Epsilon Auriage:
200 Years of Astronomical History

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PVAO Astronomy Lecture
Nebraska Nature and Visitor Center

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Background: Brian Thieme

Talk Outline

- Background Material
  - Star naming conventions
  - Single star evolution
  - Binary Star Evolution
- Epsilon Auriage
  - The discovery and history
  - Current understanding, competing theories
  - New developments from research

Star Naming Conventions

- Stellar Naming Conventions
  - The sky is divided into regions called constellations.
  - Most bright stars have Arabic names. Few (< 20) are named after people
  - Some bright stars also have a Bayer designation. Format: α,β,γ,δ,ε, … followed by constellation name.
  - Now with brighter telescopes the star names are often numerical or somehow coordinate based.
  - Stars often have many names:

Identifiers (46) :

V* eps Aur	GCRV 2970	LS V +43 23	SKY# 7879
* eps Aur	GEN# +1.00031964J	2MASS J05015812+4349241	TD1 3824
* 7 Aur	GSC 02907-01275	N30 1068	TYC 2907-1275-1
ADS 3605 A	HD 31964	PLX 1122	UBV 4807
AG+43 552	HIC 23416	PMC 90-93 131	UBV M 10528
ALS 8131	HIP 23416	PPM 47627	UCAC3 268-74264
BD+43 1166	HR 1605	RAFGL 670S	uvby98 100031964 ABV
CCDM J05020+4350A	IDS 04548+4341 A	RAFGL 670	WDS J05020+4349A
CSI+43 1166 1	IRAS 04583+4345	ROT 705	[KW97] 20-37
EM* CDS 456	IRC +40109	SAO 39955	AAVSO 0454+43
FK5 183	JP11 959	SBC7 200	
GC 6123	LF 7 +43 70	SBC9 291	

Stellar Evolution

- Where the star was, what it did there
- Where the star will be going, what it will do
- Testing Nuclear Theory
- The Astrophysical Laboratory
- We are made of stardust

