Measuring the Hubble Constant Using SBIG's DSS-7

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Abstract

The Advanced Placement physics class of Orange Lutheran High School has conducted a spectroscopic study of galactic redshift verses distance to experimentally measure the Hubble parameter. Redshifts are measured by the hydrogen alpha emission line as it is the most prominent line in the spectra. Recessional velocities are calculated via the redshift. Distances are not measured by this team but are taken from databases such as NED or SIMBAD. The goal of this work is to show the capabilities of the SBIG DSS-7 spectrograph for measuring radial velocities of bright galaxies.

1. Introduction

The role of the spectrograph in astronomy is as fundamental as the telescope. Nearly all insights into the nature of distant objects are gained through its use, including the nature of atoms, light, and the expansion of the universe. Spectrographs have long been primarily in the domain of the professional astronomer, being custom build for each application. Amateur astronomers have also had a long history of building spectrographs, partly out of interest in the construction of such an instrument, and partly due to the lack of commercially available instruments.

Santa Barbara Instrument Group (SBIG), makers of CCD cameras tailored toward the professional/amateur market, has been the exception, producing two commercially available spectrographs. SBIG's Self Guiding Scectrograph (SGS) and Deep Space Spectrograph (DSS-7) are designed to be coupled with SBIG's line of ST cameras. The SGS makes use of SBIG's unique self guiding capabilities, offering a guiding chip that is illuminated with the same light cone as the spectrograph.

The DSS-7 offers no guiding features so it's beautifully mated with SBIG's non-guiding ST-402ME using the Kodak KAF 0402ME chip. The DSS-7 is designed around a pivoting diffraction grating and a movable entrance slit which offers four resolution modes. The pivoting diffraction grating enables both view and spectral modes. Also, the DSS-7's optical design produces 2:1 image reduction in both modes, SBIG (2006).

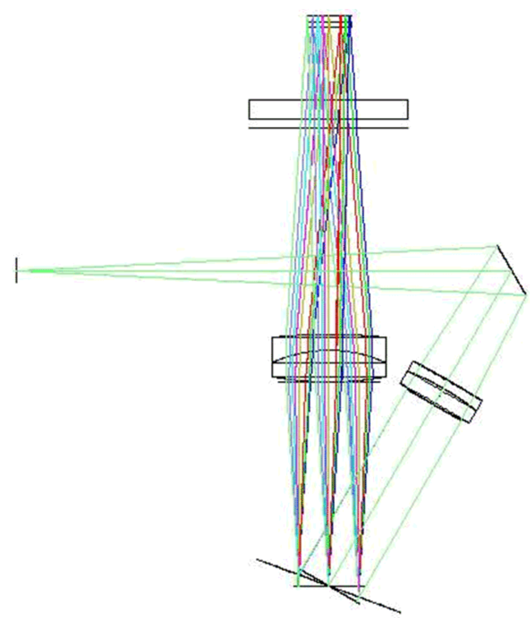

Figure 1. Optical layout of the DSS-7 spectrograph. Light enters from the left (courtesy of SBIG).

Since the DSS-7 is a lower resolution instrument than the SGS, it is 5-10 times more sensitive. With a spectral resolution of 5.4 Angstroms per pixel for its highest resolution mode, the DSS-7 easily resolves the Hα line of the Balmer series.

The DSS-7 is well suited to capture spectra of deep sky object as its name suggests. Nebulae, Clobular Clusters, and Galaxies can be studied, as well as stars with active surfaces such as Cataclysmic

Variables (CV). The authors initial study with this spectrograph involved time series monitoring of CV star AE Aquarii, noting the shifting of the Hα line due to surface flaring.

The most prominent galactic spectral feature at resolutions capable by the DSS-7 is the Hα emission line. This line tends to be strongest in Seyfert or Active galaxies duo to the large amount of hydrogen ionization associated with their cores and starburst features.

This study uses the DSS-7 to collect spectra of Seyfert galaxies with an attempt at measuring the recessional velocity of the galaxy from the redshifted Hα emission line. After the spectra are calibrated and measured, the recessional velocities are calculated and compared to published distance measurements. This comparison can yield a value for the Hubble constant and its reciprocal, the age of the universe.

2. History

The redshifted light of galaxies has been explored by astronomers since as early as 1914, with the work of Vesto Slipher, James Keeler, and William Campbell, Freedman (2002). In the 1920s, Edwin Hubble and Milton Humason measured the recessional velocities and distances to several galaxies while noticing a correlation between the two measurements. The more distant a galaxy is, the faster its recessional velocity. This relationship has come to be known as the Hubble Law and exists due to the expansion of spacetime.

$$v = H_o d$$

where v is the recessional velocity, H_o is the Hubble constant and d is the distance to the galaxy.

