# Interferometric Images Of The Transiting Disk In The Epsilon Aurigae System

**Brian Kloppenborg**[1], Robert Stencel[1], John D. Monnier[2], Gail Schaefer[3], Fabien Baron[2], Ming Zhao[4]
Hal McAlister[3], Theo ten Brummelaar[3], Xiao Che[2], Chris Farrington[3], Ettore Pedretti[5], PJ Sallave-Goldfinger[3],
Judit Sturmann[3] Laszlo Sturmann[3], Nathalie Thureau[5], Nils Turner[3], Sean M. Carroll[6]

[1] University of Denver, [2] University of Michigan, [3] CHARA/Georgia State, University, [4] JPL, [5] University of St. Andrews, Scotland, UK, [6] California Institute of Technology.

## Abstract

We have been using the CHARA Array with the MIRC beam combiner to obtain the first-ever interferometric observations of the enigmatic binary, epsilon Aurigae. The first two in-eclipse images, obtained in 2009, prove that the eclipsing body is a thin, opaque disk of material akin to transitional or debris disks. From these data we have derived a mass ratio that shows the F-type star is 3.6 ± 0.7 $M_{\odot}$, making it the less massive component in the system and thus not a high-mass supergiant as was classically believed. Four additional observations were scheduled in 2010. In this work we present reconstructed images from all epochs, and discuss the progress towards our goals: to determine the evolutionary status of the components in the binary; and define the composition, density, and temperature structure of the disk.

## Modeling Details and Results

We have modeled the system in two ways. The first model consists of a uniformly-illuminated circle for the F-star and a uniformly dark ellipse for the eclipsing body. The second model incorporates first-order limb darkening for the F-star and a smoothing coefficient for the disk.

We first fit the simple model to each epoch independently to determine initial estimates for the components in the system. We computed the average and standard deviation of the parameters and used a five-sigma limit to constrain F-star diameter and disk thickness for the second model. The parameters displayed below are the results of this second model. For the models in the table below, we adoped a constant limb darkening parameter of 0.83 determined from the average out-of-eclipse value. In three cases (2009-12, 2010-02, 2010-10) we had to constrain the models further by fixing the limb darkening coefficient and disk smoothing coefficient.

We intend to simultaniously fit all epochs to determine overall disk parameters. We will use four models for the eclipsing body: a rectangle, an ellipse, an ellipse with a central hole and a bowtie-like YSO disk. As we discover them, other applicable models will be applied.

| | | F-Star | | Disk | | | Fit |
|---|---|---|---|---|---|---|---|
| Date | MJD | LDD (mas) | LDR* ($R_{\odot}$) | Semi-Minor Axis (mas) | Full Thickness* (AU) | Smoothing Coefficient | Reduced $\chi^2$ |
| 2009-11 | 55138 | 2.304 | 154.8 | 0.417 | 0.522 | 0.221 | 2.38 |
| 2009-12 | 55168 | 2.257 | 151.7 | 0.489 | 0.612 | 0.240 | 7.59 |
| 2010-02 | 55243 | 2.398 | 161.1 | 0.550 | 0.688 | 0.240 | 2.39 |
| 2010-08 | 55430 | 2.353 | 158.1 | 0.536 | 0.670 | 0.270 | 9.21 |
| 2010-09 | 55462 | 2.340 | 157.2 | 0.508 | 0.635 | 0.232 | 3.60 |
| 2010-10 | 55492 | 2.358 | 158.4 | 0.523 | 0.654 | 0.240 | 3.22 |
| 2010-11 | 55504 | 2.354 | 158.2 | 0.570 | 0.713 | 0.233 | 5.28 |
| 2010-12 | 55543 | 2.364 | 158.8 | 0.562 | 0.703 | 0.403 | 4.67 |

* Assuming the nominal Hipparcos distance of 625 pc to the system.

## Discussion: The Star and Disk

The epsilon Aurigae system presents several challenges that have inhibited a comprehensive understanding of the system. Foremost is the cause of the 0.1 mag (V-band) 63-day quasi-periodic variations exhibited by the F-star (see poster 257.01). Secondly is the nature of the eclipsing object.

### The F-star

When the limb darkening parameter was held constant, the angular diameters of the F-star agree within the formal uncertainties. In this case it is unlikely that large fundamental mode oscillations can explain the intrinsic variability. It is possible that spots or non-radial pulsation could be the cause of the variations.

