

## INTERFEROMETRIC STUDIES OF THE EXTREME BINARY $\epsilon$ AURIGAE: PRE-ECLIPSE OBSERVATIONS

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### ABSTRACT

We report new and archival  $K$ -band interferometric uniform disk diameters obtained with the Palomar Testbed Interferometer for the eclipsing binary star  $\epsilon$  Aurigae, in advance of the start of its eclipse in 2009. The observations were intended to test whether low-amplitude variations in the system are connected with the F supergiant star (primary), or with the intersystem material connecting the star with the enormous dark disk (secondary) inferred to cause the eclipses. Cepheid-like radial pulsations of the F star are not detected, nor do we find evidence for proposed 6% per decade shrinkage of the F star. The measured  $2.27 \pm 0.11$  mas  $K$ -band diameter is consistent with a 300 solar radius F supergiant star at the *Hipparcos* distance of 625 pc. These results provide an improved context for observations during the 2009–2011 eclipse.

*Subject headings:* binaries: eclipsing — stars: atmospheres — stars: fundamental parameters — techniques: interferometric

### 1. INTRODUCTION

The prevailing hypothesis concerning the nature of the long-period eclipsing binary FK5 183 (HD 31964,  $\epsilon$  Aurigae) features an F-type supergiant star and a putative B star binary, deeply embedded in a dark, massive, 20 AU diameter cold disk (475 K; Carroll et al. 1991). In the high-mass model, the total system mass is inferred to be approximately  $29 M_{\odot}$ , with an orbital separation of 27.6 AU and eclipse period of 27.1 yr (cf. Stencel 1985).

Flat-bottomed eclipses of 2 yr duration and 0.75 mag depth optically suggest that the cold disk covers half the surface area of the F star (Huang 1965). The next eclipse is predicted to start in 2009 August. Kemp et al. (1986) analyzed polarimetry of the 1984 eclipse and argued that the disk is inclined  $2^{\circ}$ – $5^{\circ}$  from its orbital plane. Taken together with a central eclipse brightening, which has varied over the past three eclipse events, disk tilt could signal precession of the disk orientation. However, the F star outshines the cold disk by an enormous factor, adding to the mystery of the secondary itself. Low-amplitude, 67 day quasi-periodic light variations mask the relative contributions of the F star and the disk in the pre-eclipse light curve (Hopkins & Stencel 2007), and these light variations appear to have sped up from 89 days over the past few decades (Hopkins et al. 2008). Concurrently, the length of eclipse phases has been changing, eclipse to eclipse.

#### 1.1. Goals

The key question to be addressed with new observations is whether the quasi-periodic 0.1 mag variations in  $V$ -band light outside of eclipse are due to F supergiant pulsation, or to com-

ponents associated with the disk and mass transfer (Stencel 2007).

The  $V$ -band  $\sim 0.1$  mag quasi-periodic variations indicate  $\sim 10\%$  luminosity changes in the system. If these originate in F star changes in temperature or radius, they would amount to of the order of 5% in radius, and half that amount or less in temperature terms. Asteroseismic observations, such as those possible with *MOST* or *COROT*, along with high-dispersion spectroscopic monitoring of line-profile variations, should be pursued to explore which parameters are in play. Interferometry provides a potentially more direct test of diameter variations, given the success of interferometric diameter variation measurements with Cepheids like  $\zeta$  Gem with PTI (Lane et al. 2000, 2002) and  $\delta$  Cep and  $\eta$  Aql with NPOI (Armstrong et al. 2001), in which radial variations of up to 6% (a range of  $0.20 \pm 0.03$  milliarcsecond [mas]) were reported. If physical variations of the F star in the  $\epsilon$  Aur system can be demonstrated to be the cause of, or excluded from causing, out-of-eclipse light variations, study of the disk-shaped companion can be more precisely pursued. This includes interferometric imaging that could determine whether the dark disk in the Huang model actually will be seen against the F star disk.

Adopting the *Hipparcos* parallax distance of 625 pc for  $\epsilon$  Aur, the maximum apparent orbital separation is 44 mas, and the F supergiant itself, if  $200 R_{\odot}$ , should subtend  $\sim 1.5$  mas. The reported NPOI diameter of 2.18 mas (Nordgren et al. 2001) for  $\epsilon$  Aur implies a diameter of  $290 R_{\odot}$  at 625 pc. This is significantly larger than the Cepheid diameters mentioned above and the VLTI/AMBER diameter,  $142 R_{\odot}$ , for the F0 supergiant Canopus, reported by Dominicano de Souza et al. (2008). In any event, a 5% or larger radial change in  $\epsilon$  Aur

amounts to at least 0.14 mas, which is well within the 0.03 mas error limit possible with current 100 m baseline interferometers. In addition, the baseline data provided by such observations provides an important data set against which future in-eclipse observations can be compared. Thus, we provide this Letter reporting on the status of interferometric data related to the  $\epsilon$  Aurigae system.

