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A NEW EPHEMERIS AND AN ORBITAL SOLUTION OF ϵ AURIGAE

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The bright star ϵ Aur (7 Aur, HD 31964, HR 1605; $V_{\max} = 3^m0$; F0Ia+?) is an unusual eclipsing binary with a very long orbital period of 27.1 years (see Guinan & Dewarf 2002 for a recent review). Its primary eclipse started in the summer 2009 and has naturally attracted the interest of many astronomers all over the world. The aim of this paper is to present our analysis of an extensive collection of archival and new photometry, and radial velocities (RVs), and provide a new, more precise ephemeris and orbital solution for the prediction of the current and future primary eclipses and a (not yet observed) secondary eclipse. Just prior to submission of this paper, Stefanik et al. (2010; hereafter ST) published their analysis of a comparable dataset for this same star. ST presented a new orbital solution and improved ephemeris for the binary but because the data analysis approach presented here is significantly different and may provide a more accurate ephemeris, we have proceeded to publish our results also.

We compiled and digitized a large collection of RVs from the literature, including ST's dataset of 515 RVs obtained at the Harvard-Smithsonian Center for Astrophysics (CfA). These data were augmented by our new series of electronic spectra from the Dominion Astrophysical Observatory (DAO) and the Ondřejov Observatory. Altogether, these RVs span an interval of 110 years. These RV observations are summarized in Table 1 and are plotted vs. time in Figure 1¹. We also collected and digitized light curves from all six previously observed eclipses. Additionally, for the 2010 eclipse, we used standard photoelectric V photometry obtained by PC, HB, DR, DS and MW at Hvar Observatory, CCD V -band photometry obtained by ML at the Hradec Králové Observatory, and visual observations by PD reduced to Johnson V magnitude. These observations are listed in Table 2 and the individual eclipses are plotted in Figure 2².

¹RVs obtained during primary eclipse were not used in our solution because they are known to deviate from purely orbital motion. These eclipse RVs are not included in Table 1 or Figure 1.

²Some observations were not included because of their large scatter and/or insufficient coverage of a particular eclipse. We have also omitted extended datasets outside eclipse. These omitted data do not appear in either Table 2 or Figure 2.

Table 1. Journal of available RVs.

from years	observatory	No.	reference
1899–1932	Yerkes	298	Frost et al. (1929)
1901–1913	Postdam	173	Ludendorff (1924)
1928–1958	Mt.Wilson	53	Struve et al. (1958)*
1970–1971	Haute Provence	18	Castelli (1977)
1989–2009	CfA	515	Stefanik et al. (2010)
1994–2009	DAO	99	this paper**
2006–2009	Ondřejov	109	this paper**

* RVs computed from the mean of 6 lines — Fe II 4123, Mg II 4481, Fe II 4508, Fe II 4515, Fe II 4576 and Fe II 4629 Å.

** RVs computed from the mean of 5 lines — Si II 6347, Si II 6371, Fe II 6417, Fe II 6433 and Fe II 6456 Å.

Table 2. Journal of photometric observations during primary eclipses.

mid-eclipse	observer	passband*	No.	reference
1848	J.F.J.Schmidt	pv	39	Ludendorff (1912)
1875	J.F.J.Schmidt	pv	69	Ludendorff (1912)
1902	J.Plassmann	pv	29	Ludendorff (1903)
1902	F.Schwab	pv	38	Ludendorff (1903)
1929	C.M.Huffer & J.Stebbins	pe	98	Huffer (1932)
1956	K.Gyldenkerne	V	131	Gyldenkerne (1970)
1956	G.Larsson-Leander	V	106	Larsson-Leander (1959)
1983	J.L.Hopkins	V	130	Schmidtke (1985)
1983	S.Ingvarsson	V	119	Schmidtke (1985)
2010	Hvar Obs.	V	100	this paper
2010	M.Lehký	V	21	this paper
2010	P.Dubovský	pv(V)	28	this paper

* Abbreviations ‘pv’ and ‘pe’ stand for photovisual and photoelectric, respectively.