HR Diagram

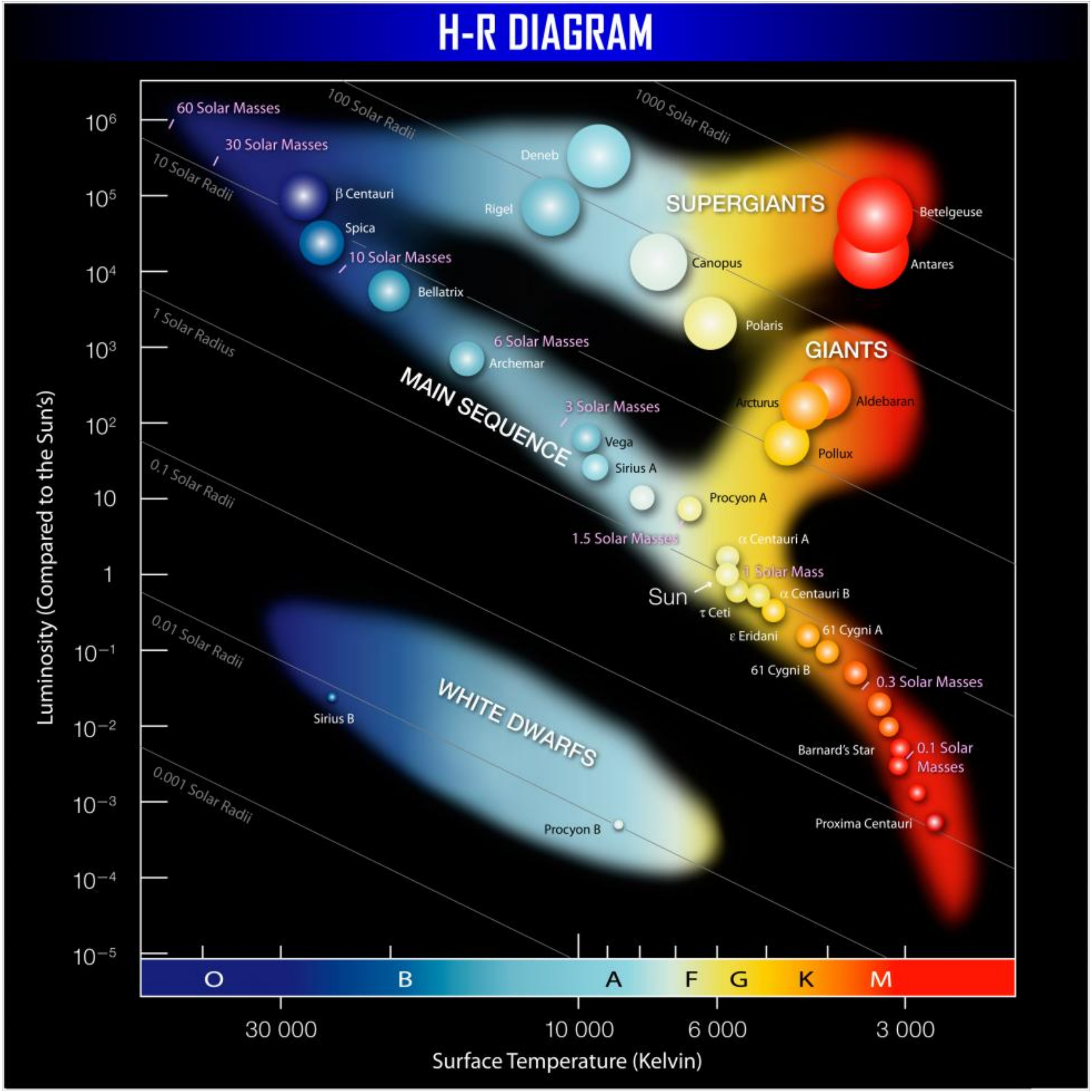
