



EPSILON AURIGAE: More Results from the 2009-2011 Eclipse Campaign*

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**Adventures in interferometric imaging
and spectro-interferometry -*

*Featuring: high-dispersion spectroscopy, spectro-polarimetry,
photometry, astrometry and more!*





The science question (since ~1915):

*... what is the nature of the 'unseen' companion to the high luminosity F supergiant star ($V=3$, $d \sim \text{kpc}$)?
?Black hole? ?B5V star? ?B supergiant? ?Other?
& what is the evolutionary status of system?*

Epsilon Aur is a single-line eclipsing binary (SB1)
& requires a lot of patience: eclipses every 27 years

Recent eclipses include 2010, 1983*, 1957** ...

*1983: little OIR interferometry, no HST, no CCDs,
... no internet, no cell phones...

** 1957: *Sputnik, Cold War, Edsels, dinosaurs...*





2009--2011 ϵ Aur Eclipse Campaign

- * Observed with a wide array of astronomical methods:
Wavelengths: X-ray to sub-mm
Resolutions: time-seconds to milli-arc-seconds
→ the most comprehensive data set to date

Evidence appears to favor a mass ratio ~ 1
→ *a fairly massive, and hence younger, pair of stars:*
F0 Ia + \sim B2V+disk @ distance of 750 pc (+/-10%)

Testable predictions have emerged:

F star oscillations → coherent series circa Dec 2014

System approaching quadrature in coming years: resolvable in IR

More research directions:

The hidden B star may have gained mass from the F star.

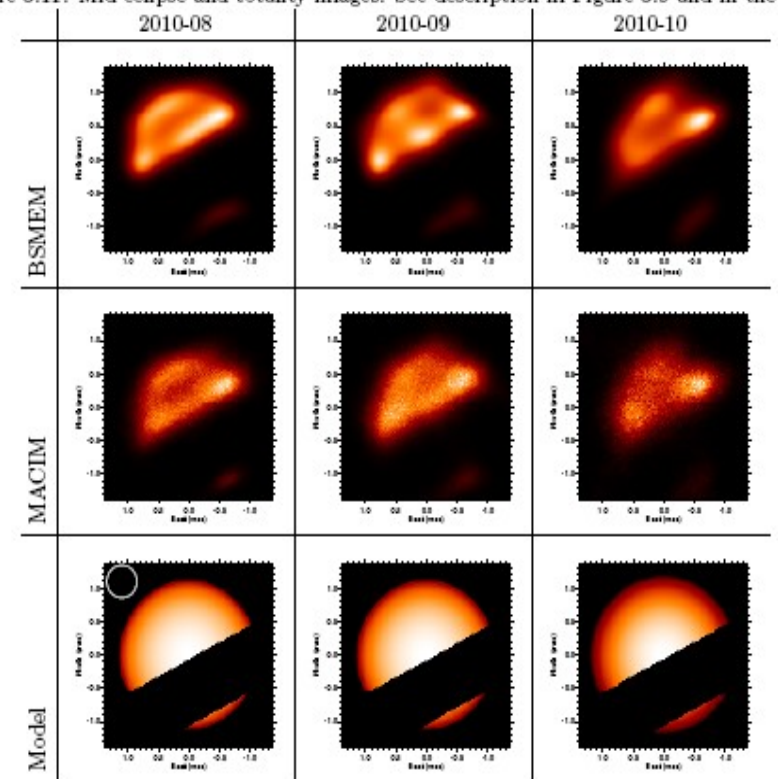
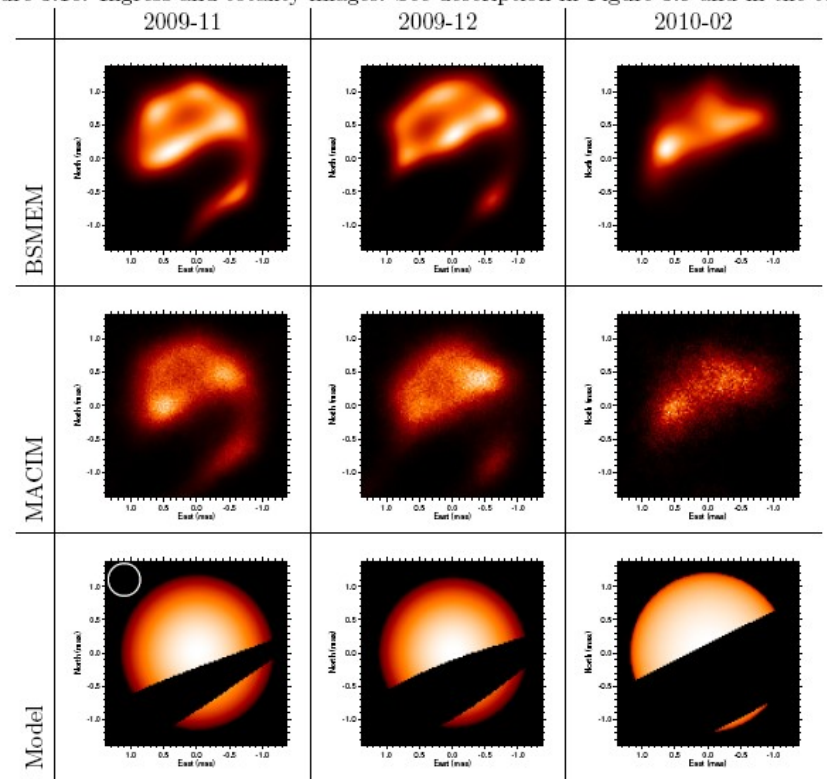
The disk itself = study of accretion, dust evolution, and dynamics.

