Towards a Full Orbital Solution For Epsilon Aurigae

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Abstract

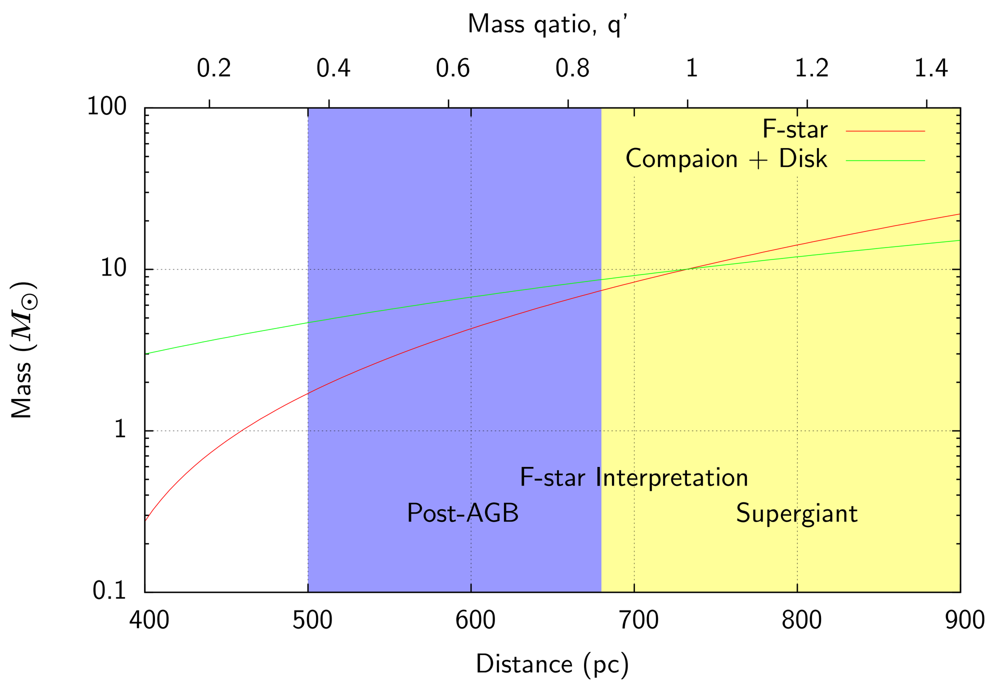
Epsilon Aurigae is an eclipsing binary with a 27-year period that has baffled investigators for almost two centuries. The data from present and prior eclipses have strengthened our knowledge of the system, but a comprehensive understanding of its evolutionary state has remained illusive. There are presently two competing views: (1)the F-star primary is a supergiant of $\sim 15\ M_\odot$ with a companion that is equally massive, yet obviously much smaller, that has yet to evolve off the MS or (2)the F-star is a post-AGB object of $\sim 4\ M_\odot$ with a MS companion of $\sim$ 6-7 $M_\odot$ that is enshrouded in an accretion disk of debris from the F-star.

Deciding between the two models depends on having an accurate distance to the system. Published parallaxes all agree within their formal uncertainties, but have error bars larger than the nominal value. We have found that all astrometric results either neglected orbital motion or relied on orbital elements that are not congruent with spectroscopy (Stefanik et al. 2010) and with the recent in-eclipse interferometric observations (Kloppenborg et al. 2010). For example, all astrometric orbital solutions (van de Kamp 1978, Strand 1959, Heintz and Cantor 1994) assumed an eccentricity that does not agree with present value, e = 0.22-0.26 (Stefanik et al. 2010, Chadima et al. 2010), rather than solving for it. Likewise the HIPPARCOS parallax used Heintz's orbit that we argue is incorrect.

We are deriving new orbital solutions for both components in the system. The solution for the F-star will use radial velocity and astrometric observations. The solution for the eclipsing object comes from the relative motion of the components implied by interferometric imaging.