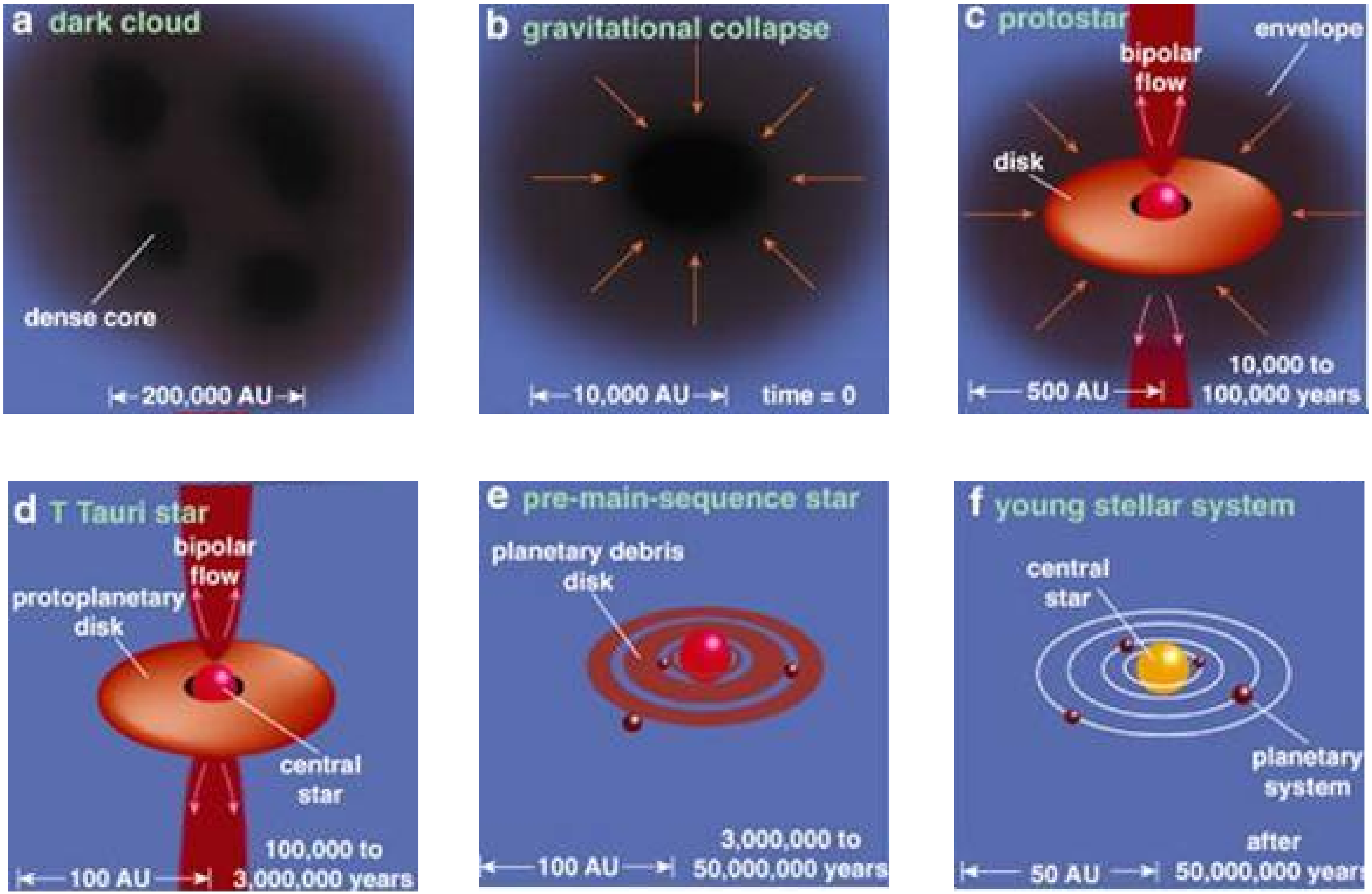


