A Look Inside the Disk in the $\epsilon$ Aurigae Binary System

Robert E. Stencel

Chamberlin and Mt. Evans Observatories, University of Denver, Denver, Colorado 80208, USA

Abstract. Interferometric imaging, combined with spectroscopy, is providing a powerful way to unlock the long-kept secrets of the enigmatic eclipsing system, $\epsilon$ Aurigae, that has puzzled astronomers for many decades. A sequence of H-band MIRC images obtained at the CHARA Array during the 2010 eclipse, is augmented with spectra obtained by a worldwide network of observers participating in the eclipse campaign. The MIRC images confirm the hypothesized dark disk, revealing it to have dimensions of $\sim$8 AU long by $\sim$0.7 AU thick, that occults the southern hemisphere of the 135R$_{\odot}$ F-star primary; however, these dimensions are dependent on the assumed distance, which still is not settled. Spectra reveal a wealth of changes caused by facets of the disk that can be associated with substructure, including possible rings, a central ionized region, and evidence for accretion onto a hot embedded object. Results reported here are due to the help of numerous observers to whom I am indebted, and support for this effort that was derived in part from a bequest of William Herschel Womble in support of astronomy at the University of Denver, from NSF grant 1016678, and from JPL RSA 1414715 to the University of Denver.

1. Introduction and Brief History

The Algol-type eclipsing binary, $\epsilon$ Aurigae, has bewitched astronomers for nearly two centuries, first because the 27-year-long interval between eclipses made study of this system a protracted, multi-generational effort, and second because the nature of the eclipsing object has, until recently, eluded explanation. Infrared photometry and imaging have decisively demonstrated that the object resembles a disk not unlike those found around other types of stars (Backman et al. 1984, Kloppenborg et al. 2010). An updated composite model of the F star plus companion disk and its central star, has been published by Hoard, Howell and Stencel (2010). The current system model—a lighter but hotter star orbited by a heavier but disk-shrouded star—begins to resemble a classical Algol type interacting binary, with an evolutionary history once described at the “Algol paradox”—how did the lighter star get to be more evolved? Answer: mass transfer as a result of Roche Lobe overflow. The unique thing about $\epsilon$ Aurigae is that the eclipses provide a tomographic scan of an astrophysical disk, and the disk itself is in a so-called transitional or debris-disk phase, not unlike the famous case of $\beta$ Pictoris.

Prior to the current eclipse, I was fortunate to be involved in co-organizing eclipse campaigns for the 1984 eclipse event, once again in collaboration with my good friend Jeff Hopkins (Hopkins and Stencel 2008). During the 1980s, the International Ultraviolet Explorer (IUE: a precursor of HST) was underway, and I was fortunate to collaborate with Bob Chapman, Tom Ake and others in obtaining the first UV spectra of epsilon...
Aurigae, in and out of eclipse (Chapman et al. 1983). Not long thereafter, infrared detectors became available, and by the mid-1990s, we took our then-new U. of Denver mid-infrared camera to the Wyoming Infrared Observatory near Laramie, and $\epsilon$ Aurigae was one of many targets on our observing list. Those data are being used now to study secondary eclipse. A Denver student from that era, who helped with the IR camera work, was Michelle Creech-Eakman, our conference host. At the same time and place, modern interferometry was being improved at Laramie by Mel Dyck, with his IRMA experiment, located near WIRO. Michelle ended up as a postdoc at CalTech and JPL where the Palomar Testbed Interferometer (PTI) and the Keck Interferometer (KI) were in development. Through Michelle, I began to pay more attention to the potential of interferometry to address the mystery of the eclipsing body in epsilon Aurigae. This led to lobbying Hal McAlister, Director of the CHARA Array, for observing time, beginning with the binary stars sessions during the 2006 IAU General Assembly in Prague. Soon thereafter, Michelle helped front a proposal for us to use PTI for diameter measurements of $\epsilon$ Aurigae. We reported a new uniform disk diameter in K band of 2.27 +/- 0.11 milli-arcsec (Stencel et al. 2008). At the same time, Hal McAlister invited me to propose for CHARA Array observations starting in fall 2008. The initial coverage was limited, but we came back in force for the eclipse ingress in 2009, using John Monnier’s Michigan Infrared Combiner (MIRC) at the CHARA Array. This led to spectacular images of the disk crossing the face of the brighter component, as featured in the 2010 April 8 issue of Nature (Kloppenborg et al. 2010) and Brian Kloppenborg’s dissertation. Since then, I have pursued a multi-wavelength campaign involving data from the following additional telescopes (instruments): HST (COS), assorted optical photometry and spectroscopy, IRTF (SpeX), Gemini (GNIRS), Spitzer (IRAC), MMT (MIRAC4), HSO (PACS, scheduled) and possibly ALMA (requested).

