Epsilon Aurigae Hydrogen Alpha Emission Line Variation: The Horn Dance

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Abstract

The Hopkins Phoenix Observatory has been doing high resolution spectroscopy on the 3rd magnitude long period (27.1 year) eclipsing binary star system epsilon Aurigae since August 2008 using a Lhires III spectrograph with a 2,400 line/mm grating mounted on a 12" Meade LX200 GPS telescope. Observations have been in both the sodium D line region of the spectrum and with near continuous observations of the hydrogen alpha region. The out-of-eclipse hydrogen alpha spectrum shows significant night-to-night variation. While many star systems exhibit a strong hydrogen alpha absorption line, like Be stars. Epsilon Aurigae also shows strong blue and red shifted emission components sometimes called wings or horns bracketing the absorption line. Unlike the Be stars where the blue and red horns remain relatively constant, the hydrogen alpha horns of epsilon Aurigae seem to be in a wild dance with continuous motion up and down. This paper will discuss techniques and result of recent out-of-eclipse high-resolution spectroscopy of epsilon Aurigae.

1. Introduction

At the Hopkins Phoenix Observatory we have spent the last 27 years doing mainly single channel UBV photometry. In 2006 we experimented with JH band SSP-4 photometry on epsilon Aurigae using an 8-inch SCT. It was discovered the signal-to-noise ratio was poor. We then purchased a 12" LX200 GPS for use with the SSP-4 photometer. After many hours of observations it was decided that the 12" was also too small to produce a good signal-to-noise ratio. Indeed, during the eclipse the signal would be poor. Experiments with a local observatory’s 16" SCT showed that a 16" telescope would produce a good signal-to-noise ratio even when epsilon Aurigae was in eclipse. We were in no position to replace the 12-inch telescope with a 16-inch so JH band photometry of epsilon Aurigae was shelved.

During the 2008 meeting of SAS a presentation on Be stars using a Lhires III spectrograph and small telescope showed that meaningful spectroscopy could be done on a star system such as epsilon Aurigae with our 12-inch telescope. A Lhires III spectrograph was then purchased and coupled with our 12-inch LX200 GPS telescope for spectral research of epsilon Aurigae in conjunction with our continued UBV single channel photon counting photometry. Because stars are usually mostly hydrogen, the spectral line for hydrogen alpha (6565 Å) usually shows some very interesting features. Therefore the primary spectral region of interest for epsilon Aurigae is the hydrogen alpha region. Other regions of interest include the sodium D line region, hydrogen gamma, calcium II, potassium and magnesium lines. During the eclipse other regions may show important changes too.

This paper will discuss spectral observations made at the Hopkins Phoenix Observatory using a Lhires III spectrograph on a 12-inch LX200 GPS telescope for high-resolution spectrometry of epsilon Aurigae.

Spectroscopy is very different from photometry. A night with high thin clouds is disastrous for photometry, but little bother for spectroscopy. In fact it may even help by adding more significant atmospheric (H2O) lines for calibration. The whole trick for imaging a star to get its spectrum is to get as many photons in the slit as possible. While having mastered CCD picture imaging will help with the spectroscopy, having the star drift around will not hurt the spectrum. As long as sufficient number of photons enter the slit a good spectrum will result. In fact drift-
ing back and forth in the slit will produce a wider spectrum, but since the columns of the pixels will have their ADU counts summed, it will not hurt. It can actually help by allowing a higher count yet not exceeding the ADU maximum for a given pixel.

2. Equipment

A Lhires III high resolution spectrograph with a 2,400 lines/mm grating is coupled to a Meade 12-inch LX200 GPS telescope via the telescope's electric focuser. Figure 1 shows an equipment block diagram.

Figure 1 High-resolution spectrometry equipment block diagram.

A DSI Pro (black case in Figure 2) monochrome CCD camera is used to monitor the position of the star to keep it centered in the slit. Guiding is done manually. We could not find a suitable software program for the guiding. Because the star image “falls” into the slit or most of it, the tracking programs seem to get confused. While a bit more effort, guiding with the telescope’s hand box push buttons seemed to work well.

A DSI Pro II (blue case in Figure 2) monochrome CCD camera with larger CCD chip is used to image the spectrum. Separate Dell Latitude laptop computers were connected to and controlled the two cameras.

It was discovered that the Lhires III has significant light leak. While not shown in Figure 2, all seams were sealed using strips of duct tape. Subsequent testing showed a great reduction of light leak. Most of the light leak appeared to be at the end of the spectrograph where the grating resides.

Figure 2. High-resolution spectrometry equipment.

3. High Resolution Spectroscopy Technique

A nightly observation required several specific steps.

