High Speed *U, V* Photometry of epsilon Aurigae's 2009-2011 Eclipse

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We present rapid cadence *u′* and *V* photometry of epsilon Aurigae during its 2009-2011 eclipse. Data is analyzed to look for both periodic and random variation. Observations are presented from two observers. The first is from Rockyford, Alberta, Canada and used a ST-7E and ST-8XME with 50mm and 135mm lenses, respectively. This observer recorded continuous filtered time series up to 11 hours long. The second is in Hereford, AZ and used a ST-10XME with a 0.36m SCT.

V Band

The V-band data was acquired from an observatory near Rockyford, Canada. The instrumentation used evolved through the period. Initially, a 50 mm focal length (FL) lens was selected, to suit an available camera (an ST-7E, with a KAF-0401E detector). This lens, and the 135 mm used later, are both Canon FD-mount lenses designed for a 35 mm film SLR camera. A Bessell-prescription V filter was mounted between the lenses and the CCD camera. The 50 mm FL was chosen so that eta and zeta Aur could be included in the field as comparison stars and for performing differential photometry on epsilon Aur. This setup was used for the first three V time series presented. The camera and lens were carried on an inexpensive fork mount (Figure 1), unguided, so the stars drifted across the field through a multi-hour imaging run. Most imaging runs were made at f/2.8 with exposures of about 20 seconds. Raw photometry from one night is shown in Figure 2.

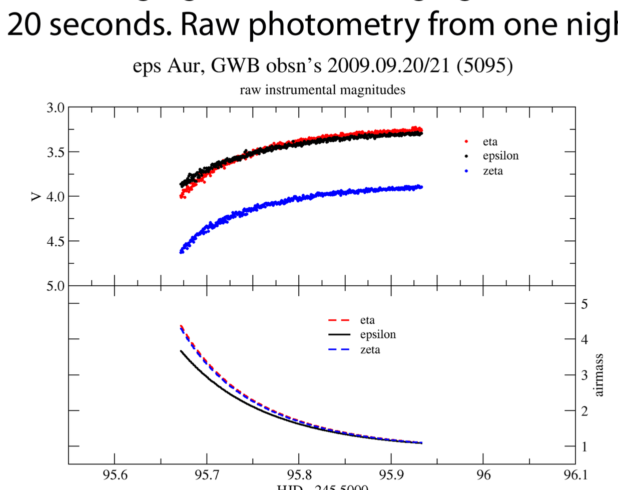

Figure 2

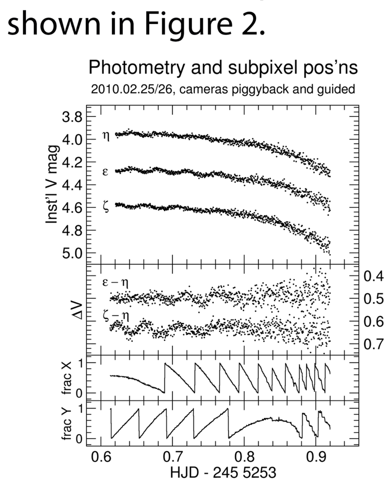

Figure 3.

When the original mount failed, the camera and lens were mounted piggy-back on a larger telescope, which was autoguided. This revealed a problem that had previously been masked. With autoguiding, stars now drifted only very slowly across the pixels. This gave rise to a spurious "signal" caused by the PSF slowly drifting across the pixels, whose sensitivity is different in the two halves of each pixel (Figure 3). Previously, the PSF moved more rapidly across pixels, randomizing this "signal" so it looked like random noise. It was thought that defocusing had guarded against this, but in hindsight the PSFs were still quite concentrated. The still-pointy defocused PSF might be due to the 4 mm of filter glass, plus other windows, behind the lens (which was not designed for any more glass between it and the focal plane), or due to imperfect lens-to-focal-plane spacing (even a few "thou" make a difference at f/2.8).

