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Editors:
Brian D. Warner
Jerry Foote
David A. Kenyon
Dale Mais

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A New Program to Search for Flare Events in Long Period Variable Lightcurves: Archived GNAT Data

Eric R. Craine

*Western Research Company, Inc. and GNAT, Inc.
3275 W. Ina Road, Suite 215
Tucson, AZ 85741
ercraine@wrc-inc.com*

Roger B. Culver

*Department of Physics, Colorado State University and GNAT, Inc.
Fort Collins, CO 80523
gnat@lamar.colostate.edu*

Adam L. Kraus

*Department of Astronomy, California Institute of Technology and GNAT, Inc.
Pasadena, CA 91125
alk@astro.caltech.edu*

Roy A. Tucker

*Goodricke-Pigott Observatory and GNAT, Inc.
Tucson, AZ 85746
gpobs@mindspring.com*

Douglas Walker

*GNAT, Inc.
Litchfield Park, AZ 85340
douglas.walker@lmco.com*

Robert F. Wing

*Department of Astronomy, The Ohio State University and GNAT, Inc.
Columbus, OH 43210
wing@astronomy.ohio-state.edu*

Abstract

Since the mid 1990s there has been an increasingly energetic debate about the reality and nature of short lived (hours to days) flare events in Long Period Variable stars. The ongoing development of a large database of lightcurves of variable stars extracted from Moving Object and Transient Event Search System (MOTESS) and Global Network of Astronomical Telescopes (GNAT) collaborative photometric survey projects offers the possibility of significantly contributing to this debate over the next few years. We describe the unique advantages of using these MOTESS-GNAT (MG) Variable Star Catalog data and outline the protocol we have developed and our progress to date. We discuss the extraction of LPVs from the MG Variable Star Catalogs, discuss their color-color diagrams, provide a summary of lightcurves developed to date, and discuss the status of a concurrent program to determine their spectral types.

1. Introduction

1.1. GNAT

The Global Network of Astronomical Telescopes (GNAT) is modeling its system of a longitudinally distributed network of scan-mode telescopes follow-

ing the designs of the Moving Object and Transient Event Search System (MOTESS), implemented at Goodricke-Pigott Observatory in Tucson, Arizona.

The MOTESS system consists of an array of three conventional Newtonian reflectors with 35-

centimeter aperture, f/5 primaries. Imaging is accomplished with thermoelectrically-cooled CCD cameras that are operated in continuous time-delay integration mode. Scanning at or near the celestial equator permits recording just over 12 square degrees of sky per hour.

In normal MOTESS operation, the three telescopes are aimed at the same declination but spread in Right Ascension at intervals of 15 to 60 minutes to produce a data stream of image triplets separated in time that reveal moving and time-varying objects. These observations, consisting of deep, unfiltered images, were originally intended for astrometric detection of asteroids.

GNAT has implemented a comprehensive data pipeline for extracting photometric measurements of all of the stars observed in each of the discrete declination bands observed with the scan-mode system. For the first declination band (designated the MG1 Survey), 48 arc minutes wide and centered at +03d18m, this has resulted in 2.5-year photometric lightcurves for 2.07 million stars with $-1 < B-R < 5$ and $R < 19$ mag.

From these stars we have created a new catalog of variable stars (the MG1 Variable Star Catalog) numbering 26,042 of which 5,271 are periodic at the 99% confidence level (Kraus et al. 2007). Only 59 of these stars were previously known to be variable and appeared as entries in the General Catalog of Variable Stars (GCVS).

Two additional surveys using MOTESS instrumentation are underway, and we anticipate adding six GNAT telescopes to the observing program. Thus, we can reasonably expect to produce data for on order of 100,000 new variable stars during the next two years.

1. 2. LPVs

Prominent among the variable stars in the MG1-VSC is the class known as Long Period Variables (LPVs). These stars are late type (M,S,C) giants with periods of $80d < P < 1000d$, and amplitudes of at least 2.5mag in the V band. The LPV lightcurves are reasonably well sampled in the MG1 data, and are generally very easily recognized by lightcurve morphology, though there are some stars that border on semi-regular types that are more difficult to conclusively categorize.