1. Open the observatory and turn on the equipment and let the cameras stabilize.

2. Turn on the neon calibrator and focus the Lhires III internal lens for narrow lines and maximum ADU counts. Typically the maximum counts were around 25,000 for 1.0 second exposures. If counts were below 20,000 the focus could be improved.

3. Take 10-1.0 second exposures of the neon lines. This is for backup calibration.

4. Find the star in the imaging camera. This is not as easy as it may seem due to the small field of view and less than perfect reflection of the slit surface.

5. Focus the star image.

6. Put the star image over the slit about 1/4 the way from the right side.

7. Star the spectrum exposure and keep the star on the slit by manually guiding using a control box to move the telescope.

It was found that an 8 minute exposure produced an image that had good Analog to Digital Unit counts (ADU) yet maximum counts were under the 32,000 ADU count limit of the software program IRIS which requires signed integer fits files. While a neon spectrum was always taken prior to epsilon Aurigae's spectrum, it was found that using the atmospheric lines in the star system’s spectrum was more accurate
and worked well. The neon images were saved for future reference.

Observations began by turning on equipment at least 30 minutes prior to imaging. Once the equipment had stabilized the Lhires III neon calibrator was turned on. The neon spectrum lines in the laptop imaging display were then focused for maximum ADU counts thus producing the sharpest focus. Focusing was done via an access cover plate on the die of the Lhires three. Removal of the plate allowed access to the large lens, which was turned to produce the focusing. The Lhires III focusing is very sensitive to temperature and a slight temperature change can cause a significant focus change. Once the focusing was done 10-1.0 second images of the neon lines were taken and stacked with darks subtracted, see Figure 3 for the neon spectrum around the hydrogen alpha region. The neon spectrum lines are located at 6332.88Å and 6598.95Å. Figure 4 shows the line profile of the spectrum.

Next epsilon Aurigae was put close to the slit on the guiding laptop screen. A close focusing of the star was then performed. The focused star was then centered on the slit, usually about 1/4 a screen width from the right side. Moving the star back and forth on the slit has the effect of making the spectrum go up and down on the imaging screen. Effort was made to keep the star in the same position in the slit (Figure 5, top image).

The main imaging was then set for a 1.0 second exposure and checked to see a faint spectrum. Since the slit cannot be seen, once the slit is found by watching the star “drop” into it and the star image is producing a spectrum, the guiding computer's cursor (+) is put over the star so tracking adjustments could easily re-center the star by knowing precisely where the slit is.

Manual tracking was used to keep the star in/on the slit. Because epsilon Aurigae is bright, only the center of the star’s light would enter the slit producing a star image on the guider screen with no center,
(Figure 5, bottom image). When all was ready an 8 minute exposure was started. Atmospheric effects tended to make the star jump around a bit, but manually adjusting the position kept the star fairly close to the best position. Once the image was taken it was saved as a 16-bit signed integer fits file (caurha-8m-1opt.fits). A folder was created to hold all files for a given observation date.

4. Software

The software that comes with the DSI Pro cameras was used to control the cameras and image the spectrum. This software is called Envisage and is part of the AutoStar Software Suite. A dark frame was automatically subtracted from the image.

Once the spectrum had been obtained, two freeware image processing programs were used. IRIS was used to do some pre-processing on the spectrum. The sky was subtracted by selecting 4 points, two above and two below the spectrum and then IRIS to subtract the sky. The resulting spectrum was then optimized and saved. A second freeware program called VSPEC was then used for the final processing. Because atmospheric lines are used for the wavelength calibration, the neon lines were not used.

5. Atmospheric Line Calibration

The caurha-8m-1opt.fits file for the observation of interest was then opened in VSPEC. A profile was created. The Atmo option was selected from the Tools - Elements pulldown menu. The Line Atmos was selected and the wavelength (lambda) region beginning 6530 set.

From the Spectrometry pulldown menu Calibration Multiple Lines ... was selected. A template with identified atmospheric lines around the hydrogen alpha region was created, calibrated and printed out previously (Figure 6).

Figure 6. Atmospheric calibration template.

This template was then rested against the line profile on the laptop screen to aid in identifying the atmospheric lines (Figure 7). With a little practice and by sliding the template back and forth slightly many of the lines become obvious. There were always some of the lines that appeared to not be present, but usually a sufficient number could be identified to make a good calibration.

Figure 7. Atmospheric line calibration.

Selecting the atmospheric calibration lines is a three part job. First the cursor is dragged over the line of the profile. Then the corresponding wavelength is clicked on in the Elements window (Figure 8).
6. Heliocentric Calibration

From the Spectroscopy pull down menu Heliocentric Correction was selected. Time of the observation (mid-point) and the observation latitude and longitude data along with the star's right ascension and declination were entered and Compute selected, see Figure 10.