## 2. OBSERVATIONS

We proposed to use the Palomar Testbed Interferometer (PTI; Colavita et al. 1999) in visibility amplitude mode,  $K$ -band, to monitor  $\epsilon$  Aurigae during the winter 2007/2008 season, on a once per month basis. The initial observing was conducted on 2007 October 18–20. The calibrators and cross-calibrator checks used are shown in Tables 1 and 3, selected and vetted following processes described in van Belle et al. (2008). PTI's  $K$ -band  $K$ -low capability over five wavelength channels presented an exceptional opportunity to precisely measure the angular diameter of the primary star in  $\epsilon$  Aur. In order to obtain accurate visibility readings from the calibration software, one must accurately select calibrators. In addition to having well-known coordinates, proper motion, and parallax, calibrators must be bright enough to be tracked by PTI, appear pointlike in nature (for PTI,  $\theta \lesssim 0.8$  mas is suitable; van Belle et al. 2008), and have nearly constant visibility measurements. Seeing and instrumental issues provide omnipresent limitations that influence the estimated errors on diameter measurements (see below).

In addition to new observations, the PTI archives included several prior measurements which help to establish a longer term baseline and check on trends. Ancillary data on  $\epsilon$  Aur include optical photometry,  $H\alpha$  and *Spitzer* IRS spectra, and MIPS data, as part of an observational monitoring campaign (Hopkins et al. 2008; see also Stencel 2007).

## 3. DATA REDUCTION AND ANALYSIS

PTI data products consist of several levels of data. Raw data from the interferometer are called Level 0 data files. At the end of the observing night, a program called `vis` (see Colavita 1999) processes the Level 0 data and creates Level 1 data files. This data is provided to the end user as a series of ASCII or FITS files for further processing.

Level 1 data consist of wide-band visibility squared ( $V^2$ ) data, spectrometer  $V^2$  data, a baseline model, reduction configuration information, an observer log, a nightly report, the catalog (schedule) file, and postscript plots of the wide-band and spectral data. This information, along with a calibration script and a baseline model (.baseline file) is processed using two programs contained in the `V2calib` package to create calibrated wide- and narrowband  $V^2$  data.

The `V2calib` package contains the source code for the wide- and narrowband calibration programs, `wbCalib` and `nbCalib`. After being compiled, these two programs automate a majority of the data-reduction process by computing calibrated  $V^2$  measurements as well as other ancillary data including  $u$  and  $v$  projections (spatial frequencies) for each calibrated scan. If one does not have a Linux-based system on which the programs can be compiled, one may also use the Michelson Science Center's web-based calibration tool, `webCalib`, to produce the same data products.

Even though the `V2calib` programs do much to simplify the data analysis, there is no guarantee that one will obtain  $V^2$  data that is reasonable without further analysis. Examining

the calibrator-derived system visibilities helps verify that this exceeds an ideal average better than 0.5, and varies smoothly over the observing night (see details at the Michelson Science Center Web site). Only two nights, 2007 October 19 and 1998 November 25, are ideal in terms of the highest system visibility requirements. As can be seen in Table 2, the derived angular diameters for these two dates agree within the errors,  $2.19 \pm 0.06$  mas and  $2.25 \pm 0.08$  mas, respectively. Lane et al. (2002) provide a clear discussion of errors in PTI data reduction, and our errors scale with the number of scans reported in their Tables 3 and 4.

We also elected to consider new and archival data points with lower calibrated system visibilities (down to  $\sim 0.2$ ), as long as the nightly system visibility varied smoothly with time. After initial results using default settings, we also switched off the ratio-correcting feature of the software to achieve more uniform results, as recommended by Rachel Akesson at MSC. In addition to system visibility requirements, one also needs to evaluate the performance of the system over an observing night. One measure of system performance can be found by cross-calibrating the calibrators. Doing this is as simple as running the `V2calib` programs with a calibration star specified as a target. Of course, this requires that the data set contain multiple calibrators during an observing night, and that there are a sufficient number of data points for the `V2calib` programs to process into meaningful data. Because all of our calibrators are selected to be unresolved (angular diameters  $\theta < 1.0$  mas), we expect to obtain  $V^2$  values close to unity. The results of cross-calibration are summarized in Table 3, where we see that several recent nights approach this criterion. Unfortunately, most of the nights with archival data did not contain more than one calibration star.