If we permit the stellar limb darkening parameter to vary, the overall $\chi^2$ improve. In particular, the $\chi^2$ for the 2010-09 and later models drop to below 3.5. In these models we see a positive correlation between angular diameter and limb darkening coefficient as is expected from the luminosity equation. These changes qualitatively agree with the variations in V-band magnitude.

The 2009 observations were used to determine orbital velocities and a mass ratio for the system. Along with an assumed mass for the B5V star inside of the disk[2], we derived[3] an estimate of 3.63 ± 0.68 $M_{\odot}$ for the F-star. When coupled with the high luminosity (30,000 $L_{\odot}$) this lends significant support to the post-AGB interpretation for the nature of the F-star.

### The Disk

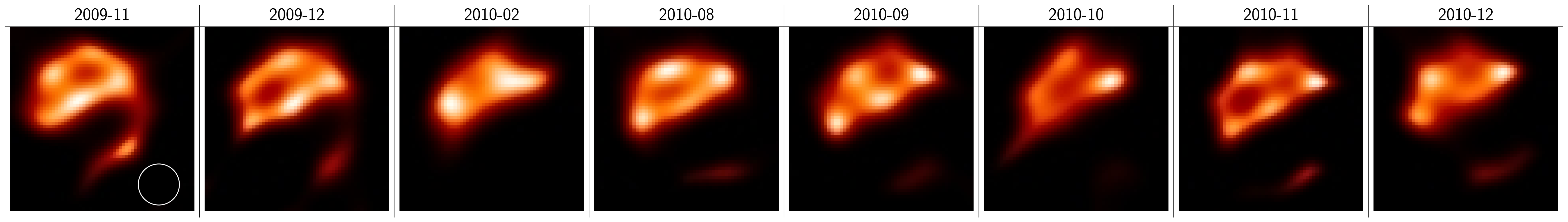
The rare opportunity to observe a disk transiting a bright source permits us to characterize the disk in epsilon Auriage perhaps better than any other. During the present eclipse several additional facts have emerged about the disk:

- The mean length of the disk: ≈ 7.6 AU, estimated from eclipse timing[2]
- A lack of solid state features around 10 $\mu$m argues for much larger particles ($>> 10\ \mu m$)[2]
- Carbon monoxide appears only after mid-eclipse (see poster 257.09), arguing that volatiles sublimate
- The shell spectrum during eclipse argues for enough gas above/below the plane of the disk to scatter F-star light towards the observer[1]

These facts tend to support the interpretation of the disk being transitional, that is, because some gas remains. It is likely to be younger than 10 Myr and solid particles have begun to form, but have not completely collapsed to the equatorial plane of the disk.

