High Resolution Spectroscopy for the Amateur: Experiences with the LHIRES III Spectrograph

Stanley A. Gorodenski
Blue Hills Observatory
9440 E. Newtown Avenue
Dewey, Arizona 86327
stanlep@commspeed.net

Abstract

This paper describes the author's experience with the high resolution LHIRES III spectrograph and other equipment used. It discusses mechanical improvements made that may have increased the calibration accuracy of the spectrograph, problems with guiding, and the need to take flat fields. It also briefly mentions the freeware software used and the types of computer programs written by the author to aid in the reduction and analysis of the spectra. An assessment is made of the method for determining equivalent width the author described in the 2011 issue of the SAS News. It finishes by illustrating the ability to study binary stars, such as V1143 Cyg, with the LHIRES III, and discusses some interesting results that were obtained on Epsilon Aurigae. The evolution of a split line centered at around 5853 Angstroms is mentioned, as well as other aspects of the Sodium D Lines region, such as the constancy of separation between the two lines.

1. Introduction

I have a two story 16'x16' observatory in Dewey, Arizona, about 7 miles from Prescott, Arizona in a straight line, at an elevation of 5,140 ft. The observatory and dome are my own designs and I constructed them completely by myself (except for the concrete and block work). For a long time all I had in it was a 12.5" Dall-Kirkham made by a machinist friend in the 1970's (see *http://users.commspeed.net/stanlep/homepagens.html* for more information about the observatory and the Dall-Kirkham). Although an excellent telescope for visual observing, to use it for serious science would have required some major retrofitting. Instead of doing this I purchased a 16" Meade LX200R in 2006 (see SAS Newsletter Vol 5, No 2 for more information about the Meade and its installation in the observatory).

For many years I wanted to get into photometry. However, building the observatory and dome was a major project taking many years that prevented me from doing this at the same time. With good intentions I had purchased a used Starlight-1 photometer but it would have been too difficult to do photometry with the Dall-Kirkham. I have always had an interest in spectroscopy and the 2005 issue of the SAS Newsletter, Vol 3, No 3, had an ad for the newly introduced LHIRES III spectrograph as a knock down kit. It had a good introductory price and so I purchased and assembled it. Shortly after this I purchased the Meade 16". Now I was ready to do some science.

2. Equipping the Observatory

To attach the spectrograph to the telescope, I attempted to use the Meade electronic focuser that came with the Meade 16" but it had a number of problems: 1) It was not strong enough to lift the weight (about seventy pounds) of the instrument package consistently at all times, 2) the 2" diameter nose of the spectrograph could not be tightened down enough in the draw tube to prevent wobble, and 3) the draw tube wobbled inside its housing.

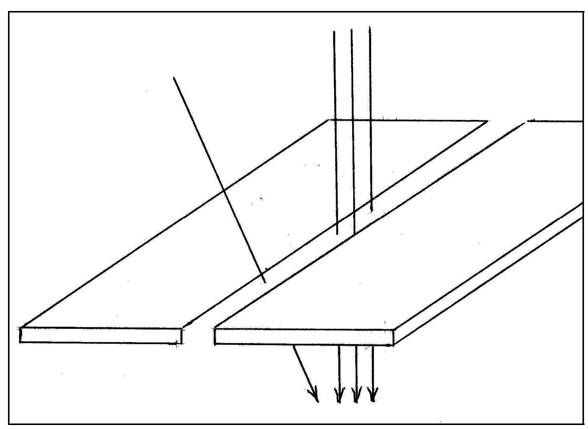


Figure 1.

I felt wobble could be a potential problem for the following reason. Figure 1 is a diagram of a slit with four incident light rays. If guiding is not perfect and the target star drifts parallel to the slit (the 2^{nd} and 4^{th} light ray from the front), all it will do is spread the image of the spectrum over a larger area on the CCD chip. Instead of it being a narrow bright line it will be wider with a reduced intensity peak. This will result in having to increase integration time to reach the ideal saturation level. If the star drifts in declination (i.e., in a direction perpendicular to the slit, the 3rd light ray from the front), all it will do is result in light loss, again resulting in having to increase integration time. However, a wobble, I think, changes the angular direction of the light ray through the spectrograph (the first light ray in Figure 1) and I think this could cause problems with getting a high quality spectrum. I do not know if this is a significant concern or if it has any detrimental effect at all, but even if there is no effect I like things to be rigidly attached. I replaced the Meade focuser with a v-grooved adapter I machined (see Figure 2).

