Putting the New Spectrometer to Work (Part II)

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in collaboration with
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Abstract

Having shown the capability of the home-built medium resolution ($R=\lambda/\Delta\lambda=3000$) f/3.5 spectrometer on the 18inch Newtonian (SAS 2012), we collaborated on three science observation projects.

Project 1 investigated the spectacular Doppler signal of the mag 6 pulsating star BWVul (velocities vary by >200km/sec in a 4.8 hr period), Project 2 searched for a velocity variationl in a faint (mag 9) suspected spectroscopic binary (SAO186171 = Zug 1 in NGC6520) which reaches barely 25deg above the southern horizon, while Project 3 observed SigOriE, a mag 6 apparent Be star with 1.2 day period where the problem was to measure the rapidly changing amplitude and shape of the Ha line to support modeling.

Each project presented unique observational and analytic challenges which will be discussed. The projects have required close Pro-Am collaboration, with the high point at Odell's hilltop house happily arguing about observing results.

Introduction

At the SAS 2012 meeting, Menke reported briefly (Menke1) on the design and construction of the homebuilt, medium resolution (R=3000), fast (f/3.5), self guiding spectrometer mounted on an 18in. f/3.5 Newtonian telescope in Maryland. The system is described in detail at our website www.menkescientific.com

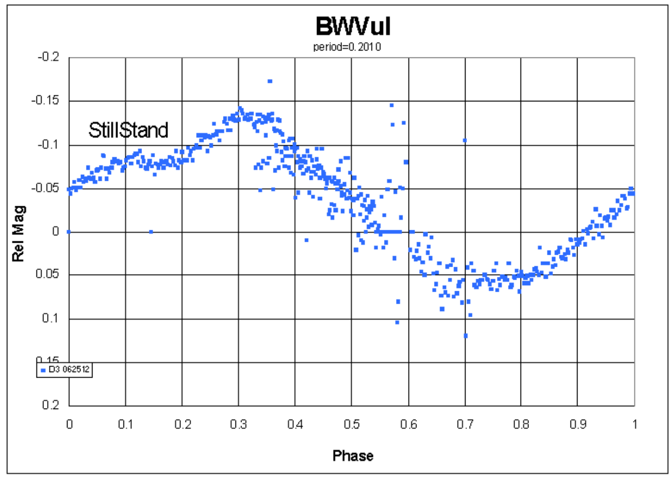
Menke also reported on the initial observing projects that demonstrated measurements of the Doppler shifts of two fast WUMa type eclipsing variables with wavelength shift precisions in the several tenths of Angstrom using simple cross correlation techniques in Excel. In general, the spectroscopic observations used remote and automatically controlled sequences of 300s exposures using the built in guider controlled by MaximDL. The SBIG ST1603 camera was also operated by MaximDL, which was used for spectrogram calibrations and conversion to tabular form. Analyses of the spectra were performed using Excel methods. With some modifications, the same methods were used in the observations reported here.

Project 1- BWVul

In seeking more interesting targets on which to learn observing and analytical techniques, Menke decided to observe pulsating β Cep class (spectral class B) stars. In some of these, radial and non-radial pulsation can cause fast (4-6 hour) variation in velocity and spectral line shape, with some attaining velocities exceeding 100km/s or about 2A

Doppler shift. The prime candidate was BWVul = SAO70596, a Class B2 III pulsating star of mag 6.5 and a period of 0.201 day.

This relatively bright star was well within the capability of the spectroscopic observing system, while the period of about 4.8hr made it feasible to obtain a whole light curve in one night. The star passes nearly overhead in August (dec=33^{o}) also assuring relatively good spectroscopic observations even in the Maryland summer weather.



Before discussing the spectroscopic results, we should mention that a series of photometric runs of BWVul were run using a C11/ST7 setup. One would expect that it would be easy to obtain a good photocurve with this 6.5mag star; however, that was not the case. A number of problems intervened:

- There are no good reference stars in the field (all are at least 4 mag dimmer)
- Weather in the summer/fall of 2012 was notable for its cloudiness and contribution to noise
- Variation in atmospheric transmission also limited the ability to use stars outside the field of view as reference stars
- To clarify structure in the lightcurve required precision to be in the 0.01 mag range.

