutter.
Figure 14. The Kzin ring: Upper left with Near lamps on. Upper right Grain of Wheat lamps on. Lower left Green maker led. Lower right extended blue LEDs on. The Servo controlled shutter is seen above the ring. (Cut away display).
Abstract
Flare stars, most commonly late K through early M stars, are being observed by an international team of small telescope scientists using new spectroscopy and photometry tools and protocols to investigate the astrophysical nature of flares. These stars are plentiful and are very likely due to their size, temperature and age to have habitable planetary zones impacted by flares.

Professional surveys of Flare stars often observe 10’s to 100’s of stars. Much of this work is accomplished using photometric techniques, with some spectroscopic measurements. Often there are only a few observations for each individual star included in the study. Our group has taken an approach that concentrates on a single flare star at a time, with multiple observers over a span of a few months when the star is most favorably observable from the ground. We make both photometric observations using multiple filters and spectroscopic observations using spectrographs of different resolving powers. This affords the opportunity to simultaneously “catch/confirm” flare events by multiple observers, with different instruments in different locations. As a cohesive group, we small telescope scientists can dedicate long periods of telescope time over an extended time period on a single target, hopefully capturing and analyzing large numbers and types of flare events. In addition to increasing our understanding of flares and flare stars, another of our goals is to show the value that Small Telescope Scientists can provide to the professional community.

This paper discusses the observation protocols, data management process, and analysis tools that we are developing to detect and measure flare activity. We show preliminary results for EV Lacerta, an active M4V Flare Star.

1. Introduction
First, what is a stellar flare? Flares are associated with magnetic forces on or near the star’s surface. Stronger magnetic forces can produce stronger flares. G-type stars like our sun have relatively weak magnetic fields of just a few Gauss. Late K and M dwarf stars have much stronger magnetic fields, a few thousand Gauss, and that increases the probability of generating flares.

The energy from a flare is released when there is a reconnection of magnetic field lines in the star’s corona. This energy is released rapidly in the form of charged particles and electrons accelerated along the magnetic field lines, from the corona down into the chromosphere, which results in heating and evaporating plasma, releasing energy from radio to x-ray wavelengths. (Jackman, James A.G. et al, 2021; Honda, Satoshi et al, 2018) This in turn impacts the blackbody temperature (visible in U, B and V filter photometry) and is also visible in the Hydrogen Balmer (HB) emission lines, Ca II H & K lines and some He I lines. (Gray, Richard O, and Corbally, Christopher J., 2009) Further, previous observations
Flares can be described as having an impulsive phase followed by a decay phase. The impulsive phase happens very quickly with the collapse of the magnetic field lines. This occurs on the order of 10’s of seconds. This impulsive phase includes the rapid rise, peak and rapid decay and is terminated with the transition to a slow decay. The slow decay phase can last several minutes to hours and is sometimes interrupted by one or more typically smaller flare-like events. (Kowalski, Adam F., 2013)

Last year we (Buchheim et al, 2021) reported on AD Leo that we had indeed been able to detect such flares through Time Series spectroscopic observations. This provided the proof of concept for a larger effort with more observers and targets, and with goals to increase our observing and analysis skills and to provide useful scientific data for the astronomy community.

2. Project History and Organization

The roots of the Red Dwarf Flare Project spawned from the bi-weekly Spectroscopy Discussion Group Zoom meetings, which were started soon after the Sacramento Mountains Spectroscopy Workshop in Las Cruces, NM in 2019. This group of active spectroscopists and those interested in spectroscopy help each other to improve skills, knowledge, and produce quality science data.

The Red Dwarf Flare Project itself began in February 2021 with a few nights of exploratory observations, asking the question, “I wonder if we can see anything…?” Can we detect a stellar flare on a known flare star with small telescopes? The answer was “yes – we can see flare events in our spectra”.

The exploratory phase was full of fits and starts, as we tried to understand our data and figure out what it might be telling us, both about our observing procedures and about the stellar activity. Some of that was frustrating and confusing at the time, but it is likely that the Silicon Valley notion of “fail early and often” worked in our favor. One obvious conclusion was that the more hours of observing time, the more flares we would likely detect.

We soon found out that not only could we detect stellar flares with our spectrographs and with photometry (and sometimes confirm them by one or more observers), but we also were detecting many flares (and accumulating a rapidly growing number of data files) for which we would need to figure out efficient processes to store, organize, count, classify, measure, and analyze.

Examining those collections of spectra led us down multiple paths: (a) creation of an online repository of spectra that was easily accessible to everyone who was involved or interested, (b) the development of tools that could streamline the analysis of the spectra, (c) wide-ranging self-education by the growing team, trying to figure out what our observations meant and how they related to the literature on stellar flares, and (d) the recognition that simultaneous photometry might greatly improve the understanding of the phenomenon.

Another thing we realized during last year’s AD Leo campaign was the need to efficiently manage communications, observing procedures, and initial spectrum processing so that we could effectively pool our collective data. This would be even more important with a larger number of geographically distributed observers using an even larger diversity of equipment.

To ensure consistent group communications, we scheduled a bi-weekly Zoom meeting at a standard time, where team members would report progress, display ongoing results, and get help solving problems. One team member (Buchheim) took responsibility for scheduling the (Red Dwarf Flare) meetings and making the meeting recordings available for anyone who could not attend in person. We also scheduled occasional guest speakers who could present on related scientific topics.

The other main communication tool was a Groups.io, Red Dwarf Group. We used the group for messaging, sharing recommended procedures, storing documents, and providing links to scientific papers of interest. We also created a Wiki on Groups.io with project information on the targets of interest, and to showcase recent spectra and photometry.

3. Observation Procedures

3.1 Spectroscopy

How to observe stellar flares? As mentioned above, we are searching for flares on M dwarf stars which by their nature are not particularly bright in optical wavelengths. Few M dwarf flare stars are known to be brighter than V magnitude 9. For many astronomy projects, small telescopes to some degree can make up for smaller apertures by taking longer exposures and stacking them, if necessary, when working faint targets. The problem with stacking exposures when searching for flares is that we lose temporal resolution.

If our exposure time is too long, we may miss a short duration flare entirely, or at least have no clear notion about the time of maximum flare energy. On
the flip side, if our integration time is too short, we may not have enough SNR to reliably differentiate the flare from the noise in the spectrum. Flare detection and analysis is a competition between SNR and cadence, and this is especially the case for small telescopes.

Another challenge is that we do not know when or if a flare will occur. As we found and reported last year in (Buchheim et al, 2021) good observing procedure calls for long observing runs, sometimes 8 hours or more to increase the odds of detecting a flare.

As spectroscopists we desire high resolution and as broad a wavelength range as possible from near UV to near IR. For most of us small telescope scientists, this is difficult to realize, if not impossible. Rather, depending on our equipment, we are either able to get a wide wavelength range with low resolution between $R = 500$ to $R = 1000$ or a much narrower wavelength range at higher resolutions. In the case of one of our team members, (Martin), this results in $R = 3500$ for the H Beta line. Also, higher resolution requires longer exposures times, as the light is dispersed across more pixels on our cameras.

Though experimentation and testing, we found that integrations times of 2-5 minutes were productive for detecting flares spectroscopically.

We chose known flare stars with V magnitudes less than 10 for our project. So far, we have observed one season of BY Draconis (BY Dra), a K4Ve+K7.5Ve star, one season of EV Lacertae (EV Lac), a M4.0V star and two seasons of AD Leonis (AD Leo) which is a dM3 star. For our northern hemisphere observers, we sequenced the flare star project targets as they became practically visible for runs that would last at least 3 hours. This paper focuses on the data collected and processed for the initial EV Lac season.

A typical spectroscopic observation entails taking a Ne/Ar calibration lamp image followed by (7 or more) spectra of a Reference star (typically a Miles Reference star) that is near in altitude and azimuth to the target star. Then, after making a short slew to the Target star, another calibration lamp image is taken followed by a long uninterrupted acquisition sequence of target star spectra, following the target across the sky from low altitude in the east to low altitude in the west, obstructions notwithstanding. This can produce 100 or more spectrum files for one observing night. Ordinarily, the individual target exposures would be stacked using a tool such as ISIS (Reference to C. Buil software) to produce one high SNR 1D spectrum for the target. But in the case of a flare star, this standard process misses the point. Any flare that only lasted a few minutes is entirely “averaged” out across the 100+ spectra (Figure 1 at the end of this paper). What we need instead is to process each individual exposure as a single 1D spectrum. Fortunately, ISIS offers a way to produce these individual 1D spectrum files in addition to producing the single stacked spectrum.

So far so good. However, our ability to accurately response correct each individual 1D spectrum, especially at the blue end, becomes less reliable as the target moves through an ever-changing air mass. This leaves the observer two choices: 1) Ideally there would be a Reference star observation at the same airmass for each target spectrum, but this clearly is not practical as it requires stopping target acquisition, slewing to a Reference star to take its spectrum, and then slewing back to the target star, which entirely defeats our effort to detect flares, especially those of short duration. 2) More practically however, we recommended that the observer take a Reference star spectrum at the same airmass as the target star at the beginning of the night, stop target acquisition and take another Reference star spectrum near zenith and then go back to the target star and finish, if possible, with a Reference star spectrum taken at the same airmass as the target before shutting down.

3.2 Photometry

Flare stars are more detectable in filters that are designed to pass light toward the blue end of the spectrum. Although “U” filter might be ideal based on our readings of professional papers, (Kowalski, Adam F., 2013) our observatories are typically at low altitude and in or near large population centers. These are not ideal conditions for gathering photons with a “U” filter. So, for this study we chose to work with two filter band passes.

- Johnson/Cousins V filter
- Johnson/Cousins B filter

Magnitude 10 stars are not difficult to observe in “B” and “V” filters with small telescopes. This is fortunate as the much of the energy in a flare is found in the continuum which rises and typically decays very quickly. Short cadences of 10 to 20 seconds are achievable and necessary to detect some of the very fast flare events. Note that TESS observes some targets with a 20 second cadence.

Photometry, in addition to being a valuable tool for detecting flares is also important for determining the energy in a flare which will be used to determine flare flux in ergs/cm²/sec/Å. (See accompanying papers by Boyd, Buchheim in this Symposium).
4. Data Management

With multiple observers collecting data on several targets over several months, we needed to carefully organize data storage and 1D spectrum file naming. We created a shared Google drive for storing the files and developed a simple folder hierarchy. The Google drive was organized by Target Star/Observer/Civil Observation Date. Each observer was responsible for uploading their individual 1D spectra to this folder structure, with the @pro*.fit spectrum files named by ISIS, the spectra processing software that we used. We then ran a File Renamer utility (created in Python specifically for this renaming task) to copy and rename each spectrum file with a unique, standard file name of Target/Observer/Julian Date (JD), resulting in, for example:

/GoogleDrive/Red Dwarf/EV Lac/Woody Sims/2021-10-27/EV_Lac_Forrest Sims_2459515.6284.fit

Note that we use a variant of Modified Julian Date (MJD) for all data stored in .CSV files and in the database. We subtract 2450000 from the Julian Date, resulting in an MJD of the format 9541.3498, for example.

Managing photometry data was more straightforward. Each photometry observer was responsible for processing their data, generating an AAVSO extended format data file, and uploading the data to the AAVSO International Database.