The equipment was changed in an effort to reduce this noise. The new setup uses an ST-8XME camera, with a KAF-1603ME CCD detector. This chip employs microlenses, which funnel all the light through one side of each pixel, thereby avoiding the sensitivity differences between the two halves of the pixel. It is also twice as large (4x the area), so a longer focal length can be used and still have a similar field-of-view. A 135 mm lens was used, again at f/2.8. This larger aperture would demand shorter exposures, thereby increasing scintillation noise, so an ND8 filter (decreases the light by a factor of 8) was placed in front of the lens. This route was taken, rather than stopping down the lens, because the latter increases the depth of field, working against defocusing, which is still desirable even with the microlensed camera.

Unfortunately, weather conditions since switching to this new setup have been poor, so the hoped-for noise reduction has not been fully tested. The 4th night of data presented here used this setup.

Images were dark-subtracted and flatfielded (using a light-box flat) in the normal manner.

Due to epsilon Aurigae's low position in the night-time sky for much of this eclipse, images were taken at airmasses as great as 13. Even the small (2.6 degree) separation between epsilon and eta caused their light to traverse airmasses that differed significantly so each star was corrected for its own airmass before forming a differential. Airmass correction used a primary extinction coefficient derived for that night from the time-series of eta Aur (Figure 4).

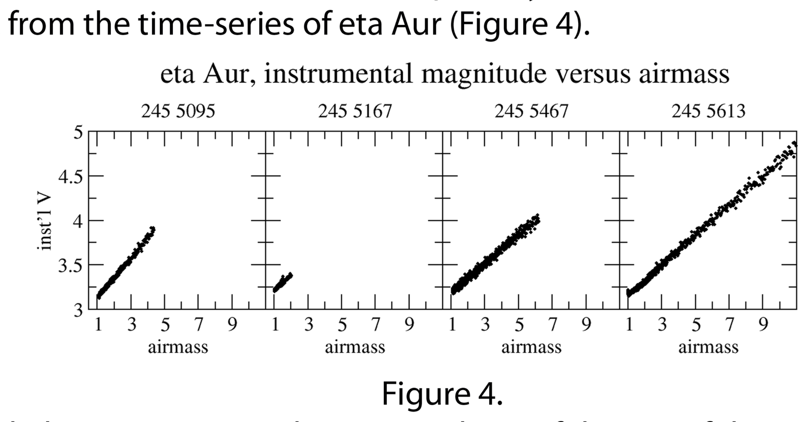

Figure 4.

Differential photometry turned out not to be useful, most of the time. On nights when differential photometry might be desired, to cope with varying sky conditions, the wide separation between epsilon and eta resulted in different cloud effects. So the first 3 nights of data shown were selected from "photometric" nights, and are the actual instrumental magnitudes (after correction for first-order extinction due to changing airmass), not differential magnitudes.

The exception was for the 4th night presented here. It is the best available night for the time period, but there were slowly varying transparency changes through the night, so that forming a differential of eps – eta, after correcting each for its own airmass, yields a more usable time-series.

Figure 5 shows the four V-band time series on epsilon Aurigae that are analyzed in this paper.

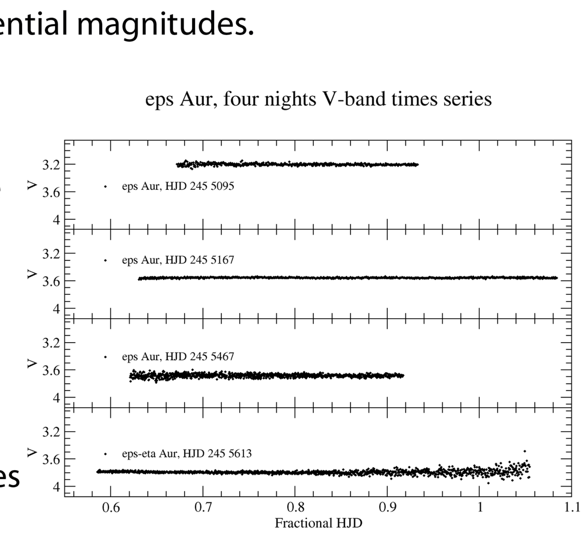

Figure 5.