Here we provide more details of the new datasets. The DAO CCD spectra were obtained by SY and PDB and have a linear dispersion of 10 \AA mm^{-1} . The Ondřejov CCD spectra were obtained by PH, PŠ, MŠ, MW and a few other observers and have a dispersion of 17 \AA mm^{-1} . Both the DAO and Ondřejov datasets cover the spectral region around 6300–6700 Å. Their initial reductions were carried by SY and MŠ in IRAF. Rectification and RV measurements of the spectra were carried out by PC using the SPEFO (Horn et al. 1996, Škoda 1996) program’s capability to compare direct and inverted line profiles. The zero point of the RV scale was determined by measurement of selected telluric lines (Horn et al. 1996). The Hvar dataset is actually *UBV* photometry carefully reduced to the standard system (Harmanec, Horn and Juza 1994). The Hradec Králové CCD *BVRI* photometry was obtained with a 2.8/29 Pentacon auto lens and SBIG ST-5C CCD camera. The visual estimates by PD, reduced to Johnson *V*-band magnitude scale, were carried out using a modified version of Argelander’s method developed by S. Otero (Štefl et al. 2003). It is based on a cone vision and calibration technique used to minimize the effects of extinction and colour differences. We are making all new RVs and photometric datasets available with the electronic version of this paper³; the remaining RV and photometric data are already accessible from the electronic version of ST.

³5937-t1.txt – t5.txt

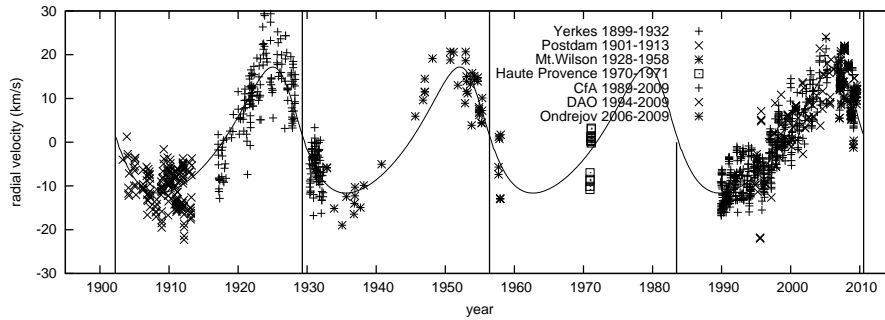


Figure 1. RVs used in the orbital solution and the derived PHOEBE fit (curve). The vertical lines denote individual eclipses (during which RVs were not used in the solution). Plotted RVs are corrected for their individual γ velocities.

We used two independent programs, PHOEBE 0.31 (Prša & Zwitter 2005) and FOTEL (Hadrava 2004), to derive new orbital solutions and formal light-curve solutions. All data sets were assigned weights inversely proportional to the squares of their rms errors derived from preliminary solutions. In FOTEL, we allowed calculations of individual systemic (γ) velocities for individual spectrographs. Since PHOEBE can treat only a single RV set, we used RVs with individual γ velocities subtracted. It turned out that the rms errors per observation for the RV sets in Table 1 were between 4 and 6 km s⁻¹. This indicates that the scatter is dominated by the intrinsic variations of the F star because the actual measurement errors are typically less than 1 km s⁻¹. The RV solutions were used to derive the orbital eccentricity (e), longitude of periastron (ω) and RV semiamplitude of a primary K_1 , and the resulting values were then held fixed in the light-curve (LC) solutions. This is because the photometric data used only covers orbital phases near primary eclipse and, therefore, these data do not constrain the eccentric orbit. LC solutions were used to derive an improved ephemeris, assuming a mass ratio fixed at unity, and inclination fixed at 87°. The derived photometric period was held fixed again for the final iteration of the orbital solution, evaluated using the *unconstrained system* option in PHOEBE.

The final photometric ephemerides (based exclusively on the LC solutions) are:

$$T_{\text{prim.min.}} = \text{HJD} (2455402.8 \pm 1.0) + (9890^{\text{d}}26 \pm 0^{\text{d}}62) \times E \text{ (PHOEBE)},$$

$$T_{\text{prim.min.}} = \text{HJD} (2455403.7 \pm 1.1) + (9890^{\text{d}}98 \pm 0^{\text{d}}50) \times E \text{ (FOTEL)}.$$

The epoch of primary minimum was allowed to vary independently for both the RV and LC solutions. We strongly prefer the more accurate value from photometry. For instance, the epoch of the primary minimum from the final RV solution in FOTEL at HJD 2455347 differs significantly from the above ephemerides. ST arrived at the same conclusions from their orbital solution; they obtained the epoch of the primary minimum at JD 2455136 (compared to their photometric minimum at JD 2455413). ST suggested that the gravitating companion responsible for the orbital motion need not be the same as the extended gaseous structure responsible for the eclipses. However, they also noted that intrinsic radial velocity variations in the F supergiant's atmosphere might bias the orbital solution, thereby accounting for the discrepancy between the photometric and RV solutions. We carried out an orbital solution in which the epoch of photometric mid-eclipse was held fixed and found that the resulting rms error was virtually identical to that of a solution converged with the epoch free to vary. This result strongly suggests that the discrepancy is due to intrinsic RV variations of the F supergiant and not due to asymmetry in the companion's structure.