We soon found that it was difficult to visualize the data coverage from photometry and spectroscopy, so initially, we created a shared Data Timeline view using Google Sheets (Figure 2 at the end of this paper). Each observer added a cell indicating an observing session and used cell color coding to indicate the initial status of the observations. Any cells with possible detected flares also contained a comment with approximate flare JDs.

The shared Google Sheet also contained a Tab with a preliminary data summary of all spectroscopic observations (Figure 3 at the end of this paper). This Tab provided a quick numeric overview of all potential flare activity and served as a base for one method of calculating flare frequency.

Finally, we created a Tab for each observing day, with detailed Equivalent Width (EW) data from our processing tools, and graphs (Figure 4) of the Equivalent Widths over time. As our data volume has grown, we are now starting to use reports from a database of observations to replace these spreadsheet-based tools.

5. Data Analysis

Our observations have yielded flares in many sizes, durations and even shapes. We use PlotSpectra (Lester 2017) to display the individual 1D spectra. With this software we can identify time spans where we see a change in the intensity of an emission line. (Figure 5) shows an example of the H Alpha line profile in quiescence and at the peak of a flare. PlotSpectra can be used to measure the Equivalent Width of each line profile. However, it is a tedious task to perform for each 1D spectrum.

It is useful to find characteristics that can be measured despite the size and shape of a specific flare. In reviewing numerous professional papers, we found a set of common measurements, some of which we could apply to our data.

We have focused on the following spectroscopic measurements:

1) Flare frequency

Flare frequency is most often expressed in units of events per hour or events per 24-hour period. So even if some observation time series do not detect a measurable flare, the observations are still important in tabulating flare frequency results. Further we attempted to sub classify detected flares by flare classification.
2) **Flare classification**

Simple “classical” flares have a relatively large amplitude and a rather smooth decay. As described earlier the rise is rapid, seconds to a few minutes, followed by a rapid decline with a clear transition to a more gradual decline. Complex flares may begin looking like a simple flare but be interrupted by multiple peaks (although typically lower in amplitude that the first peak) and have durations from minutes to hours.

3) **Flare duration**

Flare duration is the elapsed time between flare start and end times. This is most often expressed in hours and minutes. The difficulty in determining flare duration is precisely identifying the start and end times. We chose the start time as the time when the EW increased above the quiescent level and the end time when EW fell back to the quiescent level. (Figure 5)

4) **Equivalent Width (EW) Ratio**

Equivalent Width (EW) (Figure 6) is a way of measuring the strength of a line minus the amount of energy from the background continuum. This is done by replacing the real line with its core and wings with one that has the same power (Area) but which has sharp edges that drop immediately to zero intensity. The equivalent width is then the width of this false line in Å. Absorption lines result in positive EW values and Emission lines in Negative EW values. For presentation in this paper where we are looking at emission lines, we ignore the “sign” and report positive values for EW. The EW Ratio is the ratio of the flare peak EW to the quiescent EW. Note that the quiescent EW is different depending on the emission line.

5) **t_{1/2}**

\( t_{1/2} \) is the time duration of the FWHM of the flare light curve, which can also be applied to Equivalent Width line plots of spectrum emission lines.

6) **Line broadening**

Flares are suspected to produce a broadening of emission lines (Wu, et. al, 2022). We have not detected any broadening in our spectra at resolutions of 500 to 1000 where we have too few resolution elements across the line. There is a better chance that we might detect broadening at \( R = 3500 \) (LHIRES III 1200-line grating).

6. **Software Tools**

We developed multiple software tools to analyze our spectroscopic and photometric data. We decided early on to use the Anaconda implementation of Python3 along with its scientific libraries, including Astropy, specutils, NumPy, Matplotlib, Plotly, Scipy, and others (Faes, 2018). The tools were developed and run in the VS Code environment on both Mac and Windows, and the Python code was shared with project members on Google Drive.

A key measure for detecting flares in an emission line of a spectrum is to measure the line’s equivalent width (EW) and look for changes in its value over time. We developed SpectraStats (Figure 7 at the end of this paper) to process one night’s observations, calculate and plot EWs at multiple Balmer emission lines, Ca II H & K, and select He I lines.
SpectraStats uses a JSON table with three preset wavelength ranges for each line of interest (Hβ (Hydrogen Balmer), He and Ca lines). The first range defines a short region of continuum blue ward of the line of interest. The second defines a wavelength range that encompasses the full width of the line (wide enough to accommodate the lines increased width during a flare). The last range defines a short region of continuum red ward of the line of interest. The blue ward and red ward regions thus allow us to establish a continuum level.

Before processing each individual 1D spectra we use the specutils “centroid” function to find the center of the line and shift it to its rest wavelength position for the purpose of calculating equivalent width. We then use the specutils “equivalent_width” function to calculate equivalent width (EW).

SpectraStats also calculates and accumulates statistical data on the processed 1D spectra that is then used to provide an initial measure of the statistical significance of any changes in EW over the observing session (Figure 9).

All the output data from SpectraStats are stored in appropriately named .CSV files for later loading into a database for analysis. In addition, SpectraStats generates a contour plot and a 3-dimensional surface plot of each line relative intensity with respect to time and wavelength. The surface plot is in the form of an HTML file and can be rotated and zoomed by the user within a browser. Flare intensity values can be displayed at the cursor position. This plot displays wavelength vs MJD with relative intensity on the Z axis. This plot can alternately be displayed in velocity space vs MJD. (Figure 10)

Another key measure is flare energy calculated from the photometry. We developed PhotoStats (Figure 11 at the end of this paper) to import photometric data from an AAVSO light curve download file, and using an estimated quiescent luminosity, calculate the cumulative energy in a flare.

A challenge with such a long time-series of observations is adjusting the response correction of individual 1D spectra to account for the changing airmass over the course of the night. As described earlier, ideally one would take a Reference star spectrum at an airmass that was close to the airmass of the target star at the midpoint of each target star observation. To improve the response correction, given that we only observed the Reference star at Low and High Air Mass, we developed “SpectraResponse”, again in Python.

SpectraResponse requires the observer to provide the Instrument and Atmospheric response function that they used when response correcting the spectra in ISIS. It also requires a second response function taken at large an airmass difference from the first response function as is practical. We used a naming convention...
of InstResp_lowAM and InstResp_highAM to identify the two response functions.

SpectraResponse implemented the following formula (Buchheim, Robert, 2022) to apply the airmass correction to the individual 1D spectra.

\[ I_{\text{correct}}(\lambda) = I_{\text{reported}}(\lambda) \cdot \frac{\text{Resp}_{\lambda_1}(\lambda)}{(AM_1-AM_2)} \cdot \frac{\text{Resp}_{\lambda_2}(\lambda)}{(AM_1-AM_2)} \]

Where:
- \(I_{\text{correct}}(\lambda)\) is the true exo-atmospheric spectrum of the star (in relative flux)
- \(I_{\text{reported}}(\lambda)\) is the processed spectrum of the star in relative flux
- \(AM_1\) is Air Mass of the Reference star for the first response function
- \(AM_2\) is Air Mass of the Reference star for the second response function
- \(AM_x\) is Air Mass of the Target star for observation x
- \(\text{Resp}_{\lambda_1}(\lambda)\) is the response function at Air Mass 1
- \(\text{Resp}_{\lambda_2}(\lambda)\) is the response function at Air Mass 2

We think we are onto something that will allow us to avoid interrupting continuous target monitoring without having to stop to take frequent reference star observations. We are continuing to investigate how to improve response correction when we only have reference spectra at one or two discrete airmasses. Based on initial testing, we determined that the air mass has different characteristics in different parts of the sky. We plan to investigate the impact of AOD (Aerosol Optical Depth) and other local sky conditions as second order terms to the above equation.

Finally, we developed EWLoader and EWAnalysis to help manage the large volume of collected emission line Equivalent Width (EW) data. We have thousands of 1D spectra uploaded by observers on the shared Google Drive, and for each of these we have EW measurements for one or more lines. At first, we set about looking at each observation’s EW plot vs. MJD (Modified Julian Date). (We have over 240 of these for EV Lac!) The purpose in examining each of these plots was to try and spot by eye (consensus of 3 pairs of eyes (Curry, Buchheim, Sims)) “statistically” significant changes in EW indicating the detection of a flare candidate. Then for each candidate we attempted to determine the start and end times and calculate flare duration, EW/ratio, and t1/2. This was a painstaking task, and it became apparent that a better method would be required.

EWLoader takes all of the hundreds of EW vs. MJD .CSV files produced by SpectraStats and loads the target, observer, line, MJD, EW and an Air Mass corrected flag into a SQLite database.

EWAnalysis (Figure 12 at the end of this paper) can then select data by target, line, observer, optional date range, etc. and calculate flare statistics and plot results.

Most of the flare measurements require that we identify a quiescence level of EW. It turns out that as important as knowing the quiescence level EW is, finding a good definition of quiescence is not easy.

The approach that we took was to implement several definitions and evaluate their suitability. The first is to use the median of the EW values for the selected data set, be that a single night for a single user or multiple nights for multiple observers. We also calculated a median value where we first discarded outliers that exceed the median plus 3 sigma. And the third method was to calculate the Median Absolute Deviation and then add 3 times the MAD value as a screen to discard outliers before then recalculating the median. It turns out that all three of these methods produce a “median” value that are numerically very close to each other.

We considered additional iterations of calculating a median and then discarding any additional outliers before recomputing a new mean. But on data with sparse large outliers (flares) there appeared to be little to gain. More relevant is the decision to choose standard deviation or MAD for setting a threshold above which we would consider our detection to be a flare. We found that choosing the EW threshold to be the MAD reduced median + 3 * MAD matched closely to what we counted as flares when we put three sets of eyes to the data. (Figure 13)

7. Results

The Red Dwarf Flare Star team observed EV Lac spectroscopically for over 195 hours in 73 observing sessions, plus many additional hours photometrically. This resulted in approximately 12,000 individual EW measurements from over 3,200 spectra, and over 10,000 photometric B magnitudes and 8400 V magnitudes loaded to the AAVSO database.

We have produced some preliminary results from our first observing season of EV Lac. We calculated a flare detection threshold of 3.0 MAD individually for each emission line. Choosing this statistic for a threshold for all H Beta EW measurements, we detected 31 flares over the 195 hours, for a rate of 1 flare per 6.3 hours (Figure 13). Similarly, we detected 30 flares for the H Delta emission line, and 34 flares in H Gamma. H Alpha is noticeably different with 10 flares detected.

Note that the number of flare (candidates) is highly dependent on our detection threshold and will be the subject of more detailed analysis in the future.
Figure 14: Flare Distribution Histograms produced for four prominent Balmer emission lines. Figure 14 shows the number of the detected flares for four Balmer Emission Lines, by their Equivalent Width Ratios. The EW ratio used in this graph is the ratio of the measured EW at the flare peak to the quiescent EW for that emission line.

We have not yet classified flares by type, calculated flare duration and $t_{1/2}$, or measured line broadening.

For a detailed analysis of the largest EV Lac flares, see David Boyd’s paper “Combined Spectroscopic and Photometric Analysis of Flares in the dM3.5e Star EV Lacertae” in this symposium. For a statistical analysis of Season One AD Leo, see Bob Buchheim’s paper “Time-Series Spectroscopy of Flare Star AD Leo in 2021” also in this symposium.