It should be noted that in the MG1 data reduction pipeline protocol there was an inherent bias against extraction of LPVs from the data. This bias arose from the need to construct a master reference catalog of stellar content in the observed declination strip, to which all subsequent stellar detections were com-

pared. The master catalog was ultimately made from Palomar Sky Survey observations in which the images, in two band passes, were not always made on the same night. In an effort to remove spurious detections we discarded any stars in the master catalog that exhibited “impossible” colors. This condition could accrue to bona fide high amplitude LPVs whose “colors” were reported based on images well separated in time. This bias is discussed in detail in Kraus et al. (2007) and we note it here simply to clarify the small number (about 72) of candidate LPVs in the MG1-VSC. Because we have modified the means of producing the master catalog in the future, we anticipate many hundreds of new LPV discoveries in the MG2 and MG3 catalogs currently under development.

The rationale for the project discussed here is to develop a pilot program for examining large numbers of relatively long term LPV lightcurves for the presence of flaring activity.

In this paper we discuss our protocols for identifying and extracting LPVs from the source data sets, identifying flares in the lightcurves, determining spectral types of the stars and performing a statistical analysis of the flares (if any) observed.

2. Flares in LPVs

We will leave a detailed discussion of flares in LPVs for a future report on this project. For our purposes now we note that the existence of flares of duration hours to days in LPVs has been the subject of various reports since the 1980s. The evidence for such events was sparse, the data collected and analyzed was quite inhomogeneous and of the few flares reported, many were less than compelling (indeed some events reported were not flares at all, but short-lived diminutions in the lightcurve).

By the mid 1990s more convincing reports were beginning to emerge, but debate was heated not only over possible flare mechanisms, but the reality of the flares themselves. Among the most intriguing of the flare mechanisms is one described by Willson and Struck (2001) in which the flare is a consequence of interaction between the material outflows of the star and a planet that is being engulfed by the host star.

3. Identification of LPVs

Two of the authors (ERC and DW) have on several occasions visually examined all 26,042 MG1-VSC lightcurves with a goal of identifying specific types of variable stars. In this process a list of LPVs was independently compiled by the two, and comparison yielded a working list of LPVs.

Visual examination proved extremely useful for gaining a better understanding of the nature and content of the MG1-VSC, but it is an extremely tiring and slow approach.

Our next step was to run several computer sorts on the catalog in an effort to cut it to a short list of viable LPV candidates. We first sorted the list in descending order of period, and then excluded stars with $P < 80$ d. We next sorted the list by period false alarm probability and removed those stars for which the period was highly uncertain. We then sorted this list by amplitude, and truncated it below about 1.0 mag since the unfiltered amplitudes are about half of the V amplitudes.

4. LPV Observations

The LPV observational data available in the MG1-VSC include a basic data and statistics summary, a file of reduced photometric observations, a lightcurve plot and a phased lightcurve. The summary file includes the following: RA, Dec, lightcurve amplitude, mean brightness, standard deviation about the mean, photometric error, skew of the observed data points, number of observations, $\log P$ (period), the period false alarm probability, B mag (USNO), and JHK mags (2MASS).

The photometry files are exportable to a spreadsheet program where they can be conveniently manipulated for detailed examination, including both local curve fitting and various arithmetic operations for further analysis. Included in the photometry file is a calculation of the phase of each observation, based on the period determined by the MG1 data pipeline algorithm.

5. Spectroscopy and Narrow-Band Photometry

The literature suggests that flaring in LPVs is a function of spectral type of the star; in particular there is an indication that flaring occurs preferentially in M-type Miras, as opposed to S or C type stars. It is therefore of interest, where possible, to add spectral type information to our pool of observed data. Unfortunately, it is not a trivial matter to request a series of spectroscopic observing runs at a suitably equipped observatory.

Other options more easily available to us include the following: 1) rough estimates based on (J-H) vs. (H-K) color-color diagrams, 2) dedicated small telescope spectroscopy, and 3) multi-color photometry.

In the first instance we have available JHK magnitudes for about 64% (46/72) of our program stars from 2MASS data.