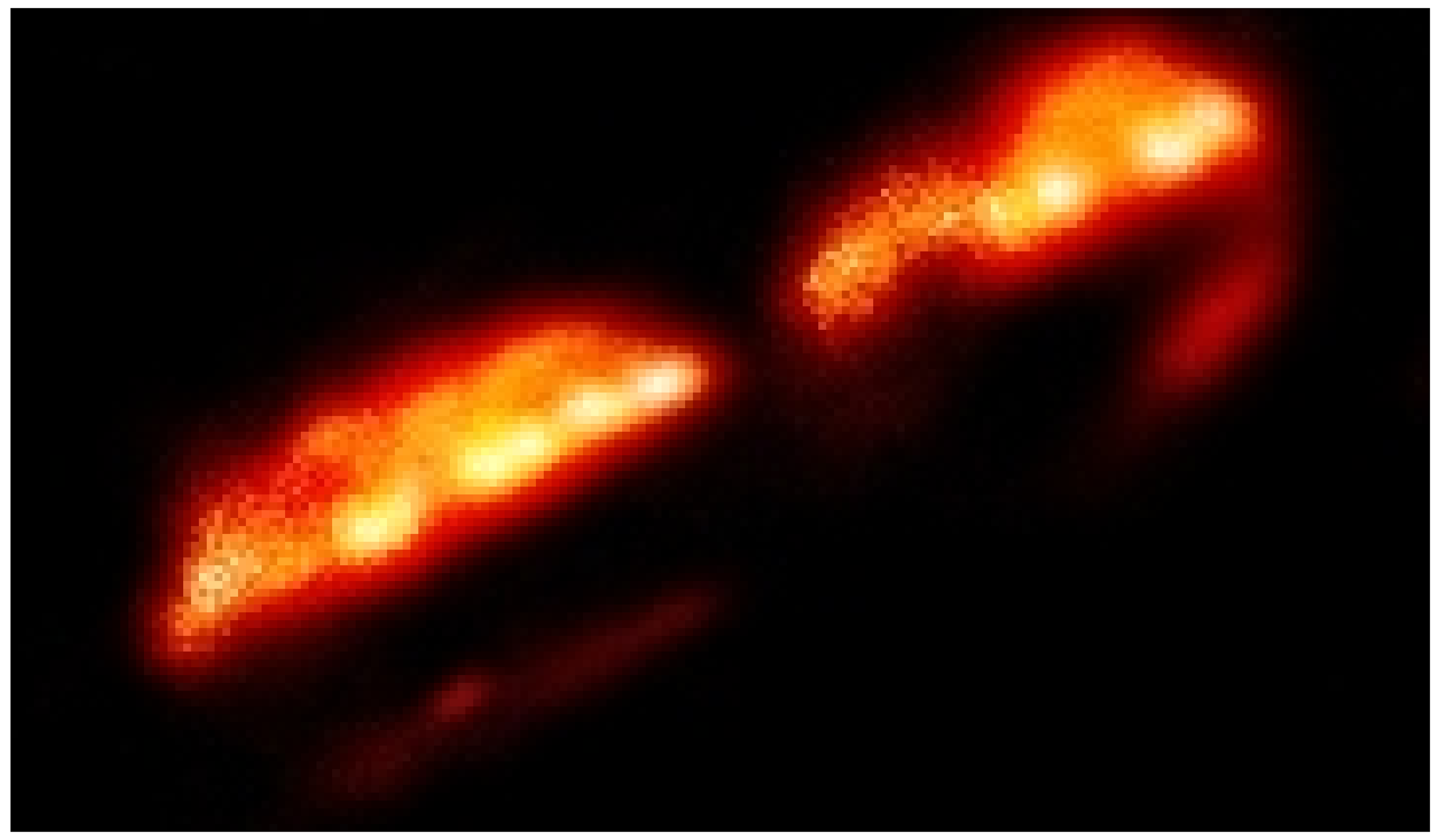
Our observations extend this knowledge to include disk substructure. The disk thickness appears to show some variations: thickening towards mid-eclipse and then again towards egress. The disk smoothing coefficient, (representative of the "fuzziness" of the disk) remains remarkably constant throughout the eclipse until 2010-12 at which time it increases by a factor of two. This sudden change could be explained by either the decreased UV coverage, or the appearance of a sublimation zone rotating into view.

