CHARA + MIRC imaging, & recent progress in understanding “epsilon Aurigae”

*Rosetta stone or Pandora's box?*

2010, the *year* of total eclipse

First of all, Thank You!

It's an honor and privilege to have access to this amazing array of telescopes...  
... and equally amazing array of people!
\( \varepsilon \text{ Aur} \) – a long history: 1920's Struve et al.; 1965, first black hole binary candidate; 1991, favored system model, high masses:

Assigning the F supergiant type implies a high mass but invisible companion object...

system distance \( \sim 625 \text{ pc} \)

Model for the epsilon Aurigae system
Today:

a changing scene

• Is the F supergiant actually a massive star, or a “phony”

• Is the disk actually observable? Is it like other disks?

• Could there be a black hole inside the disk?

• Given answers to those questions, what's the evolutionary status of the star(s) in this binary system?
The F “supergiant”

Why it *could be* a massive star, F0Ia:
- Very bright for its distance → 30,000 time solar luminosity
- Spectrum details resemble supergiant class star
  (low surface gravity, extended)
- Early F supergiant would be ~ 10 to 15 solar masses

Problems with this classification:
- Star is huge, 150X solar size, 2X similar supergiants
- Variability ~100 days → over-luminous if Cepheid-like
- Abundances: solar, but with excess Na, Ba, $^{13}\text{CO}$...
The dark companion

M/L >> 1

The cause of the primary eclipses

“Unseen” except for weak spectral lines during eclipses, and these resemble the F star spectrum

Theorized to be:
- a swarm of meteors (1924)
- a huge “infrared star” (1932)
- a cloaked Be star (1961) or BH
- a large, cold disk (1956, 1965...)
So what's new?

FOUR DEVELOPMENTS SINCE THE STATION FIRE:

1. SPECTRAL ENERGY DISTRIBUTION RESOLVED
2. CHARA+MIRC IMAGING OF THE DISK ITSELF
3. EVIDENCE FOR DISK SUBSTRUCTURE
4. XRAYS, or not.

→ A modern, comprehensive model for the binary!
Development #1: A complete Spectral Energy Distribution

Spectrum of Binary Star Epsilon Aurigae
Spitzer Space Telescope • IRAC • IRS • MIPS
NASA / JPL-Caltech / D. Hoard (Spitzer Science Center/Caltech)
**System properties: B5V star (5.9Mo)**