At the moment small telescope spectroscopy is being explored by one of the authors (RAT) as discussed in some detail elsewhere (Tucker 2007). The instrumentation used is the Santa Barbara Instruments Group, Inc. (SBIG) SGS self-guided spectrograph, mounted on a Celestron 14 [Torrance, CA] that has been retrofit with a precision drive and privately re-figured diffraction limited optics.

The SGS spectrograph has a high-dispersion grating providing a dispersion of 1.07 Angstroms per pixel and a spectral range of 81.8nm. The low-dispersion grating provides a dispersion of 4.3 Angstroms per pixel and a spectral range of 327nm. The spectrograph may be used to obtain low-resolution spectra of objects as faint as about $V = 15$ mag with the Celestron 14, depending upon operating parameters, final signal-to-noise desired, and spectral class of the object being observed.

One of the authors (RFW) is using his narrow-band system to observe LPV candidate stars with the 0.9-m telescope of Cerro Tololo Inter-American Observatory in La Serena, Chile. This system, described elsewhere (Wing 1971; MacConnell et al. 1992), is an important far-red narrow-band tool for investigation of late-type M and C stars. The system defines pseudo-continuum colors, along with TiO, VO and CN band strengths, and is particularly useful for classifying M stars in our sample.

6. Preliminary Results

The LPV identification process described above yielded a working list of 72 LPV candidates, some of which are not classical Mira-type lightcurves, but are clearly long period variables meeting the other criteria for selection. An example lightcurve (Figure 1) and phased curve (Figure 2) are plotted using photometry from the MG1-VSC database. We note that for the MG1-VSC compilation, only the A and C MOTESS telescope images were reduced. The B telescope images are, however, available in the archive and in the event that a potential flare, or other interesting anomalous event, is observed, the B telescope image can also be measured for added clarification.

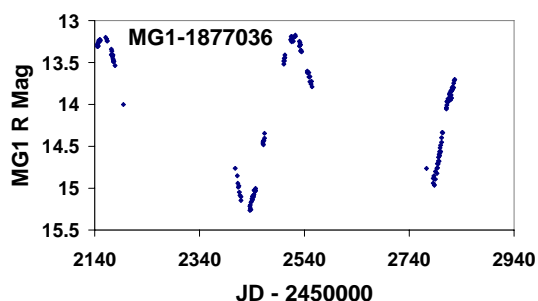


Figure 1. MG1-VSC lightcurve of LPV MG1-1877036.

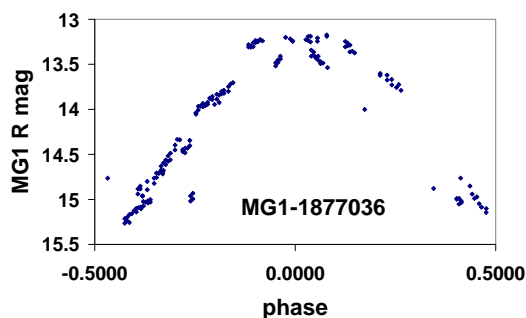


Figure 2. A phased lightcurve of LPV MG1-1877036.

It appears from Figure 2 that the shape of the lightcurve does not remain completely constant, a characteristic of these stars, since even making small changes in the period will only align parts of the curve, and the approximate period is clear from Figure 1. Nonetheless, it is possible from these data to make reasonable predictions of maxima to assist in our spectroscopic observations.

It is of some interest to consider the amplitude histogram of high amplitude stars in MG1-VSC, as shown in Figure 3. This histogram should be compared with that of Figure 1 in Wozniak et al. (2004). The disparity between these figures is caused by the aforementioned selection effect in our prototype data reduction pipeline that discriminates against extraction of large amplitude LPVs from the MG1 survey images. Because this condition has been corrected in the MG2 and MG3 survey strip data reductions, we can anticipate adding several hundreds of Mira LPVs to our candidate list upon completion of the MG2-VSC and MG3-VSC.

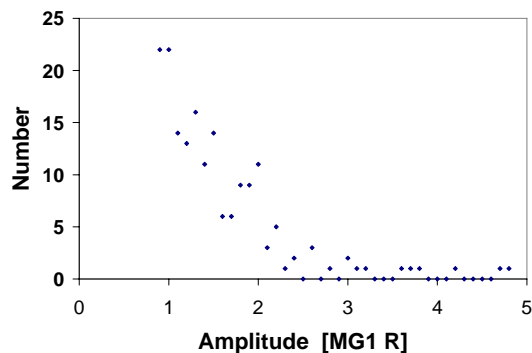


Figure 3. Histogram of amplitude distribution of a select group of high-amplitude variables in the MG1-VSC database. These are stars with very low false alarm rates in their periodogram analyses, hence likely LPV candidates.