Figure 1.

The spectrograph nose slides over it as shown in Figure 3. This design completely eliminated all wobble (note the four stainless steel allen head screws. These screws have tapered ends to match the v-grooves of the adapter). In Figure 3 is also shown the ST-8XME imaging camera, and the Meade DSI I guiding camera.

With this setup I had to use the telescope manual focus to focus the target star for guiding. With increased use, manual focus (the long bottom knob at the back of the OTA in Figure 3) started feeling rough in one direction. Consequently, I felt I needed an electronic focuser to eliminate having to use manual focus. This would avoid further wear and possible future problems. However, I also wanted an electronic focuser so that I could lock the primary mirror of the 16" telescope and thereby eliminate mirror movement as a possible source of spectral error. For those who are not familiar with this (poor?) design feature of the Meade telescope, the mirror lock is the upper knob at the back of the OTA in Figure 3.

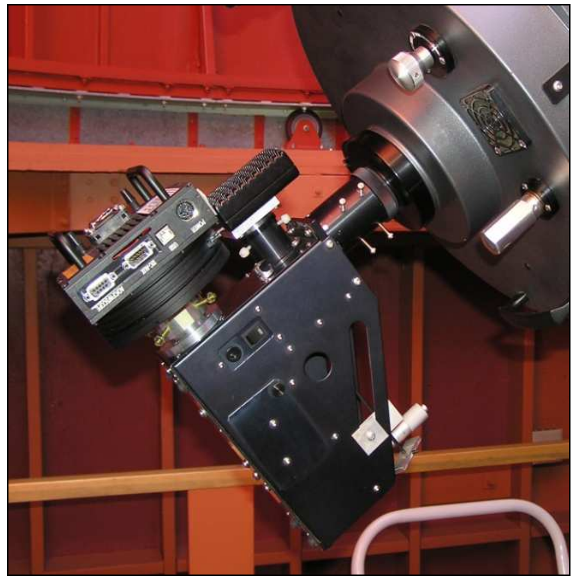


Figure 3.

Figure 4.

Some of the focusers I found on the internet that could handle a heavy load were Crayford types. These were fairly expensive but aside from the cost, I do not like the Crayford design because not only is there still the possibility of slippage even though they are designed to handle a heavy load (the manufacturers of the Crayfords admit this), the intense pressure the roller(s) has(have) to be under does not appeal to me. I came across Starlight Instruments which makes one that is relatively inexpensive and uses a helical gear. A helical gear will not slip and it is not under intense pressure. I bought the Feathertouch FTF

3015-B-A, and the add on developed by Starizona which gives it the electronic focus capability. The electronic focus developed by Starizona works great. Figure 4 shows what the focuser looks like with the instrument package attached.

The Starlight focuser is a real work of art, but I discovered a number of problems. One is that the spectrograph still wobbled in the draw tube eyepiece holder, like it did in the Meade focuser, even though I tightened down the spectrograph nose as much as I dared. To correct this problem I removed the compression ring from the draw tube eyepiece holder and replaced the thumb screws with tapered allen head stainless steel screws. Then I drilled three tapered holes near the base of the nose of the spectrograph. These tapered holes are offset so that when the screws are tightened the front plate of the spectrograph is pulled against the back surface of the focuser, thereby, eliminating all wobble. Figure 5 shows the modification I made to the nose of the spectrograph.

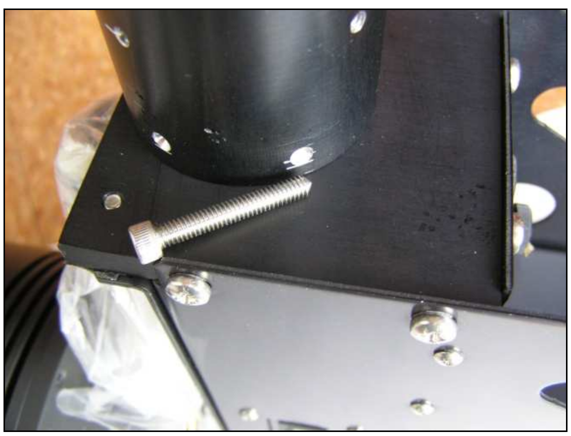


Figure 5.