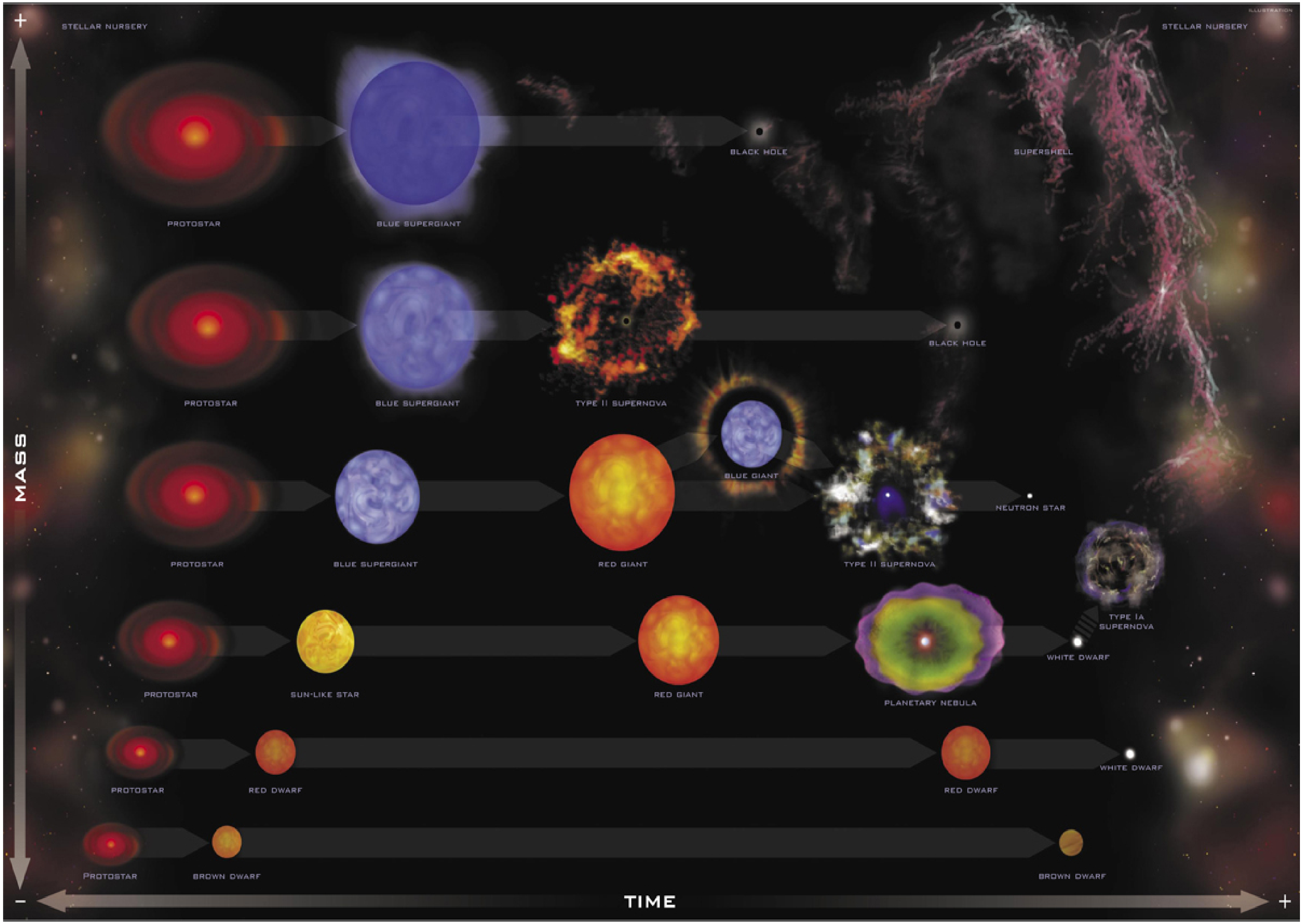
Image Courtesy of Museum of Flight

Single Star Evolution



Images Courtesy of SSC IR Compendium

Mass Dictates Evolution*



Images Courtesy of CHANDRA EPO

* Composition changes evolution too, but it's a second-order contribution

Substellar Objects

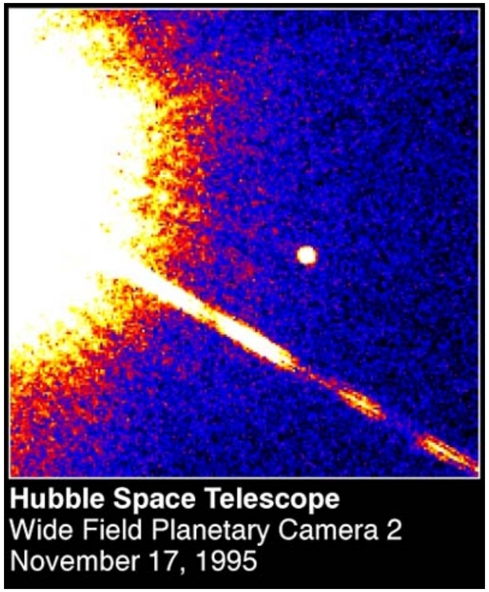
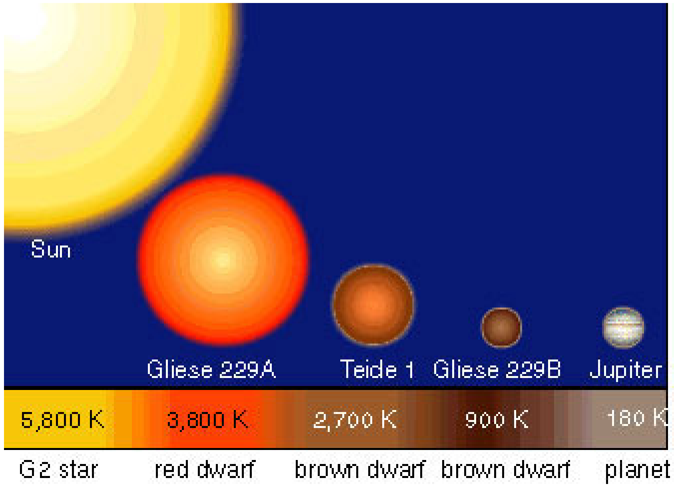