![Figure 10. Heliocentric data entry window.](image)

Finally the Enter key is pushed and the wavelength and position entered into the calibrating equation (Figure 9). After at least a half a dozen lines had been identified the Calcul button in the Non linear calibration window was clicked. The line profile was then calibrated to the atmospheric lines. The spectrum still needed to be adjusted to account for the Earth's movement both around the Sun and its rotation. This was done by making a heliocentric calibration.

![Figure 9. Non-linear calibration window.](image)

The Infos... window was then displayed showing the calculated information including the Heliocentric Correction (Corr. Lambda A) and Air mass, see Figure 11. While there are several calculation results listed, only the wavelength calibration (-0.585 Å) and air mass (1.0166) were of interest.

![Figure 11. Heliocentric info window.](image)
From the **Operations** pulldown menu **Translate**... was selected. Here the heliocentric correction (**Corr. Lambda** (Å)) value -0.585 Å was entered and **Apply** clicked on, see Figure 12.

![Figure 12. Heliocentric translation.](image)

The corrected plot was saved. The wavelength centers, the equivalent widths of the blue and red horns and the main absorption line were then determined.

### 7. Normalization

So far the Y (vertical) axis is the intensity in counts (see Figure 13).

![Figure 13. Raw profile with actual Y-axis intensities.](image)

To determine equivalent width the profile must be normalized. A section of the continuum that is fairly level is selected by clicking and dragging the cursor over the area and clicking again (Figure 14). This selects the area to be used for the normalization.

![Figure 14. Selecting area for normalization.](image)

From the **Operations** pull down menu **Normalize** was then selected. The Y-axis is then changed with 1.00 being where the continuum is. Absorption is below the line and emission above.

To specify the line of interest the cursor is placed at a point with the intensity close to 1.00, clicked and dragged to the right to the next point with intensity close to 1.00 and clicked again (Figure 15). Usually the points will not be exactly 1.0 so the closest position to 1.0 is used.

![Figure 15. Selecting computation area.](image)

To activate the computations on the area selected, from the **Spectrometry** pulldown menu, **Computation preferences...** (Figure 16) was selected.
8. Observational Results

8.1 Sodium D Line

A representative out-of-eclipse spectrum of the sodium D lines was taken for reference. Figure 19 shows the spectrum and line profile.

8.2 Hydrogen Alpha

Near continuous observations of the hydrogen alpha region of epsilon Aurigae were made at the Hopkins Phoenix Observatory from August 2008 through March 2009. Figure 20 shows a typical spectrum and line profile of the hydrogen alpha region of epsilon Aurigae. Figure 21 shows the detail.
9. Spectral Data

There are several types of data that can be extracted from a spectrum's line profile. These include, equivalent width (EW), Violet or Blue EW to Red EW (V/R) ratios and wavelength centers to determine Doppler shifts. Note that because this is high resolution spectroscopy and the spectral region is small, the continuum is relatively level so no response or continuum calibration was done.

9.1 What is Equivalent Width?

Expressing a line profile's parts Equivalent Widths allows expressing of the part's significance. The area under the curve between the profile part and the continuum is the EW of that part. The area is equal to the Intensity (normalized to 1.0 for the continuum) times EW in angstrom (Å).

Figure 22 shows a diagram of an emission spectral curve. The area between the curve and the continuum is the EW of the curve. There is some debate on the sign of the EW. In the days of film spectroscopy it seems areas below the continuum (absorption lines) were considered positive while curves above the continuum (emission lines) were considered negative. This is a bit against common sense as usually values above a line are normally positive and negative below the line. In fact many professional papers in the last few years use the emission EW as positive and absorption EW as negative. The bottom line is it is best to specify what convention is used when reporting EW. For this paper we use the convention of positive EW for above the line (emission) and negative for below (absorption).

Figure 23 shows a hypothetical hydrogen alpha spectrum. The blue absorption line has an EW of -0.1. The blue emission line has an EW of +0.2. The main absorption line has an EW of -0.6 and the red emission line has an EW of +0.3. The values can then be checked against other spectra for changes.
Along with the EW is a term called the VR ratio can be specified. This the ratio of the violet (V) or blue emission line EW to the red (R) emission line EW. In this case the V/R is 0.84.

10. Data Archiving

In addition to the large imaging files, even summarized spectroscopy data can generate a lot of data quickly. A means of archiving the data is desired. A FileMaker Pro database program was developed to handle this job. Thumbnail images of the spectrum profiles are stored for each image along (full sized images can be seen by just clicking on the image) with observational information and extracted data. Figure 24 shows a screen shot of the main screen.

Table I lists the equivalent widths of the blue and red horns and absorption line, center wavelengths of each and VR ratio.

