Interferometric Studies of the extreme binary, ϵ 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 ϵ 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 +/- 0.11 milli-arcsecond 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: techniques: interferometric, stars: atmospheres, binaries: eclipsing, stars: fundamental parameters

1. Introduction

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

Flat-bottomed eclipses of two years 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 to 5 degrees from its orbital plane. Taken together with a central eclipse brightening that has varied over the past 3 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 F star and disk in the pre-eclipse light curve (Hopkins and Stencel, 2007), and these light variations appear to have sped up from 89 days over the past few decades (Hopkins, Schanne and Stencel, 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 magnitude variations in V-band light outside of eclipse are due to F supergiant pulsation - or - due to components associated with the disk and mass transfer (Stencel 2007).

The V band $\sim$ 0.1 magnitude 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 order 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 interferometric diameter variation measurement successes with Cepehids like ζ Gem with PTI (Lane et al. 2000, 2002) and δ Cep and η Aql with NPOI (Armstrong et al. 2001), wherein radial variations of up to 6% (a range of 0.20 +/- 0.03 milli-arcsecond, hereafter, mas) were reported. If physical variations of the F star in the ϵ 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 can 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 ϵ Aur, the maximum apparent orbital separation is 44 milli-arcsec (mas), and the F supergiant itself, if 200 solar radii, should subtend $\sim$ 1.5 mas. The reported NPOI diameter of 2.18 mas (Nordgren et al. 2001) for ϵ Aur implies a diameter of 290 solar radii at 625 pc. This is significantly larger than the Cepheid diameters mentioned above and the VLTI/AMBER diameter, 142 solar radii, for the F0 supergiant Canopus, reported by Dominicano de Souza, et al. (2008). In any event, a 5% or larger radial change in ϵ 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 dataset against which future in-eclipse observations will be compared. Thus, we provide this Letter reporting on the status of interferometric data related to the ϵ 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 ϵ Aurigae during the winter 2007/08 season, on a once per month basis. The initial observing was conducted on 2007 October 18-20. Calibrators used and cross-calibrator checks 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 5 wavelength channels presented an exceptional opportunity to precisely measure the angular diameter of the primary star in ϵ 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 point-like in nature (for PTI, $\theta \lesssim 0.8$ mas is suitable (van Belle et al. 2007, 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 establish a longer term baseline and check on trends. Ancillary data on ϵ Aur includes optical photometry, H α and Spitzer IRS spectra and MIPS data, as part of an observational monitoring campaign (Hopkins, Schanne and Stencel 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 (1999b) - 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 consists 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 narrow-band V^2 data.

The $V2calib$ package contains the source code for the wide- and narrow-band 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 may 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, one cannot be guaranteed to 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 website). Only two nights, 2007 Oct 19 and 1998 Nov 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 +/- 0.06 mas and 2.25 +/- 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 Akeson 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 contains 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 its errors are then fit to a model. We elected to use the Uniform Disk (UD) model in which:

$$V^2 = \frac{(2J_1(\pi\theta B/\lambda))^2}{(\pi\theta B/\lambda)^2} \tag{1}$$

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 ($\sqrt{u^2+v^2}$), θ is the stellar angular diameter in radians, and λ 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 non-linear, 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 2×10^{-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 8×10^{-16} at a maximum. Take note that this is several orders of magnitude below any error that arises from ΔV^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.

4. Discussion

The error-weighted mean K-band uniform-disk angular diameter for ϵ Aurigae derived from 12 nights between 1997 and 2008 at the Palomar Testbed Interferometer is 2.27 +/- 0.11 mas. These values are consistent with the published NPOI and earlier Mrk III optical band values of (UDD) 2.18 +/- 0.08 mas and (LDD) 2.17 +/- 0.03 mas (Nordgren et al. 2001), although arguably slightly larger at 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 timespan were measured on a (nearly) N-S baseline. We note that Kemp et al. (1986) indicated a polar axis position angle for the F star of 5 to 45 degrees, and our few N-W baseline points may appear slightly larger on that axis. We also checked for luminosity-related changes. The V magnitude during 2007 Oct (RJD 4393-6) was 3.035, but by 2008 Feb (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 N-W baseline then) and a Mimir spectrum obtained shortly afterward did not show any significant changes to the weak Brackett emission, however (see Clemens et al. 2008 - 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 and Kitamura (1986) provided evidence that the F supergiant star was shrinking at a rate of 16% eclipse to eclipse (27.1 years), based on 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 year PTI interval reported here. Within the dispersion of PTI measurements, we do not confirm any decrease of this magnitude, or have evidence for significant changes in diameter over the past 10 years, assuming 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 instead 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 625pc 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, Schmidt-Kaler 1965; Allen ApQ 4th Ed.), suggesting 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 ϵ Aurigae, as well as a careful determination of effective temperature from a spectral energy distribution study.

Further progress in the study of ϵ Aurigae should be possible by applying interferometric imaging to the eclipse event during 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 pseudo-binary 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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Table 1: Calibrators for HDC31964 used during observations.

Star Name	RA	DEC	μ_{RA}	μ_{Dec}	Parallax (Hipparcos)	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*	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*	4 52 47.757	+42 35 11.85	-0.01107	0.00011	0.00631	0.280	0.027
HD 32630*	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

*from van Belle et al. (2008).

Table 2: Diameters obtained from Wide-Band Visibility mode data.

UTDate, JD-2,450,000	GMT start	Baseline*	Nscan sets**	Mode	V^2	UDD [mas]	Error [mas]	V [mag]
2007Oct19, 4393	09:57	NS	14	K-low	0.516	2.19	0.06	3.036
2007Oct20, 4394	10:21	NS	6	K-high	0.544	2.16	0.12	3.036
2007Oct21, 4395	10:45	NS	3	K-low	0.583	1.90	0.13	3.036
2007Dec23, 4458	04:41	NW	6	K-low	0.574	2.36	0.14	3.046
2007Dec24, 4459	04:48	NW	6	K-low	0.565	2.37	0.11	3.043
2008Feb16, 4513	03:05	NW	2	K-low	0.527	2.60	0.15	2.98
2008Feb17, 4514	04:48	NW	5	K-low	0.572	2.28	0.15	2.98
2008Feb18, 4515	03:01	NW	5	K-low	0.624	2.25	0.12	2.98
Archival Data								
1997Oct22, 0744	11:54	NS	1	K-low	0.376	2.50	0.17	2.986
1997Nov09, 0762	09:38	NS	2	K-low	0.438	2.32	0.09	2.977
1998Nov07, 1125	10:25	NS	4	K-low	0.515	2.09	0.10	2.997
1998Nov25, 1143	10:19	NS	2	K-low	0.458	2.25	0.08	2.998
1998Nov26, 1144	10:20	NS	1	No Cal Stars				2.998
2005Dec11, 3715	06:33	NW	1	No Cal Stars				3.02
2006Jan31, 3766	04:27	NW	83	No Cal Stars				3.08

*N-S baseline, 109 meters; N-W baseline, 86 meters.

*Each Level 1 scan set consists of 2 or more integrations of 25 sec 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	$\langle$Cal $V^2\rangle$	$\langle$Error$\rangle$	$\langle$ Sys $V^2\rangle$	$\langle$Error$\rangle$
2007Oct19	HD29645	0.95	0.05	0.66	0.02
2007Oct19	HD29203	0.95	0.05	0.66	0.01
2007Oct20	HD30138	0.87	0.06	0.46	0.02
2007Dec23	HD30138	0.90	0.08	0.30	0.02
2008Feb18	HD30138	0.67	0.08	0.37	0.02