What are the goals of this current work? We seek to derive the disk density (in radial and scale-height terms), deduce the disk gas/dust ratio and material composition, identify the central star, the disk age, and system evolutionary status. In collaboration with Brian Kloppenborg and others, we also seek to learn the evolutionary status of the bright component, epsilon Aurigae A, as discussed in these proceedings and elsewhere.

For perspective on the timing and phases of the eclipse, using Reduced Julian Date (RJD) notation, defined here as RJD = JD - 2,400,000, the eclipse began RJD 55,050 (2009 August, $V = 3.0$), with totality reached by RJD 55,200 (2010 Jan, $V = 3.75$). Mid-eclipse occurred close to RJD 55,400 (2010 Jul/Aug). Totality ended RJD 55,620 (2011 Feb/Mar, $V = 3.80$) and the end of eclipse was approaching as this manuscript was submitted, circa RJD 55,750 (2011 July, $V = 3.00$). Solar conjunction occurs in May/June annually, so the observations reported here were constrained largely to fall and winter seasons. Eclipse light curves in UBVRIJH were obtained by campaign observers, and these show low amplitude variations, especially at shorter wavelengths (convective hot spots on the F star?), with a 65-day quasi-period, throughout the eclipse and out of eclipse as well.

It is important to note that the eclipse is asymmetric in almost every measure: (1) ingress is less steep than egress; (2) early totality is less faint than late totality; (3) disk-enhanced but optically thin spectral absorption lines are weaker prior to mid-eclipse than after mid-eclipse, etc. The hypothesis that explains some of this has to do with the external heating of the disk by the companion F-type star and our orbital-phase-dependent views of differential heating effects, as proposed by Takeuti (1986,
2011). These effects can be explored by infrared spectra obtained throughout eclipse and possibly beyond.

A series of 0.8 to 4.5 micron moderate-resolution spectra of epsilon Aurigae were obtained with the SpeX instrument at NASA IRTF, between 2008 and 2011 by myself and Brian Kloppenborg, as well as John Rayner and Michael Sitko (Stencel et al. 2011a). These spectra are dominated by the F-star continuum and the Brackett, Paschen and Pfund series of hydrogen lines in absorption, except for Brα, which has previously been noted to be in emission (Backman et al. 1985). Spitzer IRS spectra similarly show Hα in emission, suggesting these series are dominated by recombination. Indeed, differentiating the out-of-eclipse spectra with in-eclipse spectra shows that the profiles in eclipse are shallower and wider—the difference resembles a pure emission, recombination spectral series.

Another curiosity discovered during the 1983 eclipse was the emergence of molecular CO (2-0) absorption bands at 2.3 microns after mid-eclipse (Hinkle and Simon 1987). SpeX and Gemini North GNIRS observations confirm the same behavior after mid-eclipse in 2010. An interpretation of this has to do with the external heating of the disk, driving volatiles, like CO, off surfaces. These heated portions of the disk rotate increasingly into view after mid-eclipse. Herschel Space Telescope sub-mm observations are scheduled to attempt detection of related lines of CO and H₂O.

The SpeX observation series was instrumental in the discovery of strong He I 10830A absorption during mid-eclipse (Stencel et al. 2011b). The significance of the 10830A line is that it arises from a 20-eV metastable triplet state that can be populated by recombination of He ions. This behavior, along with hydrogen, is strongly indicative of a heated central region in the disk, and possibly a vertically extended nebula. Solar conjunction in June strongly limited any observations prior to mid-eclipse in July/August 2010, but we will assume the distribution to be symmetric. To interpret the appearance of the enhanced 10830A absorption, we explore an He-ionization model for the disk center. From the appearance of transient CO bands, Hinkle and Simon (1987) deduced a column density $n_{CO} = 3 \times 10^{20}$ cm$^{-2}$, implying $n_H \sim 1.5 \times 10^{24}$ cm$^{-2}$ (for solar abundances). This value is consistent with the lack of soft X-rays, reported by Wolk et al. (2010), $n_H \sim 1.25 \times 10^{24}$ cm$^{-2}$. Adopting disk dimensions reported by Kloppenborg et al. (2010), a column through the 4-AU radius disk implies a volumetric number density of $2.6 \times 10^{10}$ cm$^{-3}$, and this plus an opacity estimate were the basis for the earth-mass disk we deduced from interferometric imaging.