As a result, only a low quality lightcurves were obtained with up to 0.05 scatter on a curve of amplitude 0.2 mag (the best is shown in Figure 1. However, late in the observing season, experiments were performed using a tiny (1mm diameter) filter of about 10% transmission (produced using a photographic method) placed on the CCD cover glass. The telescope was then controlled to place the target star image onto the filter, leaving the remainder of the FOV at essentially full sensitivity. This allows longer exposures without saturating the target star while simultaneously obtaining good s/n on the reference star(s). We anticipate using this method to obtain much better light curves in autumn 2013.

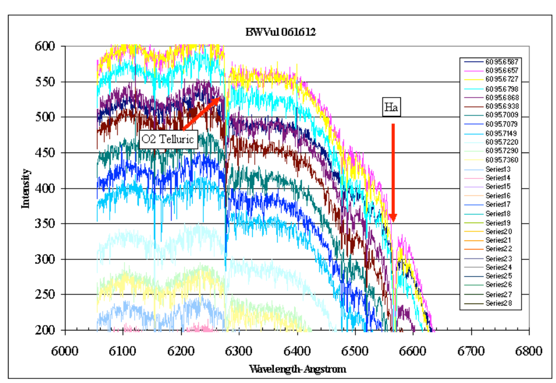
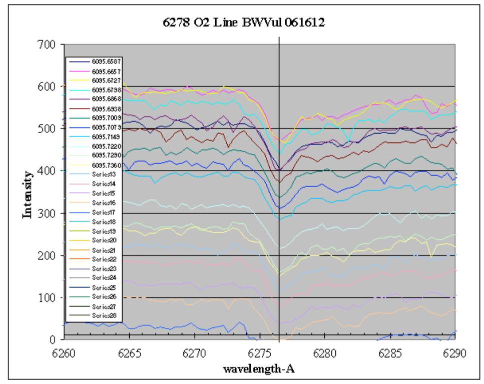
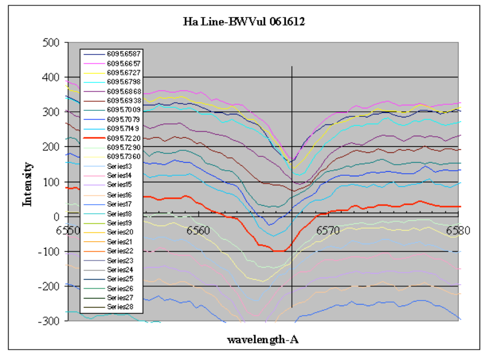


Figure 2 shows the set of ten minute spectra from the first observing night (of 18 sessions), stepped in time from top to bottom. while Figures 3 and 4 show the expanded view of the 6283A O2 telluric line and the 6563A Ha line. Figure 3 showing the telluric line shows that the wavelength calibration of the spectrometer remained constant during the



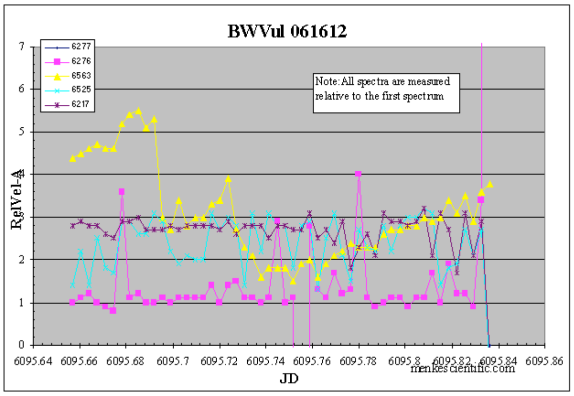


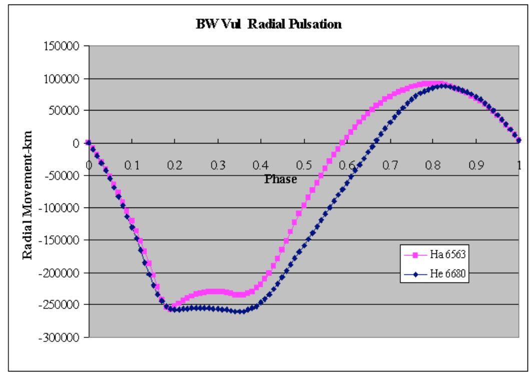
observing session. Figure 4, however, instantly shows the huge Doppler variation in the Ha line as it moved first to the red, then to the blue. In later sessions, five minute spectra were taken to achieve better time resolution, and the wavelength scale was also shifted to 6200-6800A, thus still covering the telluric and Ha while adding coverage of the He 6678A line.