The regions of Carbon-rich and Oxygen-rich LPVs are delineated in Cox (2000). Though not definitive, because of significant overlap of these regions, the diagram is of some utility. In particular it allows us to explore properties of stars that are at the extremes of color ranges in this diagram and address the question of whether they really belong in our candidate list.

In order to obtain spectra of the LPV candidates with the small aperture system we are using, it is necessary to observe near maximum light. We have used both the calculated period in the MG1-VSC, and visual study of the cataloged lightcurves to create a table of predictions of next maxima for the next two years.

The (J-H) and (H-K) colors of our 72 program stars are plotted in Figure 4.

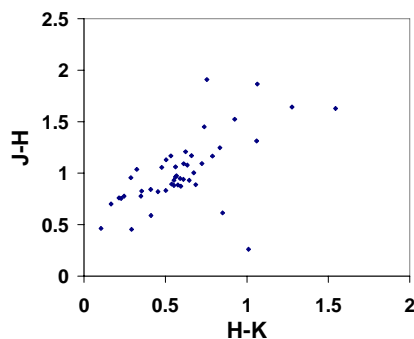


Figure 4. (J-H) vs. (H-K) color-color diagram for the LPV candidates extracted from the MG1-VSC.

At this writing we have obtained spectra for a half dozen LPV stars in our MG1-VSC list. Because of the limited light gathering power of the small system we are constrained to observing stars not much

fainter than $V = 15$, and it is to our advantage to tune the spectrograph to operate in the red region of the spectrum, typically about 600 – 920nm, where these red stars are bright. An example of one of these spectra appears in Figure 5.

The cool star spectral atlas of Turnshek, Turnshek, Craine and Boeshaar (1985) provides spectra of Morgan-Keenan standard stars very comparable in both resolution and wavelength coverage to the spectra we are now obtaining for our sample of LPVs. Comparing with the atlas spectra indicates that the SGS spectra are completely adequate for distinguishing M, S and C stars in our data.

We have also initiated the narrow-band photometry program at Cerro Tololo Inter-American Observatory with five stars observed to date and the next observing run scheduled for April 2007. We are at a very early stage of this observing program, but do note that all of the stars observed thus far are late type M giants (M5 – M9).

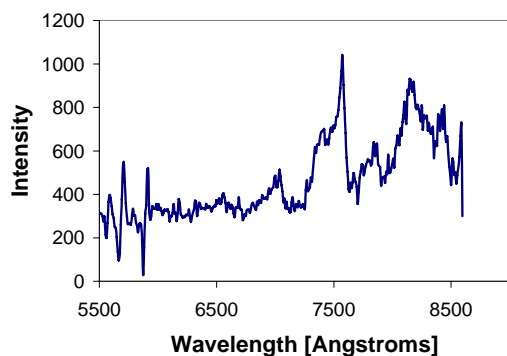


Figure 5. SGS spectrum of MG1-1291327 consistent with an M6 III LPV.

There are conflicting reports in the literature with regard to the phase of the lightcurve during which flare events are likely to be detected. Before starting the search we undertook to characterize phase coverage of our photometric observations. To accomplish this we divided the phase curves into quadrants: minimum, maximum and rising and descending legs of the phase curve. We then sorted our observations by phase and counted the number of observations in each phase.

The MG1-VSC was based on measurements of images from two of the telescopes in the MG1 survey, ideally yielding two nearly simultaneous, independent photometric measurements of each of the stars, these pairs separated by 40 minutes of time. This ideal is not always achieved: at the beginning or end of the observing season for a given star, that star may be only observable by one of the fixed tele-

scopes in the network, or, there may be any of a number of problems with a single image, such as seeing degradation, cosmic ray events, etc.