After eliminating this problem, I discovered that, just as with the Meade focuser, the draw tube wobbles in its housing. However, this wobble can be eliminated by tightening a (one) brass knob (the 2nd brass knob from the back of the telescope in Figure 4). I thought I would have to loosen this knob each time I focus, but according to Starlight I can tighten the knob to the point where it just eliminates wobble without damaging the focuser, or the Starizona focus motor.

Another problem is the mechanism to lock the focuser in a desired rotational position around the optical axis. It is fixed in place by finger tightening three large brass knobs (two of them can be seen in Figure 4). However, because the brass knobs are nylon tipped, accidentally bumping the spectrograph can cause the rotational setting to shift. When this happens I have to again reset the rotational orientation of the spectrograph.

Finally, I am not happy about weight of the Starlight focuser. The aluminum adapter I machined (Figure 2) to replace the Meade electronic focuser weighs only 2/3 of a lb. The Starlight focuser weighs an additional four lbs, a 7-fold increase in weight. To make matters even worse, the focuser adds another 3” or so to the back of the OTA and this increases the moment of the instrument package. This means more counterbalance weight is needed. The adapter I machined is the best solution to the wobble, but, of course, it doesn’t have electronic focus.

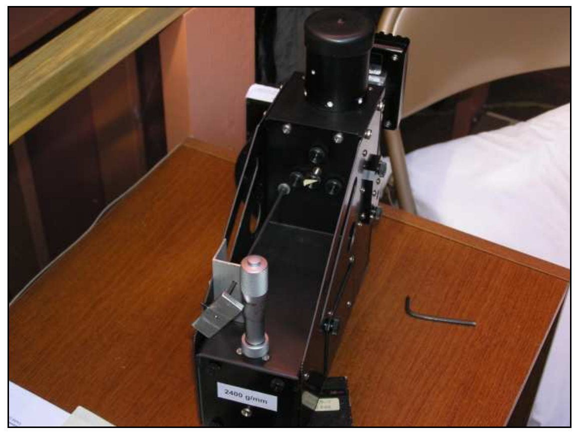


Figure 6.

There are a few modifications I made which may have improved the calibration accuracy of the target spectrum. To calibrate the target spectrum, one needs a calibration spectrum immediately before and after the acquisition of the target spectrum. The calibration spectrum in the LHIRES III is obtained from a neon lamp built into the spectrograph. To get a calibration spectrum requires manually positioning the neon lamp over the slit by turning a knob at the front of the spectrograph. This mechanical act can upset the mechanical stability of the spectrograph and result in a shift of the calibration spectrum relative to the target spectrum. To reduce this potential affect, some owners of the LHIRES have added a stepper motor to turn the knob. I do not have the electronics capability to do this, but I noticed that I could more easily move the lamp from the back of the spectrograph with an allen wrench. Figure 6 shows a permanently mounted allen wrench for this purpose.

Another change I made was replacing the adapters that attach the ST-8 camera to the spectrograph. I felt the ones that came with the unit were too light duty with too many treaded parts and so I machined my own. The machined adapters are the bare (non-anodized) aluminum parts in Figure 7.