Part of the analytic challenge is how to handle the volume of data. Each night can produce 40-60 spectra, which must receive inspection, calibration, and analysis. As in the work reported at SAS2012, Excel spreadsheets were used for this work. To track the movements of the various spectral features, Excel automatically fitted polynomials to the curves to compute the center wavelengths. From raw images to finished analysis took approximately 15 minutes for a night of data.

The result of each night is a plot of the wavelength shift vs. time or phase. Graph 4 shows the first night data wavelength change in A (all spectra wavelengths are relative to the first spectrum taken). One sees that the telluric lines are at constant wavelength within approximately 0.1A, but the Ha line shifts approximately 4.5A in a sawtooth fashion. The positive slope shows that the velocity of the shell (or other mechanism) that is causing the Ha absorption is accelerating toward the red, i.e., receding from us, i.e., contracting toward the center of the star. This continues until the first "fall" in the Doppler curve when it decelerates, continues for about an hour, falls, then repeats the curve.

What does this mean? Clearly, the almost constant rate of change in the velocity (Doppler) curves shows that the acceleration is essentially constant over this phenomenon (in fact, the curves of Doppler shift are not straight, but curve slightly upward). One can integrate the velocity curve to obtain the displacement. Because these spectra provide only relative wavelength values, in this data set one must force closure of the integral by requiring that the displacement of the shell return to its starting point. This will yield the displacement curves for the Ha and He lines as shown in Figure 5 which appears to show the surface or shell contracting, hitting bottom and bouncing, then undergoing the major expansion and subsequent contraction. The difference between the Ha and He behavior is real: they do not behave exactly the same. Note that the end points are "arbitrarily" chosen to be phase=0 and 1, so the curves for Ha and He each show the relative radial movement of that signal. That is, the phase at which the values are equal may not be as the graph appears to show. Finally, note that the spectral curves are averaged over the stellar disc, so that the actual velocities and displacements will be substantially greater if we were able to isolate data from the center of the stellar disc.





Using only a largely automated Excel analysis of the data obviously is not the most sophisticated analytic method, so these results must be considered preliminary. Also, some of the assumptions implicit in the analysis are not correct: Both the literature and inspection of spectra show that not only do the lines shift in wavelength, but in some cases they change shape and actually become double. Thus, a simple Excel curve fit of the data to derive the shifts of the center wavelength are only capturing the most basic of the real phenomena.

There is evidence in the literature that the period of BWVul sometimes undergoes "sudden" shifts, and earlier data show that there are cycle to cycle variations in the lightcurve. These spectroscopic data also appear to show possible variation from cycle to cycle in the spectral shifts, and of course, there may be future changes in the behavior. Although these data already can support additional modeling at this time, it is surely useful to obtain these types of data in future observing seasons to watch for such changes.

In August 2012, after about two months of taking data on BW Vul, while using Google to try to obtain information about what was known of this pulsating star, I noticed on one paper the author Andrew Odell at a location given as Flagstaff, AZ. Given that Lowell Observatory is in Flagstaff, I Googled his name, found that he had been a university professor and researcher, and still had an email address. I wrote, he responded, and we began a collaboration that quickly moved into a very useful relationship for both us. ProAm in action!

Project 2-Zug1

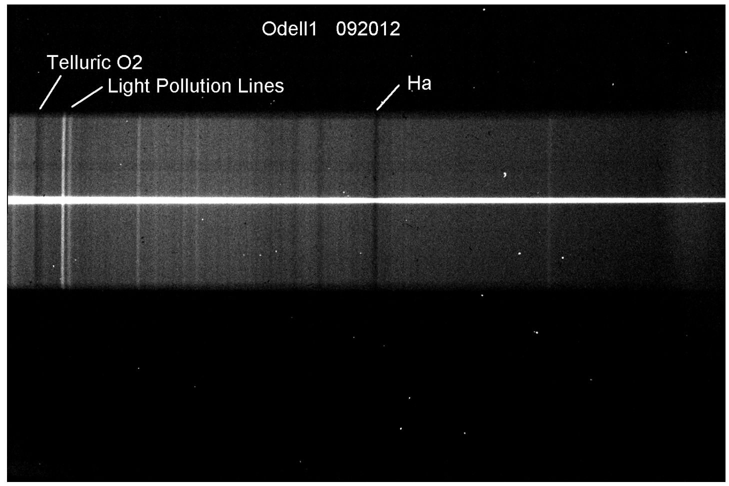
Coming to the end of the BWVul observing season, Odell proposed another project concerning the cluster NGC6520, in which a star identified as Zug1 (=SAO186171) had a somewhat anomalous radial velocity. [about Zug XX] Odell suggested that perhaps this star was not a cluster member, or that perhaps (based on binary statistics) it might be a spectroscopic binary. Would I be interested in using my system to observe this star?