→ **F star ~ 2 – 3 Mo, disk << 1Mo**

ε Aurigae from the Far-UV to the Mid-IR


**TABLE 2**

**The Model**

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Adopted Distance, $d$ (pc)</td>
<td>625</td>
<td>HIPPARCOS (Perryman et al. 1997)</td>
</tr>
<tr>
<td></td>
<td>Inclination, $i$ (°)</td>
<td>$89 \ (\gtrsim 87)$</td>
<td>this work, Lissauer et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Orbital Separation, $a$ (AU)</td>
<td>18.1–19.6</td>
<td>this work</td>
</tr>
<tr>
<td>F Star</td>
<td>Spectral Type</td>
<td>F0 II–III? (post-AGB)</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Temperature, $T_F$ (K)</td>
<td>7750</td>
<td>this work, Castelli (1978)</td>
</tr>
<tr>
<td></td>
<td>$\log g$</td>
<td>$\lesssim 1.0$</td>
<td>this work, Castelli (1978)</td>
</tr>
<tr>
<td></td>
<td>Radius, $R_F$ ($R_\odot$)</td>
<td>135 ± 5</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Angular Diameter, $D_\alpha$ (mas)</td>
<td>2.01 ± 0.07</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Mass, $M_F$ ($M_\odot$)</td>
<td>2.2–3.3</td>
<td>this work</td>
</tr>
<tr>
<td>B Star</td>
<td>Spectral Type</td>
<td>B5V</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Temperature, $T_B$ (K)</td>
<td>15,000</td>
<td>Cox (2000)</td>
</tr>
<tr>
<td></td>
<td>$\log g$</td>
<td>4.0</td>
<td>Cox (2000)</td>
</tr>
<tr>
<td></td>
<td>Radius, $R_B$ ($R_\odot$)</td>
<td>3.9</td>
<td>Cox (2000)</td>
</tr>
<tr>
<td></td>
<td>Mass, $M_B$ ($M_\odot$)</td>
<td>5.9</td>
<td>Cox (2000)</td>
</tr>
<tr>
<td>Disk</td>
<td>Temperature, $T_{disk}$ (K)</td>
<td>550 ± 50</td>
<td>this work</td>
</tr>
<tr>
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<td>Radius, $R_{disk}$ (AU)</td>
<td>3.8</td>
<td>this work, Lissauer et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Height, $H_{disk}$ (AU)</td>
<td>0.475</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Assumed Mass, $M_{disk}$ ($M_\odot$)</td>
<td>$\ll 1$</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Inferred Dust Grain Radius, $r_{grain}$ ($\mu$m)</td>
<td>$\gtrsim 10$</td>
<td>this work, Lissauer et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Transmissivity Factor</td>
<td>0.3</td>
<td>this work</td>
</tr>
<tr>
<td></td>
<td>Emissivity Factor</td>
<td>2.43</td>
<td>this work</td>
</tr>
</tbody>
</table>
Evidence argues the binary star sep $\sim$10 - 20 milli-arcsec epsilon Aurigae is 625 parsec away. At that distance:

1 arcsec (5 micro-radians) spans 625AU
1 milli-arcsec (5 nano-radians) spans 0.625 AU

$\rightarrow$ Required telescope size (at near infrared, 2 microns):

$5 \times 10^{-9}$ radians / $2 \times 10^{-6}$ meters = 250 meters...

Where can I find a telescope that large?
The CHARA Array at Mount Wilson Observatory

Please note: much of the following should be considered EMBARGOED INFO...
What we saw last autumn...

Early gen image by John Monnier. Note movement of dark disk toward right. Also note: leading edge in Nov not sharp; training edge in Dec 'truncated' ...and what are those “hot spots”? 
Evidence for the dark disk

Epsilon Aurigae Eclipse (CHARA-MIRC)

The movie! http://www.ns.umich.edu/podcast/video2.php?id=1211
UV coverage was excellent for the first pair of images, but much less for the Feb 2010 data (understandably). However, the model can help reconstruct images from far fewer samples – with a risk of lost detail...
Third eclipse epoch confirms the trend, within model limitations.

Follow-up obs needed, 2010-11

Mid-eclipse is 4 Aug 2010 // Totality ends Mar 2011 // Eclipse ends May’11
What this initial interferometric imaging has told us, so far...

Fitted ellipse indicates relative motion of objects: 25 km/sec

F star motion, previously measured from radial velocities, was 15 km/sec during observing timeframe

→ disk component = 25 – 15 = 10 km/sec

IMPLIED MASS RATIO: 2 / 3 → F star is lighter than companion!

SED model says disk contains B5V star, nominal 6 Msolar
→ F star, despite high luminosity, is < or = 4 M solar

this is not a normal high mass supergiant...
...more likely some terminal stage of evolution...
Also from the interferometry results

SED disk dimensions and interferometric image opacity
→ disk mass from volume and dust opacity:
With assumed dust opacity $\sim 10 \text{ cm}^2/\text{gm}$:
  
  density $= 1 / [\text{opacity} \times \text{length}] \sim 10^{-10} \text{ kg/m}^3$
  
  disk volume: $7 \times 10^{34} \text{ m}^3 \rightarrow \text{disk mass} = 10^{25} \text{ kg} < M_{\text{earth}}$

disk scale height consistent with SED values and these: $\sim \frac{1}{2} \text{ AU}$
Development #3: a rotation curve for the disk

Ferluga (1990) shell line monitoring & light curve model, 1983 eclipse, led to his multi-ring disk model (units are AU).