For our initial sample of LPVs, Figure 6 shows the percent of observations in each of the minimum, ascending leg, maximum, and descending legs respectively where the observation was captured in at least one of the telescopes. Figure 7 describes the same summary of observations where images were captured in both telescopes on the same night. Thus, we have a reasonable distribution of observations across all of the phases of the LPV lightcurves.

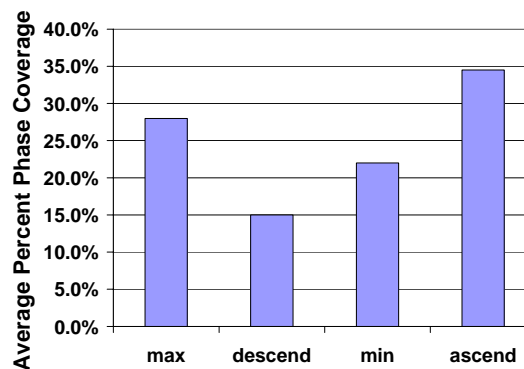


Figure 6. Average phase coverage of photometric observations with at least one telescope (100% is the sum of all of the observations).

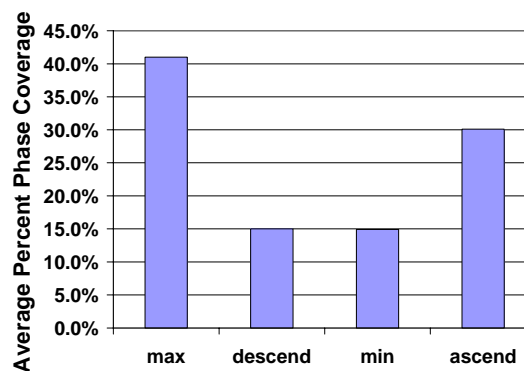


Figure 7. Average phase coverage of photometric observations with two telescopes (100% is the sum of all of the observations made with two telescopes).

Our protocol in searching for flare events is to use a spreadsheet program to plot the lightcurves, enabling fast and easy zooming on regions of interest for a higher resolution look at the lightcurve. We then visually examine the lightcurves looking for possible flares; such an event is generally easily discernable by the time it reaches amplitude 0.1-0.2 mag. Unlike some previous reports of single data point “flare

events”, we require that we see the event in two of our telescopes.

Suggestive single point events can be checked by making after-the-fact measurements of the corresponding B telescope images (see Figure 8).

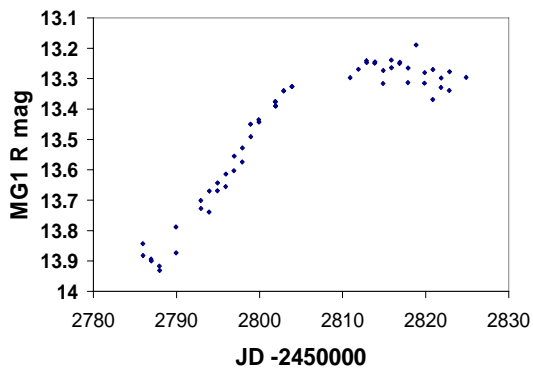


Figure 8. A portion of a maximum in the lightcurve of MG1-1639503.

In this case there is an anomalous point at JD 2452818, but it is a single point and thus not characterized as a likely flare. Upon examination of the original images it was determined that this was a spurious measurement. Most of the observations shown in Figure 8 are pairs of observations from two telescopes.

In addition to visual examination of the lightcurves, we are exploring the application of statistical algorithms for analytical extraction of candidate flare events, following methodologies suggested by Wozniak et al. (2004).

7. Conclusions

The GNAT program is producing catalogs and photometric data archives of very large numbers of newly discovered variable stars, of which many hundreds are expected to be LPVs. Our experience to date is that the phase curves of the LPVs are well sampled, usually with pairs of nearly simultaneous, independent observations, yielding an excellent data base for characterizing flaring rates.

We have initiated a supplementary program of spectroscopy and multi-color photometry to determine spectral types of most of these LPV candidates and we are refining a protocol to examine the lightcurves for short term flare events.

We expect to complete examination of the MG1-VSC candidates this year, and anticipate expanding the effort to many more LPV candidates in 2008 using the MG2-VSC and MG3-VSC databases.

8. Acknowledgements

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