LETTERS

Infrared images of the transiting disk in the ε Aurigae system

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Epsilon Aurigae (ε Aur) is a visually bright, eclipsing binary star system with a period of 27.1 years. The cause of each 18-month-long eclipse has been a subject of controversy for nearly 190 years[1] because the companion has hitherto been undetectable. The orbital elements imply that the opaque object has roughly the same mass as the visible component, which for much of the last century was thought to be an F-type supergiant star with a mass of ~15$M_\odot$ ($M_\odot$, mass of the Sun). The high mass-to-luminosity ratio of the hidden object was originally explained by supposing it to be a hyperextended infrared star[2] or, later, a black hole[3] with an accretion disk, although the preferred interpretation was as a disk of opaque material[4,5] at a temperature of ~500 K, tilted to the line of sight[6,7] and with a central opening[8]. Recent work implies that the system consists of a low-mass (2.2$M_\odot$–3.3$M_\odot$) visible F-type star, with a disk at 550 K that enshrouds a single B5V-type star[9]. Here we report interferometric images that show the eclipsing body moving in front of the F star. The body is an opaque disk and appears tilted as predicted[7]. Adopting a mass of 5.9$M_\odot$ for the B star, we derive a mass of ~(3.6 ± 0.7)$M_\odot$ for the F star. The disk mass is dynamically negligible; we estimate it to contain ~0.07$M_\oplus$ ($M_\oplus$, mass of the Earth) if it consists purely of dust.

We collected data using Georgia State University's Center for High Angular Resolution Astronomy (CHARA) interferometer[10] with the Michigan Infra-Red Combiner (MIRC)[11]. The CHARA Array is located on top of Mount Wilson, California, and consists of six 1-m telescopes capable of 15 baselines ranging in length from 34 m to 331 m. The longest baseline provides resolutions up to 0.5 mas (28×10^{-9} degrees) in the H band (λ = 1.50–1.74 μm).

All data presented in this Letter were collected during the start of the 2009–2011 eclipse on 2009 November 2–4 and 2009 December 2–4 (see Supplementary Table 1 for details). Each four-telescope configuration provides six visibilities, four closure phases and four triple amplitudes simultaneously in each of MIRC's eight narrow spectral channels across the H band. There were four pre-eclipse observations during 2008 November–December which verified that the F star is not highly asymmetric and aided in planning the 2009 observations. These data are consistent with the results obtained using the Palomar Testbed Interferometer[12] (a uniform-disk diameter of 2.27 ± 0.11 mas in the K band (λ = 2.00–2.38 μm)) and therefore are not discussed in this Letter.

We reduced and calibrated the data from MIRC against seven calibration stars (Supplementary Table 2) using the standard reduction pipeline[13], producing nightly OIFITS[14] data files. Files from each of the three consecutive nights of observation in 2009 were merged to produce a single OIFITS file for each sequence of observations. The resulting *U*–*V* plane, power spectrum and closure phase coverage (see Supplementary Fig. 1 for interpolated *U*–*V* plots) is arguably the most complete so far in optical interferometry.

The 2009 data provided ample *U*–*V* coverage for interferometric imaging. We performed image reconstruction for the figures presented in this Letter using the Markov Chain Imager[15] and BiSpectrum Maximum Entropy Method[16,17] software packages. The theory behind image reconstruction is common to these packages, based on the minimization of the χ^2 datum plus a regularization function, but they use significantly different approaches to implement it: global stochastic minimization by simulated annealing and a local gradient-based approach, respectively. Despite the differences in implementation[13,18], the images produced by these packages are in remarkable agreement. This is proof of the soundness and reliability of the reconstructed images, and because of this we present only the MACIM images in this Letter.

Figure 1 shows the 2009 November and 2009 December observations, in which we see a single object with a circular outline that is notably darker in the southeast quadrant. In the December image, the overall size of the dark region has grown, but the size of the circular object has remained nearly the same. The northern hemisphere of the circular object shows variations in brightness at the 15% level that we believe approximate our photometric errors. The obscuration in these images was not seen or implied by our previous data sets and we interpret the obscuring object to be the theorized disk in the system. The compactness of the disk across the two epochs provides direct evidence that the disk is geometrically thin but optically thick.

We attempted to model the obscuration using parabolas, ellipses and rectangles with and without smoothed edges, using the reconstructed images as a guide. A satisfactory fit to the visibilities and closure phases was obtained by using a smoothed-edge obscuring ellipse whose semimajor axis was fixed to 6.10 mas (on the basis of eclipse timing and well-known orbital parameters[9,19]), combined with a power-law limb-darkened stellar component. The nine remaining parameters (stellar diameter, stellar limb-darkening coefficient, ellipse semiminor axis, ellipse position angle, ellipse smoothing coefficient and the coordinates, *x* and *y*, of the ellipse centroid for both 2009 November and 2009 December) were simultaneously fitted using a Levenberg–Marquardt least-squares minimization algorithm. The combined fit has a reduced χ^2 of 4.69 and predicts an F-star limb-darkened diameter of 2.41 ± 0.04 mas, or a uniform-disk diameter of 2.10 ± 0.04 mas. The semiminor axis for the ellipse is 0.61 ± 0.01 mas.