Note: A value of 9999.999 indicates no data.

The equivalent widths for the blue and red emission horns and the main absorption line are plotted in Figure 25.

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**Figure 23. Equivalent widths of Hydrogen Alpha.**

**Figure 24. Spectrum data entry.**

**Figure 25. Equivalent width plot.**
11. Horn Dance

The hydrogen alpha region of epsilon Aurigae has been doing a wild dance. An animated .gif can be seen at

http://www.hpostar.com/EAurHA.gif

Reloading the page will replay the animation. There are 45 images in the animated .gif with observations beginning 11 August 2008 and ending 13 April 2009. Figure 26 shows the last frame of the animation.

While the left blue emission horn and center absorption line remain fairly stable, the right red emission horn varies greatly, going from non-existence to close to the size of the blue horn. A variation in wavelength can also be seen referenced to the 6565 Å line. This would appear to indicate changes in radial velocity. While the profiles were carefully calibrated for wavelength (using both atmospheric lines and accounting for a heliocentric adjustment), a more accurate calibration maybe necessary for more precise determination of the radial velocity variations.
## Table I. Epsilon Aurigae Equivalent Widths and Line Wavelengths

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12. Discussion and Conclusions

The interpretation of the astrophysical hydrogen alpha line profile (also known as Balmer alpha) at 6563Å is made difficult by optical depth effects in stratified stellar atmospheres (Mihalas, 1978). Because of the great abundance of hydrogen in stars, photons do not travel far from their point of origin before getting absorbed and/or scattered by other hydrogen atoms. Thus, any simple mapping of emitting structures tends to be complicated by these intervening transformations. Additional information such as multiple wavelength data, polarization and/or high resolution imaging is needed to clarify the situation – even in the well-studied solar atmosphere!

Hydrogen alpha in epsilon Aurigae was studied by Struve and Elvey (1930), Adams and Sanford (1930) and Wright & Kushwaha (1957). These observers noted that outside eclipse, the red and blue emission wings/horns were often nearly equal. However, before and during ingress, the blue emission became stronger. This is consistent with the results presented in Table 1, where V/R > 1. During totality, the central absorption strengthens and becomes dominant (often hiding the emission wings), and during egress, the red emission tended to be the stronger. We will certainly watch for this pattern to recur during the current eclipse cycle. It is instructive to compare this reported variation with the overall radial velocity changes expected during eclipse, as shown in the Figure 27 from Lambert & Sawyer (1986).

![Figure 27. Radial velocity plot.](image)

What could give rise to the variable hydrogen alpha emission in epsilon Aurigae? There are several possibilities, each of which presents challenges to interpret fully and model numerically. First (starting from the F star), an equatorial ring encircling it, analogous to Be stars, has been proposed (Cha, et al. 1994; Kemp, 1985). If the disk is supplied by material from stellar pulsation, we might expect a clearer correlation between the light curve and blue/red equivalent width variations in general and during eclipse phases.

Second, one might imagine that variable hydrogen alpha emission arises from inhomogeneous mass transfer between the F star and the eclipse-causing disk, as in the model proposed by Struve (1956). The F star would need to be near its Roche overflow limit diameter for this to be viable, and the transfer stream would be eclipsed during certain phases.

Could some of this material contribute to the asymmetry of the eclipsing disk, which exhibits “lagging indicators” that persist past fourth contact (Lambert & Sawyer, 1986)? Changes to the classic hydrogen alpha profile during eclipse argue strongly that variations arise in and around the eclipsing disk. Perhaps these are mainly in a heated region facing the F star, visibility of which varies through eclipse. During pre-eclipse and ingress, rotation of the heated region is away from earth, the moving atmosphere of which produces an inverse-P Cygni emission profile in hydrogen alpha. During mid-eclipse, the heated region is obscured and hydrogen alpha absorption dominates. During egress and post-eclipse, rotation of the heated region is toward earth and a P Cygni emission profile is produced. This scenario unites the radial velocity and hydrogen alpha profile descriptions.

To account for the previously reported decreasing quasi-period of the light variations and the changing length of totality (Hopkins et al., 2008), active accretion in the eclipsing disk core could be involved. Bottom line: this star has the capacity to surprise, so careful spectroscopic and photometric monitoring throughout eclipse is still needed.

13. Acknowledgements

We wish to thank numerous correspondents and observers who have provided ideas and data to help provide context for studies during this eclipse cycle. Special thanks goes out to Olivier Thizy for his help and inspirations with using the Lhires III spectrograph and to Robin Leadbeater for his kind and patient support helping decipher the spectroscopy software and produce useful data. We gladly acknowledge support of the estate of William Herschel Womble’s bequest in support of astronomy at the University of Denver.

14. References