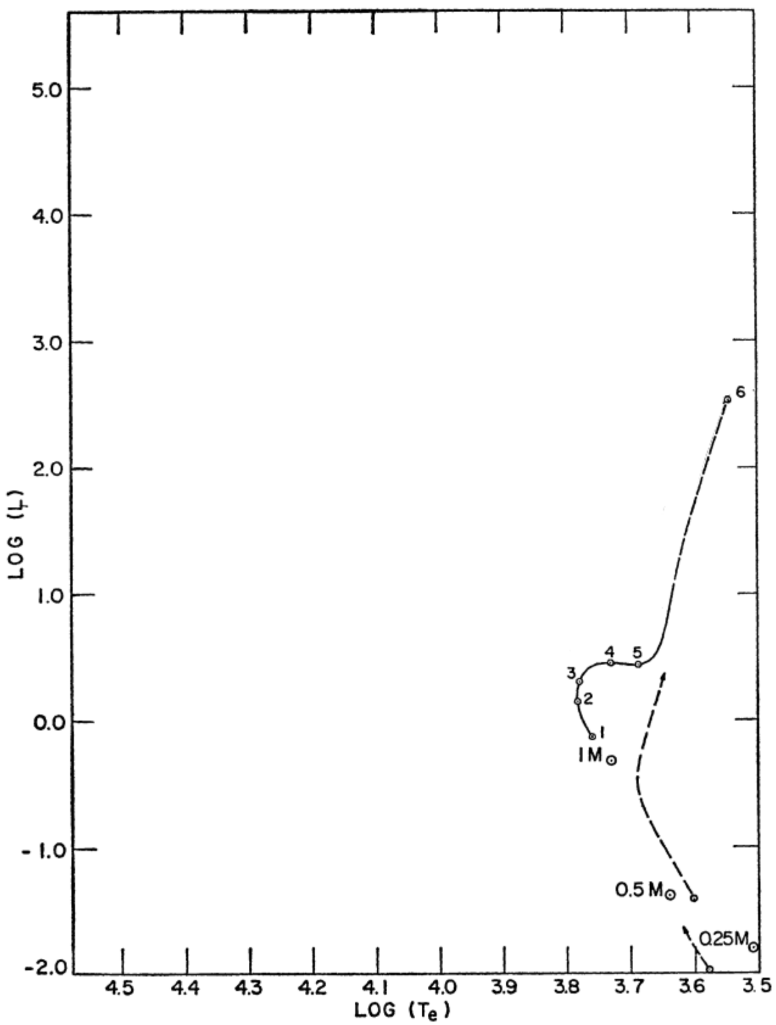
Image Courtesy of HST Gallery
PRC95-45 STSCI OPO



American Scientist/Linda Huff

- No Hydrogen Fusion
- Powered by gravitational collapse, Deuterium (^2H or ^2D) burning
- Masses below 0.085 M_o (~75 $M_{jupiter}$)
- $T_{eff} \approx 900$ K
- Sometimes Show Stellar-like activity

Low mass stellar evolution



Evolutionary Tracks, adapted from Iben (1967)

- $M_o < 0.3\ M_o$ remains on MS for more than T_{hubble}
- $M_o > 0.3\ M_o$ H in core exhausted, climbs up RGB
- H burning in shell, star swells. He ash falls on core
- He core becomes degenerate
- $M < 0.4\ M_o$ core degeneracy never lifted, becomes He white dwarf

Intermediate mass stars

- $0.4 < M_o < 6\text{-}10\ M_o$
  Degeneracy is lifted (He flash)
- Core expands, H-burning damped, star contracts
- Star moves into horizontal branch He burning produces C- and O- ash
- Shell He and H burning causes star to swell, move back towards RGB
- During AGB phase star undergoes mass loss
- Fusion ceases, star contracts maintaining Luminosity
- Evolves into planetary nebulae whose core becomes a WD