The Evolutionary State

The key objective of the first author's dissertation is to disentangle the evolutionary state of the system. The slight overabundance of s-process elements (Sadakane, 2010), but otherwise "normal" spectral features implies it is a F-type Supergiant. However; the ratio $^{12}CO/^{13}CO = 10 \pm 4$ (Hinkle and Simon 1987, Stencel et. al. 2011) appears only after mid-eclipse and disappears after the eclipsing body has moved out of the line of sight. This low ratio implies that advanced nuclear processing has happened in this system.



By determining the distance to the system, and using interferometric observations of ingress/egress the mass ratio can be determined. By way of the mass function $f(M)$, the masses of both components can be determined. If the F-star $\lessapprox 8\ M_\odot$ it is likely a post-AGB object. If the mass is greater than 8 $M_\odot$ the F-star is a supergiant. This is illustrated in the figure above.

Published Parallaxes

There are eight estimates for the parallax of ϵ Aur. Below we feature the three with the smallest uncertainty. The remaining parallaxes were determined from photographic astrometry and were at the limits of detection.

Name	π_{abs} (mas)	π_{dyn} (mas)	Distance (pc)
HIPPARCOS	1.53 ± 1.29		653 ± 551
Heintz	3 ± 2	1.65 ± 0.15	606 ± 55
Van de Kamp	1 ± 1	1.72 ± 0.08	587 ± 27

Parallaxes from Yerkes, McCormick and Allegheny photographic data also exist, but all resulted in values less than their uncertainties.

The π_{abs} values are either determined by traditional means (see, van Leewen, 2007) or by using long-term astrometric data to solve the following equation using a minimization routine (i.e. least squares)

$$\vec{X} = \vec{X}_0 + \vec{\mu}t + \pi\vec{P} + ORBIT(\Omega, i, \omega, \alpha, e, \tau, P)$$

where π is the absolute parallax and the other symbols have their traditional meaning.

The HIPPARCOS result is quite interesting because the error is 2-3 times greater for ϵ Aur than for nearby stars. Using a revised orbit does not improve the solution (van Leewen 2011, private communication). At 653 pc the F-star would be roughly 0.62 AU in diameter, therefore the presence of spots or other inhomogeneities on the surface of the F-star could significantly alter the parallax by shifting the photocenter.

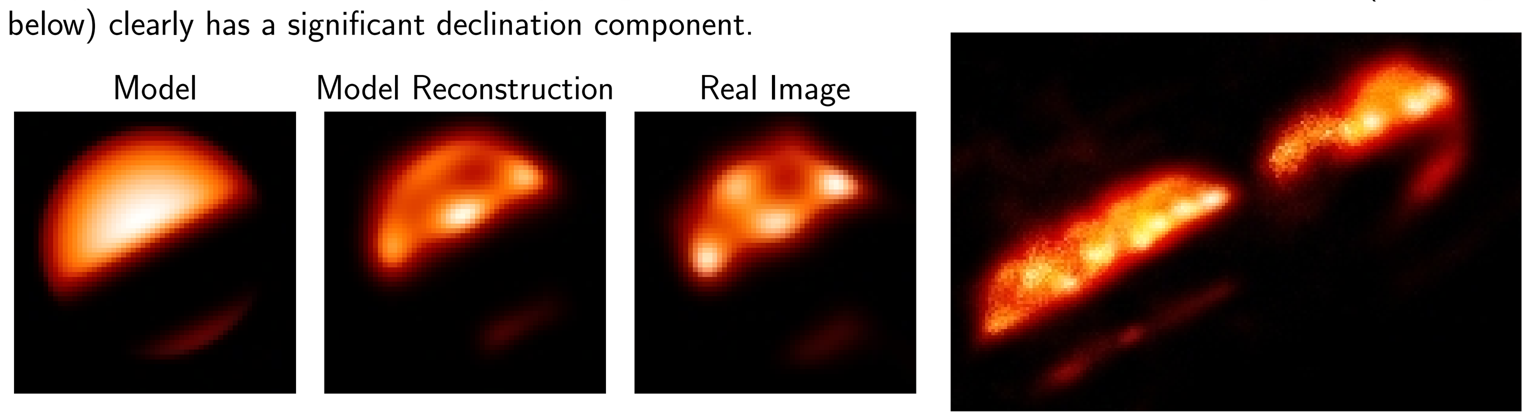
Existing Orbital Solutions

Three orbital solutions were derived from long-term astrometric observations taken at two different observatories. Van de Kamp (1978) collected 1090 plates on 331 nights between 1938 and 1978 at the Sproul observatory. Heintz et. al. (1994) extended these results with an additional 32 nights of data, resulting in 44 years of data. Strand (1959) used 124 plates of data taken over 59 nights between 1926 and 1958 at the Yerkes observatory. The published results are summarized below:

	Ω	i (deg)	ω	α (mas)	e	τ	P (days)	π_{abs} (mas)	π_{dyn} (mas)
Heintz	264	87	0 *	22.4 ± 1.8	0.07 *	33372	9891 *	3 ± 2	1.65 ± 0.15
Van de Kamp	92 ± 3	89 ± 3	29.8 ‡	22.7 ± 1	0.20 *	33353	9891 *	1 ± 1	1.72 ± 0.08
Strand		72	350 ‡	14 ± 4	0.33 *		9891 *	6 ± 3	1

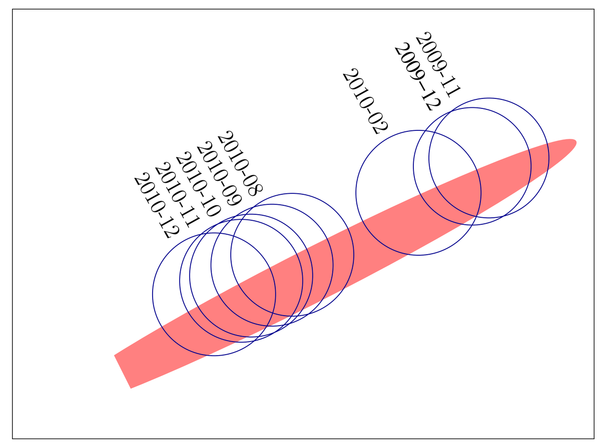
*assumed extrinsically. † is (HJD − 2400000). ‡ not stated in publication, but implied via. references.

In comparison with modern spectroscopic orbital solutions, the Van de Kamp orbit appears to agree best. However, the new inconsistency between Van de Kamp's orbit and the interferometric data is that Van de Kamp's orbital motion is almost entirely in right ascension, while the motion of the occulting cloud (see images below) clearly has a significant declination component.



The system was observed during the 2009-2011 eclipse with the CHARA interferometer in H-band (Kloppenborg, 2010, 2011). The above reconstructed images show the F-star has straight edges whereas the reconstructed best-fit model is round. This indicates the F-star may have an asymmetric structure or may be undergoing non-radial pulsation.

Combining the eight CHARA epochs using the motion observed during ingress results in the image to the right. The remarkable consistency of the disk thickness shows a value of $110 < \Omega < 130$ should result from any new orbital solution



There are four modern and eight historical spectroscopic orbital solutions for ϵ Aur. These solutions tend to predict a mid-eclipse date that is two-years earlier than observed. It is believed the intrinsic variability of the system (see plot below) skews the time of periastron. Stefanik's and Chadima's solutions "b" alleviate this issue by using eclipse times as ancillary information in their solutions.

	ω	$a_1 sin(i)$ (1E6 km)	e	τ (days) †	P (days)	f(m) $M_\odot$
Chadima a	41.2 ± 3.1	1897 ± 50	0.256 ± 0.012	34816 ± 23	9890.26 ± 0.62	3.05 ± 0.24
Chadima b	43.3 ± 4.0	1883 ± 33	0.249 ± 0.015	34842 ± 97	9890.98 ± 0.50	3.00 ± 0.16
Stefanik a	29.8 ± 3.1	1876 ± 30	0.290 ± 0.016	34425 ± 76	9882 ± 17	2.69 ± 0.13
Stefanik b	39.2 ± 3.4	1835 ± 29	0.227 ± 0.011	34723 ± 80	9896.0 ± 1.6	2.51 ± 0.12
Wright	29.8 ± 3.1	2000	0.200 ± 0.034	33346 ± 278	9882 ± 17	2.69 ± 0.13
Morris	347.8 ± 15.8	1970	0.172 ± 0.033	33331 ± 0.42	9890 *	3.12
Kuiper	350	2014	0.33	33717	9890 *	3.34
Ludendorff	319.7	1887	0.35	32402	9900	2.7

*assumed extrinsically. † is (HJD − 2400000).

