Imaging the transiting disk in the epsilon Aurigae system

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What is epsilon Aurigae?

Open research questions

Enter interferometry
  - Examples of data
  - Images
  - Modeling (Bayesian)

Results

Conclusion
The First (?) Discovery

1846-1847 Eclipse of epsilon Aurigae; Image Credit: Gussow (1936)

Den Stern in der Ziege des Fuhrmanns sehe ich oft gegen ζ und η so schwach, dafs er kaum zu erkennen war. Hat man dies schon beobachtet?
-Fritsch (1824)
Photometric Monitoring:
- System dims by ~50% every 9890 days (27.1 years) (Ludendorff, 1903), stays faint for ~2-years

Spectroscopic Monitoring:
- Epsilon Aurigae is a single line spectroscopic binary
- Dimming thought to be due to an eclipse.

System composition
- Visible component is F0Ia
- Other component: unknown
Background on eps Aur

1912: Ludendorff
- A swarm of meteorites, 10-100 um in diameter.

1937: Struve et al.
- A large semitransparent infrared orbited by an F-type supergiant.

1938: Schoenberg et al.
- A super-cool star that forms solid particles during convection
Background on eps Aur

- 1965: Huang
  - The first analytical model supporting a disk-like object as the cause of the eclipse.

- 1986: Kemp
  - Obtained polarimetry during the 1983 eclipse, argued that the disk is inclined.
1989: Henson
- F-star might be undergoing non-radial pulsation.

\( (l = 2) \)

- \( m = 0 \)
- \( m = 1 \)
- \( m = 2 \)

\( (l = 3) \)

- \( m = 0 \)
- \( m = 1 \)
- \( m = 2 \)

1990: Ferluga
- Tweaked the Huang model, proposed the disk consisted of a series of rings.
1983-2012: Long-term photometry

Kloppenborg et al (2012, submitted)
2009 Model of Eps Aur

- **F star**: ~15 solar masses, ~300 solar diameters
- **Dark companion**: Disk and star(s) = ~14 solar masses
- **Central star(s)**: Disk temp. 500 kelvins

**Solar System**
(Sizes of Sun and planets not to scale)

- Sun
- Earth
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune

**Epsilon Aurigae**

Kemp (1983)
Some of the Research Questions

The system:
- What are the fundamental parameters (mass, radius, luminosity) of the components in the system?
- What is its evolutionary state?

The eclipse:
- What causes it?
- Orbital parameters?
- Fractional coverage?

The eclipsing body:
- Composition (gas, dust, debris?)
- Dynamic stability (inside: one or two stars?)

The F-star:
- What causes the out-of-eclipse variations?
2009-2012 Eclipse Photometry

epsilon Aurigae Photometry: JD 2454800 - 2456000 (2008 Nov. 29 - 2012 March 13)
CHARA, 2008 Sept. (pre-eclipse)
CHARA, 2009 Nov. (eclipse ingress)
CHARA, 2009 Nov. (eclipse ingress)
CHARA, 2011 Nov. (post-eclipse)
**Enter OI Imaging**

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**Epsilon Aurigae Eclipse (CHARA-MIRC)**

Kloppenborg et al. (2010)

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**OI Imaging Shows**

- The eclipsing object is disk-like
- Polarization-predicted impact parameter **might** be wrong
- Potential surface features

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Kemp (1983)
Model independent images

*Quick reconstructions using BSMEM (1.4 mas Gaussian prior, 0.05 mas/pixel). Artifacts abound...
Modeling: SIMTOI

- Simulation and Modeling Tool for Optical Interferometry
- Generates interferometric observables from geometrical models
- Models are fully 3D and time-dependent
- First interferometric modeling tool to use GPU acceleration (via. my OpenCL Interferometry Library)
- Multiple minimization engines
- Bayesian model selection
- Find it on GitHub
Implied light curves

Ingress Slopes as a function of semi-major axis

-0.1

Mag

Days past periastron (HJD - 2454515)

lc data
α = 15, i = 88
α = 17, i = 88
α = 18, i = 88
α = 20, i = 88
α = 30, i = 89
α = 40, i = 89
Implied light curves

Light curve as a function of Disk Height

- Mag
- Days past periastron (HJD - 2454515)
Implied light curves

Light curve as a function of inclination

Days past periastron (HJD - 2454515)
Implied light curves

Light curve implied by out-of-plane disk

- Days past periastron (HJD - 2454515)
- Mag

- lc data
- $\theta = -1$
- $\theta = 0$
- $\theta = +1$
Detriments of rendered modeling

Artificial minimia:
- Mixing discrete (i.e. pixels) with continuous probability can lead to jump discontinuities in the posterior probability distribution
- Easily fixed by using minimization engine that is aware of discrete probability on some variables.

Longer execution times:
- A DFT or NUFFT is $O(n^2)$ or $O(m + n \log(n))$
- Partially alleviated by GPU computing.

Benefits:
- Geometry really considered, obscuration super easy.
- Modeling complex objects (i.e. eps Aur, non-radial pulsation, eclipsing binaries, spots) is easier.
- Implementing a new model is as simple as rendering it.
Interferometric Data: Summary

PTI
- 24 obs. → 21 epochs
- 1997-10 to 2008-11

CHARA (MIRC, CLIMB)
- 39 nights → 16 epochs
- 2008-09 to 2011-11

NOI:
- 35 Nights → 14 Epochs
- 2006-02 to 2010-04

Images:
- Star is round (spots?)
- Southern half eclipsed
- Disk theory likely correct

Bayesian Modeling:
F-star:
- LDD ~ 2.27 mas
- LCD ~ 0.66

Disk:
- Height ~ 0.75 mas
- Diam. ~ 9.9 mas
- Edge decay ~ 1.9

System:
- Total semi-major axis
  \( \alpha \) ~ 36.2 mas
- \( \Omega \) ~ 298 deg.

Noteworthy:
- F-star shrinking by ~ 1% / year?
Conclusion

Interferometric images:
- Show that a disk is responsible for the eclipse
- Give us an idea of what we need to model

Interferometric model fitting:
- Provide estimates of
  - Stellar parameters (diameter, darkening coefficient)
  - Disk parameters (diameter, height, edge opacity, flaring)
  - Orbital parameters (alpha_T, Omega, inc)