Disk sub-structure? You betcha!
Tomography of the disk: new data, neutral potassium line monitoring
epsilon Aurigae  K I 7699A line excess absorption during eclipse

Contacts: I

CHARA: 1 2 3

THREE HILLS OBSERVATORY

NOTE THE STEP FUNCTIONS! (Leadbeater & Stencel, 2010 arXiv 1003.)
How to interpret the stepwise changes in equivalent width in the K I 7699A line?

Simplest explanation involves similar excitation conditions across this portion of the disk, but changing DENSITY → concentric shells or rings.

Given the MIRC image opacity, disk is likely opaque at 7699A too, which implies we could be seeing optically thin 'atmospheric' shells extending above the disk.

Low excitation excesses in K, Na in eps Aur are reminiscent of radiation-induced excesses in exospheres of Mercury and Io.
The Nature Letter result is now only part of the story. ...CHARA+MIRC merely saw Rings “C” & “F”

The neutral potassium E.W. results, nearly to scale:

```
|   |   |   |   |   |   
|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 |
| AU|
```

*Stella incognito

**Ring:**

- **F** star in Feb
- **E**
- **D**
- **C** in Dec
- **B**
- **A**

Ring thicknesses ~ 50% of measured, to avoid overlap

Disk tilt exaggerated for clarity (sin i ~ 1)

Disk motion

Dynamical age? Rings/gaps = resonances &/or planets? Alternatives? →

R.Stencel, 24Feb2010
Keplerian fit with B5V star in disk
Further data will confirm/challenge this model

Disk rotation curve, $v(r)$
Currently under study – optical depth of K I line ~ 1, disk “atmosphere” heating from F star (Lissauer 1996), locations of expected resonances in system...
Mid-eclipse brightening: central clearing, and/or gravitational lens?

Mid-eclipse, 2010 August 04

Composite of 1955 & 1983 light curves, 100 day grid
Wish list:

Now that we can 'predict' the rest of eclipse events –

• Mar'10-Mar'11, CHARA+MIRC time, monthly monitoring

• NIR acquisition and tracking cameras for CHARA → extend into daytime; take advantage of the early morning seeing that solar astronomy at Mt. Wilson uses.

• Keck NIRSPEC time – high res 2+4 um CO profiles

• *Plus ANY/ALL earth & sky telescopic resources for the mid-eclipse lensing event: 4 Aug. 2010 3Mo F star and 6Mo B star aligned to 1 milli-arcsec (however, star to star sep vs dist → tiny lensing)*
Development # 4: a lack of Xrays

XMM-Newton, March 02 2009, 25 ksec -
Wolk, Pillitteri, Guinan & Stencel 2010 in prep.
...a deficit of counts w.r.t. X-ray background...
a place to hide the mass lost from the F star?

Fig. 1.— PN smoothed image (0.25-8.0 keV) on power law scale, centered on ε Aurigae (indicated by the ‘plus’ sign). The three circles indicate 10″, 15″ and 20″ extraction radii.
So, where does this leave us? 

ε Aur, a changing scene

• Is the F supergiant actually a massive star, or a “phony”?  
  *SEEMS TO BE IN A POST-AGB LIKE STATE*

• Is the disk actually observable? Is it like other disks?  
  *DISK DETAILS ARE EMERGING! Models needed.*

• Could there be a black hole inside the disk?  
  *PROBABLY NOT, BUT STAY TUNED*

• Given answers to those questions, what's the evolutionary status of the star(s) in this binary system?  
  *Algol paradox again...*  
  *MASS TRANSFER vs MISSING MASS...*
What's next?