CHARA+MIRC

Breakthrough Interferometric Imaging results: Kloppenborg, Stencel, Monnier, et al. 2010 Nature, & 2013 ApJ in prep

Figure 3.10: Ingress and totality images. See description in Figure 3.9 and in the text.

Figure 3.11: Mid eclipse and totality images. See description in Figure 3.9 and in the text.



Source: U of Denver dissertaiton 2012 Brian Kloppenborg, advisor Robert Stencel

INGRESS
Autumn 2009

AFTER MID-ECLIPSE
Autumn 2010



Imaging results, in context

- * The eclipse-causing companion **is** a dense, thin disk (as seen by MIRC in H-band, 1.6 microns)
- * Inclination ~ 89 degrees \rightarrow No sign of a “central opening” (had been suggested by previous authors)
- * Disk composition? *Unknown*. Disk sub-structure? *YES!*
- * The disk is asymmetric, based on photometry:
 - Eclipse is deeper after mid-eclipse at U & B band
 - Eclipse is deeper before mid-eclipse at J & H band& asymmetric, based on spectroscopic monitoring ...
 - stronger absorption lines after mid-eclipse



Photometric results: UBVRIJH

<http://www.aavso.org/sites/default/files/jaavso/v40n2/647.pdf>

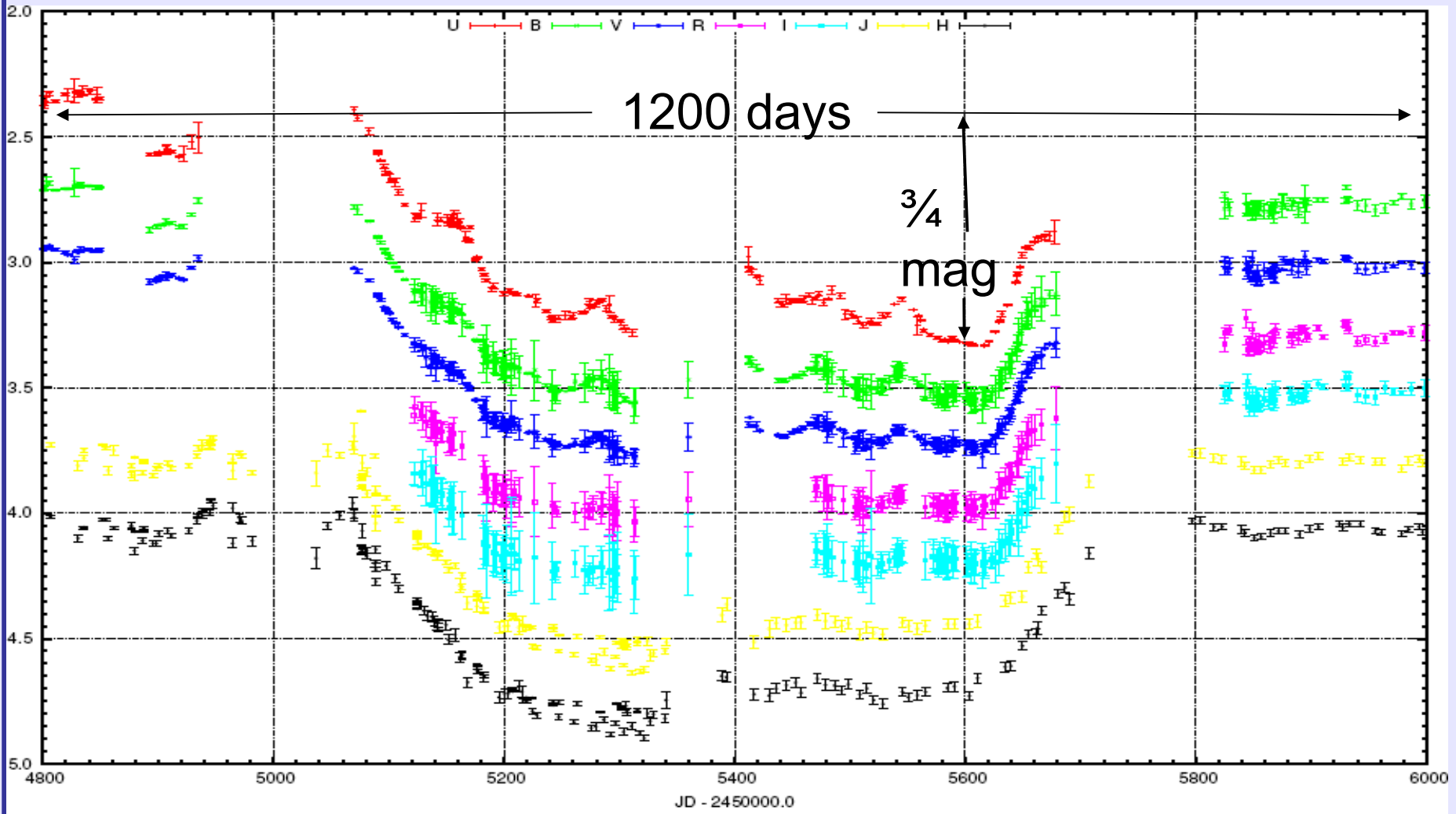
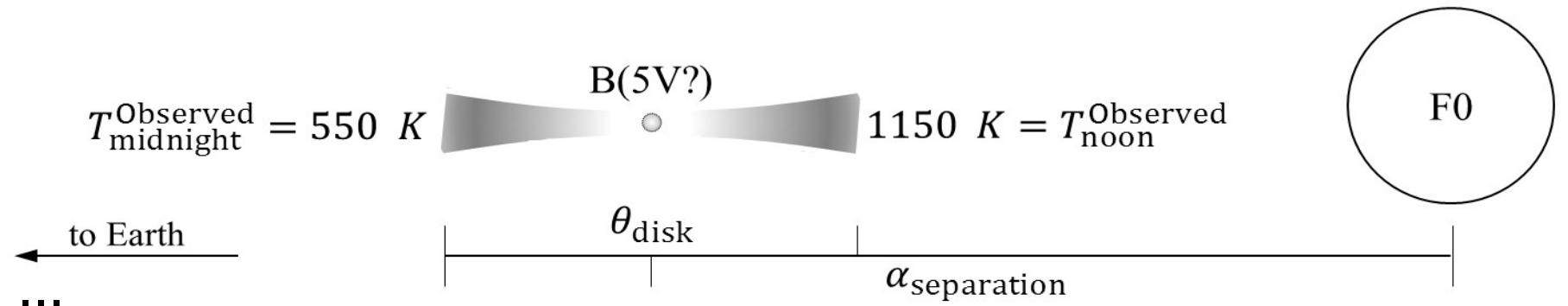
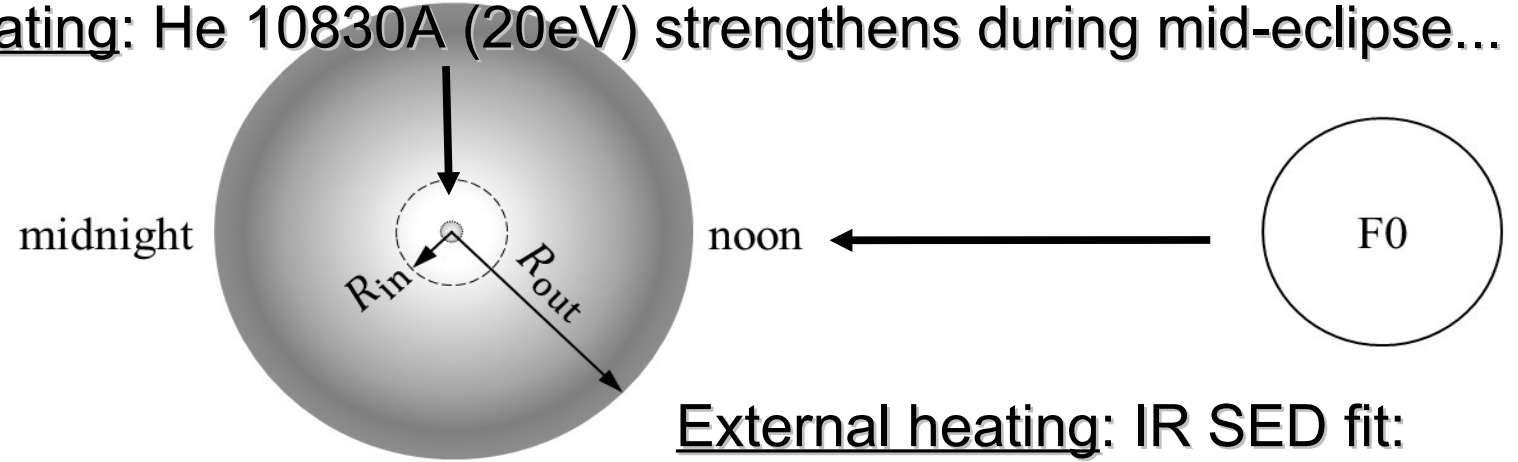