As the universe expands, distance between galaxies grows larger causing the light from those distant galaxies to become redshifted. The proportionality constant (slope) of velocity to distance is known as the Hubble constant and it's currently estimated value is between 65 and 85 km/sec/Mpc.

This team attempts to follow in the footsteps of Hubble and Humason, at least in part, by measuring the recessional velocities of several bright Seyfert galaxies.

3. Data Collection

Spectra were collected at the Mill Creek Observatory, located in the San Bernardino Mountains of Southern California at 1783 meters above sea level during the month of March/April 2008 with no moon in the sky. The optical instrument used was a Celestron C14 SCT at prime focus mounted to a Paramount ME controlled by the Bisque observatory software suite. The DSS-7 is coupled to the SBIG ST-402ME controlled by CCDOps and cooled to -8.0 degrees C.

Integration times vary from 300-1200 seconds, added in multiples of 300 second images. Using the 100 micron slit, which projects on the CCD as 50 microns, sufficient signal was collected during 300 second unguided images. The Paramount's excellent tracking enabled more than 300 seconds exposure without guiding but mirror shift in the SCT was the limiting factor in exposure time. Even with some shift of the object across the slit during the exposure (approximately 2 arcseconds), the extended nature of the galaxy provided even illumination during the entire exposure.

Spectrum capture using the SBIG setup is quite simple using CCDOps to control the DSS-7 and the ST-402ME. Spectroscopic imaging differs slightly from typical image capture making use of only three key functions in CCDOps. A special DSS-7 window allows for image capture, slit viewing, and spectrum capture.

The image capture feature allows for timed exposures of the object to enable the user to maneuver the area of interest onto the proper position of the chip. During image capture, the slit is removed from the light cone and the diffraction grating is pivoted to the 0^{th} order, produce a reflecting surface. A software generated, adjustable box marks the slit outline and makes lining the object up with the slit easy. Slit viewing mode allows an image of the slit and the sky to be viewed together so that the user can move the software generated box over the slit of choice. The Paramount's precise motion and software controls make arcsecond adjustment routine.

Once the object is in line with the slit of choice, spectrum capture mode is enabled. In this mode, the slit is moved into the light path and the diffraction grating is pivoted to produce a 4130 Angstrom spectral range, nicely covering the width of the KAF 0401ME chip. The camera and spectrograph are lined up so that the spectrum spreads out along the horizontal dimension of the chip and the slits are arranged along the vertical.

4. Data Reduction and Calibration

The data frames were reduced using MaxIm DL. Each data frame was dark subtracted, flat field divided and hot/cold pixel corrected before combination. The combined data frame was then cropped for the slit height of 30 pixels . All data frames were captured in the 100 micron slit.

Visual Spec (VSpec) was used for data binning, wavelength calibration, and barycenter calculations. Wavelength calibration was done using a hydrogen emission tube outside the spectrograph. The optical system was simply pointed at the emission tube and a reference frame was taken. The frame was then cropped around the 100 micron slit. Two calibrations were made on each data frame, using the Hβ line at 4861 angstroms and the Hα line at 6563 angstroms. Two reference points will enable VSpec to compensate for any non-orthogonal alignment between the spectrograph and the optical system such as might cause the spectral dispersion to be non-linear.

Barycenter calculations were made using VSpec's label tool. Simply selecting the emission line by clicking and dragging the computer mouse over the intensity distribution enables VSpec to find the center of the distribution. The wavelength of the center of the distribution was used to calculate the redshift (z).

5. Data Analysis

Data analysis consisted of four steps:

1. Calculate redshift.
2. Calculate recessional velocity from redshift.
3. Insure proper unit conversion.
4. Compare recessional velocities measured from spectra to published distances to galaxies derived from methods independent of an assumed Hubble constant.

Redshift (z) for the galaxies measured was relatively small, thus recessional velocities were non-relativistic. The non-relativistic redshift equation

$$1 + z = \frac{\lambda(obs)}{\lambda(ref)}$$

was used, where $\lambda(obs)$ is the wavelength observed and $\lambda(ref)$ is the reference wavelength from the emission lamp at rest with respect to the telescope.

Recessional velocities were then calculated using

$$v = cz$$

where c = speed of light (2.99 x 108 m s^{-1})
z = redshift.

There were a total of eight galaxies for which redshifts were found, but only five of those galaxies had published distances that were independent of an estimated value for the Hubble constant (see Table). The measured recessional velocities and distances of those five galaxies are compared in figure 2.

The slope of the relationship between recessional velocity and distance is the Hubble Constant. Currently favored values for Ho range from 65 -85 km/s/Mpc, and the value measured in this study was 64 km/s/Mpc.

Error estimations are limited to variances in the barycenter value provided by VSpec. If slightly more or less of the dispersion to be used in the calculation of the barycenter was selected, its value varied by approximately 1-2 Angstroms. Propagating this variance through the calculation provided an estimation of the peak to peak error to be 123 km/s/Mpc. The error bars in figure 2 indicate this range.