For the central star, we adopt B5V, based on SED fit to FUV (Hoard, Howell and Stencel 2010), and ask if the duration of the excess He 10830A absorption is consistent with a B5V star radiation field. The 10830A feature persists no more than 150 days past mid-eclipse. Estimating disk motion at 15 km/sec, this timing implies a scale size equal to 1.3 AU. Modelling this central clearing as a Stromgren sphere, we write: $R_s = (3/4\pi\alpha)^{1/3} N_{\alpha}^{1/3} n_h^{-2/3}$. Using for the He recombination rate, $\alpha = 1.2 \times 10^{-13}$ cm$^3$/sec, and $n_H = 3 \times 10^{10}$ cm$^{-3}$, and with $N_{FUV}(B5V) = 7.0 \times 10^{41}$ photons/sec, we find that $R_s = 0.05$ AU, which is too small relative to the observed 1.3 AU He 10830A zone. Although the system’s spectral energy distribution seems to rule out a hotter central star, we note that $N_{FUV}(B0V) = 1.6 \times 10^{46}$ photons/sec yields the right size region, $R_s = 1.3$ AU. Alternately, sub-ionization line pumping, or a lower density disk could account for the B5V He zone, but the latter might deflect the x-ray column density constraint.

A possible solution to this could come from a modest amount of gas accretion. Starting with $L_{accr} = GM^* \dot{M} / R^*$, where $\dot{M} = 1 \times 10^{-6}$ M$_{\odot}$/yr (which is essen-
tially one earth mass/year (Pequette, Stencil and Whitney 2011), we find that the B5V star can produce sufficient numbers of FUV photons to lead to the -AU zone required: 1.7 x 10^{35} erg/sec, or 4 x 10^{45} photons/sec (at 10^7 K, but unrealistically assuming all the photons produced are capable of ionizing Helium at wavelengths shortward of 505A), yielding a He+ Stromgren radius of 0.85 AU. Despite the efficiency assumption, we still prefer the B5V case in order to match the dynamical constraint from the optically thin neutral potassium velocity curve that traces disk rotation (Leadbeater and Stencil 2010). As Pequette et al. noted, re-supply of disk material is required to sustain the disk over the many decades of eclipse observations, potentially from collisional interaction of planetesimals embedded in the disk. Larger bodies can increase the total mass without substantially affecting the opacity.

As a check on this assumption, we compute the implied hydrogen (H II) region for this accretion rate. While recombination rates from hydrogen are slightly higher, so is the recombination rate, along with the number of photons, N_{505A} exceeding the number N_{912A} from a 10^7 K blackbody source. These approximately balance, and the hydrogen ionization sphere is of comparable dimension. However, more careful calculations of this will be needed, including the use of a more realistic spectrum input, density distribution, etc. For completeness, note that HST Cosmic Origins Spectrograph far-UV data were obtained at three epochs near mid-eclipse and into egress phases (Howell, Hoard and Stencil 2011). These confirm general far-UV continuum plus emission-line characteristics seen previously in FUSE and GHRS data, as reported by Ake (2006), and Sheffer and Lambert (1999).

As discussed in Brian Kloppenborg’s contribution in these proceedings, application of constraints provided by interferometric imaging of the disk during eclipse, along with radial-velocity curves and eclipse light-curve constraints, provide an information set that should be able to provide a consistent orbit, masses and description for the eclipsing binary, epsilon Aurigae. The brighter, presumed more evolved, star is likely to be experiencing changes, and these are the subject of ongoing interferometric imaging with the CHARA Array and MIRC in its new 6T mode. Similarly, new infrared and sub-mm techniques may allow direct study of the disk outside of eclipse, finally liberating observers from the long wait between eclipses.

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References


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