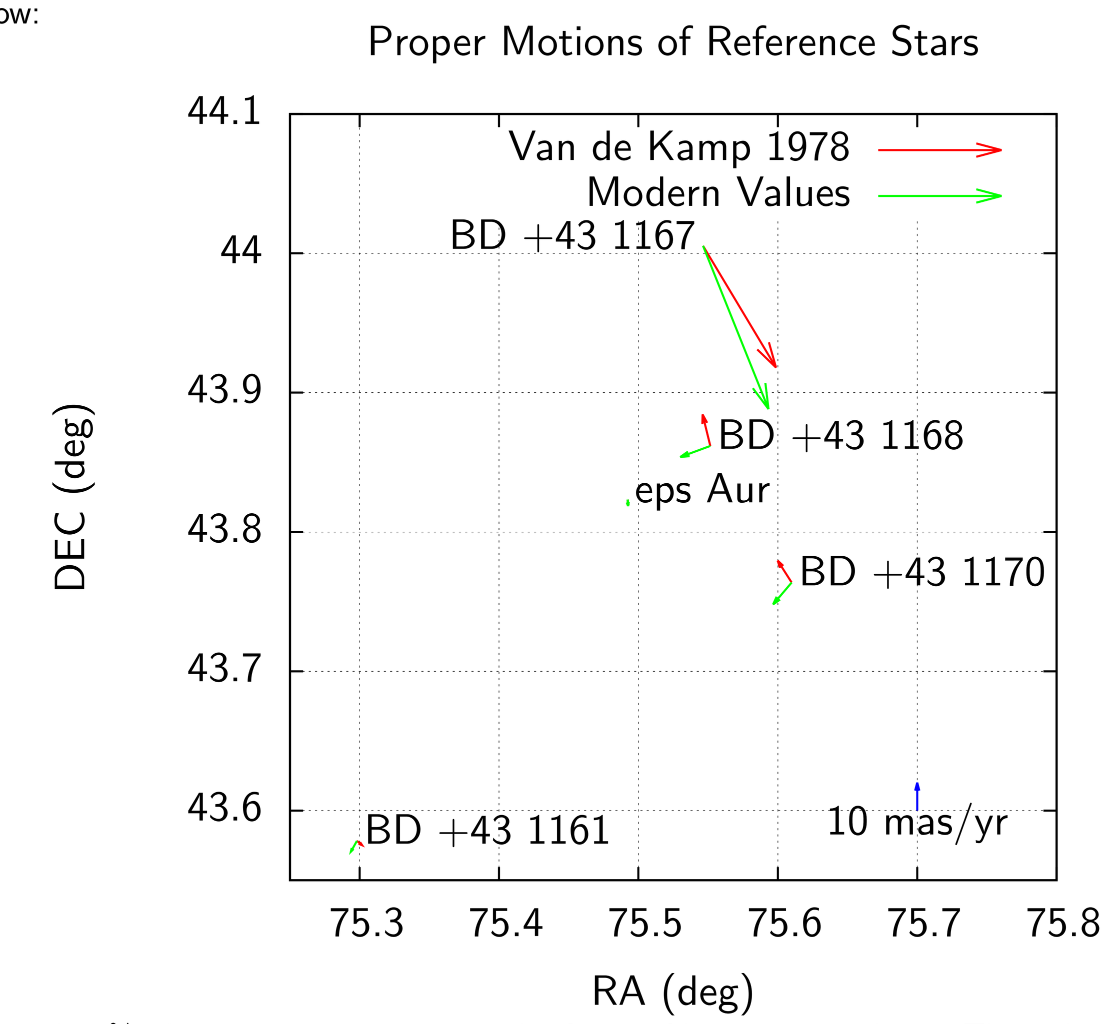
An estimate for the distance to the system may be determined by solving $d = a_1/tan(\alpha_1)$. Given that α_1 from Van de Kamp and Heintz do not vary significantly, despite the large differences in orbital parameters, we may assuming $\alpha = 22.7 \pm 1$ mas. Combined with $a_1 sin(i) = 1876 \pm 30 \times 10^6$ km, and $sin(i) \approx 1$, then $d = 552 \pm 25$ pc, implying the post-AGB interpretation for the system is correct. In light of the disagreement with Ω we have decided to compute a unified orbital solution using the RV, Sproul astrometric, and CHARA interferometric data.