## Model Independent Images

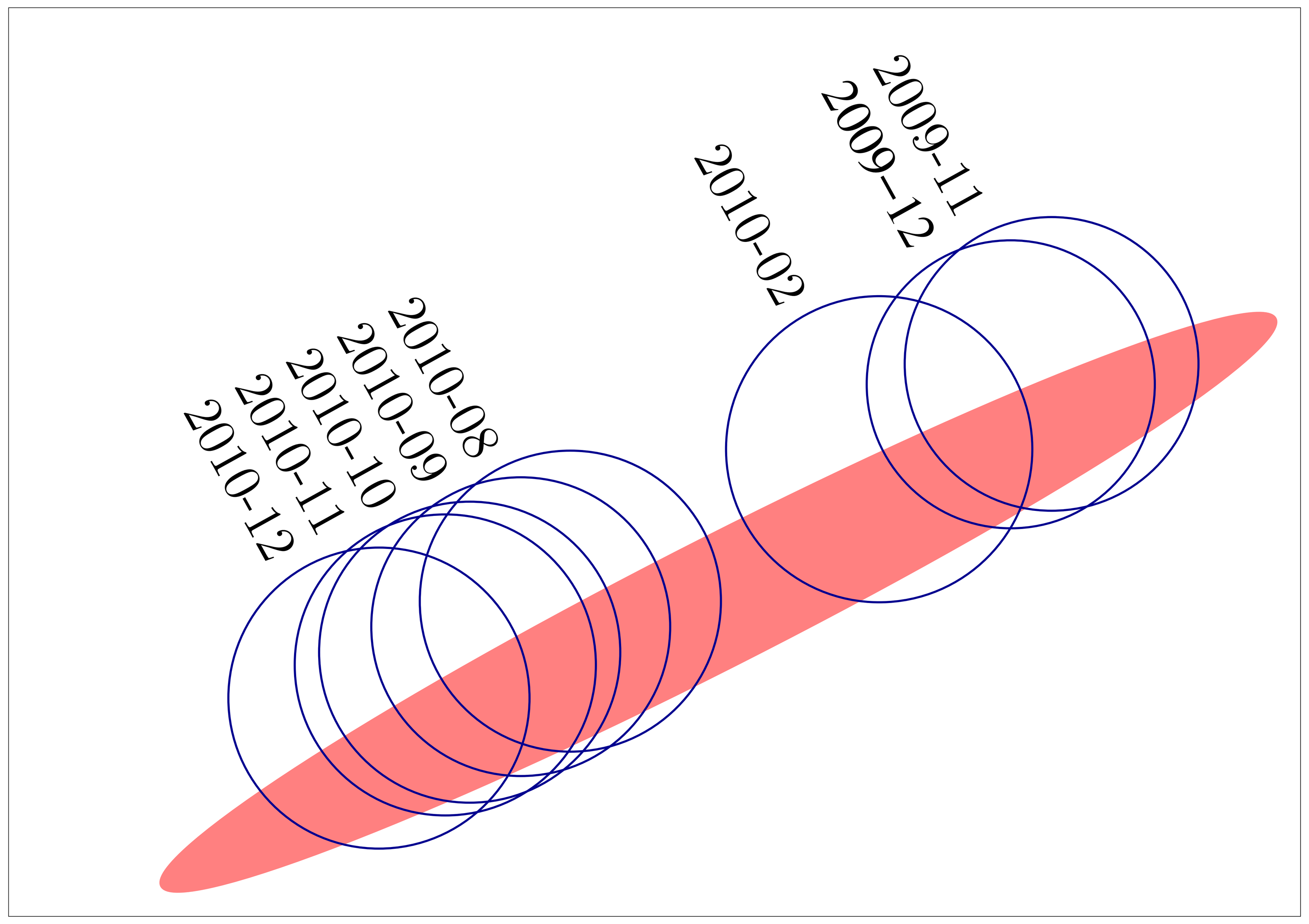



We have reconstructed an image for each of the eight epochs of 2009-2011 eclipse of epsilon Aurigae. The images from 2009 show the ingress phase of the eclipse. The closest image to mid-eclipse (2010-08) does not show any signs of a central opening/clearing as was theorized from photometry of the 1983 and prior eclipses. Data for the images was taken at Georgia State University's Center for High Angular Resolution Astronomy (CHARA) array using the Michigan InfraRed Combiner (MIRC) in eight spectral channels across the H-band. The 0.5 mas H-band resolution of CHARA is indicated by the white circle. This scale is preserved in all images unless otherwise noted. These above figures are reconstructed using the Bispectrum Maximum Entropy Method (BSMEM).

## The Silhouette of the Disk



The outline of the eclipsing object is backlit by the F-star during the 2009-2011 eclipse of $\epsilon$ Aurigae. The above composite image was formed from eight individual frames reconstructed using the Markov Chain Imager (MACIM). Positioning is determined from an orbit derived from recently published orbital elements combined with our interferometric observations. The eclipse began in August 2009 and is predicted to end in May 2011.




A schematic diagram showing the elliptical model for the eclipsing object and the position of the F-star in each epoch. The diameter of the F-star is drawn (to scale) according to our model fits. The disk parameters are based on the mid-eclipse thickness and approximate photometric contact times.