Analysis

epsilon Aurigae has an underlying variability beyond that of the eclipse (Shapley, 1928). To remove its effects, each night's data was detrended by applying a linear fit and analyzing the residuals. The data was then visually inspected and put through a Date Compensated Discrete Fourier Transform (DCDFT) (Ferraz-Mello, 1981) to search for periodic signals. Analysis was done with the *VStar* Java open source software package, developed by a team of Citizen Sky participants (Henden, et al. 2010) led by David Benn and freely available at sourceforge.net/projects/vstar/. Each night was analyzed separately, followed by an analysis of the aggregate data of each bandpass. Finally, a weighted wavelet Z-transform (WWZ - Foster, 1996) was run on the aggregated data of each bandpass to look for short term and fluctuating periodicity. WWZ is a data-compensated wavelet analysis designed for analysis of unevenly sampled time series data.

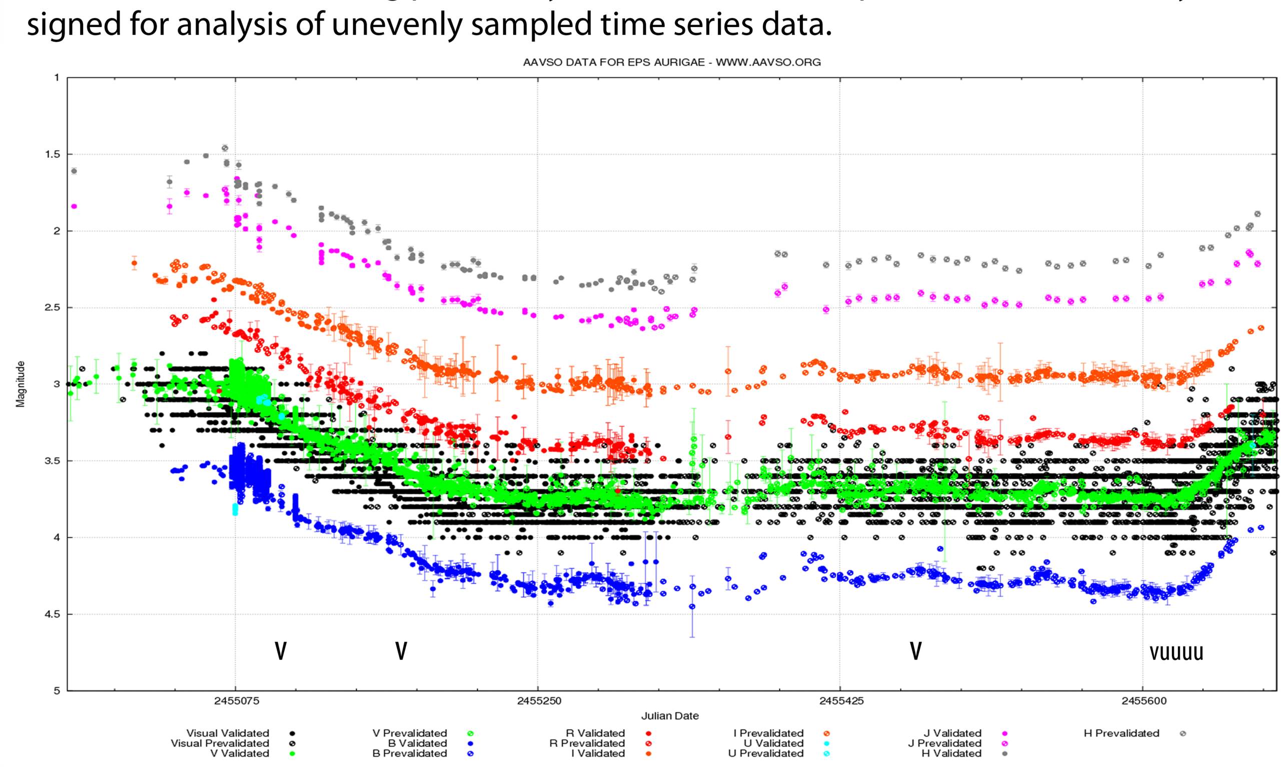

Figure 6. The AAVSO International Database BVRIJH light curve of epsilon Aurigae's current eclipse. Points marked *V* and *U* are when data presented in this poster were acquired.