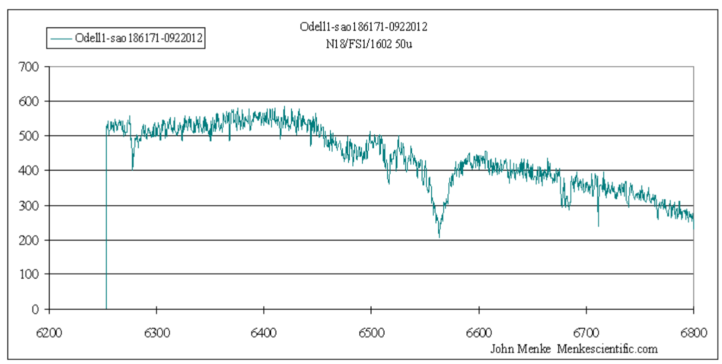
Observing Zug1 would have challenges:

- The magnitude was only 9.6, at the lower effective limit of my system, and would require more than an hour of data to achieve reasonably low noise levels for a spectrum

- Declination was -28deg, thus (especially in late summer) would be low in the sky and subject to poor observing conditions and relatively short observing windows

Never the less, we decided to begin and conducted 25 sessions (every adequate night) over the following 8 weeks. In general, I obtained data each night for as long as possible, again using 5 minute exposures. With 10-30 exposures per night, the averaged spectra provided about S/N=25-30. Figure 7 shows sample spectrogram from Sep 20, 2012 from a short session including twilight. Figure 8 shows the rather noisy spectral curve after removal of continuum, background, etc.

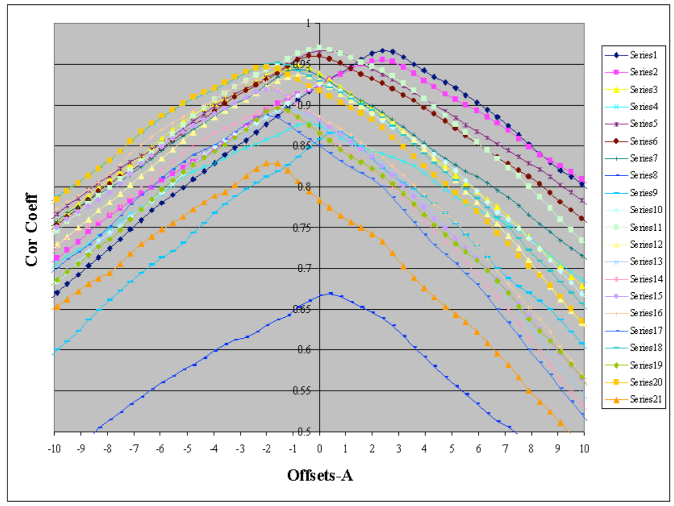




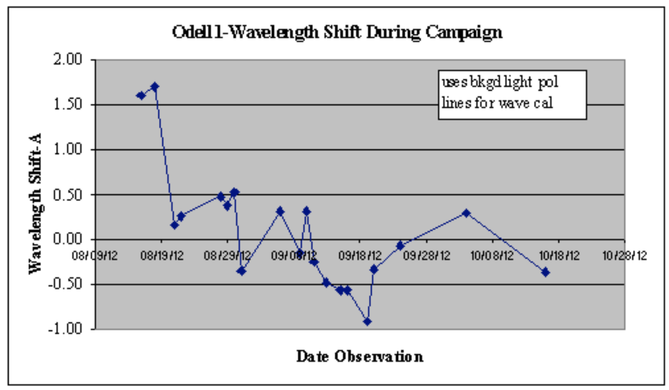
To determine the session to session Doppler shift in the target spectral features, we used cross correlation analysis over the range 6500-6700A, thus including the target star Ha and other lines in the region. Using the cross correlation function in Excel (Menke1XX), we compute the correlation coefficient between the same spectral region of the target star spectrum and a reference (artificial) stellar spectrum for a similar class star. We then step the wavelength scale of one spectrum relative to the other, calculate the new correlation coefficient, and plot the result over a wide range of wavelength differentials. We then identify the wavelength shift that yields the best (largest) correlation value as a measure of the actual wavelength offset or shift. This analysis is conducted on the spectrum from each night of data. As shown in Figure 9, this process yields a set of cross correlation curves, one for each session, in which the peak of each correlation curve vs. offset wavelength shows the target data wavelength shift that maximizes the correlation coefficient against the reference spectrum.