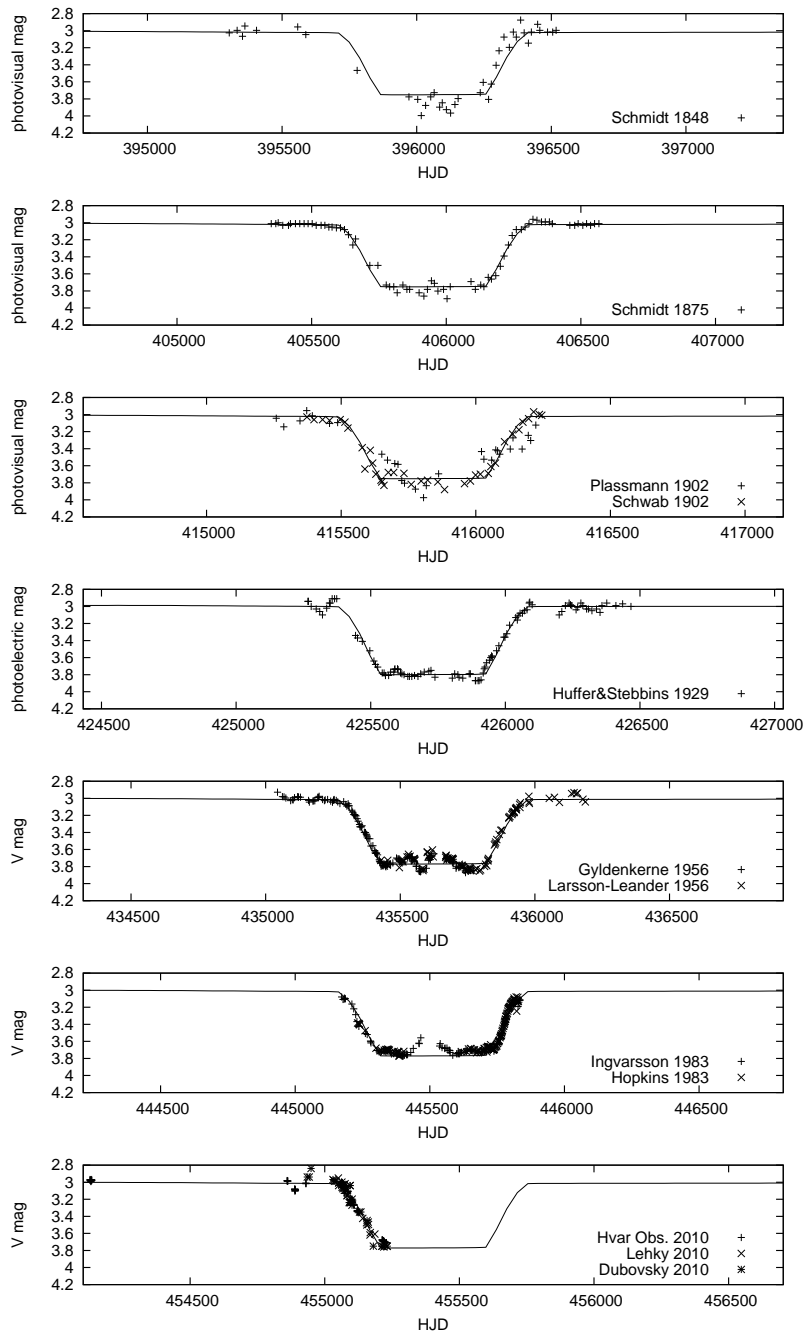


Figure 2. Light curves from the last 6 eclipses, the current 2010 eclipse, and the PHOEBE fit (solid curve) are shown. Each measurement set is corrected to its individual 'zero level' magnitude. Mid-eclipse epochs have been centered using the new ephemeris and have been plotted on the same magnitude scale to facilitate visual comparison.