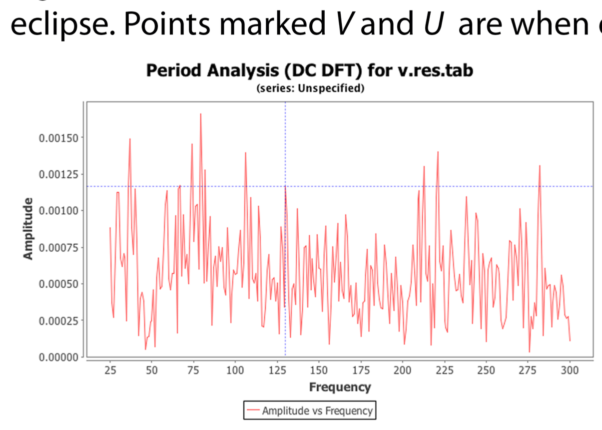

Figure 7.

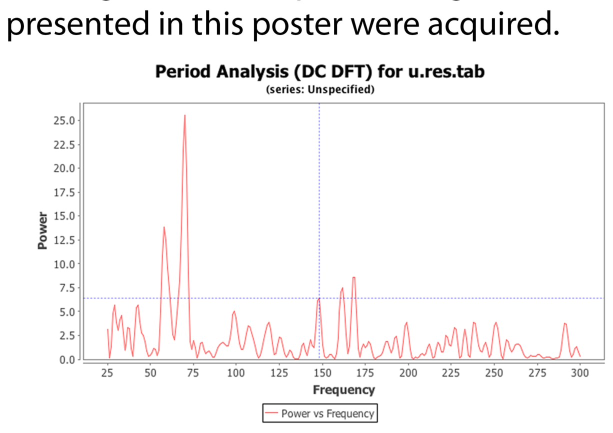

Figure 8.

DCDFT analysis of the individual nights of data found no periodic signals in the *V*-band data (Figure 7). Only one night showed any periodic signal in the *u′*-band - JD2455621 (February 28-March 1, 2011) (Figures 9 & 10). The period is 71.3 +/- 0.01 cycles/day (20.2 minutes) with an varying amplitude of *u′*=~0.4 magnitudes. However, autoguiding corrections are likely the source (see the *u′*-band section for discussion). The variation does not appear on any other evening. Also, on the same evening a 2.4 hour variation was detected (Figure 13 - right). We can attribute it to no known systematic source. The observing run was not long enough to determine whether it was periodic.

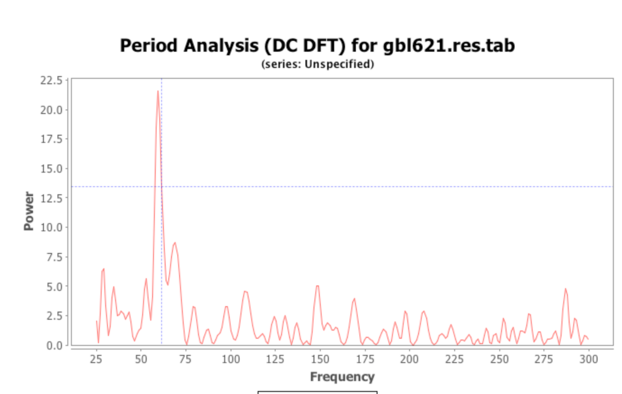

Figure 9.