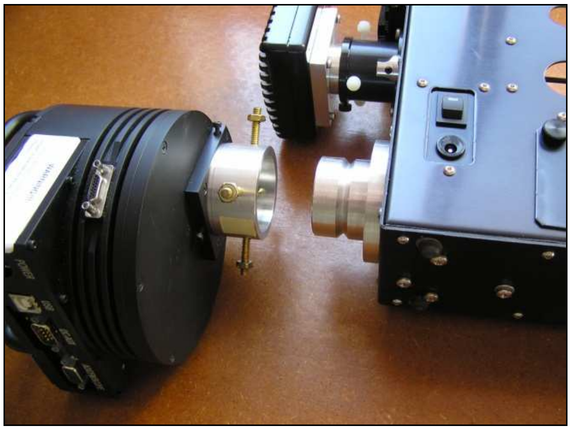


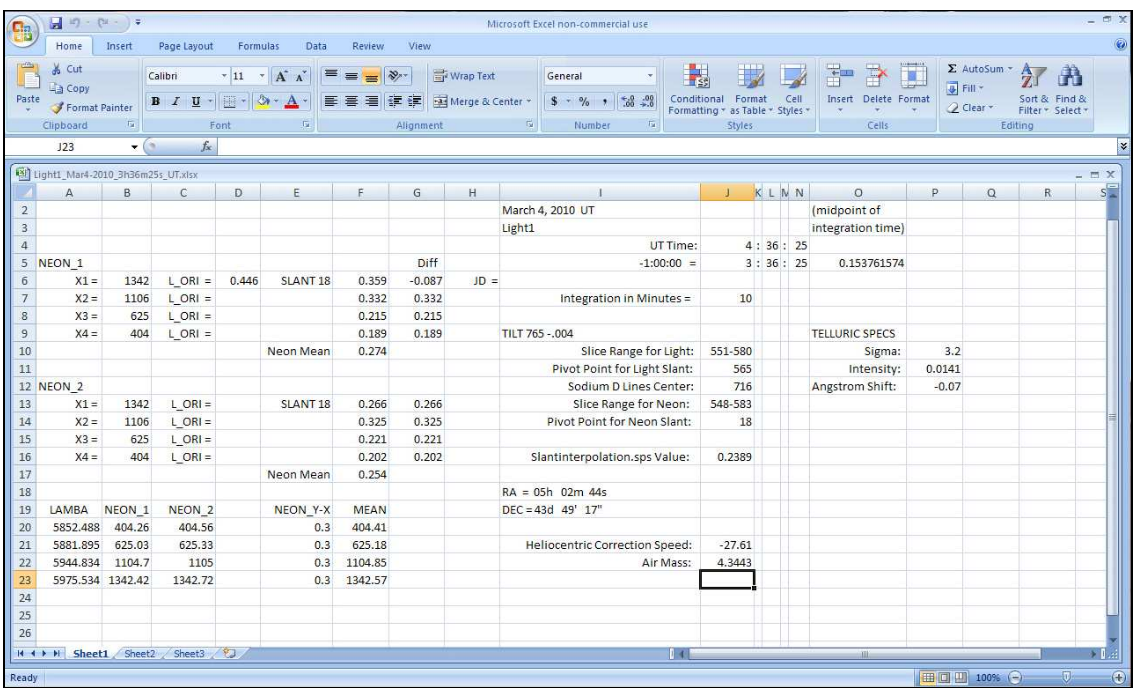
Figure 7.

Figure 7 shows the camera is attached to the spectrograph with four tapered #10 brass screws. The v-groove was offset a small amount so that when the brass screws are tightened they push the male adapter (the adapter attached to the spectrograph) against the back of the female adapter (the adapter attached to the camera), thus eliminating any possibility of movement.

I do not know if the changes I made improved calibration accuracy but I think they have. It has been stated in the Spectro-L discussion group (Spectro-L@yahoogroups.com) that one can at best expect no more than a 0.1 of an Angstrom accuracy using the internal neon lamp. I am getting better than this. Out of a sample of 51 spectra only 9 were off by more 0.05 A, and 33 were only off by no more than 0.03A, the rest falling in between 0.03A and 0.05A.

3. Software

I use CCDSOFT to image the spectrum and do the dark subtraction. Currently, I am using an old version of IRIS, ver 5.57, to reduce the spectra. This includes flipping the spectra so the blue is on the left side, making tilt and slant corrections, removing the sky background, and optimizing the final spectrum for input into VSPEC. These reductions in IRIS involve much more than the quick description just given. I use Audela to get the Gaussian line center estimates of the neon spectral lines (the calibration lines). I use VSPEC to calibrate the target spectrum (usually a multiline, i.e., at least three neon lines, calibration using the neon line center estimates from Audela), correcting the spectrum for instrumental response, fine tuning the calibration with telluric lines, removing the telluric lines after fine tuning, and performing a heliocentric correction. I keep a record in an EXCEL spreadsheet (Figure 8) of all my steps in reducing a spectrum so that I can reproduce a reduction if needed. The final step in VSPEC is to create a TXT file of the fully processed, i.e., reduced, spectrum. The .txt file is input into SPSS programs I write for analysis, graphing, computing equivalent widths, and other statistics. SPSS has very good pro-