Objectives

- Determine why Van de Kamp's orbit is incongruent with interferometry.
- Digitize the Sproul astrometric measurements.
- Re-derive an orbital solution using RV, Sproul astrometric, and CHARA interferometric data.

Results

- One reference star (BD +43 1161) in Van de Kamp 1978 was misidentified as BD +43 1169. The proper motions for this star are small, therefore the impact to the published orbital solution were minimal.
- Proper motions used for the remaining reference stars are in disagreement with modern values (Hog 1999, Roeser, 1988). In his notes, Van de Kamp indicates the reference stars have residuals in excess 0."1 by 1973, but no indication of how this was corrected were discussed in the 1978 publication. Therefore we believe the 1978 solution is in error. The proper motions used by Van de Kamp and modern values are shown in the figure below:



- E.J. has found 25% of 1090 plate measures in the Sproul Observatory archives. These data have been digitized by B.K. and checked for consistency.
- The raw plate measures were taken by two individuals with slightly different "personal scales." Some plates appear to have been rotated by 45° while being measured. We have taken this into consideration in our solutions.
- An interesting note is that the proper motion for ϵ Aur in the Van de Kamp solution is **40** times greater in right ascension, and **9** times greater in declination *and in the opposite direction* of what HIPPARCOS indicates. Other proper motion estimates are widely scattered and inconsistent.

Future Work

- The digitized Sproul data will be used for a new astrometric solution.
- BK will conduct a simultanious fit to the RV, Sproul, and CHARA data to derive a unfied orbital solution.

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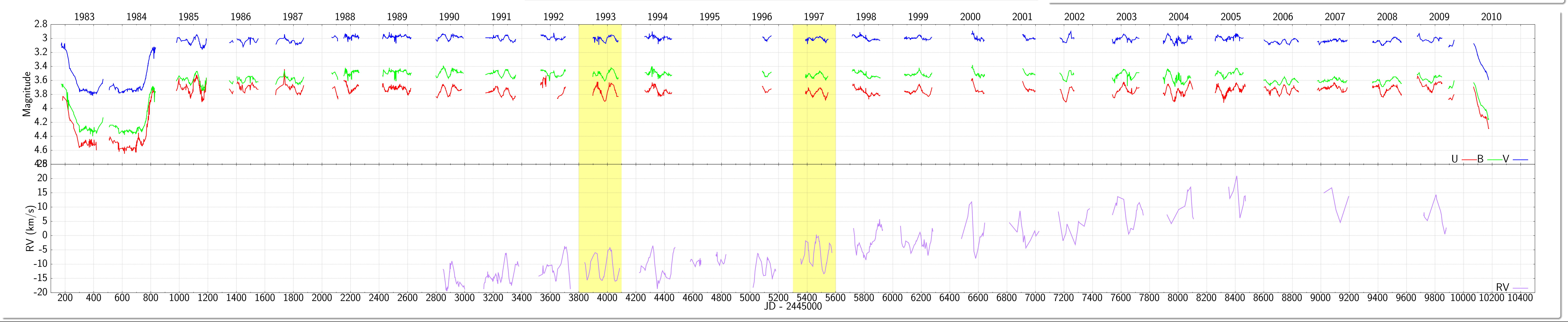
Acknowledgements

The authors thank L. Boyd and J. Hopkins for use of their photometric data in the plot below. The RV data in the same plot come from R. Stefanik's and P. Chadima's publications.

B.K. and R.S. are grateful for support under NSF grant 10-16678 and the bequest of William Hershel Womble in support of astronomy at the University of Denver.



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