8. Conclusion

We have gained considerable experience in organizing a project which involves many observers, time zones, and heterogeneous equipment. We employed modern tools like Zoom, Google Drive, Google Sheets, Python, SQLite, and open-source libraries. This experience will prove valuable for our ongoing study of Red Dwarf Flare Stars.

We have developed flare star observation protocols and created software tools for managing and analyzing large volumes of spectroscopic and photometric data. These tools include SpectraStats, PhotoStats, SpectraResponse, and EWAnalysis. We are continuing with tool development, while also adding Season One and Two AD Leo, BY Draconis, and CR Draconis data to the existing EV Lac data in the SQLite database. This will enable us to test multiple scenarios and assumptions about quiescent levels and flare detection thresholds. This will also allow us to develop algorithms for bringing us closer to automating the calculation of flare durations, flare equivalent duration, line broadening, and $t_{1/2}$.

9. Acknowledgements

We have been fortunate to have professional guidance in carrying out this project from Dr. James Jackman (Postdoctoral Research Scholar in Astronomy at Arizona State University).

10. References


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Figure 1: This composite spectrum of EV Lac is produced from 43 x 4 minute stacked exposures. Note that any flares occurring during this nearly 3 hour observing session will averaged into the resulting single spectrum.
Figure 2: Shared Google Sheet Showing EV Lac Spectroscopic and Photometric Observations Timeline. Individual observers update this timeline with their observations, which are then immediately visible to other team members.

Figure 3: Shared Google Sheet showing possible flare events. Note that this manual effort is in the process of being replaced with automated detection of flare data in the database.

Figure 7: SpectraStats User Interface showing H Beta processing of LISA spectroscope data from one observing session. Options are available to control the display of EW and Contour Plots, as well as selecting a range of MJD’s to process.
Figure 11: PhotoStats Photometry Flare Energy Estimate. The upper chart shows B Magnitudes for an observing session, and the lower chart shows the estimated start and stop times of a flare event. Note that the horizontal grid scale is slightly different between the two charts.

Figure 12: EWAnalysis User Interface
Figure 13: H Beta EW by MJD for All EV Lac Observers for the Entire EV Lac Observation Season. Candidate flares occurred on days where the EW exceeded the flare threshold.
Time-Series Spectroscopy of Flare Star AD Leo in 2021

Robert K. Buchheim
Spectroscopy Discussion Group & Lost Gold Observatory
Bob@RKBuchheim.org

Forrest Sims
Spectroscopy Discussion Group & Desert Celestial Observatory

Sean Curry
Spectroscopy Discussion Group & Yank Gulch Observatory

Jack Martin
Spectroscopy Discussion Group & Huggins Spectroscopic Observatory

Abstract

AD Leo is a well-studied flare star, but spectra of its flares are still relatively rare. In 2021, we accumulated a large data set of time-series spectra showing AD Leo’s flares in the optical band. Here, we report the Flare-Frequency Distribution derived from this data set, and some other statistical observations from this project. Our results compare favorably with previous published investigations.

1. Introduction

During the 2021 observing season, a small group of us monitored the well-observed known flare star AD Leo with small-telescope spectrographs, to assess our ability to observe stellar flares. That effort was successful (Buchheim et al., 2021), but did not include any quantitative analysis of the flare activity. Here, we report on some statistics of the flare activity that was observed during the 2021 campaign.

2. Observations

We made time-series observations of AD Leo using Shelyak ALPY (R≈ 500) and LISA (R≈ 1000) spectrographs. The individual exposures were either 4 or 5 minutes (with occasionally runs of 3-minute exposures), and normally the time-series exposures were made continuously for most of the night. The observations were made on 26 nights, accumulating 150 hours of observing time (not counting overlaps where two observers were active). More than 2200 spectra of AD Leo were collected. On several nights, we had two observers “on target”, and their results were nicely consistent, showing that the variations in emission lines that we were seeing were real, not artifacts generated by the observers.

The raw spectra were reduced in the standard way using the ISIS software (by Christian Buil). A typical spectrum profile of AD Leo (without a flare) is shown in Figure 1.

Figure 1: Spectra of AD Leo (no flare). These have been flux-calibrated for determination of $F_C$ (as described in the text).
Since we do not have simultaneous photometry for 2021, we treat all of the spectra as “relative Intensity”, and base all of our analysis on measurements of the time-varying Equivalent Widths of the lines.

The 1D spectral profiles were analyzed using the Python code “SpectraStats”, developed by Sims and Curry (Sims et al, 2022, in these Proceedings) to yield tables of Equivalent Width vs time, for several emission lines. This code examines each spectral profile around each emission line, re-centers the line on its laboratory wavelength (to correct for small wavelength shifts during the night, that we assume are caused by flexure or temperature change in the spectrograph), computes a linear fit to the continuum region above and below the emission line, and computes the line Equivalent Width. The output is a CSV file of EW vs time for each emission line, plus a set of CSV files containing other parameters of the spectra around each emission line.

The net result is a large collection of time-series spectra, displaying the changing emission features of the star. In this paper, we report on some statistical analyses of this collection.

3. Flare Detection

For this work, the flare detection algorithm was a very subjective “eyeball” assessment. Each nightly EW plot was examined in two ways. First, the SpectraStats “standard deviation vs wavelength” was used to assess whether there was, somewhere during the night, a 3-sigma change in the emission line flux. If “yes”, then it is presumed that at least one flare occurred on that night; if “no”, then we assume that there are no flares that night (although we visually examined the EW plot, anyway). Second, the EW vs time curve was examined to identify any events that show a visually obvious rise in EW above the local background level, spanning at least 3 data points (~15 minutes), and showing evidence of the event in at least 2 of the Balmer emission lines. The flare Start and End times of each event are estimated by visual examination of the plot. The Python code “EWStats” sets the nightly quiescent level, EW0, at the 10th percentile value of the EW’s seen during the night (i.e. 10% of the data points are below this value). It also refines the Start and End times and the corresponding EW values (EWstart and EWend) which are used to fit a sloped baseline beneath the flare, for use in the flare-energy calculations.

We are working on a more objective, statistically grounded algorithm for detecting and identifying flares, and establishing the Quiescent level, but that is not yet ready. Hopefully, the visual/subjective approach used here can be used as a test case for proposed automated routines and will enable us to assess their performance in terms of false-positives and missed-detections.

3.1 Characteristics of Typical Flares

While each flare is unique, a few “typical” flare profiles are seen repeatedly in this collection.

Figure 2 shows a flare profile that we have called a “FRED” (fast response, exponential decay), rising rapidly from the nightly quiescent level and then gradually fading back into it. This is similar to what Kowalski et al (2013) call an “impulsive” flare profile. These range from large-amplitude, long-lived events, to small-amplitude, short-lived events. It can be difficult to pick the smallest ones out of the random fluctuations of EW.

![Figure 2: Typical “FRED” (or “impulsive”) flare profile.](image)

Figure 3 shows a flare that is similar to what Kowalski et al (2013) called a “gradual” flare – a slow rise and slow fall, making a fairly symmetric “hump” event. It is not unusual to see quite a jagged profile to these events. The jaggedness might be real (e.g., indicating that this is actually a collection of smaller rapid-fire events), or it might be simply some sort of noise. We treat each of these as a single event for the purposes of power and energy calculations, unless there is a compelling reason to divide it into multiple events.

It sometimes appears as if a small flare arises during the decline phase of a preceding, larger flare (or rarely, during the rise phase of a subsequent large flare). Figure 4 shows such an event, that might be a single flare with a couple of flashes on the decay portion or might be a large FRED whose decay overlaps with two smaller FRED flares. We make no hypothesis about the actual phenomenology at the star. For flare-counting and for power and energy calculations, we followed Davenport et al (2014), and whenever feasible, the small FREDs were treated as separate flares, whose energy is calculated by the area
above the decay trend-line of the larger event. These are coded as “overlapping” in our flare library. In some cases, it was not practical to measure the power or energy of the small flare, in which case it was simply included in the power/energy calculation of the larger flare.

Of course, there are also situations where only a portion of a flare is captured – a probable flare may begin before the observation session started, or it may still be in progress when the observations session ended. Figure 4 above contains an example of a flare that had apparently peaked before the observing session began. Such partial flares are not included in the flare count, nor in the Flare Frequency distribution, since we have only a lower limit to the flare energy.

3.2 Equivalent Width, Flare Power, and Flare Energy

We did not have simultaneous photometry to accompany the spectroscopy during the 2021 AD Leo campaign, and the AAVSO does not contain many photometric observations during our observing campaign. This makes it impossible to flux-calibrate this set of spectra. Our analysis here is based solely on measured Equivalent Widths of the emission lines. It implicitly assumes that the overall brightness (e.g., B- or V-mag) of the star did not change noticeably, and that the flares did not affect the “continuum” flux level. This is certainly an under-estimate of the flare power and energy, particularly for the largest events, because it ignores any change in the continuum flux from the star during a flare (see Boyd et al, 2022, in these Proceedings). We report here only the “emission line” power/energy.

During a flare, we observe that the strength of each emission line rises.

Figure 5 illustrates the quiescent emission line (FQ), and the emission line observed at a point in time during the flare (Fobs). The shaded region represents the increment of flux created by the flare: FFlare(λ) = Fobs(λ) – FQ(λ). The units of flux received at Earth are erg/s/cm²/Å, and wavelength is in Å.

We would like to know the power that was emitted by the star to create this increase; and then integrate the power-vs-time curve to find the total energy released by the flare (in that emission line). It turns out that the changing Equivalent Width of the line provides this information.

The defining equation of Equivalent Width is

\[ EW = \int \frac{F_C - F}{F_C} \, d\lambda \]

where F(λ) is the spectral flux from the emission line, and Fc(λ) is the continuum level. The integration extends over the (user-defined) wavelength region containing the emission line feature of interest. Note that this equation makes the EW of an emission line a negative number. Purely for viewing convenience, all of the EW graphs in this paper present the absolute
The resulting energy is given as the integral of the power over time, as expressed by the fundamental equation:

$$E = \int_{t_1}^{t_2} L(t) \, dt$$

where $E$ is the total energy emitted by the flare, $L(t)$ is the power at time $t$, and $t_1$ and $t_2$ are the start and end times of the flare, respectively.

The quiescent level of continuum flux ($F_Q$) is the background level of continuum radiation that is present in the absence of a flare. It is measured in ergs/cm$^2$/s/Å.

The quiescent Equivalent Width ($EW_Q$) is the measure of the absorption in the continuum that is present in the absence of a flare. It is calculated as the integral of the continuum absorption over the wavelength range of interest.

The flux received at Earth from a star ($F$) is given by:

$$F = \frac{L}{D^2}$$

where $L$ is the luminosity of the star, $D$ is the distance to the star, and $F$ is the spectral flux density received at Earth.

The spectral flux received at Earth is related to the spectral flux received from the flare by:

$$F_{flare} = F \cdot \frac{D}{D_{flare}}$$

where $D_{flare}$ is the distance to the flare.

It is common in the stellar flare literature to report the power and energy in the Ca II (K) line as a separate parameter. However, we have not done any analysis on it as a separate parameter.