The wavelengths of the peaks vary over a range of about 5A, but the question is how much of this is due to real wavelength calibration shifts and how much to instrumental or other effects? The spectrometer resolution is 2A and the dispersion is 0.4A per pixel, but the goal is to achieve as good a calibration of the wavelength over several months as possible.

The spectrometer did not at that time have an easy to use method for high precision wavelength calibration; however, in each spectrum I could use the telluric O2 line at 6283 and/or the two light pollution lines near 6305 and 6310A (generally present thanks to the high humidity and high clouds). The telluric O2 line suffered from deepening and shape changes as the star altitude decreased, plus was subject to the substantial noise in the spectra. Comparing the two calibration methods showed substantially better results (ie, less scatter in the wavelength of spectral features) when using the light pollution lines as references.



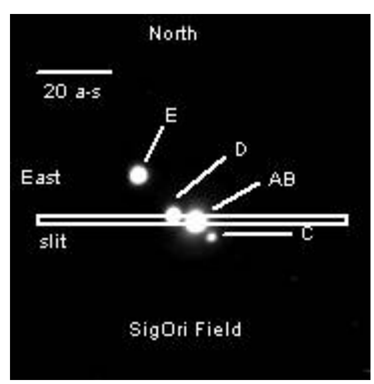
After calibration using light pollution lines, the resulting apparent wavelength changes during the campaign are shown in Figure XX . There is no apparent binary cyclic signal within the data set, plus it appears that there is "noise" at the 0.3-0.5A level. Using Excel to create a synthetic spectrum onto which noise could be added, I was able to show that noise typical of the actual spectra could easily produce the wavelength measurement noise seen in the data.



Thus, it would appear that with this equipment and a target this faint, the lower limit of sensitivity to detect a binary would require approximately 25-50km/sec variation in the Doppler shift (0.55-1.0A). So far, there is little evidence that this star is a binary. At the next observing season, we expect to take additional data to verify the lack of a binary signal.

Project 3-SigOriE

Odell then suggested an additional project. Sigma Orionis is a small cluster of stars as shown in the field image in Figure 11. The bright star is SigOriAB, a close visual double of about 0.25a-s separation. SigOriC is the 9mag component to the southwest, while SigOriD is the 6.5mag component about 12a-s to the east. SigOriE is 6.7mag, 20a-s to the northeast. Although it is a Be emission star, it also contains substantial He. SigOriE is the protptype of the Intermediate Helium Rich stars, comprising about a dozen cases where the helium lines



are often somewhat stronger than the hydrogen lines.

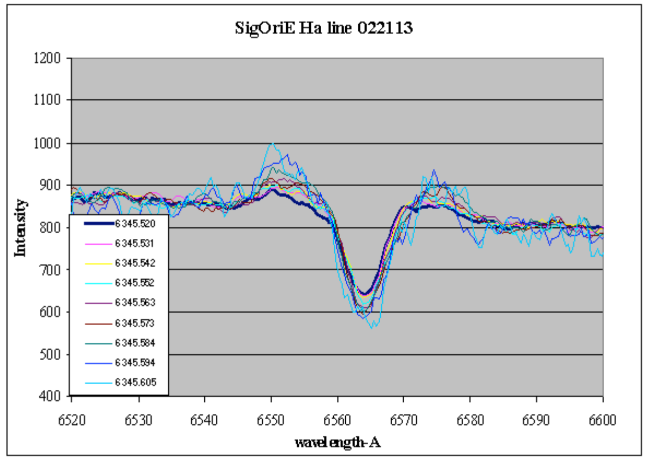
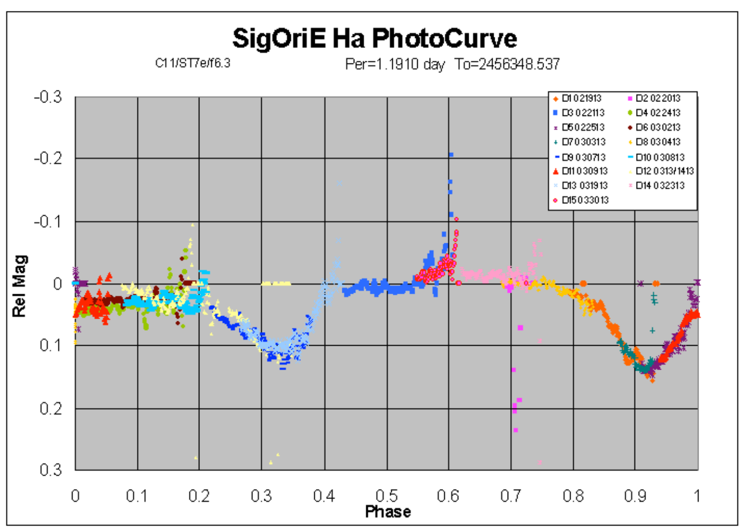