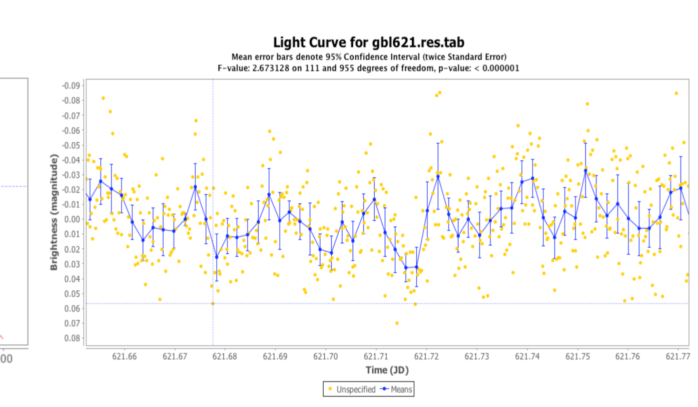

Figure 10.

DCDFT and WWZ analysis of the combined V-band and u′-band datasets also found no periodic signals (Figure 11). The period in the JD2455621 data appears clearly in the WWZ analysis, but does not appear to be correlated with any other periodic activity.

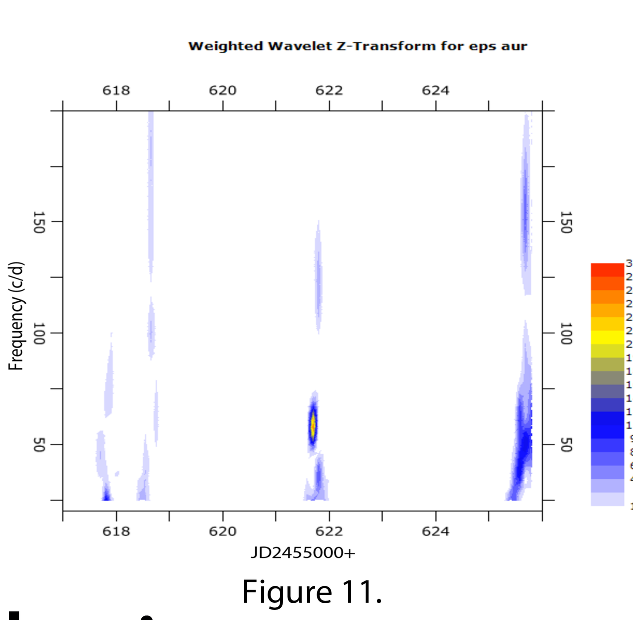

Figure 11.

Conclusion

Preliminary analysis of the data does not find any clearly periodic variation on time scales of 25-300 c/d. We believe the amplitude limits of our period search to be, on average, 0.01 magnitudes in *V* and 0.5 magnitudes in *u′*. There is a possibility of *u′*-band variation on one evening, but we cannot rule out systematic effects and it has not been seen on any other evening. On that same evening we detected multiple hour variation, but the observing run was not long enough to determine whether it was periodic. We have hundreds of hours of additional data that have not been reduced and will continue our investigation.

Bibliography

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u′ Band

The *u′*-band observations were made with a Meade 14-inch telescope at a private observatory in Hereford, AZ. The CCD is a SBIG ST-10XME, and it was binned 2x2 for unguided exposure times of 10 seconds. We acquired over 39 hours of of *u′*-band high cadence monitoring with an average rate of one image every 16 seconds.

Observing at *u′*-band is difficult for several reasons. **1)** Atmospheric extinction is high due to Rayleigh scattering and stratospheric ozone absorption (Figure 12). The Hereford Arizona Observatory is at 4700 feet altitude, and extinction at *u′*-band is typically 0.45 magnitudes per airmass.

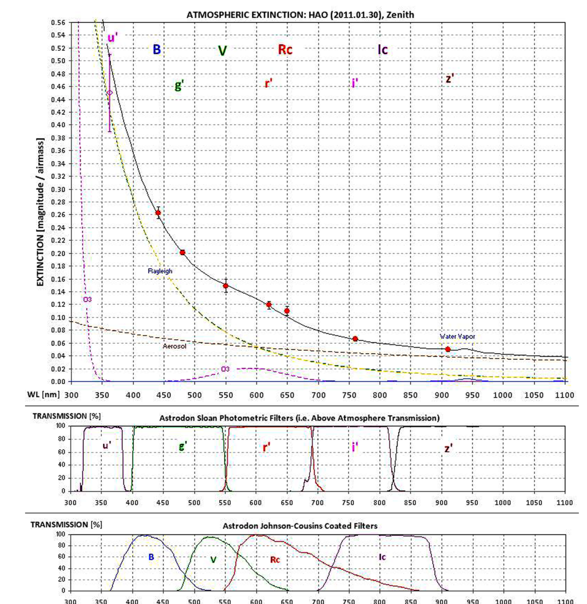

Figure 12.