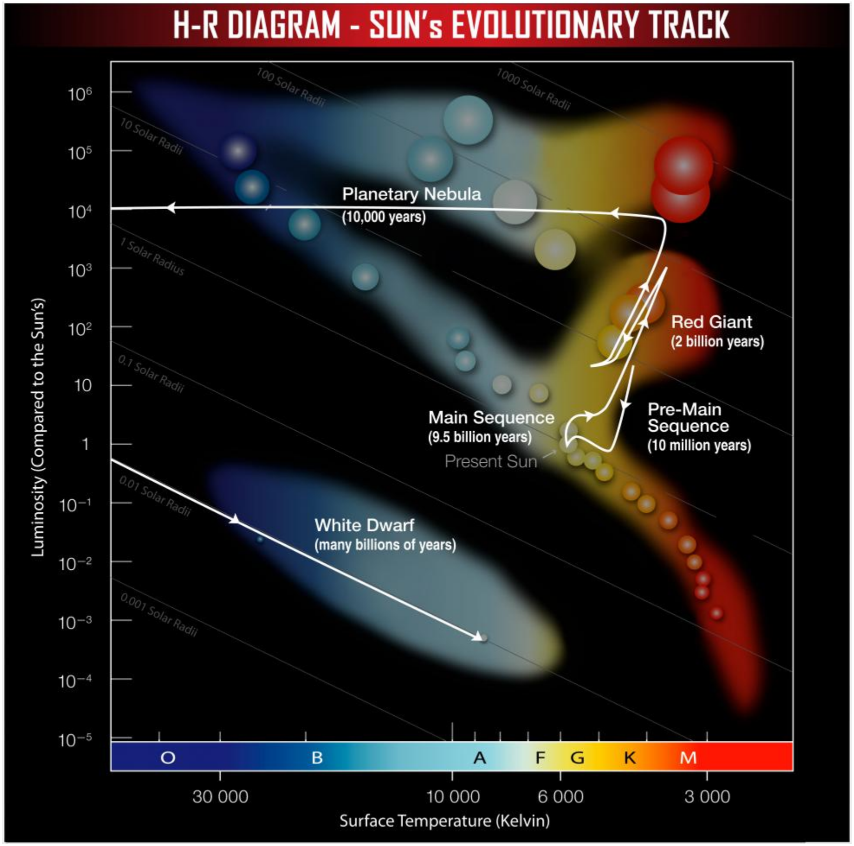
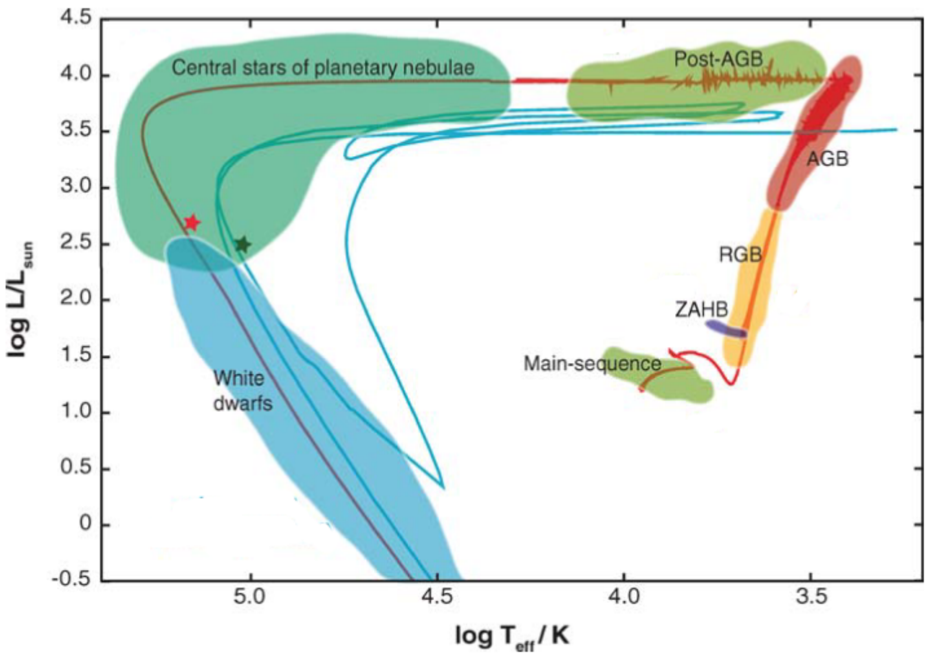


Image Courtesy of Museum of Flight

Intermediate-mass phase: Post-AGB

- Low to intermediate initial mass
- (1 - 8 M_o) transitioning between AGB and PN
- Not very well understood
- Fairly short lived (102 − 103 yr)
- Often shrouded in dust with silicate or carbonate features in the IR
- Look like Supergiant in many respects
- Detailed Spectral Analysis needed, will reveal s-process elements
- Several Unstable Pulsation Modes Evolution of a 2M_o star (Herwig, 2005)