The puzzling case of the dusty disc and the phony star

The variable star epsilon Aurigae has perplexed astronomers for decades, but **Keith Cooper** finds that its latest eclipse is beginning to yield some long awaited answers.
“It's not over 'til it's over…”

- Ingress began August 2009
- Totality started Jan 2010
- Mid-eclipse predicted for August 2010
- Totality ends March 2011
- Eclipse ends May 2011
- Next eclipse starts 2036
In play:

Observational thrust:  
Mid-eclipse observations

Interferometric imaging  
(MIRC plus VEGA & PAVO)

Infrared spectra

Other data

Relevance:  
Central opening in disk?

Disk shape, scale height, opacity structure

Re-appearance of CO – “perhaps from sublimating comets”
Limits on dust properties

UBVRIJH, SMEI, HST...
Inspiration... & outreach opportunity: www.citizensky.org ...

Help Us Solve a 175-year-old Mystery.

You can contribute to the understanding of the universe that we all share.

Help us solve the mystery of epsilon Aurigae, a star that has baffled scientists since 1821. You don’t need any prior scientific training—we will give you all of the tools you need to become a citizen scientist.

Everyone, regardless of science background, can play a role in the Citizen Sky Project... discover yours! Get involved and you can do things like:

- Learn about Astronomy
- Observe Stars
- Collaborate
- Create Theories
- Study Data
- Publish Papers

New forum topics
- why 38 the value of zeta Aur?
& How Tweet it is...

www.twitter.com/epsilon_Aurigae

Jeff Hopkins reports faintest V mag yet, 3.77! Near a minimum of the out-of-eclipse variations superposed atop total eclipse. Keep looking.

Not so good news - the access road to Mt.Wilson has sections destroyed by mudslides... no more observing for weeks/months... :-(

Good news! Spitzer Space Telescope will stare at eps Aur again during April with its IRAC imager, measuring new infrared energy channels.
Thanks for listening.
Any questions?
End of slides, backup slides follow...
Backup slides
A 20th century mystery

- Binary star theory (1912), Algol paradox
- The rise of astronomical spectroscopy
- Quantum theory & spectrum interpretation
Single-lined spectroscopic binary

Orbital period = 27.1 years
Mass function = 3.2 M_solar

Primary eclipse
JD 2,455,200 = 2010 Jan

Secondary eclipse
JD 2,451,500 = 1999 Nov

Disk & B star orbit

F star orbit

NOT QUITE TO SCALE
epsilon Aurigae KI 7699 line (pre eclipse component substracted)
Absorption in zones of differing radial velocity
THO data
Alternative view of K I structure, accounting for pre/post mid-eclipse asymmetries (need a good disk model)
Observed disk motions: is it +/- 30, or +20, -40?
Keplerian disk velocities

secondary mass
5.9 Mo

disk, a (AU) | a^3/M | P(yr) | v(circ, km/sec)
--- | --- | --- | ---
1 | 0 | 0 | 72
2 | 1 | 1 | 51
3 | 5 | 2 | 42
4 | 11 | 3 | 36
5 | 21 | 5 | 32
6 | 37 | 6 | 30
7 | 58 | 8 | 27
8 | 87 | 9 | 26
9 | 124 | 11 | 24
10 | 169 | 13 | 23

...EGRESS

...INGRESS
Disk optical depth 'asymmetry' due to counterclockwise rotation
Among the possible causes of the observed discontinuities are:

(1) nested ring structure related to disk Keplerian sub-structure and tidal resonances with the F star,

(2) nested parabolic arcs representing a cometary evaporation of the disk in the presence of the F star UV radiation,

(3) optical depth variations enabling study of different portions of the disk, particularly in terms of ingress (morning) and egress (evening) sides of the disk, relative to exposure to F star UV radiation.

Combinations of these effects are possible, plus unanticipated complications are inevitable, given the long history of studies of this star.
Alternately, it is useful to recognize the presence of the F star has at least three effects on the disk:

(1) heating the top and bottom of the disk given that the F star diameter (1.5 AU) subtends nearly twice the thickness of the disk (0.9 AU);

(2) heating of the facing portion of the disk, and

(3) tidal effects (resonances).