For each candidate flare, the EW vs. time in four Balmer lines (H$\alpha$, H$\beta$, H$\gamma$, H$\delta$) is used to calculate the power vs time and total energy in each line during the flare. In most of the flares, there was no measurable response in the Ca II (K) line, but for a few of the flares, the power and energy in the Ca II (K) line could be calculated. It is described below.

Since flare energy is the integral of the power over time, a low-amplitude, long-lived event can release as much energy as a high-amplitude short-lived event. The longest-lasting flare observed in this project was nearly 4 hours from start to end, and this is certainly not an upper limit on flare duration. Wu, et al (2022) report spectroscopic observation of a flare (on a different star) that lasted nearly 7 hours.

The EWStats code records the peak power of each flare, but that represents the average power over the ≈ 5-minute exposures used for these spectra. That does not come close to resolving the impulsive rise and fall of a flare (as is seen on fast-cadence photometry). So the peak power inferred from our spectroscopy is such an under-estimate of the underlying peak power that we have not done any analysis on it as a separate parameter.

It is common in the stellar flare literature to extrapolate from the observations and infer the total bolometric energy in a flare. We do not do that: we are reporting only the power and energy within the emission lines, as observed.
4. Flare Frequency Distribution

Flares generally occur randomly in time. The key feature of the randomness is that low-energy flares are relatively common, and flares of high energy are relatively rare. The standard statistical model for this is a power law:

\[ \nu = \mu E^{-\alpha} \]

Where \( \nu \) is the flare rate (in hr\(^{-1}\)), \( E \) is the flare energy (ergs, in the emission line), \( \mu \) is a rate constant, and \( \alpha \) is the power-law index [see, for example, Loyd et al (2018)]. The standard display of this phenomenon in the literature is a “Flare Frequency Distribution” (FFD), plotting the cumulative flare rate (flares/hour) or cumulative number of flares in a campaign, versus flare energy. The power law forms a straight line on a log-log plot:

\[ \log(\nu) = \log(\mu) - \alpha \cdot \log(E) \]

[see Lacy et al (1976)].

The theoretical Flare Frequency Distribution faces two observational effects, illustrated in Figure 7.

The chance of seeing the highest-energy flares is limited by the observing time: we expect the data at the upper left of the curve to get ragged, and possibly “turn over” (reduced slope) simply because we didn’t observe for long enough to see the highest energy flares.

For the low-energy flares, at some point the flare has such a small peak, or such a short duration, that we can’t reliably distinguish it from noise. As a result, the “observed” flare rate will fall off more rapidly than the power law’s prediction.

Our compiled library of flares, showing each flare’s integrated energy in each of the Balmer lines, was used to create a flare frequency diagram for AD Leo. Figure 8 shows the FFD for the sum of the four Balmer lines.

The “Balmer sum” FFD has a slope of \( \alpha = 0.90 \), which is consistent with \( \alpha = 0.82 \) reported by Lacy et al (1976) for U-band flare energy in AD Leo, and with \( \alpha = 0.93 \) reported by Loyd et al (2018) for FUV flare energy in AD Leo.

Figure 9 shows the individual contribution of each of the Balmer emission lines. The slopes of the individual Balmer lines range from \( \alpha = 0.87 \) for \( \text{H} - \delta \) to \( \alpha = 0.95 \) for \( \text{H} - \gamma \) – probably not a statistically significant difference.

We emphasize that the flare energy reported here represents only the energy contained in the emission lines. Boyd et al (2022, these Proceedings) shows that high-energy flares release quite a bit of their energy as a rise in the continuum level in the blue and UV spectral regions. Hence, our “emission-line-only” energy is an understatement of the total energy released by large flares.
4.1 Measurement uncertainty of EWs

In order to put error-bars on the EW measurements, we applied the analysis by Vollmann & Eversberg (2006). Their key result is:

\[ \sigma_{EW} = \sqrt{1 + \frac{\langle F_C \rangle}{\langle F \rangle} \cdot \frac{(\Delta \lambda - EW)}{SNR}} \]

where
\( \langle F_C \rangle \) is the average flux over the continuum region
\( \langle F \rangle \) is the average flux over the line region
\( \Delta \lambda \) is the width of the line region (Å)

EW is the measured Equiv Width
SNR is the Signal-to-Noise ratio in the spectrum at the emission line of interest.

The SNR is determined from the continuum region on the blue side of the emission line. The analysis program SpectraStats (Sims & Curry 2022, in these Proceedings) normalizes the local continuum to unity, and examines each wavelength bin within the continuum region on each spectrum profile. The standard deviation, over all spectral profiles, is plotted as a function of wavelength, as shown in the example in Figure 10.

The SNR used in Vollmann & Eversberg’s formula is just \( SNR = AVG(1/\sigma_\lambda) \), where the average is taken over all wavelength bins in the continuum region. Our uncertainty in EW ranges from \( \sigma_{EW} \approx 0.25\text{Å} \) for H-alpha to \( \sigma_{EW} \approx 0.70\text{Å} \) for H-delta [and \( \sigma_{EW} \approx 1.05\text{Å} \) for Ca II(K)].

4.2 What does “Quiescent” mean?

In the equation relating change in EW to flare power, we glibly identified EWQ as the “Quiescent” value of Equivalent Width of a line, which (since the star is continuously in emission) presumably means the EW when the star is most quiet. However, consider a plot of the entire data set of EW vs time, as shown in Figure 11.

Each column of dots represents a single night. The bottom of each column is the smallest value of EW observed that night, and the top of the column is the largest EW observed. The tall peaks represent large-amplitude flares. The bottom values do not seem to be bounded by a constant floor (“Quiescence”), but rather vary noticeably, and randomly, from night to night. Some of that fluctuation is doubtless due to measurement uncertainty. Some of the nights showing elevated minimum EWs are situations where the entire night represented the rise or decline phase of a very long-lived event. In other cases, there is no obvious reason for the elevated “nightly minimum” EW level.

The nightly fluctuations of EW are intriguing, but we have not yet done a satisfying analysis of them. Figure 12 shows the EW vs time for the Balmer lines, and the cumulative distribution function (CDF) of H-gamma EW, on a “quiet” night, with no obvious flares and a generally flat-line EW trend. H-gamma is illustrative – all of the lines showed a similar nearly-vertical CDF. The CDF curve appears to be what would be expected from a random fluctuation around a constant value, with a pretty small standard deviation.
Figure 12: Example of EW fluctuations and CDF of Hγ EW, on a quiet night.

Figure 13: EW Fluctuations and CDF of Hγ on a night that showed (a) a large flare and (b) a minimum EW noticeably higher than the “quiet” night shown in Figure 12. The “quiet” night CDF is also shown for comparison in the right panel.

Figure 14: Changes in EW of the Balmer lines are well correlated, overall: the Balmer lines tend to “rise and fall together” during a flare.

4.3 Time evolution of Balmer lines during a flare

Subjectively, we observe that during a flare, all of the Balmer lines rise and fall together. The EWs of the lines are well-correlated overall, as illustrated in Figure 14 which shows the entire data set of ALPY-measured EWs.

However, this correlation hides an important feature of their time-evolution during large flares.

Kowalski et al (2013) introduced the FWHM of the photometric or spectroscopic light curve of a flare (which they call “t1/2”) to characterize the time-evolution of power released during the flare. They reported a relationship between t1/2 and the Balmer line emission: the longer the wavelength, the longer t1/2 is. That is, the longer the wavelength, the more slowly the line returns to quiescence after a flare. Kowalski et al (2013) name this the Balmer “time decrement” and note that it is related to the way the star’s chromosphere reacts as it relaxes from the flare.
and fairly large $\sigma_{EW}$. Nevertheless, it is interesting to
see how the Ca II(K) line correlates with the
Balmer lines on the largest flare: see Figure 16. There
is a strong hint that rise of the Ca II(K) emission is
delayed, relative to the Balmer lines, and that its decay
might take longer. Kowalski et al (2013) saw a similar
result for some of their large flares.

5. Conclusions, and directions for the future

This effort suggests that small-telescope
observations of stellar flares can add useful data sets
for the study of the flare phenomenon. Because of the
increasing availability of affordable spectrographs,
amateurs can devote more observing-hours to flare
stars than professionals can. The results reported here
lend credence to the idea that our spectra can be used
to measure the emitted energy in different emission
lines, and for different stars, to augment other lines of
observation.

There are also some lessons for future flare-star
monitoring campaigns:

- As in other variable-star spectroscopy
campaigns, there is huge value in having
simultaneous photometry to accompany the time-
series spectroscopy. We have done that with the
2021 EV Lac campaign, and also very intensively
with our 2022 AD Leo campaign (for which analysis
has barely begun).

- It seems that examination of the larger flares
would benefit from better time-resolution in the
spectroscopy. We have begun experimenting with
shorter exposures to achieve better time resolution
(albeit with lower SNR). We will also examine the
feasibility of stacking the short-exposures into
synthetic long-exposures prior to extracting the
spectra, to pull more detail out of the spectra.

- We have collected many hours of higher-
resolution spectra (LHires spectrograph), that has not
yet been analyzed. We hope that detailed analysis of
this collection will enable us to see shape changes in
the emission line during large flares, and possibly
velocity changes during the strongest flares.

- Our ability to repeat spectro-photometric
campaigns year after year for some stars (such as AD
Leo) might enable a search for stellar cycles
analogous to the solar 11-year sunspot cycle.

- Our 2022 observations of AD Leo were
timed to coincide with TESS Sector 48, which
contained AD Leo. The analysis of our spectroscopy
and photometry will be compared to the very-broad-
band photometry from TESS.

- Loyd et al (2018) point out that FFD’s from
emission lines of different formation temperatures
might provide a probe to different regions in the stellar atmosphere. Our flare spectra from LISA and UVEX might be able to contribute here (e.g., He-I lines seem to show a good response in some LISA spectra). We should investigate this.

6. Acknowledgements

We are grateful for the advice and assistance that Dr. Chris Corbally and Dr. James Jackman have given us, and their enthusiasm for our efforts at small-telescope spectroscopy.

This research has made use of the VizieR catalogue access tool. CDS, Strasbourg, France (DOI: 10.26093/cds/vizier). The original description of the VizieR service was published in 2000, A&AS 143, 23.

This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

7. References


Combined spectroscopic and photometric analysis of flares in the dM3.5e star EV Lacertae

David Boyd
davidboyd@orion.me.uk

Robert Buchheim
bob@rkbuchheim.org

Sean Curry
sxcurry@gmail.com

Frank Parks
fgparks@mac.com

Keith Shank
kasism@verizon.net

Forrest Sims
forrest@simsaa.com

Gary Walker
bailyhill14@gmail.com

John Wetmore
john@azdesertskies.com

James Jackman
jamesjackman@asu.edu

Abstract

We report the methodology and results of an observing campaign mounted by a dedicated group of well-equipped small telescope scientists to study the dM3.5e flare star EV Lacertae. Concurrent photometry and spectroscopy of EV Lac was obtained on 10 occasions between October 2021 and January 2022. Spectra were calibrated in absolute flux using B band photometry and 12 flares with amplitude greater than 0.1 magnitude were identified. Calculation of flare luminosities gave B band flare energies between $\log E = 30.8$ and $32.6$ erg. Flare-only spectra were obtained by subtracting mean quiescent spectra. A Planck function fitted to the blue continuum of the brightest flare spectrum gave a black-body temperature of $18,780 \pm 530$ K. We measured the energy emitted during each flare in the Hα to Hε Balmer emission lines and investigated how flares evolved in time. We found clear evidence of a delay between the rapid, coincident peaks in photometry and flare continuum, and the later peaks in Balmer emission lines. We found the rate of flux decay in the Balmer lines varied with their wavelength with the shorter wavelength lines decaying more rapidly, while the He I 5876 Å line decayed more slowly than the Balmer lines.