Evolution of a 2M_o star (Herwig, 2005)

Massive Stars

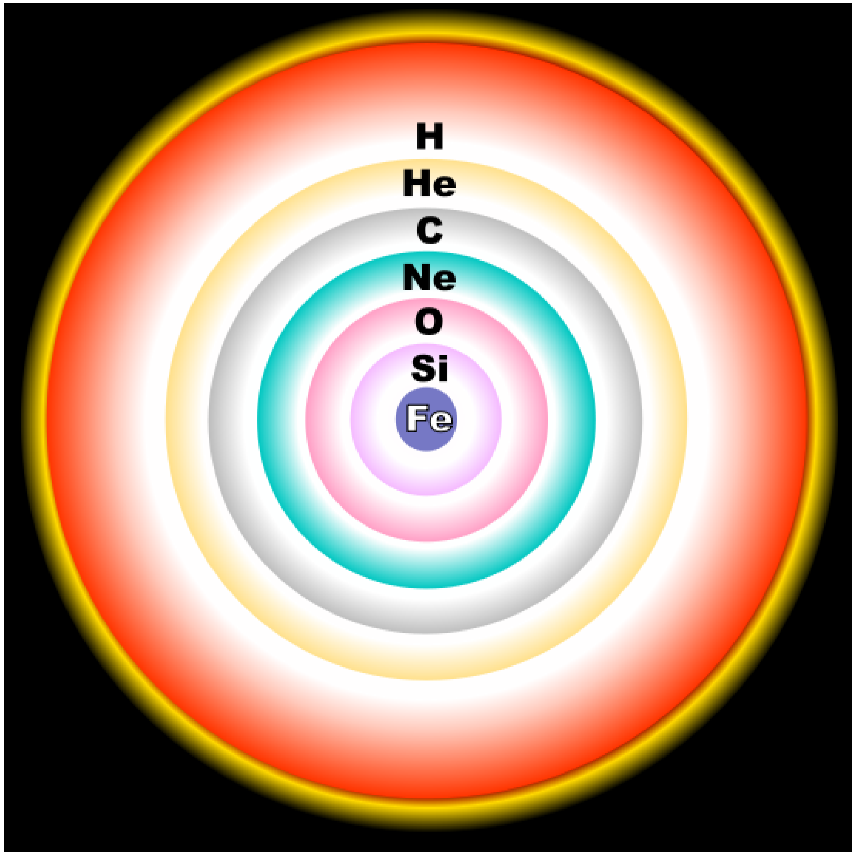
- $M > 10\ M_o$
- Burn Nuclear Fuel Quickly
- HR Diagram Becomes Mostly Useless
- Envelope cannot respond fast enough.

Dominant fuel	T_c	Duration	Important products
Carbon	5×10^8 K	10^3–10^4 yr	Ne, Na
Neon	8×10^8 K	10^2–10^3 yr	Mg, some O
Oxygen	1×10^9 K	< 1 yr	Si, some S, etc.
Silicon	3×10^9 K	days	^{56}Ni

Stellar Timescales (Hansen, 2004)

Massive Stars

- $M > 10\ M_o$
- Burn Nuclear Fuel Quickly
- HR Diagram Becomes Mostly Useless
- Envelope cannot respond fast enough.
- Stars Become Highly Layered



Layering in Highly Evolved Stars
(Wikimedia Commons)

Massive Stars

- $M > 10 M_o$
- Burn Nuclear Fuel Quickly
- HR Diagram Becomes Mostly Useless
- Envelope cannot respond fast enough.
- Stars Become Highly Layered
- Core Collapse