Figure 2.5: UBVRIJH Photometry JD 2454800-present

Thermal structure of the transiting disk: asymmetric heating...



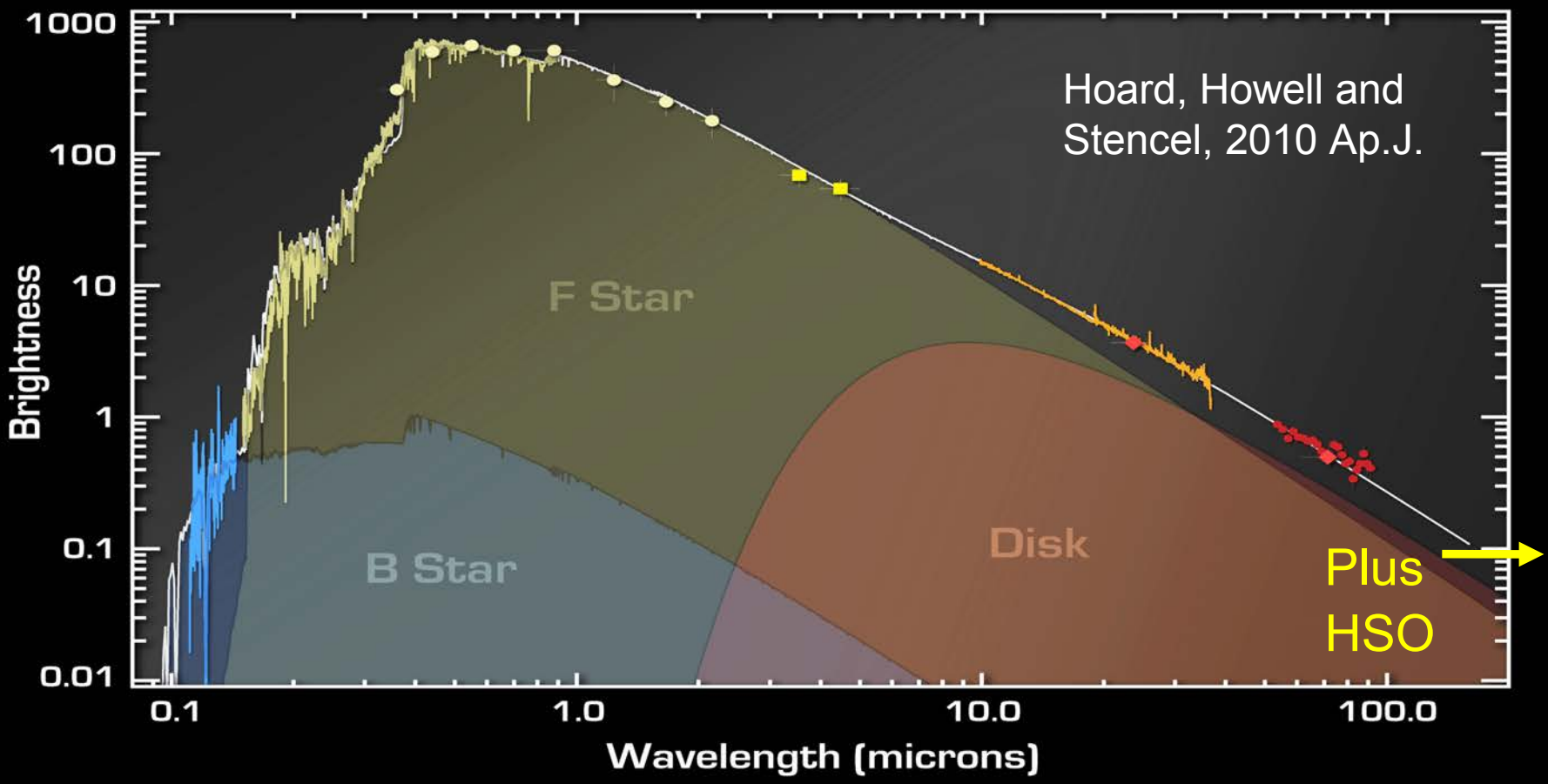
... Internal heating: He 10830A (20eV) strengthens during mid-eclipse...



... External heating: IR SED fit:
dawn 550K at 'midnight', 1150K at 'noon'...

- + Transient CO absorption during 'dawn' phase
- + Persistent Br alpha & Na 2.2 micron emission lines
- + Applying disk code MC-RT to model all this... (Richard Pearson...)

epsilon Aurigae: Spectral Energy Distribution



Spectrum of Binary Star Epsilon Aurigae Spitzer Space Telescope • IRAC • IRS • MIPS
NASA / JPL-Caltech / D. Hoard (Spitzer Science Center/Caltech) ssc2010-02a



Photometric results: disk mass from HSO sub-mm fluxes

(Hoard et al. 2012)

$$M(\text{dust}) = F_{\nu} \lambda^2 d^2 / (2 k T_{\text{dust}} \kappa_{\nu})$$

$$F(250 \mu\text{m}) = 57 \text{ mJy} = 3 \times 10^{-22} \text{ W/cm}^2/\text{micron.}$$