Light1_Mar4-2010_3h36m25s_UT.xlsx

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
2									March 4, 2010 UT						(midpoint of	
3									Light1						integration time)	
4									UT Time:	4	:	36	:	25		
5	NEON_1						Diff		-1:00:00 =	3	:	36	:	25	0.153761574	
6	X1 =	1342	L_ORI =	0.446	SLANT 18	0.359	-0.087	JD =								
7	X2 =	1106	L_ORI =			0.332	0.332		Integration in Minutes =	10						
8	X3 =	625	L_ORI =			0.215	0.215									
9	X4 =	404	L_ORI =			0.189	0.189		TILT 765 -.004						TELLURIC SPECS	
10					Neon Mean	0.274			Slice Range for Light:	551-580					Sigma:	3.2
11									Pivot Point for Light Slant:	565					Intensity:	0.0141
12	NEON_2								Sodium D Lines Center:	716					Angstrom Shift:	-0.07
13	X1 =	1342	L_ORI =		SLANT 18	0.266	0.266		Slice Range for Neon:	548-583						
14	X2 =	1106	L_ORI =			0.325	0.325		Pivot Point for Neon Slant:	18						
15	X3 =	625	L_ORI =			0.221	0.221									
16	X4 =	404	L_ORI =			0.202	0.202		Slantinterpolation.sps Value:	0.2389						
17					Neon Mean	0.254										
18									RA = 05h 02m 44s							
19	LAMBA	NEON_1	NEON_2		NEON_Y-X	MEAN			DEC = 43d 49' 17"							
20	5852.488	404.26	404.56		0.3	404.41										
21	5881.895	625.03	625.33		0.3	625.18			Heliocentric Correction Speed:	-27.61						
22	5944.834	1104.7	1105		0.3	1104.85			Air Mass:	4.3443						
23	5975.534	1342.42	1342.72		0.3	1342.57										
24																
25																
26																

Figure 8.

gramming and statistical capabilities. I have been using SPSS for over 25 years and so I am knowledgeable of its capabilities. IRIS and VSPEC are freeware. SPSS is not but I purchased it at a good price years ago.

4. Data Analysis

I use an SPSS computer program I wrote to estimate equivalent width (EW). The EW estimation method I use is the one I developed as described in the SAS Newsletter Vol 9, No 2. To briefly describe it, the first step is to identify those parts of the spectrum that are obviously not noise (such as absorption and emission lines). Once these are identified their intensity values are set to system missing in the SPSS program. What is left is considered to be noise for estimating a continuum.

The second step is to select a range of noise values around the line (whose EW is being estimated) to estimate a continuum with a polynomial least squares regression model. Generally, I have found it is not a good idea to use a large range on either side of a line. Why it is not a good idea is shown in Figure 9.

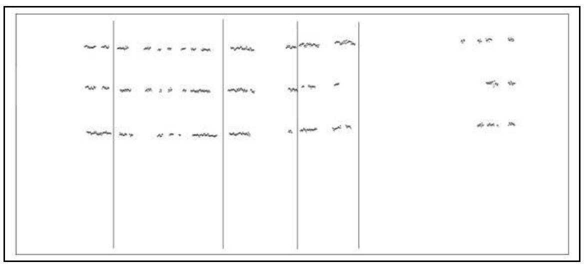


Figure 9.

Figure 9 are plots of what were deemed to be noise for three spectra. The spectra were taken within a half hour of each other, all had the same integration time and camera cooling, and each one was integrated on a different area of the CCD chip. To estimate the continuum for the Sodium D lines (the vacant area between the 2nd and 3rd lines from the left) one could use the entire range of the spectrum. However, upon a study of the graph it can be seen minor differences exist in the noise levels prior to the first line, and the noise values are quite variable between the third and fourth lines (from the left) in intensity and shape. Also, the group of noise values at the extreme right end of the graph could potentially have a large regression model leveraging effect and, thereby, result in a poor estimate of a Sodium D lines continuum. Consequently, for estimating a continuum for the Sodium D lines in this example, I would use the noise values between the 2nd and 3rd lines. By extension, it should be apparent that, generally, it would not be a good idea to use the same range of data to estimate one continuum for two or more lines (one exception being the Sodium D lines).

Once a continuum is estimated I determine the beginning and end points of a line (from an overlay graph of the estimated continuum and actual data points) and then run the complete SPSS program to get an output of equivalent widths and 95% confidence limits.

As can be seen from an example output titled “Equivalent Width Data for Epsilon Aurigae”, my SPSS program can estimate the EW for up to four lines (the 5853A line, the two Na D lines, and the 5978A line) at a time. I could modify my program to do more lines if the need ever arises.