2) Focal reducers have anti-reflection coatings optimized for *V*-band, and at *u′*-band a single-coating focal reducer is very reflective, causing flat fields to be contaminated by an unwanted pattern of reflected light that could ruin differential photometry results. Some of the Epsilon Aurigae observations were made with such a focal reducer, so these image sets had to be re-processed with a modified master flat field. Later observations were made without a focal reducer. **3)** The throughput of a *u′*-band filter is very low, approximately 1% compared with V-band. Therefore, autoguiding with a 2-chip CCD can't be counted on, so all the u′-band observations reported here were performed with occasional manual guiding corrections. The polar axis misalignment was such that manual corrections had to be made at approximately 15 minute intervals in order to assure that Epsilon Aurigae stayed within a 3 'arc area on the CCD pixel field. Because of the possibility that systematic errors in the flat field correction underwent changes at ~ 15-minute intervals any detected periods between about 65 and 100 cycles per day may be due to these corrections. **4)** The field-of-view included only one star with sufficient S/N for use as a reference. This star was 5.4 magnitudes fainter than Epsilon Aurigae, so the precision of the epsilon Aurigae light curve is dominated by this star's S/N. A typical 10-second image exhibited an RMS of 14 mmag per image. Observing sessions on 14 nights produced a total of 39 hours, from which four sessions were chosen for this analysis of variability.

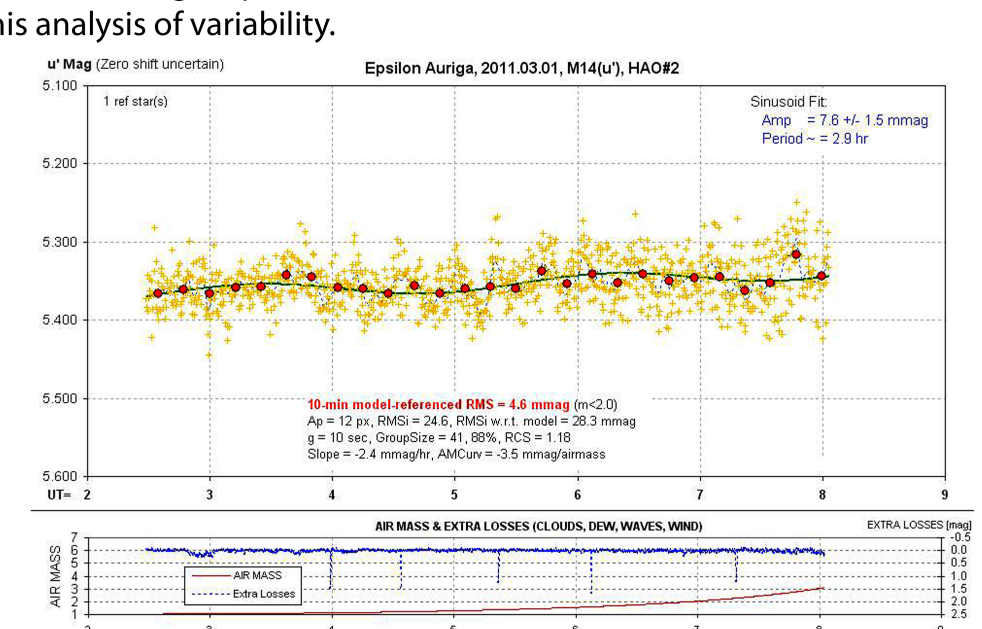

Figure 13.

Acknowledgements

The long term light curve is courtesy of the AAVSO and hundreds of international observers. Data is freely available at www.aavso.org. Citizen Sky is funded by National Science Foundation award DRL #0840188. Billings ackowledge the use of the tools IRAF, Starlink and WCSTools.