1. Introduction

Stellar flares are explosive events that occur when magnetic reconnection in the corona accelerates charged particles down into the chromosphere, heating the plasma and releasing energy across the electromagnetic spectrum (Benz & Güdel 2010). Flare output at visual wavelengths has been modelled as a combination of a fast, short-lived rise in the continuum produced by hot black-body radiation and a slower rise and decay in Balmer emission (see Kowalski 2013 for references). The occurrence of high-energy flares increases in later spectral types becoming most frequent in magnetically active M dwarfs. As M dwarfs are the most common stars in the galaxy, they are also the most common hosts of exoplanetary systems. The space weather environment around these stars will have a profound effect on the habitability of their planets and this has stimulated an increasing level of interest in understanding the nature and frequency of stellar flares.

EV Lac is a well-known flare star with mass $0.350 \pm 0.020$ $M_\odot$, radius $0.353 \pm 0.017$ $R_\odot$, luminosity $0.0128 \pm 0.0003$ $L_\odot$ and effective temperature 3270 $\pm 80$ K (Paudel 2021). It has a rotation period of 4.378 days (Pettersen 1980), faster than the 5.78 day mean rotation period of M dwarfs in both the K2 and SDSS...
surveys (Popinchalk 2021). Fast rotation contributes to development of a strong magnetic field. Its spectroscopic type has been variously described as dM3.5e (Reid 1995), M4.0V (Lépine 2013) and M4.5e (Joy & Abt 1974). Several analyses of flares in EV Lac have been published (Paudel 2021 and references therein) but few of these have included extensive, simultaneously obtained photometry and spectroscopy. We are now able to address that deficiency.

2. Observing campaign

Members of the group observed EV Lac with either photometry or spectroscopy or both whenever local weather conditions and personal circumstances permitted. A repository for collecting project data was set up on a shared Google Drive and managed by the group (see Sims et al. in these proceedings). This included a timeline showing when datasets were obtained making it possible to quickly identify occasions when concurrent photometry and spectroscopy was available. It also contains a list of the equipment used by members of the group. Analysis of the data reported here was performed with custom Python software which made extensive use of the Astropy package (Astropy Collaboration 2018).

3. Photometric observations

Photometric observations were made with telescopes in the range 0.1 to 0.4 m, mostly with Johnson-Cousins (J-C) B band photometric filters. This passband was chosen as light output from flares increases towards shorter wavelengths (Paudel 2021, Kowalski 2013) but recording efficiency in the UV passband under our observing conditions is low. A small number of observations were also made using J-C V band filters to observe changes in the colour index of EV Lac during flares. Photometric images were bias, dark and flat corrected and instrumental magnitudes obtained by aperture photometry using the software AIP4WIN (Berry & Burnell 2005) or Maxim DL (Maxim DL). Comparison star magnitudes were obtained from the AAVSO chart for EV Lav (AAVSO/VSP) and used to convert instrumental to absolute magnitudes in the J-C system. Time was recorded as Julian Date (JD). In order to establish a consistent timeframe between datasets recorded concurrently, times recorded in FITS headers were derived from internal computer clocks synchronised to internet time servers (NIST, NPL). Exposures ranged between 20 and 120 seconds depending on aperture used and conditions. B band photometric observations contributing to this analysis totalled 38.7 hr. A journal of photometric observations contributing to this analysis is given in Table 1 (at end of paper).

4. Spectroscopic observations

Spectroscopic observations, usually covering most or all of the range 3600 Å to 7500 Å, were made with low resolving power ALPY (R~500) and LISA (R~1000) spectroscopes (Shelyak Instruments 2022) with 23 μ slit width, auto guided on 0.3 m class telescopes and processed with the ISIS spectral analysis software (Buil 2022). Spectroscopic images were bias, dark and flat corrected, geometrically corrected, sky background subtracted, spectral profile extracted, and wavelength calibrated using integrated ArNe calibration sources. Spectra of a nearby star with a known spectral profile from the MILES library of stellar spectra (Falcón-Barroso 2011) situated as close as possible in airmass to the target star at the time of observation were obtained both immediately before and immediately after the spectra of EV Lac. By adopting a parameterisation of atmospheric transmission as a function of airmass (Vidal-Madjar 2010), we were able to correct for instrumental and atmospheric losses at the airmass of each spectral image. Spectra were typically integrated for 300 seconds giving spectra of EV Lac with a signal-to-noise ratio (SNR) between 50 and 100. Spectroscopic observations contributing to this analysis totalled 40.8 hr. A journal of spectroscopic observations contributing to this analysis is given in Table 1 (at end of paper).

5. Analysis of photometric data

Examination of photometric light curves identified datasets containing flares with a recognisable, well-defined profile and B magnitude amplitude greater than 0.1 magnitude. This threshold was chosen as inspection of smaller possible flares indicated that in our low-resolution spectra, poorly-defined and/or lower amplitude flares did not yield data of sufficient quality for the quantitative analysis described here. Between October 2021 and January 2022 simultaneous photometry and spectroscopy were obtained during 10 observing sessions containing 12 flares of sufficient quality for analysis. B magnitude light curves of these 12 flares are shown in Figure 1 (at the end of the paper). They show that flares come in many forms ranging from rapidly rising and falling to slowly rising and gradually decaying, with new flares sometimes occurring before quiescence is reached. From our limited statistics, it appears that flares of this amplitude occur in EV Lac on average approximately every 3 hours.
The start and end times of flares were identified by visual inspection of the photometric light curves as the times at which the flux level started to rise above the quiescent level and either returned to the quiescent level, a second flare began, or the observing session finished. All light curves were thus divided into flares and quiescent regions.

In order to find the mean quiescent B magnitude during each observing session, magnitudes were histogrammed and a quadratic polynomial fitted to the faint magnitude peak in the histogram. The magnitude corresponding to the maximum value of the quadratic was taken as the mean quiescent B magnitude for that session. This was converted to an absolute B magnitude using the distance modulus of EV Lac determined from its distance of 5.05 parsec derived from the parallax measured by Gaia (Gaia Collaboration 2021). The B band quiescent luminosity in erg/s during each observing session was calculated from the absolute B magnitude using B band solar luminosity and absolute solar B magnitude on the Vegamag system as transmitted through the same B band filter profile used for our observations. The mean B band quiescent luminosity over all observing sessions was $3.14 \pm 0.10 \times 10^{29}$ erg/s.

Each photometric B magnitude was converted to a B band luminosity in the same way and B band luminosities of each flare obtained by subtracting the B band quiescent luminosity. These B band flare luminosities were integrated over the time span of each photometric exposure to find the energy in erg contributed to the flare by that exposure. The total energy emitted by the flare in the B band was then found by integrating these contributions through the duration of the flare. Table 2 (at end of paper) gives information about times, magnitudes and energies of the 12 flares.

We also recorded a series of V magnitude measurements concurrently with B magnitudes on 26 November 2021. This enabled us to derive the mean quiescent B-V colour index of EV Lac to be $1.64 \pm 0.04$. From Pecaut & Mamajek (2013) this colour index corresponds to an effective temperature of around 3200 K and spectral type between M3.5V and M4V. In Figure 2 we show B-V peaking at 1.37 and 1.25 during the two flares recorded that night. A B-V colour index of 1.25 corresponds to an effective temperature of the star at the peak of the larger flare of around 4200 K.

6. Analysis of spectroscopic data

An average B magnitude was calculated for each spectrum by converting photometric B magnitudes obtained within the exposure time of the spectrum to fluxes, averaging these fluxes over the duration of the spectrum and converting this back to a B magnitude. Using the procedure described in Boyd (2022), each spectrum was then calibrated in absolute flux in FLAM units using this concurrently obtained B magnitude for each spectrum. This procedure made use of CALSPEC spectra (Bohlin 2014) to establish a zero-point B magnitude for the B band filter used for these observations. Given the relatively close distance of EV Lac we assume negligible interstellar reddening so no correction for this is applied to our spectra. According to Reiners (2018), the radial velocity of EV Lac is 0.19 km/s which is more than an order of magnitude below our ability to detect so no velocity correction was made.

For each observing session, all spectra recorded while EV Lac was in quiescence were averaged to find a mean absolute quiescent flux and its standard deviation at each wavelength. The mean absolute quiescent fluxes for each observing session are shown in Figure 3. Apart from the spectrum recorded during the final session on 14 January 2022, which has a slightly higher flux level, the others are very similar indicating that the quiescent energy output of EV Lac was relatively stable between October 2021 and January 2022. TiO molecules form in the atmosphere of cool M-type stars and produce the deep absorption bands seen in the quiescent spectra of EV Lac.
Given that all spectra in a session will have been recorded under similar conditions and processed in the same way, we take the standard deviation of flux at each wavelength as a measure of the uncertainty in measuring the flux at that wavelength for all spectra in that session. This variation within a session may be caused by random small atmospheric changes not tracked by our algorithm for correcting atmospheric losses as a function of airmass. Dividing the flux of the mean quiescent spectrum in each observing session by its standard deviation at each wavelength gives the SNR at that wavelength. We found SNR was greater than 10 and sometimes as high as 30 over most of each spectrum except below 4250 Å where equipment throughput gradually reduces. We calculated an average SNR over the wavelength range of each Balmer line to use when estimating uncertainty in the flux in these lines.

The mean quiescent spectrum for each session was subtracted from each spectrum during a flare to create the flare-only spectra. The peak flare-only spectrum obtained on 21 November 2021 is shown in Figure 4 with H I and He I emission lines identified plus a weak line of He II 4686 Å and possibly the Mg I triplet at 5167, 5173 and 5184 Å. The “humps” in the flare-only spectrum beyond 6000 Å are a result of TiO absorption bands becoming shallower during a flare relative to their depth in quiescence, possibly because of molecular dissociation in the flare. Subtracting the quiescent spectrum then produces these humps in the flare-only spectrum. Figure 5 compares Balmer line profiles in flux calibrated spectra at flare peak and quiescence. This shows that line flux, continuum level and line width in the Hβ, Hγ and Hδ lines grew much more during the flare than they did in the Hα line. At flare peak, line width increased to ±1500 km/s compared to ±500 km/s in quiescence.

As a check of the consistency in our measurement of B band flare energy, each flare-only spectrum was multiplied by the transmission profile of our B filter to give the B band flux in the spectrum in erg/cm²/s. This was integrated over the time interval of each spectrum and multiplied by 4πd², where d is the distance to EV Lac, to give the B band energy in each flare-only spectrum in erg. Integrating the energy recorded in each flare-only spectrum over all spectra in the flare gives another measure of the total B band energy in the flare. Comparing this with the measurement we obtained for the B band flare energy from photometry we find that, averaging over all flares, the two estimates of flare energy differ by only 1%.