I like this method for computing EW because it gives me greater flexibility than exists in some spectroscopic software, it has greater statistical validity, and it can be better defended than some of the other simpler methods. However, all these presumed advantages may be swamped out by a small degree of subjectivity in telluric line removal, the somewhat subjective determination of the beginning and end of a line, other random effects near a line that can affect continuum estimation, improper (or no) flat fielding, the resolution of the LHIRES, and the fact that the continuum estimate, at the non-professional level, is usually somewhat a guess to begin with. It may be some of the simpler and quicker methods to compute equivalent width may produce equally good estimates. This is something I have not looked into.

I have looked at many spectra for the same star taken on the same night on different parts of the CCD chip (with equal integration times and cooling temperatures) and for the most part the shapes of the spectral profiles agree very close with one another. At times there are some minor disagreements. I am not sure what the causes of these are, but it could reflect the need to take flat fields. Currently, I have the slit on my spectrograph set at 22 microns, which is very narrow. Because of this small size I was not

Line	yyyy	m	d	Time	Min	EW	Max	Start	End	Å/pix	S.D.	All	Miss
5853A	2010	3	4	03:36:25	0.0422	0.0560	0.0698	416	432	0.132	2325.54	360	152
Na D1	2010	3	4	03:36:25	1.2957	1.3247	1.3536	684	715	0.132	2418.27	336	176
Na D2	2010	3	4	03:36:25	1.2032	1.2331	1.2631	729	761	0.132	2418.27	336	176
5978A	2010	3	4	03:36:25	0.0679	0.0836	0.0993	1364	1381	0.132	2291.98	84	46

Table I. Equivalent width data for epsilon Aurigae. The *Min/Max* values are the lower and upper limits for EW. *Start/End* are the line start/end values. *All* gives the number of all cases while Miss gives the number of missing cases.

able to get enough light through the spectrograph, in a reasonable integration time, for a flat with two 90 watt Halogen lamps illuminating a white surface. However, even without a flat correction nearly all spectra taken on the same night are generally in very good agreement with each other and I am getting good results. I will continue to work on getting a flat but it seems there is some contention, at least among some of the non-professional spectroscopists, as to whether a flat is necessary and whether a flat could introduce unwanted effects by subtracting an effect that is not present under the actual conditions of getting a star spectrum.

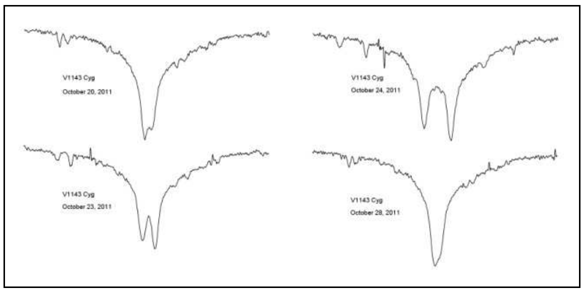


Figure 10.

A big problem is guiding on faint stars, but even on brighter stars it is hard for me to guide accurately enough to get a tight bright line. I have tried a number guiding software that support the Meade DSI I camera. Meade's Envisage software is unstable and frequently crashes. MaximDL worked good but I could not justify spending $565 for a package that will only be used for guiding. I tried Astroart but I was unable to center the guide star (which is also the target star) over the slit. I am currently using PHD and it seems to work okay but on a faint star I frequently get a message saying the signal to noise is low. A lot of times when this happens I lose guiding. I am restricted to guiding software that support the Meade DSI cameras which is a problem. At some time in the future I will have to break down and get another, and better, guiding camera.

Now I would like to show some of the things that can be done with the LHIRES. Figure 10 are spectra I took of the binary V1143 Cyg. Because it is a 5.9 magnitude star, I had to integrate an hour with the 22 micron slit width, but even with an hour's integration time the peak intensity of the spectrum was still only about 5% of saturation. I was not happy with the spectra because I could see more noise in their profiles than I am used to seeing on much brighter stars like Epsilon Aurigae. However, Dr. Dirk Terrell analyzed them, came up with a velocity estimate of 131 km/sec, and said this shows I can do pretty good work with the system I have. This favorable assessment amazed me, because, as I said, I was only reaching about 5% of saturation.

Figure 11 is the classic P Cygni profile of P Cyni itself. The noise in this profile is unbelievably low. I think this is partly the result of a scale effect caused by the emission line being over four times the magnitude of the continuum level.