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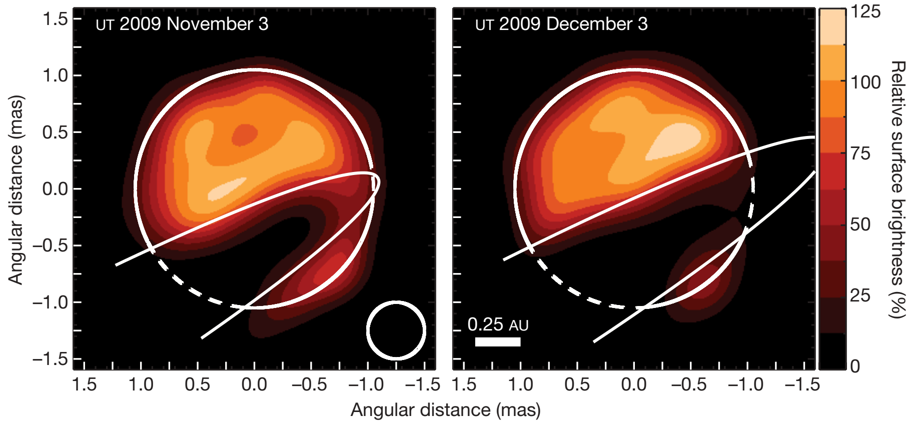

Figure 1 | Synthesized images from the 2009 observations. The model discussed in the text is superimposed in white on the images. A circle with a diameter of 2.27 mas is drawn for the F star and the position of the ellipse for each epoch is shown. The colour scale shows surface brightness relative to the pre-eclipse value, calculated assuming respective eclipse depths of 0.40 and 0.53 mag for 2009 November and 2009 December based on the ongoing AAVSO monitoring. The CHARA H-band resolution (0.5 mas) is shown in the bottom right of the 2009 November image. The reconstructed images are drawn in the equatorial coordinate system with north up and east to the left.

The ellipse has a position angle of 119.80 ± 0.74 degrees with a full-width-at-half-maximum smoothing length of 0.38 ± 0.05 mas. Between 2009 November and 2009 December, the position of the ellipse centroid moved 0.62 ± 0.14 mas west and 0.34 ± 0.06 mas north.

Although χ^2 is large, the model does an excellent job of reproducing the observed drop in H-band flux (0.40 and 0.53 mag for 2009 November and 2009 December, respectively); we therefore consider the model a good approximation for the leading edge of the disk. Adding additional parameters to the model could reduce χ^2, but without additional knowledge of the disk (that is, regarding the presence or otherwise of a central opening or flaring), such parameters would not add unique information to a physical model of the system. The ellipse model implies a northwest motion between the two images, along a line with a position angle of 296.82 ± 6.85 degrees. In the limiting case in which the disk is considered infinitely thin, the above parameters imply that the disk has a minimum inclination of $i = 84.30 \pm 0.15$ degrees.

Adopting the ε Aur distance of 625 pc (ref. 20) estimated by the European Space Agency's High Precision Parallax Collecting Satellite, we may derive estimates of the disk's physical extent. If the disk were viewed edge on (that is, at $i = 90$ degrees), then the maximum thickness of the disk, equal to twice the semiminor axis of the ellipse, would be 0.76 ± 0.02 AU. The disk is observed to move 0.43 ± 0.08 AU over the observation interval, which implies that it has a speed of 25.10 ± 4.65 km s^{-1} with respect to the F star. Using spectroscopic orbit parameters[21] and assuming an orbital inclination of 88 ± 2 degrees (ref. 9), we compute a translational speed of 15.42 ± 0.42 km s^{-1} for the F star's motion relative to the centre of mass of the system. Given the relative motion of the disk, subtracting the F star's motion yields 9.66 ± 4.67 km s^{-1} for the disk speed relative to the centre of mass.

These speeds imply that the ratio of the F-star mass to the companion mass is 0.62 ± 0.12, providing modest evidence that the companion is the more massive component in the system. Ultraviolet data implies the presence of a hot source inside the disk and can be fitted[9] by assuming the presence of a B5V star. Adopting $(5.9 \pm 0.1)M_\odot$ as representative of the mass of a B5V star and treating the disk as having negligible mass, we obtain $(3.63 \pm 0.68)M_\odot$ for the mass of the F star. The mass function[21] for the system, $2.51 \pm 0.12 M_\odot$, implies that the lower end of the mass range is preferred.

The mass of the disk can be estimated from the volume and a plausible density. If we assume a characteristic near-infrared opacity of $\kappa = 10$ cm^2 g^{-1} and adopt a range of characteristic length scales between the resolution of CHARA and the size of the disk's semi-major axis (that is, 1.75 ± 0.87 AU), the density of the disk is $(3.82 \pm 2.70) \times 10^{-12}$ kg m^{-3}. Modelling the disk as a cylinder with a radius of 3.81 ± 0.01 AU and a height of 0.76 ± 0.02 AU, we find the mass of the disk to be $(2.22 \pm 1.57) \times 10^{-7} M_\odot$, or about $0.07 M_\oplus$. For a density based on interstellar dust-to-gas ratios, the total disk mass could rise to $7 M_\oplus$, or $(2.22 \pm 1.57) \times 10^{-5} M_\odot$, which is much less than the mass of either stellar component, making the disk mass dynamically negligible. If the disk were composed of large particles, its mass would be much greater.

Direct imaging of the ε Aur system has demonstrated the validity of the disk model for the previously unseen companion. The elliptical appearance of the disk seems to be more consistent with a model of a tilted thin disk[7] rather than one of a thick disk seen edge on[4]. With these images and a simple model, we have estimated the dimensions and masses of the components in the system. Even with the aforementioned results, the system has problems that remain to be solved. The evolutionary history of the system must be reconsidered. The optically thick but geometrically thin nature of the disk suggests it is a debris disk rather than a young stellar object as would be required by the short evolutionary timescales in the high-mass $(15 M_\odot)$ picture. The tilted-disk model predicts a central hole that should be observed as a mid-eclipse brightening[8]. Therefore, photometric and spectroscopic measurements should be made as frequently as possible to create a longitudinal profile of the disk. When combined with geometry derived from additional interferometric observations, the composition, density scale height and temperature structure of the disk may be determined and an evolutionary scheme established.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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