Figure 12 sample 300s spectra taken over several hours in the Ha region exhibiting the "emission wings" on the Ha line. One of the interesting aspects of the star is that the wings and the depth of the Ha absorption line vary with a 1.19 day period. The challenge is to identify the mechanisms that give rise to the observations. Note that the wings have central wavelengths about 10A away from the Ha line, and there is emission in the wings that begins nearly 15A away from the Ha (corresponding to a Doppler velocity of approximately 750km/s).

The observing project included two components. The major effort was to take time series spectra of the Ha-He region (6200-6800). In parallel, I observed the photocurve to determine the ephemeris and to assist in scheduling spectroscopic observations. Both photometry and spectroscopy were made difficult because the observations began relatively late in the observing season (target object already near the meridian at dusk) and observing sessions were short (3-5 hr). The period of 1.19 days meant that only every five days would the same portion of the star reappear, though with a modest offset. As usual, coupled with bad weather, this meant that it would take several months to obtain the full phase curve with the most interesting part of the curve the last to be measured!

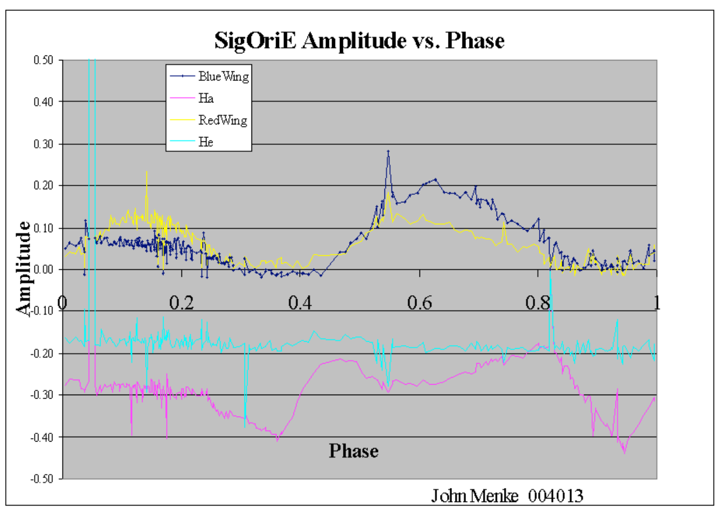
The photometry was made easier by the presence of SigOriAB. Although it is a binary, it is not eclipsing and serves quite well as a reference star, with cross checks to several other field stars. In addition, the stars are of similar spectral class, so on nights when the session could continue well below 10deg altitude (AirMass>5), the reference and target stars extinctions remained very similar. Because the expected amplitude of the curve was low (about 0.02mag in V), a 70A Ha filter was used both to improve S/N (because most of the intensity variation is in the Ha region), and to improve the spectral tracking between the target and the reference star as it moved toward the horizon. The resulting photocurve (with no data removed) is shown in Figure XX.



Each spectroscopy session began by taking a spectrum of SigOriAB (which also showed SigOriD), then continued with 300s exposures of SigOriE for the rest of the session for a total of 17 sessions over a seven week period. Again, the spectra were analyzed in Excel, using polynomial fits to the features of interest (telluric O2, Ha blue wing, Ha, Ha red wing, and He) to obtain the central wavelengths and blue and red wavelengths at the FWHM of each feature. To make this process easier, I also instituted a normalization process within Excel in which I fitted the smooth areas of the spectrum (ie, away from the features) with a spline fit curve [XX ref], then used this curve to normalize the continuum/background to a value of 1. Deviations from this new baseline can then be read directly and easily computed and compared.