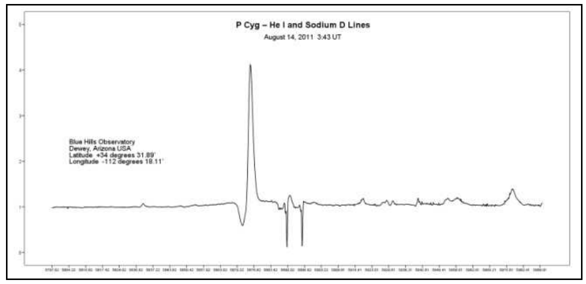


Figure 11.

Figures 12 and 13 are two graphs in press for the special edition the JAAVSO on the Epsilon Aurigae campaign.

In Figure 12, a graph of equivalent widths of the Na D1 line, a number of things can be seen. First, the equivalent widths are at a low point at mid-eclipse. This is expected because there is less disk material at this point that contributes to the absorption line. After mid-eclipse the EW's gradually increase until a high point is reached at 3rd contact. This again is expected. After 3rd contact there is a decline, and this is expected since the disk is now on its way to clearing the primary star. Far after 4th contact, when the primary star should be clear of the disk, the EW's are still significantly non-zero. This indicates the disk material does not end at forth contact, but continues significantly further.

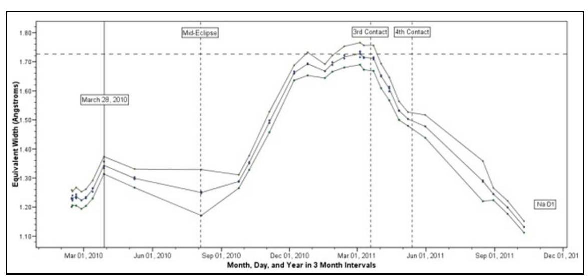


Figure 12.

The low point prior to March 28, 2010 is hypothesized to be either the result of a void in the disk, or a ring structure. Evidence for the latter has been seen by some astronomers (Leadbeater *et al.*, 2010, Seebode *et al.*, 2011). The sharp downturn in radial velocities in Figure 13 also confirms this interpretation.

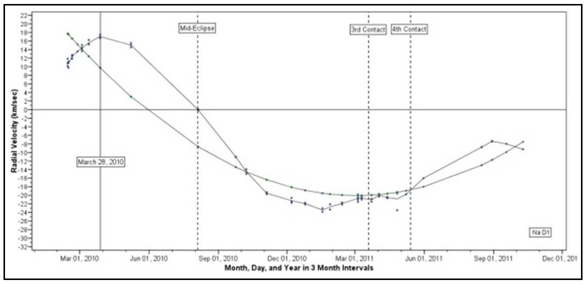


Figure 13.

The shape of the radial velocity (Figure 13) curve from about May 6, 2010 to about November 1, 2010 is what is expected of a disk with a central clearing around a primary object. The predicted date of mid-eclipse was August 4, 2010, although this will probably change as more data comes in. Based on the two Sodium D lines and taking into account that the Epsilon Aurigae system is moving toward Earth at about 2.5 km/sec, I came up with a mid-eclipse date of August 17, 2010. Finally, the continuation of a significant non-zero radial velocity after 4th contact supports the equivalent width interpretation that the disk continues well after 4th contact.

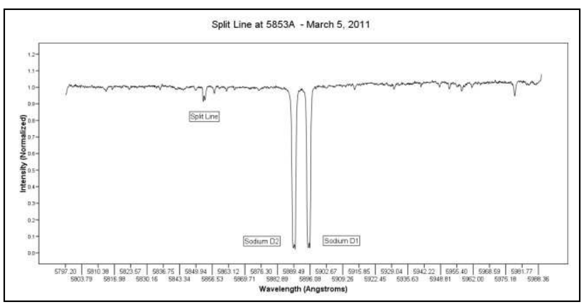


Figure 14.

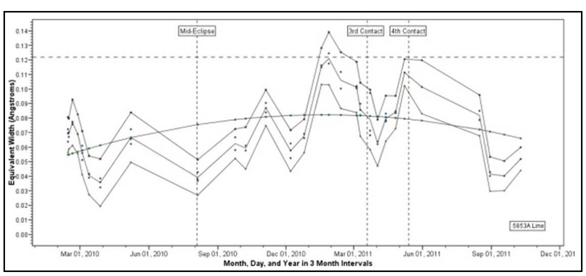


Figure 15.