Table 3. New RV and LC solutions compared to those of Wright and Stefanik.

element	PHOEBE	FOTEL	Wright	Stefanik
$T_{\text{periastron}}$	$2454596 \pm 23^*$	$2454622 \pm 97^*$	$2453130 \pm 280^*_{\#}$	$2454515 \pm 80^*_{\#}$
$T_{\text{prim.min.}}$	2455402.8 ± 1.0	2455403.7 ± 1.1	$2455323_{\#}$	2455413.8 ± 4.8
$T_{\text{sec.min.}}$	$2451681 \pm 120^*_{\dagger}$	$2451610 \pm 180^*_{\dagger}$	–	–
P (d)	9890.26 ± 0.62	9890.98 ± 0.50	9890 (assumed)	9896.0 ± 1.6
e	0.256 ± 0.012	0.249 ± 0.015	0.200 ± 0.034	0.227 ± 0.011
ω ($^{\circ}$)	41.2 ± 3.1	43.3 ± 4.0	346 ± 11	39.2 ± 3.4
K_1 (km s^{-1})	14.40 ± 0.38	14.30 ± 0.25	15.00 ± 0.58	13.84 ± 0.23

* Errors from RV solutions. \dagger Errors are semianalytical estimates. $\#$ Epochs recalculated for the authors' original periods.

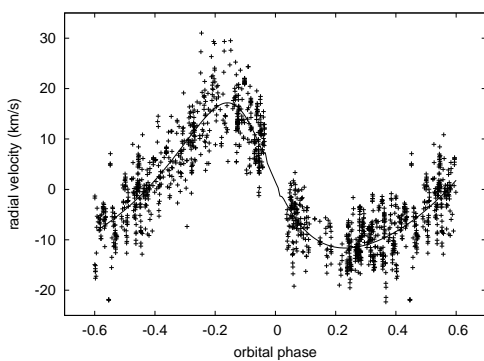


Figure 3. A phase plot of all RVs used in the orbital solution, and the derived PHOEBE fit (solid curve). Plotted RVs have been corrected for their individual γ velocities. Note that PHOEBE also accounts for rotational effect during eclipse.

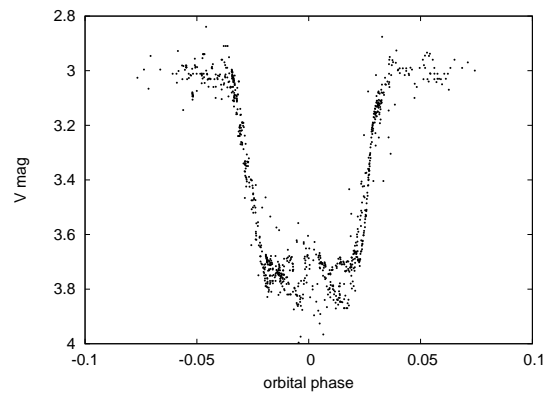


Figure 4. A phase plot of all photometric observations used in the ephemeris calculation. Each measurement set has been corrected for individual 'zero level' magnitude.

We present our orbital solutions in Table 3, along with those of Wright (1970) and ST. A phase plot, using our new ephemeris from PHOEBE, of all RVs and photometry is shown in Figure 3. Note that our new solutions, obtained with two independent programs, agree within their respective errors. Our ephemerides predict the next primary mid-eclipse will occur on July 25-26, 2010, and the next secondary mid-eclipse in 2027. The previous secondary eclipse should have occurred in 2000. When compared to Wright, we obtain a significantly different orientation of the orbit in space (longitude of periastron ω), a higher eccentricity (e), and a different epoch of the primary minimum. Our results are much closer to the ST solution, but we still disagree with ST by more than the estimated errors. At the request of the referee, we mention that the resulting relative photometric radii from the LC solutions were 0.045 and 0.216 from PHOEBE, and 0.058 and 0.218 from FOTEL. We caution the reader, however, not to give these values much weight since neither program can treat disks; both assume two stellar bodies.

Two important conclusions about ϵ Aur, which disagree with the generally accepted model, follow from our study:

1. Inspection of Figs. 2 and 3 shows that the idea of a central brightening inside the eclipse, interpreted as evidence of a hole in the disk (see, e.g., Carroll et al. 1991), should be reconsidered. Note that the 'flat' part of each recorded eclipse is different and what is seen are most probably the physical light variations, similar to the out-of-eclipse

variability. Of course, the final conclusion will come from a detailed analysis of colour changes and other types of observations and from the photometry secured this summer.

2. The right panel of Figure 3 shows that claims of variability in the width and duration of individual observed eclipses, which have been used to infer a decline in the primary's radius over time (Saito 1986), are not supported by the data. It is apparent that the cyclic but irregular physical light variations affected the different eclipses differently. It will be difficult to obtain a 'pure' eclipsing light curve without a better understanding and quantitative description of these light changes.

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