7. Empirical flare parameters

Several parameters have been proposed in the literature to characterise properties of flares. One is $t_{1/2}$, defined by Kowalski (2013) as the time interval between half maximum on the rise of the flare and the same height on its decay, in other words the full width at half maximum (FWHM) of the flare. This is independent of the shape of the flare profile. We measured the $t_{1/2}$ parameter on our B band photometric luminosity profiles of flares, and these are listed in Table 2 (at end of paper).

Another measure that has been widely adopted for the longevity of flares is the equivalent duration defined in Gershberg (1972) as the ratio of flare-only energy in a specific band, in our case the B band, to quiescent luminosity in the same band. This is also independent of the flare profile. Table 2 (at end of paper) also contains values of equivalent duration for each flare.
8. Black-body temperature and spectral type

The region of the continuum, excluding emission lines, from 4000 to 5200 Å in our flare-only spectra rises approximately linearly at the blue end and matches the profile of a hot black body. Kowalski (2013) lists 6 regions of the continuum which were fitted to a Planck function to estimate the equivalent black-body temperature of the flare-only continuum during a flare. After experimenting, we modified these regions to better match regions of the continuum in EV Lac which show no obvious emission features and are beyond the extended wings of emission lines during flares. These regions are: 4120 - 4200 Å, 4370 - 4450 Å, 4700 - 4750 Å and 5040 - 5120 Å.

In most cases the flux level of the peak flare-only spectrum was too low to yield a reliable fit of a Planck function to these continuum regions, but in the three most energetic flares we obtained the black-body temperatures given in Table 2 (at end of paper). The black-body curve for 18,780 ± 530 K fitted to the peak flare-only spectrum on 21 November 2021 is shown in Figure 6. On 26 November we found a black-body temperature of 10,266 K for the larger of the two flares recorded that night. For a brief period at the peak of the flare, the flux profile of the flare-only continuum is similar to that of an A type star with such a black-body temperature. This contrasts with an effective temperature from the B-V colour index at the peak of 4200 K. This is the effective temperature for the M dwarf star as a whole which has been slightly increased above its quiescent level by the flare.

![Figure 6. Black-body curve for 18,780 K fitted to the peak flare-only spectrum on 21 November 2021.](image)

We were also able to fit a Planck function to the same continuum regions of most of the mean quiescent spectra. Averaging these effective temperatures over the quiescent spectra gave a mean black-body temperature of 3022 ± 231 K. This is approximately one standard deviation below the temperature expected for a spectral type between M3.5V and M4.0V (Pecaut & Mamajek 2013) as indicated by our B-V colour index. This cooler temperature could be explained by the presence of star spots, although we are not able to confirm this.

9. Analysis of flare energy in emission lines

Working at low resolving power, we are able to record many of the Balmer lines in each spectrum. In previous studies, higher resolving powers are often used to examine in detail the behaviour of individual emission lines (see for example Johnson 2021). To find the energy emitted during a flare in a specific emission line, we linearly interpolated the continuum under the line between regions of the continuum outside the line and integrated the area between the line profile and the interpolated continuum to obtain the integrated flux in the line in erg/cm²/s. In doing this we were careful to set the continuum regions used for interpolation far enough away from the peak wavelength of the line that they did not include the wings of the line as these expanded at the peak of the flare (see Figure 5). We did the same with the mean quiescent spectrum to find the integrated quiescent flux in the line, and then subtracted this from the integrated flux in the emission line to obtain the flux from the flare in the line in erg/cm²/s. The flare flux in the line was then multiplied by the time interval between spectra and integrated over all spectra in the flare to get the total flux emitted by the flare in the line in erg/cm². Finally, this was multiplied by 4πd², where d is the distance to EV Lac, to give the total energy in erg emitted by the flare in that emission line.

The energy emitted in each of the Hα to Hδ Balmer lines in each flare is given in Table 3 (at end of paper). At our resolution the He I line is blended with the Ca II H line while the nearby Ca II K line is well resolved. On the basis that the two calcium lines have broadly similar strength (Rauscher 2006), we constructed a pseudo He line by subtracting the Ca II K flux from the He + Ca II H line flux and include this as ~He in Table 3. There is visible evidence in some of the higher resolution spectra of emission lines of He I 4471, 5016, 5876 and 6678 Å and He II 4686 Å, but only the He I 5876 Å line yields reliable quantitative measurements in some of the larger flares. These are also included in Table 3.

As Figure 5 shows, the Hα line does not respond strongly during flares and as a consequence its flare energy cannot be measured as reliably as for the other Balmer lines. Figure 7 shows that, particularly in the more energetic flares, flare energy in the Hδ to Hε lines decreases progressively at shorter wavelengths.

We added up the flare energy emitted in the Hβ to Hε lines, which all lie within the B band, and show in Figure 8 a histogram of the ratio of this to the total flare energy emitted in the B band for all flares. On average, these Balmer lines contributed 41 ± 16% of the total energy emitted in the B band.
Temporal evolution during flares.

As mentioned in the introduction, stellar flares have been modelled as a combination of a short-lived rise in the continuum followed by a slower increase in hydrogen Balmer emission. Our typical spectral integration time of 300 seconds limits our ability to resolve events in time as calculations of flux are quantified per spectrum. The smaller the time difference between events, the lower the probability they would occur during different spectra and thus be resolved. In less energetic flares where spectra have lower SNR, the sequence of events is less clearly defined. To investigate temporal evolution during flares, we have therefore focused on the three largest flares numbered 7, 9 and 10 in Table 2 (at end of paper). These all have B band flare energies greater than $10^{32}$ erg. As noted earlier, the Hα line generally did not respond strongly during flares making it difficult to resolve clearly how it evolved over time. We therefore concentrated our temporal analysis on the Hβ, Hγ, Hδ and He I 5876 emission lines.

We measured the integrated flux in these lines in each spectrum as the flares progressed to find the spectrum in which emission peaked. We also measured the changing flux level in the continuum adjacent to each line to find when the continuum peaked. Figure 9 shows the relationship between the peaks in flux in emission lines and associated continuum for the three largest flares as a function of time since the flares started. During the largest flare on 21 November 2021, each of the emission lines peaked one spectrum later than their associated continuum. In the other two flares, emission lines and continuum peaked during the same spectrum. In all cases flux in the continuum decayed quickly after the peak. Flux in the Balmer lines decayed faster the shorter their wavelength. Flux in the He I 5876 Å line remained high for longer than the Balmer lines before then decaying rapidly. This is similar to behavior reported in Hawley & Pettersen (1991) for AD Leo.

In these plots, bands of colour are used to represent estimates of one standard deviation of uncertainty in line and continuum flux. This accrues from two sources. One is the uncertainty in the flux level of each spectrum as determined from the standard deviation in quiescent flux described earlier. The other is the uncertainty in defining the level of the interpolated continuum under emission lines because of local variations in the continuum on either side of the line. Both these sources propagate into the uncertainty in line flux.

We also observed that the peak in B band photometry always occurred during the same spectrum as the peak in continuum flux. This is consistent with our finding that on average around 40% of the energy in a flare is in the Balmer lines. The remaining 60% must be in the B band region of the continuum and cause the observed peak in continuum flux.

The more rapid decay of shorter wavelength Balmer lines can be quantified in the wavelength dependent behavior of the $t_{1/2}$ parameter of Balmer lines in the three largest flares. Given the low time resolution of our spectra, calculating $t_{1/2}$ involves interpolating between flux values on the rising and falling edges of the lines. These measures of FWHM of the lines are tabulated in Table 4 and plotted in
Figure 10 which includes fitted linear relations to show the trend in each case. The slope of these lines is a measure of a “Balmer line width decrement” in which lines with shorter wavelength have narrower width and more rapid decay. All three flares show similar behavior to that shown in Fig 18 and related text in Kowalski (2013). The widths of flares in the Balmer lines are several times larger than their widths in B band photometry given in Table 2 (at end of paper).

In Figure 11 we plot the slope of these linear relations for \( t_{1/2} \) vs the corresponding flare rise time. This shows a strong tendency for faster-rising flares to produce emission lines which decay more rapidly. These flares appear to follow a lifestyle: “Live faster, die younger”.

11. Summary and conclusions

Working as a collaborative group of small telescope scientists, we observed 12 flares of the dwarf M star EV Lac with B band amplitude greater than 0.1 magnitude for which we recorded concurrent spectroscopy and photometry. We calibrated spectra in absolute flux and calculated B band flare energies in the range \( \log E = 30.8 \) to 32.6 erg. We subtracted mean quiescent spectra to obtain flare-only spectra and calculated the energy emitted in Balmer emission lines during each flare. We fitted a Planck black-body temperature of 18,780 ± 530 K to the blue continuum of the brightest flare spectrum and temperatures of 10,533 ± 810 K and 10,266 ± 226 K for two other bright flares. Although our time resolution was limited, we observed in the brightest flare that flux in the continuum peaked before flux in the Balmer emission lines and that flux in the continuum decayed faster than flux in emission lines. We found that the shorter wavelength Balmer lines decayed faster. We also found an inverse relation between the rise time of flares and the rate at which emission lines decayed.

The behaviour we see during flares is consistent with models describing an impulsive release of energy generating a rapid brightening and rise in continuum emission followed by a slower release of energy in the stellar atmosphere through emission lines as excited hydrogen atoms recombine and de-excite.

These results demonstrate that useful information on flare stars can be obtained through coordinated amateur observations using concurrent spectroscopy and photometry.

12. Acknowledgements

We acknowledge with thanks use of the AAVSO International Database for recording our photometry and use of the BAA Spectroscopy Database for recording our spectroscopy. This research has made use of NASA’s Astrophysics Data System Bibliographic Services. DB is grateful to the British Astronomical Association for financial support to attend the symposium.

13. References

AAVSO/VSP, https://app.aavso.org/vsp/
Table 1. Journal of photometric and spectroscopic observations

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Table 2: Parameters of 12 recorded flares of EV Lac.

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<td>70.1</td>
<td>11.92</td>
<td>11.71</td>
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<td>31.92</td>
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Figure 1. B magnitude light curves of 12 EV Lac flares with concurrent photometry and spectroscopy.

Table 3. Energy emitted in Hα to Hε and He I 5876 Å emission lines during each flare (where measurable).

<table>
<thead>
<tr>
<th>Flare no</th>
<th>Date</th>
<th>Hα</th>
<th>Hβ</th>
<th>Hγ</th>
<th>Hδ</th>
<th>~Hε</th>
<th>He I 5876</th>
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<tr>
<td></td>
<td></td>
<td>(erg)</td>
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<td>1.25E+31</td>
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</tbody>
</table>
Figure 9. Temporal evolution of emission and continuum flux in the three largest flares
A CubeSat for UV/Optical Pro-Am Astronomy

Douglas Walker  
Prime Solutions Group, Inc.  
dougwalker@psg-inc.net

Kevin France  
Department of Astrophysical and Planetary Sciences, University of Colorado  
kevin.france@colorado.edu

John C. Martin  
University of Illinois Springfield Henry R. Barber Research Observatory  
jmart5@uis.edu

Ken Spencer  
Astronomy Association of Arizona  
astrologyassociationarizona@gmail.com

Dirk Terrell  
Department of Space Studies, Southwest Research Institute  
terrell@boulder.swri.edu

Abstract

Prime Solutions Group, Inc. (PSG) in partnerships with Southwest Research Institute (SwRI), the University of Colorado at Boulder, the University of Illinois, and the Astronomy Association of Arizona (AAA) are proposing the development, launch and operation of a CubeSat mission for stellar astronomy.