For $d=750 \text{ pc}$ and $T_{\text{dust}} = 550\text{K}$ and

$$\kappa_{\nu} = 3 \text{ cm}^2/\text{gm} \text{ (Jura et al., 2001)} \rightarrow$$

$$M(\text{dust}) = 1.2 \times 10^{31} \text{ gm} \text{ (~6 Jupiter masses)}$$

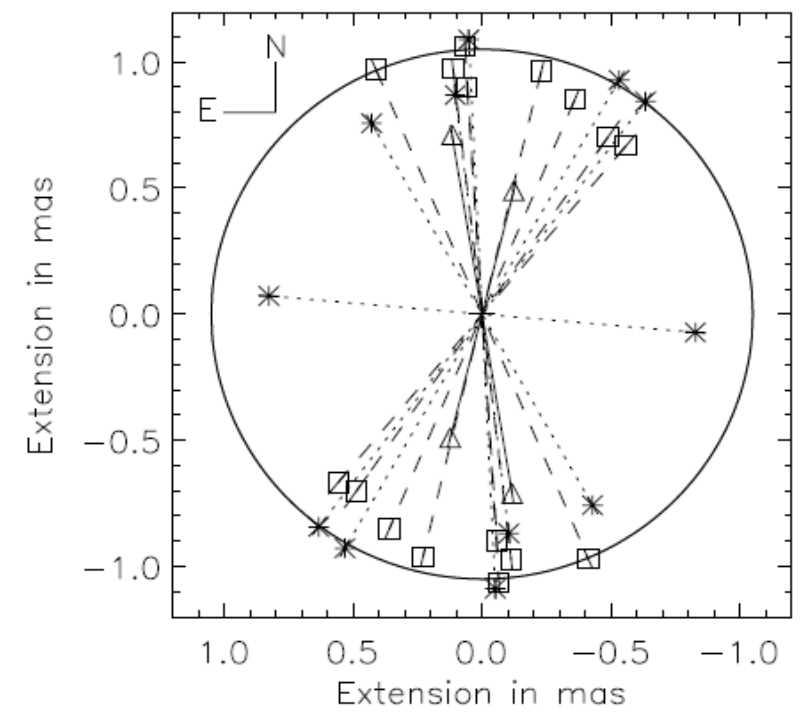
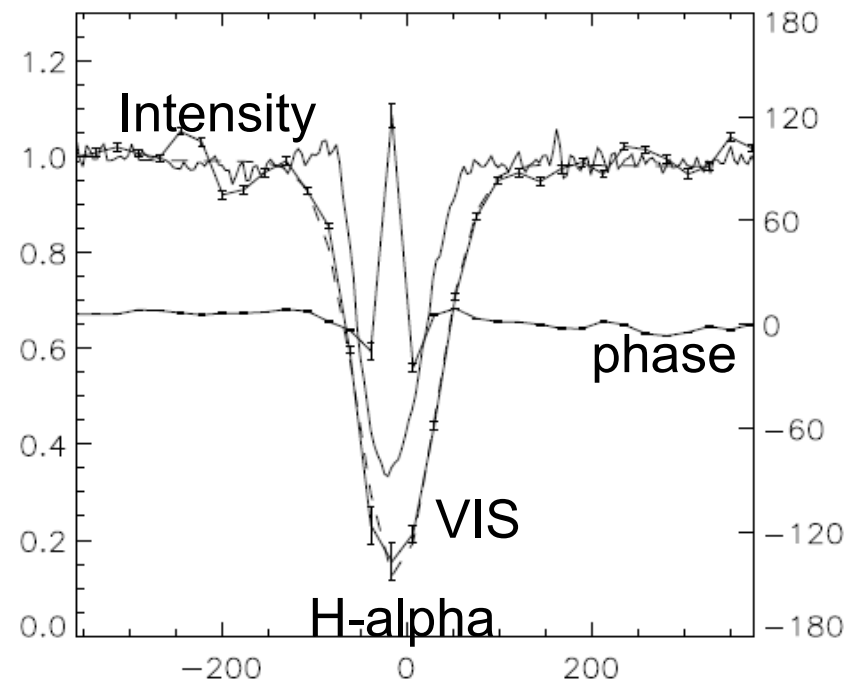
(if gas/dust ~ 100 , this could be a problem.., or κ too big?.)