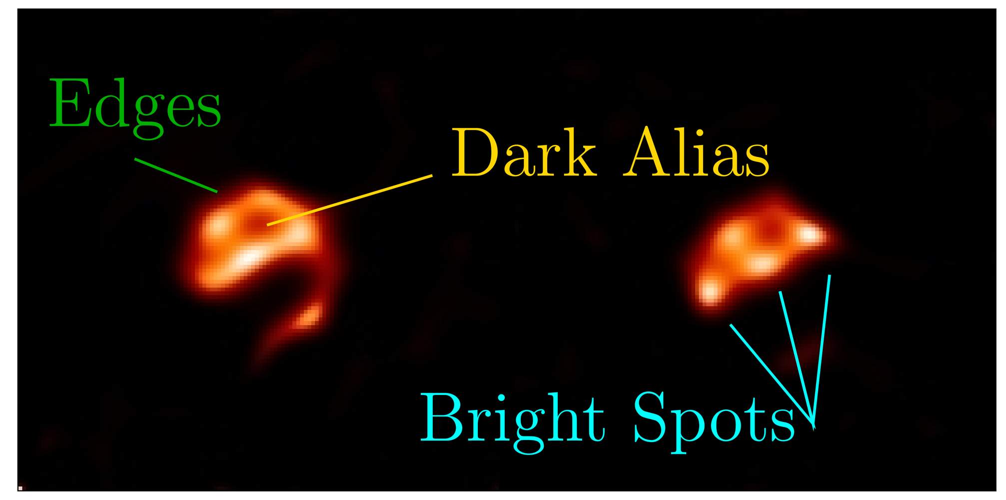
## Acknowledgements

We are grateful to the firefighters who defended Mount Wilson Observatory from the Station Fire, and L. Webster and the staff at Mount Wilson Observatory for facilitating our observations. The CHARA Array, operated by Georgia State University, was built with funding provided by the US National Science Foundation (NSF), Georgia State University, the W. M. Keck Foundation and the David and Lucile Packard Foundation. CHARA is operated under continuing support from the NSF. This research is supported by the NSF as well as by funding from the office of the Dean of the College of Arts and Science at Georgia State University. J.D.M. acknowledges funding from the University of Michigan and the NSF. MIRC was supported by funds from the NSF. B.K. and R.S. thank J. Hopkins for ongoing photometry and are grateful for the bequest of William Herschel Womble in support of astronomy at the University of Denver and NSF grant AST 10-16678.

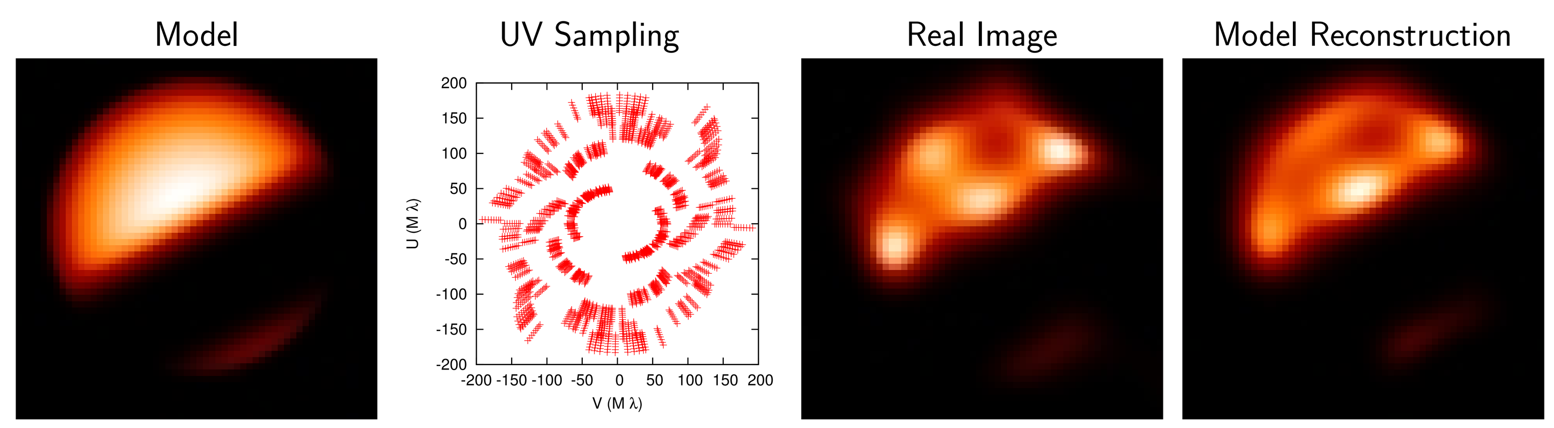
## Artifact Determination

Although the large-scale structures in our reconstructed images are likely correct, the finer details could be artifacts introduced by the image reconstruction process. Our initial assumptions are that the straight-edge features on the F-star are due to UV coverage, the dark spot in the northern hemisphere is an alias of the eclipsing body covering the southern hemisphere, and the appearance of bright spots in the northern hemisphere are artifacts of the reconstruction process.