After the data reduction, the  $V^2$  data and their errors are then fit to a model. We elected to use the uniform disk (UD) model, in which

$$V^2 = \frac{[2J_1(\pi\theta B/\lambda)]^2}{(\pi\theta B/\lambda)^2}, \quad (1)$$

where  $J_1$  is the first-order Bessel function (approximated using the first seven terms of the power-series expansion),  $B$  is the projected baseline  $[(u^2 + v^2)^{1/2}]$ ,  $\theta$  is the stellar angular diameter in radians, and  $\lambda$  is the wavelength of light at which the data was obtained. Given the limited data set, we did not pursue more elaborate models for the source size, at this time.

Because this function is nonlinear, we elected to create a lookup table. This table consisted of values of  $(\pi\theta B/\lambda)$  from 0.9 to 2.36 (inclusive) in 0.00002 step increments, and their corresponding  $V^2$  values. Using this method, we were able to match the  $V^2$  readings from PTI with the  $V^2$  values in our table to within  $2 \times 10^{-5}$ . After a  $V^2$  match was obtained, we used the corresponding  $(\pi\theta B/\lambda)$  value to solve for the angular diameter. Using this method, we calculated the theoretical error in angular diameter that would result from a 0.00002 increment in  $(\pi\theta B/\lambda)$  to be  $8 \times 10^{-16}$  at a maximum. Note that this is several orders of magnitude below any error that arises from  $\Delta V^2$  measurements, e.g., seeing. The errors on measurements reported here are seeing-dominated, and future observations need to take care to include a larger number of scans and cross-calibrator measurements to reduce overall uncertainties.

TABLE 1  
CALIBRATORS FOR HDC 31964 USED DURING OBSERVATIONS

Star Name	R.A.	Decl.	$\mu_{R.A.}$	$\mu_{Decl.}$	Parallax ( <i>Hipparcos</i> )	UDD (mas)	Error (mas)
HD 23838 .....	3 50 04.420	+44 58 04.28	-0.03780	-0.02682	0.00941	0.877	0.055
HD 29203 .....	4 38 05.877	+46 14 01.15	0.02569	-0.02157	0.00568	0.587	0.102
HD 29645 <sup>a</sup> .....	4 41 50.256	+38 16 48.65	0.24153	0.09788	0.03203	0.542	0.009
HD 30138 .....	4 46 44.478	+40 18 45.33	0.00899	-0.0371	0.00736	0.784	0.047
HD 30823 <sup>a</sup> .....	4 52 47.757	+42 35 11.85	-0.01107	0.00011	0.00631	0.280	0.027
HD 32630 <sup>a</sup> .....	5 06 30.892	+41 14 04.10	0.03060	-0.06841	0.01487	0.374	0.079
HD 34904 .....	5 22 50.314	+41 01 45.33	-0.01249	0.00294	0.01087	0.339	0.021

<sup>a</sup> From van Belle et al. (2008).

#### 4. DISCUSSION

The error-weighted mean  $K$ -band uniform-disk angular diameter for  $\epsilon$  Aurigae derived from 12 nights between 1997 and 2008 at the Palomar Testbed Interferometer is  $2.27 \pm 0.11$  mas. These values are consistent with the published NPOI and earlier Mrk III optical band values of (UDD)  $2.18 \pm 0.08$  mas and (LDD)  $2.17 \pm 0.03$  mas (Nordgren et al. 2001), although arguably slightly larger at the  $K$  band compared to these optical band results. Knowledge of the optical light curve was provided by  $UBV$  photometry obtained in parallel at Hopkins Phoenix Observatory (see Hopkins et al. 2008). No clear correlation could be seen among the limited variations in the derived diameters and the optical light curve, to the limits imposed by the measurement errors. The majority of diameters spanning the longest time span were measured on a (nearly) north-south baseline. We note that Kemp et al. (1986) indicated a polar axis position angle for the F star of  $5^\circ$ – $45^\circ$ , and our few north-west baseline points may appear slightly larger on that axis. We also checked for luminosity-related changes. The  $V$  magnitude during 2007 October (RJD 4393–4396) was 3.035, but by 2008 February (RJD 4515) had reached  $V = 2.98$ , an unusually bright maximum, even though the 67 day phasing suggested that a minimum should have occurred then. That latter epoch also featured an usually asymmetric  $H\alpha$  profile, with a strong blue emission wing and redshifted absorption core. However, the diameters appeared similar (albeit on a north-west baseline then), and a Mimir spectrum obtained shortly afterward did not show any significant changes to the weak Brackett

emission (see Clemens et al. 2007, Fig.14). Additional baseline coverage might reveal azimuthal changes, perhaps associated with proposed equatorial rings (Kemp et al. 1986).