Interferometric results: CHARA+VEGA

Mourard, Harmanec, Stencel, et al. 2012 A&A 544, 91.

D. Mourard et al.: A high angular and spectral resolution view into the hidden companion of ϵ Aurigæ.

HJD=55824.863



System more extended in core of H-alpha (total eclipse) → constraint on disk gas scale height & central mass; phase tracks eclipse motion.



What more can we conclude from CHARA+VEGA observations?

During the total eclipse phase in 2010, when the disk was in the line of sight, we saw broadening of the H α absorption and a drop of the visibility curve, consistent with the addition of neutral hydrogen in the line of sight, **extended above and below** the height of the interferometrically imaged disk itself (atm+wind?)

- **Scale height** of the gaseous component of the disk material, and, based on some additional assumptions, points to a mass of the central object being >8 Msun for a distance of 750 pc.
- Results can be **tested** during coming observing seasons as the star moves from eclipse phase, **toward quadrature**.



Additional results

Detection of **He I 1.0830 micron absorption line** with IRTF/SpeX, greatly strengthened during mid-eclipse
→ FUV, *Stromgren region around disk-centered star.*

(Stencel et al. 2011 Astron. Journal)

Detection of a **mass transfer stream** – seen with high dispersion optical spectroscopy, between 3rd and 4th contacts (spring 2011) and in photometry during egress.

Said stream is **strangely enhanced in Rare Earth elements** – s-processing & possible radiative transfer effect; *mining shares now on offer.* (Griffin & Stencel, PASP submitted).

Enhanced ¹³C detected with high-resolution IR spectra (GNIRS), only late eclipse phase, confirming 1983/4 reports.

Looking forward

Approach to quadrature (~ 2020) should reveal a lot more about hotter side of the disk

...Disk should remain observable in mid/far-IR

?Presence of any persistent molecules?

...Monitor F star interferometrically

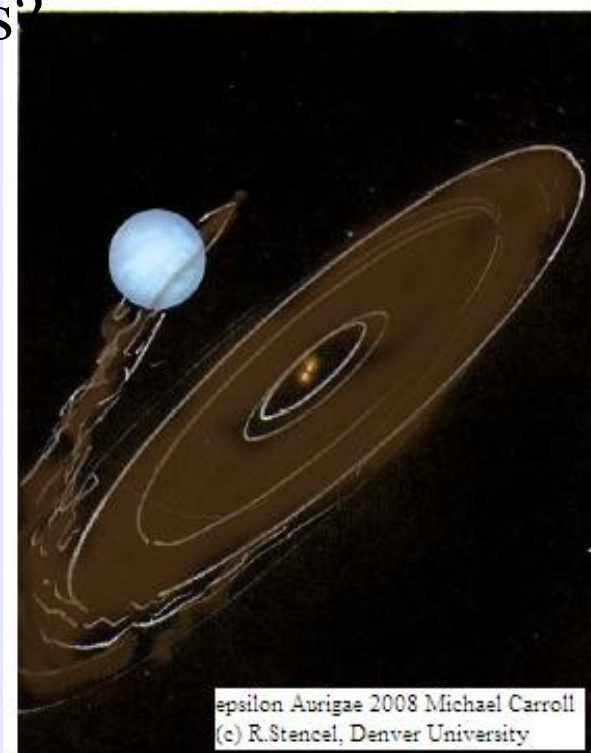
Evidence for surface activity

?Dec 2014 coherent pulsation?

...Continued spectroscopic monitoring

Ongoing VEGA efforts

ESPADONS & more





What else?

Summer AAS topical conference, featuring sessions on interferometry (*Hal, Gerard*), on epsilon Aurigae (*several*), Kepler results (*Daniel*), and more:

<http://aas.org/meetings/aastcs-3>



G

iants of Eclipse



Monterey CA USA | **28 July - 2 August 2013**

Thank you for listening
Questions?