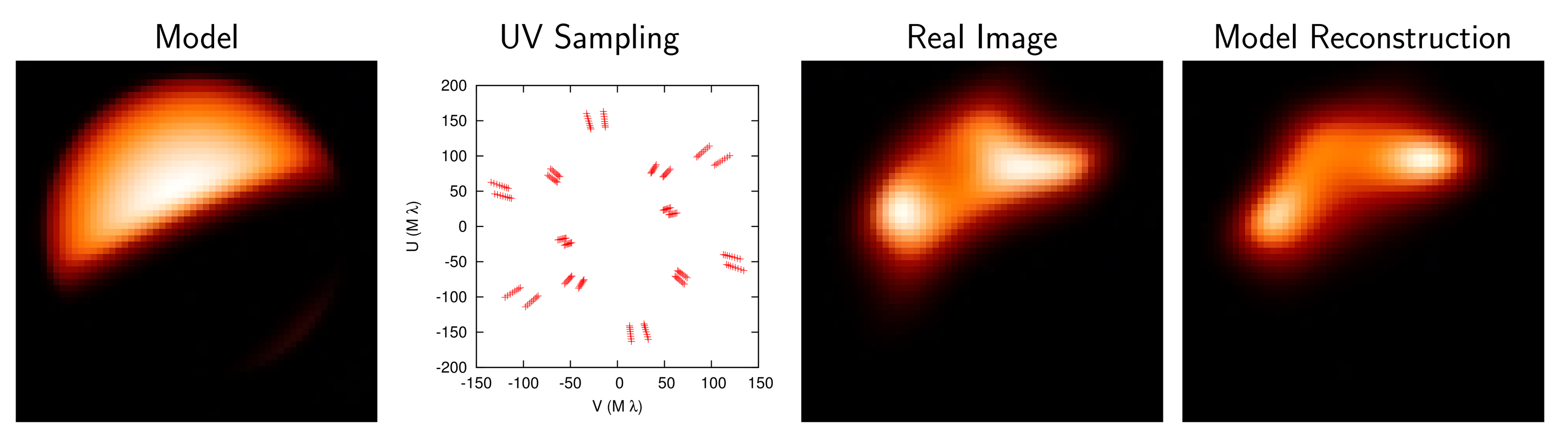
To test these assumptions, we first reconstructed the images using two different methods. The first is BSMEM which searches through the parameter space by a gradient-based approach and is assisted by maximum entropy principles. The second method is MACIM which generates images making frames of randomly activated pixels. If a frame agrees with the data, it is kept, if the frame disagrees with the data it is penalized. Resulting frames are stacked to generate the final image.




Both programs are capable of recovering details that are below the formal resolution limit of CHARA in H-band. Furthermore the F-star is not round, and surface details are present. To test the validity of these features we used images generated from the best-fit models and sampled them in the same UV locations as the actual data. For each visibility and triple amplitude we copied the corresponding uncertainties from the actual data. Then we reconstructed the resulting data using both BSMEM and MACIM.




The above images from 2010-09 implies that the three bright spots appearing along the equator along with the darker appearance in the background in the northern hemisphere are likely artifacts of the image reconstruction process. Although it was anticipated that the straight-edge features on the F-star would reappear in the reconstructed model, they did not. Lastly the visibility of the southern pole on the F-star appears to be real.




The 2010-02 data and simulations shown above were quite intriguing. The images reconstructed from the real data imply that the southern pole is fully covered by the eclipsing object which qualitatively agrees with a minimum in the V-band magnitude from photometry. We have found that the UV coverage in this data set (the equivalent of two 4-telescope observations) cannot reproduce the southern spot in our model; however, given the limited coverage we believe the image fidelity is too poor to trust this "missing feature."

## References

[1] Ferluga, S. and Mangiacapra, D.: 1991, *Astronomy and Astrophysics (ISSN 0004-6361)* **243**, 230
[2] Hoard, D. W., Howell, S. B., and Stencel, R. E.: 2010, *The Astrophysical Journal* **714(1)**, 549
[3] Kloppenborg, B., Stencel, R., Monnier, J. D., Schaefer, G., Zhao, M., Baron, F., McAlister, H., Ten Brummelaar, T., Che, X., Farrington, C., Pedretti, E., Sallave-Goldfinger, P. J., Sturmann, J., Sturmann, L., Thureau, N., Turner, N., and Carroll, S. M.: 2010, *Nature* **464(7290)**, 870