The stellar observatory mission will consist of a ground and space-based UV/optical telescope system designated as the Ultraviolet Follow-on Observatory (UFO). This proposed CubeSat will be a 12U system housing a 250mm telescope and designed for a four-year plus mission timeline in high Earth orbit. A camera capturing simultaneous UV/optical observations will first be developed and tested on a ground-based telescope before being designed and integrated into the CubeSat. UFO will follow in the footsteps of the successful launch and operation of the Colorado Ultraviolet Transit Experiment (CUTE) and the planned launch of the Star-Planet Activity Research CubeSat (SPARCS) which are paving the way for this new era in CubeSat space-based astronomy. The operation of UFO (UV wavelength range of 280nm to 390nm (UVB to UVA) for ground based and 240nm to 390nm (UVC, UVB, UVA) for space based) will expand on these missions. This will demonstrate that small telescope observations in the ultraviolet frequency can provide valuable data to the astronomical science community and will help fill a critical need in the observational ultraviolet astronomy gap until NASA’s Large UV/Optical/IR Surveyor (LUVOIR) mission launches in the early 2040s timeframe.

We present the proposed high-level mission concepts and designs for the CubeSat and describe the mission goals. The primary science objectives will be discussed as well as the unique role it will play in this ambitious project.

1. Introduction

Astronomical photometry covers the range of the electrometric spectrum from ultraviolet (UV) at 200 nanometers (nm) through the visible portion into the near infrared (NIR) at 1500 nm. The UV portion of astronomy research reveals a wealth of information about hot and energetic processes in astronomical objects contributing valuable information to the scientific community. Due to atmospheric absorption, UV astronomy can only be successfully conducted outside the atmosphere in the space environment thus it is not the focus of many current or past astronomical investigations. Only a few current large space missions, such as the Hubble Space Telescope (HST) and the Neil Gehrels Swift Observatory cover the UV spectral range, some of them only in the near-UV (NUV). This UV research field is currently sparsely addressed but of scientific interest for the larger scientific community. With the growth rate of the use of small satellites such as SmallSats and CubeSats, the opportunity to provide means of research for UV astronomy are now becoming possible. With the HST
currently approaching end-of-life and the Gaia end-of-mission timeline being around the 2025 timeframe, we are beginning to enter a period without any good UV satellites in orbit, Yatsu et al. (2019). This proposed UV/Optical CubeSat project can provide good UV photometry in a very “general purpose” orbiting observatory. While this CubeSat is a prototype, a major goal is to keep it inexpensive and as such, it can easily be replicated to create a serial constellation of UV observing satellites that will help fill a critical need in the observational UV astronomy gap until NASA’s Large UV/Optical/IR Surveyor (LUVOIR) mission launches in the early 2040s timeframe.

2. Background

CubeSats are a class of research spacecraft called nanosatellites. CubeSats are built to standard dimensions (Units or “U”) of 10 cm x 10 cm x 10 cm. CubeSats can be configured in 1U, 2U, 3U, or 6U sizes where weight is typically less than 1.33 kg (3 lbs.) per U, Loff, (2018). CubeSat sizes are shown in Figure 1. In 1999, California Polytechnic State University (Cal Poly) Professor Jordi Puig-Suari and Bob Twiggs, a professor at the Stanford University Space Systems Development Laboratory developed the CubeSat specifications to promote and develop the skills necessary for the design, manufacture, and testing of small satellites intended for Low Earth Orbit (LEO). Academia accounted for the majority of CubeSat launches until around the 2013 timeframe, when more than half of launches were for non-academic purposes, and by 2014 most newly deployed CubeSats were for commercial or amateur projects, CubeSat Database (2022).

A CubeSat Design Specification has been developed Rev.14.1, to help guide CubeSat construction, CubeSat Design Specification (2020). The CubeSat specification accomplishes several high-level goals, Call for CubeSat Proposals (2008). The main reason for miniaturizing satellites is to reduce the cost of deployment using the excess capacity of larger launch vehicles or a “ride share” option. The CubeSat design specifically minimizes risk to the rest of the launch vehicle and payloads making rideshare possible. Encapsulation of the launcher–payload interface takes away the amount of work that would previously be required for mating a satellite with its launcher. Unification among payloads and launchers enables quick exchanges of payloads and utilization of launch opportunities on short notice.

2.1 Colorado Ultraviolet Transit Experiment

The Colorado Ultraviolet Transit Experiment (CUTE) is a 4-year, NASA-funded project to design, build, integrate, test, and operate a 6-unit CubeSat (30 cm x 20 cm x 10 cm). A cut-away is shown in Figure 2. CUTE is planned to have a 1-year nominal mission lifetime and was successfully launched in late September 2021, Launch of Cute (2022). It has completed commissioning processes and is now in scientific data operations. Using near-ultraviolet (NUV) transmission spectroscopy from 255 nm to 330 nm, CUTE will focus on characterizing the composition and mass-loss rates of exoplanet atmospheres by measuring how the NUV light from the host star is changed as the exoplanet transits in front of the star and passes through the planet’s atmosphere. Transit light curves created from CUTE observations will provide constraints on the composition and escape rates of these atmospheres and may provide the first concrete evidence for magnetic fields on extrasolar planets.

The keys to understanding these systems are spectral coverage in the appropriate bandpass and the ability to follow the systems for several orbital periods. CUTE is designed to follow the systems of interest for several orbital periods to provide low resolution spectroscopy of critical atmospheric tracers (Fe II, Mg II, Mg I, OH) that are inaccessible from the ground.

CUTE was designed at the University of Colorado, Boulder and the Laboratory for Atmospheric and Space Physics (LASP) and built by Blue Canyon Technologies. Dr. Kevin France (co-author) is the Principal Investigator of the CUTE mission at LASP.
2.2 Star-Planet Activity Research CubeSat (SPARCS)

Arizona State University’s Star-Planet Activity Research CubeSat (SPARCS) is a NASA-funded astrophysics mission, devoted to the study of the UV time-domain behavior in low-mass stars, ASU SPARCS (2022). It is a 6U spacecraft where the solar power panels extend like wings from one end. The deployed on-orbit configuration is shown in Figure 3.

Low-mass stars are important targets in the search for exoplanets residing in the habitable-zone. Over its scheduled 1-year mission, SPARCS will stare at approximately 10 stars in order to measure short term- (minutes) and long term- (months) variability simultaneously in the near-UV and far-UV. The SPARCS scientific payload consists of a 9-cm reflector telescope and two high-sensitivity 2D-doped CCDs. The payload will be placed on a Sun-synchronous terminator orbit, allowing for long observing stares for all targets. Launch is expected to occur in the 2023 timeframe.

SPARCS will also be capable of "target-of-opportunity" ultraviolet observations for the rocky planets in M-dwarf habitable zones soon to be discovered by NASA’s Transiting Exoplanet Survey Satellite (TESS) mission. This will provide the needed ultraviolet context for the first habitable planets that the James Webb Space Telescope will characterize.

2.3 Ultraviolet Follow-on Observatory

A search of literature shows in addition to the missions above, several Earth orbiting UV CubeSat telescopes in the discussion stage but no funded projects. To help bridge the observing gap between the end-of-life of the CUTE and SPARCS missions and the launch of LUVOIR, a follow-on CubeSat mission is being proposed, the Ultraviolet Follow-on Observatory or UFO. This proposed CubeSat will be a 12U system housing a 250mm telescope. A series of three CubeSats are being proposed where each is designed for a four-year plus mission timeline in high Earth orbit. The continuation of the CubeSats observing timeline will fill the approximate 15-year observing gap described above. A camera capturing simultaneous UV/optical observations will first be developed and tested on a ground-based telescope before being designed and integrated into the CubeSat.

The operation of UFO will expand on the previous missions and demonstrate that small telescope observations in the ultraviolet can provide valuable data to the astronomical science community and will help fill a critical need in the observational ultraviolet astronomy gap until LUVOIR becomes operational, NASA GSFC (2022).

3. Program Objectives

The primary science objective for this project is to provide simultaneous observational data in the UV
wavelength range of 280nm to 390nm (UVB to UVA) for ground based and 240nm to 390nm (UVC, UVB, UVA) for space based. The optical wavelength range of both systems will be 400nm to 750nm. Because it is small aperture, it can handle “bright” objects and events that are beyond the bright limit of larger satellites.

The secondary objective is to provide synergy with ground-based amateur and university level observatories. Systems at this level can provide excellent time-series photometry and spectroscopy of bright targets that are out of range for larger observatories. Science mission objectives are broken out by the following areas.

Solar System
- Venus. Observations will fill continuous observations gap between NASA missions
- Pluto. Observations of atmosphere via stellar occultations.
- Asteroids
- Trans Neptunian Objects

Exoplanets
- Planetary eclipses
- Atmospheric detections

Stellar systems
- Globular clusters
- Open clusters
- Contact binaries
- Eclipsing binaries

Galactic
- TBD

The general astronomical community
- Provide access for advanced amateur, university faculty and professional astronomers to conduct follow-up observations of objects of interest.
- Allow astronomers to conduct original research.
- Provide opportunities for graduate students to perform original research.

3.1 A Benefits/Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) is an indicator used in industry that shows the relationship between the relative costs and benefits of a proposed project. An analysis was conducted to determine the benefit of the UFO project in relation to other systems.

3.1.1. Science BCR

The science results and benefits of any observational system are difficult to quantitively measure. An approach taken here is to determine the cost of a published paper in a peer reviewed journal as the ratio of cost of system operations over the number of papers. Table I shows the results of comparing the HST and the Las Cumbres Observatory (LCO) against the estimated cost for the UFO project.

Table I is based on the assumptions that the UFO total project cost is approximately $11.13 M and that the number of published papers is 75% of what has been accomplished with the LCO. This preliminary analysis shows a very good potential payback for science results for funds invested.

3.1.2. Education BCR

A similar analysis was carried out for estimating the cost for reaching students in both the high school, college, and university level. The AAA will be taking the lead in developing the introduction and public outreach event.

For a relatively small amount of funds, high school and university level students can be reached with introduction of STEM related activities.

<table>
<thead>
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<th>System</th>
<th>Operations Cost ($M)</th>
<th>No. Peer Review Articles</th>
<th>Cost/Paper Ratio ($K)</th>
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<tr>
<td>Hubble Space Telescope</td>
<td>$16,000</td>
<td>18,000</td>
<td>$888.89</td>
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<td>Las Cumbres Observatory</td>
<td>$44.37</td>
<td>431</td>
<td>$102.95</td>
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<td>UFO</td>
<td>$11.14</td>
<td>323</td>
<td>$34.47</td>
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Table I Benefit-Cost Ratio of UFO compared to other systems.

<table>
<thead>
<tr>
<th>Event</th>
<th>Cost per Event ($M)</th>
<th>No. Students Reached</th>
<th>Cost/Student Ratio ($)</th>
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<tr>
<td>High School Seminar</td>
<td>$3,000</td>
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<td>$4.50</td>
</tr>
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<td>University</td>
<td>$3,000</td>
<td>1,400</td>
<td>$15.00</td>
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</table>

Table II - Benefit-Cost Ratio of Educational Aspects of UFO.