Thus far, we are ignoring additional effects of the point-like (10 solar radii) B5V star presumed to be present in the center of the disk itself.
→ Tomography of the star

Hint of photospheric bright spots in the MIRC images...

Out of eclipse light variations, ~0.1 mag, ~100 days, v.v.blue

Could these be 'asteroseismic' – e.g. tops of giant convective cells, tidally enhanced at sub-disk longitudes?

“Easy answer” - seek Doppler imaging followup...

(thanks, Paul Hemenway for the suggestion)
Disk rotation curve, $v(r)$

Leadbeater & Stencel 2010 arXiv; the 1986 coverage by Lambert & Sawyer was too sparse.
Today's topic: “Hobby-horse”...

A hobby horse (or hobbyhorse) can be several things [wikipedia]:

* "Irish Hobby" or "hobby" ; an extinct type of horse.
* A toy horse, consisting of a model of a horse's head, usually wooden, attached to a stick. This is often used by children to simulate riding a horse, see hobby horse.
* A toy horse suspended by springs from a frame
* The figure of a horse fastened around the waist in the Morris dance.
* Euphemistically, in Shakespearean times, a prostitute or promiscuous woman...

* Someone's favorite topic, to which he constantly reverts.
How does it work? By combining telescopes:

Each pair of telescopes produces an antenna pattern on the sky, perpendicular to the baseline, and resolves \( \frac{\lambda}{\text{baseline}} \).

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Resolution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 meter</td>
<td>0.1 arcsec</td>
</tr>
<tr>
<td>10 m</td>
<td>0.01”</td>
</tr>
<tr>
<td>100 m</td>
<td>0.001”</td>
</tr>
</tbody>
</table>

= 1 milli-arcsec

*at 550 nm (V band)

Compare with VLA, New Mexico
3 cm, radio telescope
27 km max spacing
\( \rightarrow \) micro-radian resolution \( \rightarrow \)
What to expect during eclipse?

Image space $\rightarrow$
Scale is Milli-arcsec (nano-radians)

Interferometric view with fringes

Direct test of the Huang disk model

A worthy task for modern interferometers like CHARA, NPOI, (MROI)
Polarimetry

- Some key papers (very few to choose from)

**Jack Kemp** 1986 Astrophys. Journal

_Epsilon Aurigae - Polarization, light curves, and geometry of the 1982-1984 eclipse_

**David Harrington & Jeff Kuhn**

2009 Astrophys Journ.

_(survey) Ubiquitous Hα-Polarized Line Profiles_

**Gary Cole,** 2010?
“Recent” (i.e. the only) results

Kemp, 1986

Fig. 2.—Model geometry of the eclipse, showing in Fig. 2a the model parameters. In Fig. 2d is a hypothetical geometry for future modeling involving a tilted, rotating primary star with nonspherical pulsations possibly correlated with the spin axis. J.Kemp et al. 1986 Astrophys. J. 300, L11.
How big a lensing effect? Huge? ... at micro-arcsec level

Hosokawa et al. (1993)

\[ \Delta \theta_x = \frac{x}{D} \left( 1 - \frac{4GM}{c^2 D \theta^2} \right), \quad \Delta \theta_y = \frac{y}{D} \left( 1 + \frac{4GM}{c^2 D \theta^2} \right). \]
Fig. 3.— An optical depth profile for a hydrostatic disk with a hole. As in the previous figure except that this is a medium opacity case (maximum optical depth = 500) with a central hole of radius 0.9 $R_D$. The diameter of possible central stars is indicated on the left - X-rays from such a star could be visible through the central hole if there were near the light of sight.
OBSERVING: Yes – see Mars! @ DU’s Chamberlin Observatory
This Saturday 2/20: 7-10pm…if clear
Be prepared for cooler temperatures