One thing I observed during my participation in the Epsilon Aurigae campaign was a split line at about 5853 Angstroms that can be seen in Figure 14. Figure 15 is an equivalent width graph of the 5853A line. From Figure 15 the split line event is estimated to start on January 27, 2011 and end on May 8, 2011 which gives a duration of 101 days.

Now I want to show some stuff that is not in the JAAVSO paper. I came up with four different methods to estimate line centers for the D2 and D1 lines. There were two categories. One was based on the beginning and end points of the line that were used to compute equivalent width. The other was a visual estimate in VSPEC of the beginning and end of a line. Within each category there were two line estimation methods: the wavelength center of the line barycenter, and the wavelength center of the VSPEC Gaussian fit to a line. Figure 16 contains four graphs, one for each of the four different methods of estimating line center, of the wavelength difference between the D1 and D2 lines vs. time.

Based on my understanding of quantum mechanics (which is very little), I would expect the separation between the two Sodium D lines to be constant. However, it can be seen that a second order polynomial model fits both Gaussian estimates, and a linear trend fits the visual-barycenter estimate. This indicates the separation between D2 and D1 is not constant but changes over time. However, a statistically significant curve could not be fit to the EW-barycenter estimate. This indicates the D lines separation is constant. Maybe some kind of line measurement bias is present in the other three estimates that result in a false change over time. The

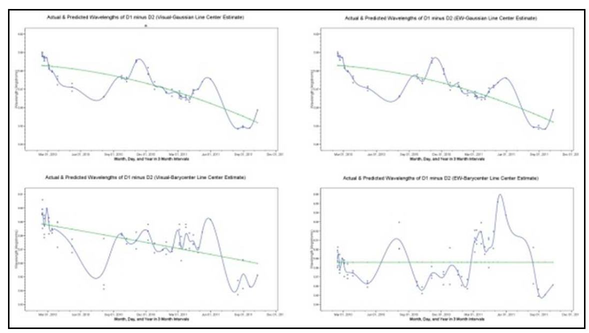


Figure 16.

Line	Method	Mean	Std Dev
Na D2	EW Barycenter	5889.79	0.3152
	EW Gaussian	5889.82	0.3033
	Visual Barycenter	5889.80	0.3028
	Visual Gaussian	5889.82	0.3032
Na D1	Barycenter	5895.77	0.3093
	EW Gaussian	5895.79	0.3084
	Visual Barycenter	5895.78	0.3072
	Visual Gaussian	5895.79	0.3085

Table II. Standard deviations of the line estimation methods.

EW-barycenter estimation method could be unbiased and be giving the correct relation, which is no relation, but it has the highest variance among all the methods. This higher variability could mean the EW-barycenter estimate was just too variable to detect a small linear relation or for a bias to be seen.

I wanted to show this to demonstrate the care one has to exercise in interpreting results. More than likely the change over time shown in three of the methods is the result of a bias in line center estimation, but wouldn't it be something if I, with an LHIRES III spectrograph and a relatively inexpensive Meade telescope, discovered a major flaw in Quantum Mechanics? On the 0ther hand, maybe there is a quantum mechanical explanation.

5. Conclusion

In conclusion, I have had a very good experience using the LHIRES III high resolution spectrograph. I think this may in part be because the seeing is pretty good at my observatory resulting in low spectral noise, I am in a desert area and so I do not have a major problem with telluric lines, my introduction to spectrometry was on a bright star (Epsilon Aurigae), because my introduction was on a bright star I was able to set the slit width near the Nyquist minimum to give me maximal resolution without adversely affecting integration time, and I have a good imaging camera, a Class I ST-8XME. Generally, it seems deviations from ideal seeing, ideal mechanical aspects, and ideal guiding has been very forgiving. If one reads all the very technical advice and very technical solutions to problems given in the Spectro-L discussion group one could quickly become overwhelmed and conclude spectroscopy is not for them. Maybe the best advice is to get good equipment (especially the imaging camera), just do it, and, at least at first, concentrate on the brighter stars.

6. References

Leadbeater, Robin; Stencel, Robert E. (2010). "Structure of the Disc of Epsilon Aurigae: Spectroscopic Observations of neutral Potassium during Eclipse Ingress." *arXiv*:**1003.3617v2** [astro-ph.SR].

Seebode, *et al*. (2011) "Ring-like Structures around Epsilon Aurigae Companion." 217th AAS Meeting, Poster Paper **257.08**.