After the 1984 eclipse ended, Saito & Kitamura (1986) provided evidence that the F supergiant star was shrinking at a rate of 16% from eclipse to eclipse (27.1 yr), based on the changing duration of eclipse totality during the past few eclipses, assuming the disk was invariant. At face value, this would result in a decrease of angular diameter of the F star by nearly 6% over the 10 yr PTI interval reported here. Within the dispersion of PTI measurements, we do not confirm any decrease of this magnitude, nor is there evidence for significant changes in diameter over the past 10 yr, assuming that the older PTI, NPOI, and/or Mrk III data do not have systematics relative to the more recent measurements. The eclipse-to-eclipse variations may be due to secular changes in the dark companion object rather than the F star—a point testable with the next eclipse. The 2.27 mas angular size reported here, when combined with the 625 pc *Hipparcos* distance, implies a primary star diameter of 308 solar diameters. This is larger than the classically derived diameter for an F0 Ia star (200 solar diameters; Cox 2000), suggesting that the star is possibly cooler than F0 and/or has an extended atmosphere due to the binary interaction. What is needed are new classification spectra of  $\epsilon$  Aur, as well as a careful determination of effective temperature from a spectral energy distribution study.

Further progress in the study of  $\epsilon$  Aur should be possible by applying interferometric imaging to the eclipse event during

TABLE 2  
DIAMETERS OBTAINED FROM WIDE-BAND VISIBILITY MODE DATA

UT Date JD– 2,450,000	GMT Start	Baseline <sup>a</sup>	$N$ Scan Sets <sup>b</sup>	Mode	$V^2$	UDD (mas)	Error (mas)	$V$ (mag)
2007 Oct 19, 4393 .....	09:57	NS	14	$K$ -low	0.516	2.19	0.06	3.036
2007 Oct 20, 4394 .....	10:21	NS	6	$K$ -high	0.544	2.16	0.12	3.036
2007 Oct 21, 4395 .....	10:45	NS	3	$K$ -low	0.583	1.90	0.13	3.036
2007 Dec 23, 4458 .....	04:41	NW	6	$K$ -low	0.574	2.36	0.14	3.046
2007 Dec 24, 4459 .....	04:48	NW	6	$K$ -low	0.565	2.37	0.11	3.043
2008 Feb 16, 4513 .....	03:05	NW	2	$K$ -low	0.527	2.60	0.15	2.98
2008 Feb 17, 4514 .....	04:48	NW	5	$K$ -low	0.572	2.28	0.15	2.98
2008 Feb 18, 4515 .....	03:01	NW	5	$K$ -low	0.624	2.25	0.12	2.98
Archival Data								
1997 Oct 22, 0744 .....	11:54	NS	1	$K$ -low	0.376	2.50	0.17	2.986
1997 Nov 09, 0762 .....	09:38	NS	2	$K$ -low	0.438	2.32	0.09	2.977
1998 Nov 07, 1125 .....	10:25	NS	4	$K$ -low	0.515	2.09	0.10	2.997
1998 Nov 25, 1143 .....	10:19	NS	2	$K$ -low	0.458	2.25	0.08	2.998
1998 Nov 26, 1144 .....	10:20	NS	1	No calibrator stars				2.998
2005 Dec 11, 3715 .....	06:33	NW	1	No calibrator stars				3.02
2006 Jan 31, 3766 .....	04:27	NW	83	No calibrator stars				3.08

<sup>a</sup> North-south baseline = 109 m; north-west baseline = 86 m.

<sup>b</sup> Each Level 1 scan set consists of 2 or more integrations of 25 s each during which fringe visibility was averaged (<http://msc.caltech.edu/software/PTISupport/v2/sum.html>).

TABLE 3  
CROSS-CALIBRATOR VISIBILITY SQUARED MEASUREMENTS

Date	Star Name	$\langle \text{Calibrator } V^2 \rangle$	$\langle \text{Error} \rangle$	$\langle \text{System } V^2 \rangle$	$\langle \text{Error} \rangle$
2007 Oct 19 .....	HD 29645	0.95	0.05	0.66	0.02
2007 Oct 19 .....	HD 29203	0.95	0.05	0.66	0.01
2007 Oct 20 .....	HD 30138	0.87	0.06	0.46	0.02
2007 Dec 23 .....	HD 30138	0.90	0.08	0.30	0.02
2008 Feb 18 .....	HD 30138	0.67	0.08	0.37	0.02

2009–2011. If the Huang model is basically correct, the passage of a dark disk, bisecting the F star surface, should produce a straightforward change in the fringe patterns—from circular symmetry of a single disk, to an asymmetry from a close pseudobinary star pair of bright limbs during totality, modulo pulsation phenomena. We ask observers with suitable resources to make this star a priority for frequent observation during this rare opportunity.

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