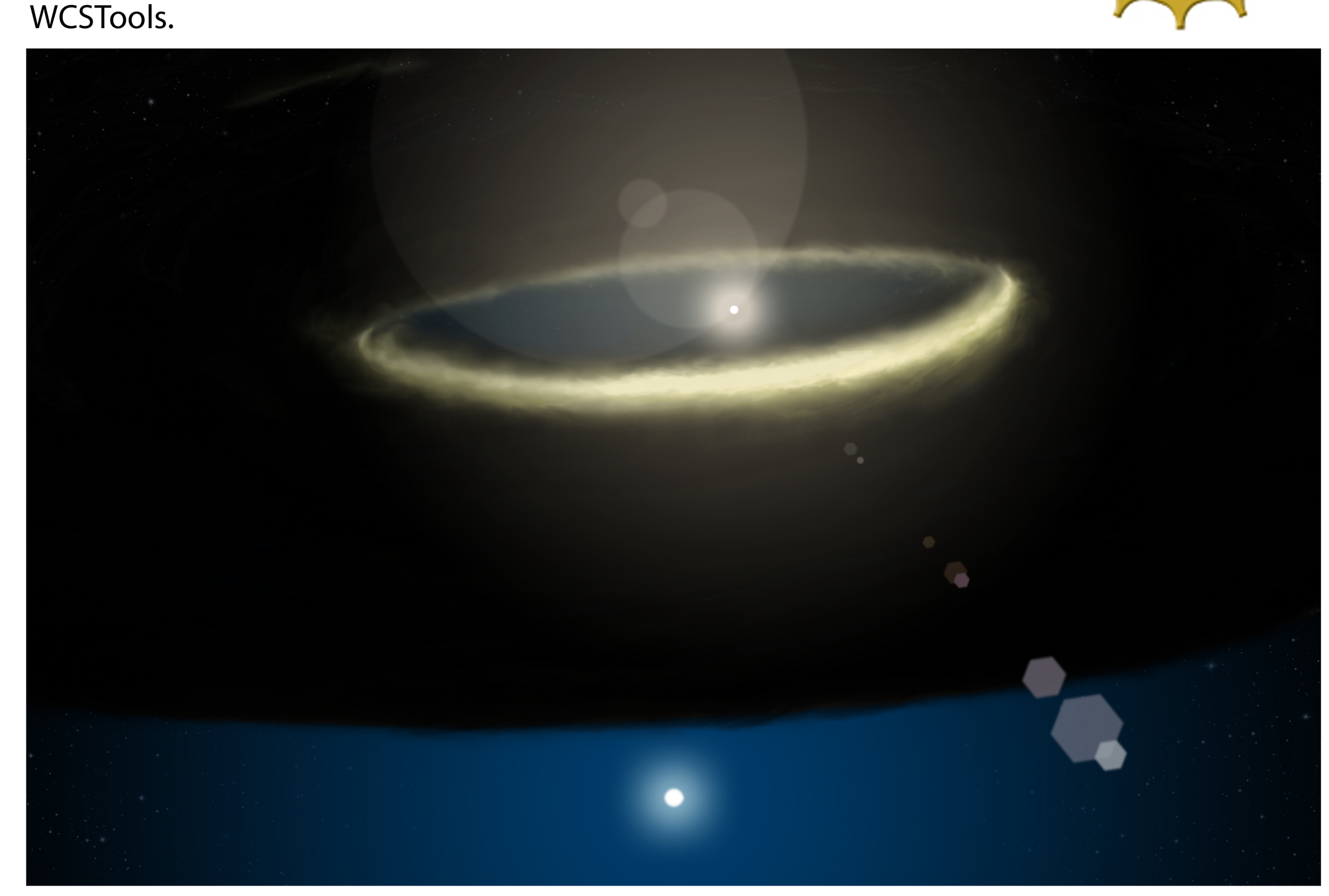

Illustration of the epsilon Aurigae system by Citizen Sky team member Nico Camargo.