6. Conclusion

The SBIG DSS-7 is a very well made and easy to use instrument. Although not a substitute for the more costly and higher resolution SGS, the DSS-7 excels at lower resolution studies like recessional velocities of extended objects. Software control through CCDOps is limited compared to standard image capture and processing through programs like MaxIm DL or CCD Soft.

Visual Spec is stable and is capable of processing data in a reliable manner. VSpec lacks useful tools for batch processing a large number of files. Intensive mouse clicking makes the work tedious.

It is clear from this study that astronomers equipped with low cost instrumentation can make meaningful measurements. Low resolution spectroscopy can not only provide meaningful data, but it can also be used in many preliminary studies for higher resolution targets, making use of the added sensitivity and lower integration times.

Although this study does not place meaningful constraints on the value of the Hubble constant, it does provide a value that is essentially within the range of currently accepted values. The study also provides a useful tool for physics education and testing the DSS-7 in an area where it has obvious strengths.

7. References

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NASA/IPAC Extra Galactic Database (NED), http://nedwww.ipac.caltech.edu/

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NGC	λobs	λlab	1+z	z	v = cz (km/s)	Published distance (Mly)	NED/simbad (z)
3077	6579.6285	6563	1.002534	0.002534	757.5684138	12.8	0.0005
3034	6589.2314	6563	1.003997	0.003997	1195.061496	11.5	0.000781
2782	6641.5501	6563	1.011969	0.011969	3578.619519		0.008583
3227	6612.2415	6563	1.007503	0.007503	2243.36561	77	0.00467
3516	6631.3225	6563	1.01041	0.01041	3112.666083	120	0.0087
4051	6602.1322	6563	1.005963	0.005963	1782.801737		0.002295
4151	6604.0517	6563	1.006255	0.006255	1870.25115	50	0.003262
5258	6575.9667	6563	1.001976	0.001976	590.7425415		0.02263

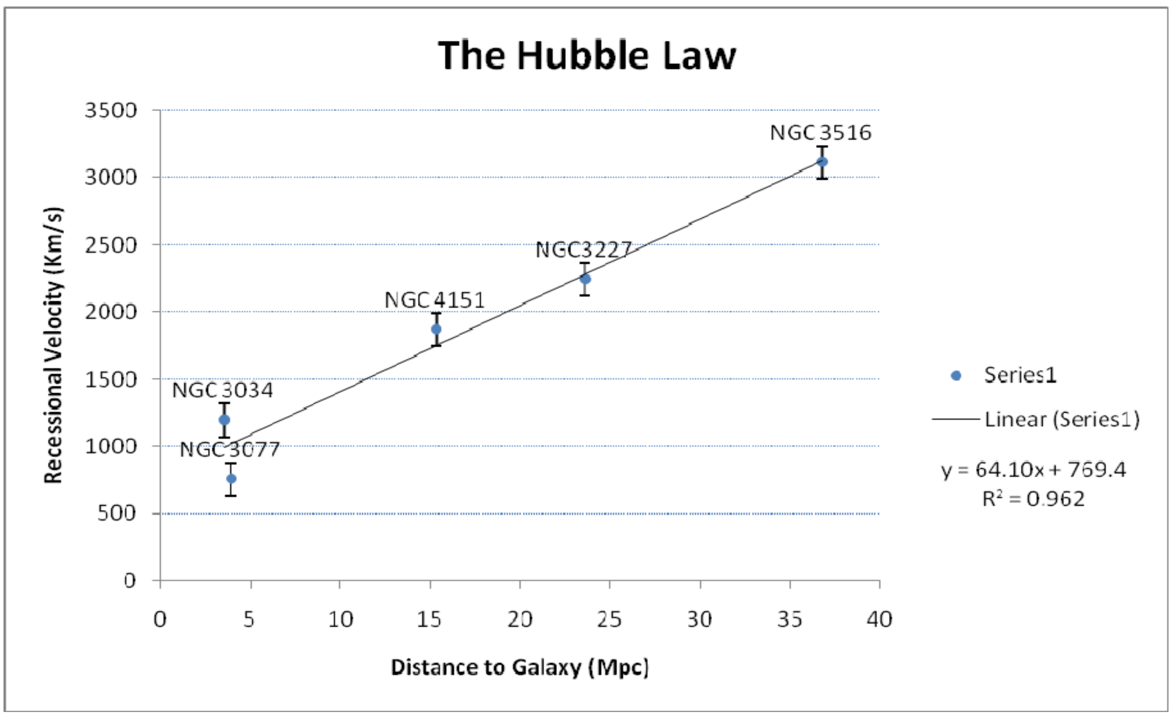

Figure 2. The Hubble Law showing data comparison.