As shown in earlier work, the wavelength stability of the spectrometer is generally better than a few tenths A in one session, and about 1 pixel=0.4A over several sessions. These winter observations were often disrupted for days by cloudy weather; however, when observing was feasible, the skies were generally quite clear, so the light pollution lines available in the Zug1 investigation were not very strong. This leaves the telluric O2 line at 6283 on each spectrum as the most feasible wavelength calibration. This star is substantially brighter than Zug1, so the data quality was better allowing wavelength calibration to approximately +/-0.4A. Remaining errors in wavelength calibration will introduce scatter (but not major trends) in graphs where data are plotted by phase because data from different sessions are intermixed.

What do the results show about the star? Referring to Figure 14, one is immediately led to a rough model of a star rotating at 1.19days, having two regions brighter in Ha-emission, roughly equal in size, but one brighter than the other. The regions are not hot spots on the star, because the star cannot be rotating at the 13A=750km/s we see at the edges of the wings. Instead, the regions appear to be emission clouds at a radius of perhaps three stellar radii (to account for the velocity), held in place as the star rotates by the known magnetic fields of the star.



At about phase=0.45, the brighter cloud begins to show as a blue shifted Ha emission on the side approaching the earth and the blue wing increases in amplitude. As the cloud crosses the star, its Doppler shift becomes smaller, and the light is absorbed by the cooler gas (both H and He) outside the star and the blue wing disappears. The cloud then comes into view again, now redshifted in the region phase=0.0-0.2 as it increases in wavelength, then is partially obscured as it circles around back of the star. Meanwhile, the second (red-shifted) spot is also moving around behind the star.

During this process, the depth of the Ha absorption line also varies in a complex way that reflects the total Ha radiation received by the observer. The simple two cloud model does not appear completely consistent with the data, thus quantitative modeling is needed (ongoing). And of course, the simple model does not identify the mechanisms that create and maintain the presumed clouds in the first place.

To gain additional insight, the wavelengths of the red and blue sides of the Ha and He absorption lines were measured. Although the data are noisy, there appear to be less than 1-2A variations throughout the cycle. Additional analysis of the data is ongoing.

This star is not yet understood. For example, a recent paper (Townsend 2013), building on work by XXX, XXX, and XXXX uses photometric data from the MXXX satellite to question XXXXX. The data reported here appear to be the most complete set of spectroscopic data available, and may help resolve many of the questions about SigOriE. Odell is conducting ongoing modeling of this star.

Tasks for the Future

All three projects will benefit from at least some additional observation. Project 1 (BWVul pulsating star) will need to be followed, while Project 2 (Zug1) will require additional observations to rule out the binary star hypothesis. Project 3, SigOriE, is a star under very active study. The present data are already useful in new modeling efforts, but additional observations may also be required.

Instrumentally, the biggest challenge (other than the ever present weather and the desire to observe fainter objects) is to develop a better wavelength calibration process to take advantage of the instrument stability. Software changes are now allowing wavelength calibration exposures using the neon source to be easily interleaved in an observation run. However, neon is not suitable in the shorter wavelength regions, so an alternative wavelength calibration is needed. In addition, it still must be proven that these methods will support 0.1-0.2A calibration. It should be noted that the pellicle guider is able to keep the stellar image position in the slit stable to well under one pixel, and has proven itself as a key element in supporting such excellent stability.

Conclusion

We have shown that a modest spectrometer and telescope, even in a poor observatory location (Maryland), can be used effectively to verify and build additional data on a long studied pulsating star (BWVul), search for a possible binary star (Zug1), and to obtain spectroscopic data that is likely to be vital in modeling a very complex magnetic, high helium, star (SigOriE). We have also demonstrated anew the benefits of ProAm collaboration.

Acknowledgement

I specifically want to express my deep thanks to Andy Odell for his participation in these projects. He has provided a reservoir of knowledge which he freely exchanges, and his patience in teaching me and in resolving confusions has been exemplary, while he has repeatedly made himself available as needed. I look forward to many more projects working with him, and in seeing the results of his modeling work on these stars. Although we have worked in a collaborative fashion, I alone am responsible for any errors in this paper.