3.2 Engineering Objectives

Model-based Systems Engineering (MBSE) is a formalized methodology that is used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems. In contrast to a more traditional document-centric engineering approach, MBSE puts models at the center of system design. The increased
Adoption of digital-modeling environments during the past few years has led to increased adoption of MBSE. In January 2020, NASA noted this trend by reporting that MBSE, "has been increasingly embraced by both industry and government as a means to keep track of system complexity." Shevchenko (2020).

A model support tool which supports this MBSE approach has been selected. The Innoslate modeling environment offers a full lifecycle software for model-based systems engineering, requirements management, verification and validation, plus DoDAF with a powerful ontology at its core, Innoslate MBSE Tool (2022).

### 3.3 Education Objectives

As first introduced in 3.1.2 above, education is a major emphasis for this project. Education objectives include the following:

- Provide education opportunities to AAA members and the general public regardless of ethnic origin, cultural beliefs, or socioeconomic status.
- Provide opportunities for high school, community college and university students to become involved in a multi-year project which can lead to high school science projects, community college special project courses and university level Capstone projects.
- Provide observational data to university faculty and professional astronomers to conduct original research in their areas of expertise.
- Provide observational data and guidance to amateur astronomers and students to conduct original research and publish their findings.
- Provide synergy between UV satellite data with ground-based data that is achievable with college and semi-professional observatories.
- Provide synergy of satellite UV photometry observations with ground-based spectroscopy.

The AAA will take the lead in emphasizing the importance and interaction of education and public outreach.

The CubeSat Design Specification Rev.14.1 specifies the basic design and major components for CubeSats. A basic design of the UFO CubeSat consists of the 12U bus structure, deployable solar panels for power generation and containing the 250mm optical telescope. An example configuration is shown in Figure 4.

A corresponding cutaway showing the internal components is shown in Figure 6.

As shown in the cutaway diagram, the typical CubeSat bus consists of about 1/3 bus electronics, ADCS and payload assembly respectively. The 12U size of the UFO is driven by the 250mm telescope.

### 3.4 Satellite Bus

Defining a standard bus, developing standard hardware components using commercial off the shelf components and a standard spacecraft frame simplifies the development of picosatellites. The CubeSat development will provide a standard spacecraft frame, a spacecraft controller, radio transceiver, attitude determination and control, solar cells, batteries, and an interface for a payload.

![Figure 4. CubeSat with solar panels deployed. (Credit Knapp 2019)](image1)

![Figure 5. Cutaway diagram showing optical telescope and subcomponents. (Credit Knapp 2019)](image2)

### 4. CubeSat Design

As a subsidiary of Raytheon Technologies, Blue Canyon Technologies, is a complete end-to-end spacecraft company and a leading provider of turnkey small satellite solutions, including nanosatellites, microsatellites, and ESPA-class satellites. Initial
discussions have taken place with Blue Canyon technologies for the development of the bus assembly. Other avenues for bus engineering and development are available to include the University of Colorado and SwRI Boulder facility.

Figure 6. Blue Canyon Technologies is one possible CubeSat bus manufacturer.

4.1 Optical Telescope

The main scientific instrument on UFO is the telescope system. Aperture Optical Sciences (AOS) designs, develops and manufactures optics for satellite imaging and communications systems. AOS develops aspheric mirrors for high energy lasers and specialize in the use of Silicon Carbide materials for extreme performance applications.

The AOS CC series is the new generation of high-performance telescopes for CubeSats, supporting 3U, 6U and 12U applications. Extensive use of Silicon Carbide (SiC) provides a telescope that is inherently athermal and low mass, ensuring consistent imaging performance and lowering launch costs. Custom solutions with apertures to 250 mm are available.

The CC Series telescope system is designed for simplicity and economy – but with its all-ceramic construction it can outperform more typical refractive designs by providing broadband, thermally insensitive performance. The standardized architecture with generalized specifications is intended to define baseline performance specifications. CC series telescopes require only minimal customization to meet customer defined mission requirements.

Figure 7. Aperture Optical Sciences 250mm CC Series telescope.

5. Ground Station Support

The Amazon Web Services (AWS) Ground Station is a fully managed service that lets you control satellite communications, process data, and scale your operations without having to worry about building or managing your own ground station infrastructure. Satellites are used for a wide variety of use cases, including weather forecasting, surface imaging, communications, and video broadcasts. Ground stations form the core of global satellite networks. The AWS Ground Station allows direct access to AWS services and associated infrastructure including a low-latency global fiber network.

Satellite command and telemetry will be provided by the AWS Ground Station network.

5.1 Target Querying and Prioritization

The spread of telescopes around the world has greatly increased the opportunities to observe all astronomical events. The light from celestial objects can be sampled with greater frequency and for longer durations when observations are passed from one telescope to the next. The Las Cumbres Observatory has been developed to provide access to astronomical telescopes located around the world to enable both amateur and professional astronomers to take advantage of transients which are astronomical phenomena whose duration can range from seconds to several years.

The heart of LCO operations is its dynamic observation scheduling system. Working without human intervention, LCO’s internet-based scheduler takes requests for observations from scientists and observers, deconflicts competing requests and conditions at each telescope site, directs individual telescopes to make the desired observations, and compiles the results. Scientists can make requests for
observations at any time as the scheduler updates the entire network plan about every 5 minutes.

The network operates around-the-clock where calibration observations are made during daytime. Observing schedules are stored at site, so telescopes can continue observing even when an external link is interrupted. Within minutes of the camera shutter closing at the telescope, the science data are calibrated and sent to the science archive for retrieval by the scientists.

The LCO system is being investigated as to whether UFO can integrate into the current LCO infrastructure and take advantage of synergism between the two systems.

Through innovative technology partnerships NASA provides these CubeSat developers a low-cost pathway to conduct scientific investigations and technology demonstrations in space, thus enabling students, teachers, and faculty to obtain hands-on flight hardware development experience. CubeSat rideshares are constrained to CubeSats 12U and smaller. The plans for UFO are to take advantage of the rideshare thus the sizing of UFO being restricted to size 12U.

6. Launch Support

NASA’s CubeSat Launch Initiative (also known and rideshares) provides opportunities for small satellite payloads built by universities, high schools and non-profit organizations to fly on upcoming launches, NASA CubeSat Launch Initiative (2022).

7. Pro-Am Science

Astronomy is one field of science where amateur astronomers can perform cutting-edge science research. These activities are usually in the form of partnering with professional astronomers in pro-am collaborations. Thanks to their ability to move and observe when and where they choose, amateurs are also often better at tracking asteroids or hunting for new supernovae than many pros. Amateurs are also branching into spectroscopy, splitting starlight into its constituent wavelengths to study the composition of stars and other celestial objects.

This UFO project is designed with pro-am astronomy research as one of the primary objectives. As the system becomes operational and knowledge of research opportunities become widely known, it is anticipated that many professional-amateur relationships will be established and flourish.

8. Project Team Organization

In order to execute this program, a series of partnerships have been established with a select set of engineering and science organizations. This mix of expertise ensures that the probability of mission development and execution is maximized. This partnership organization includes the following profession organizations.
8.1 Prime Solutions Group, Inc.

PSG is a professional engineering services company with a legacy in Intelligence, Surveillance & Reconnaissance (ISR) technology. Leveraging deep experience and expertise in synthetic aperture radar (SAR) processing, core skills in complex system-of-systems engineering, and cutting-edge applied research and development in image-based machine learning, PSG helps solve the 21st century challenges faced by both private industry and government organizations.

8.2 Southwest Research Institute

Southwest Research Institute (SwRI), based in San Antonio, Texas, is an independent, nonprofit, applied engineering and physical science research and development organization with over 3000 employees. The Institute’s Planetary Science Directorate has over 100 employees and is located in the Exeter Building at 11th and Walnut in downtown Boulder, Colorado.

The Space Science and Engineering Division’s goals are excellence in space research and the expansion and deepening of SwRI’s space research efforts. Areas of research and development include:

- Space Studies
- Planetary Physics
- Planetary Atmospheres and Surfaces
- Lunar Origin and Evolution
- Solar Physics
- Solar System Dynamics
- Astronomy
- Computer Systems
- Space Operations
- Space Technologies
- Mission Operations

8.3 University of Colorado, Boulder

In The Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder (CU) began in 1948. UC is the world’s only research institute to have sent instruments to all eight planets and Pluto.

LASP seeks to maintain and improve the capability to pursue key science questions using experimental, laboratory, theoretical, and information systems approaches. LASP is dedicated to building and maintaining a unique synergism of expertise in space science, engineering, and spacecraft operations. The progressive development and use of innovative technologies and continuing participation in new research initiatives will help ensure a strong leadership role for LASP into the future.

8.4 University of Illinois Springfield

The goal of the University of Illinois Springfield Astronomy-Physics group in the Chemistry Department is to enhance society’s ability to understand the Universe through the application of scientific problem solving. The university provides opportunities to learn about the universe through the courses which are offered, the scholarship of the faculty, Star Parties, disability-friendly support, and community updates of upcoming astronomical phenomena.
8.5 Astronomy Association of Arizona

The Astronomy Association of Arizona is a nonprofit 501(c)3 organization. Their vision is to create an environment where anyone, regardless of ethnic origin, cultural belief or socioeconomic status, succeeds in meeting their personal astronomical and education goals through state-of-the-art learning activities and unsurpassed membership benefits. Mission statements include the following:

- Our mission is to engage and educate those of all interest levels and to provide the highest quality of astronomical science to our community and beyond.
- Provide formal and informal education programs for both beginners and experienced astronomers.
- Encourage member participation regardless of their level of interest.
- Create and support programs to increase skills, broaden knowledge and focus on studies and research in specialized astronomical sciences.

9. Project Funding

The Astrophysics Research and Analysis Program (APRA) solicits basic research proposals for investigations that are relevant to NASA’s programs in astronomy and astrophysics and includes research over the entire range of photons, gravitational waves, and particle astrophysics. Awards may be for up to four years’ duration (up to five years for suborbital investigations), but shorter-term proposals are typical; four-year or five-year proposals must be well justified. APRA investigations may advance technologies anywhere along the full line of readiness levels, from Technology Readiness Level (TRL) 1 through TRL 9.

Proposals relevant to the APRA program are those that address the best possible (i) state-of-the-art detector technology development that is directly applicable to incorporation in future space astrophysics missions; (ii) science and/or technology investigations that can be carried out with instruments flown as suborbital-class payloads on balloon-borne, sounding rocket, CubeSat, or other platforms; or (iii) supporting technology or laboratory research that are directly applicable to space astrophysics missions.

The APRA funding mechanism is the source being investigated to develop the UFO program.

10. Conclusion

A 12U CubeSat containing a UV telescope is being proposed as a follow-on mission to both current the CUTE and SPARCS satellites. This CubeSat, designated as UFO, is being designed to have a mission timeline of at least 4 years after achieving science commission operations. A series of three satellites with an overlap in observing operations will be deployed to fill the UV observational gap until LUVOIR is launched in the early 2040s timeframe.

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