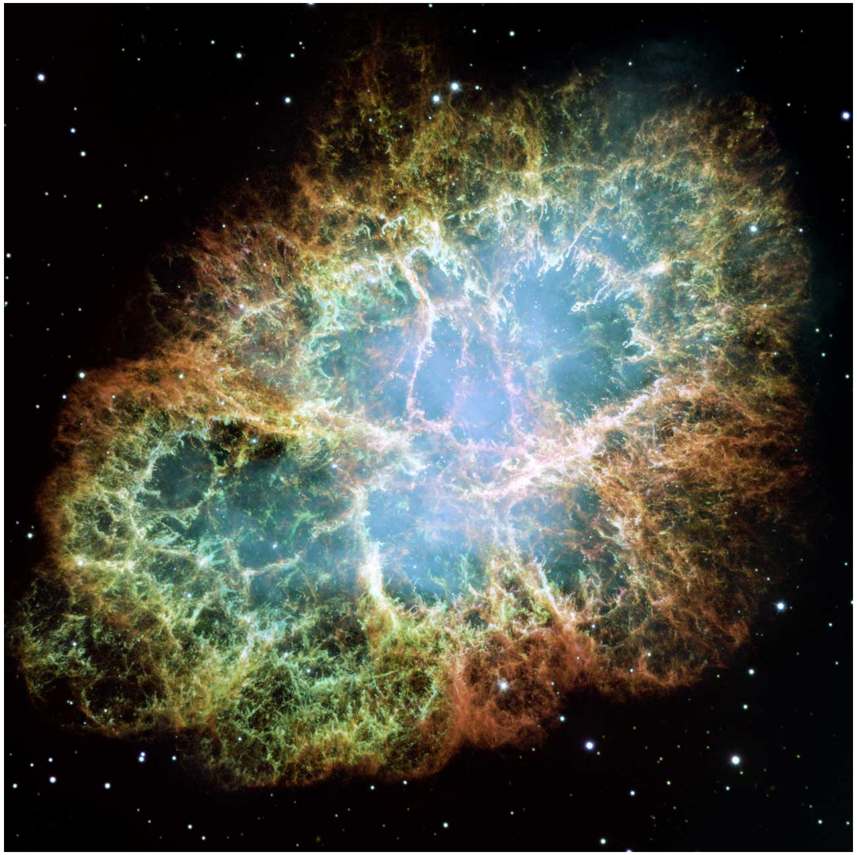


Image Credit: Hester (2005) via. HST

- Roche Lobes

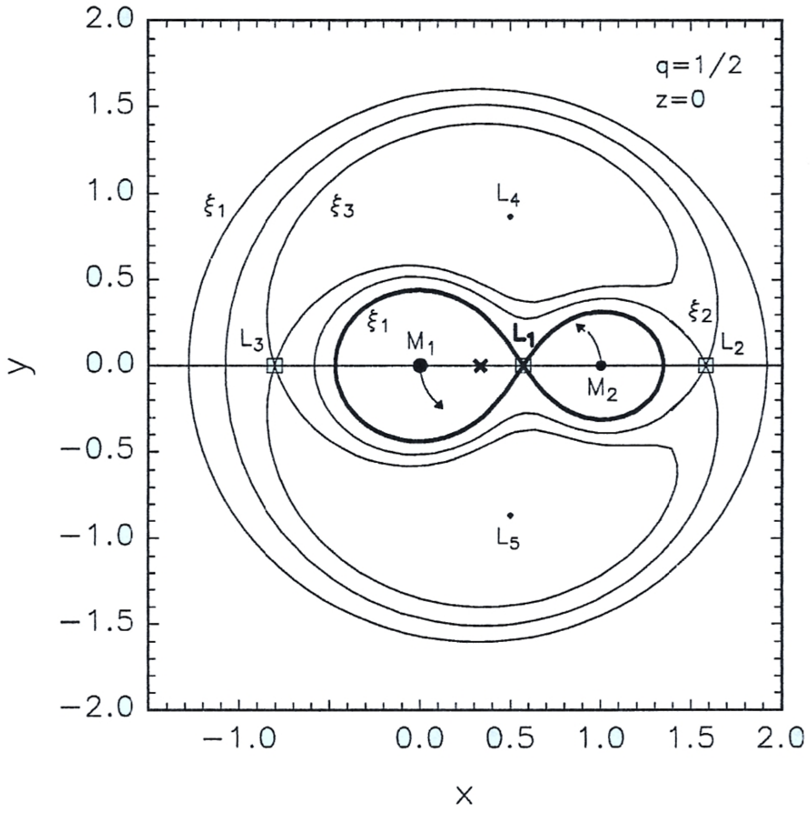


Image Credit: Hansen (2004)

Binary Star Evolution

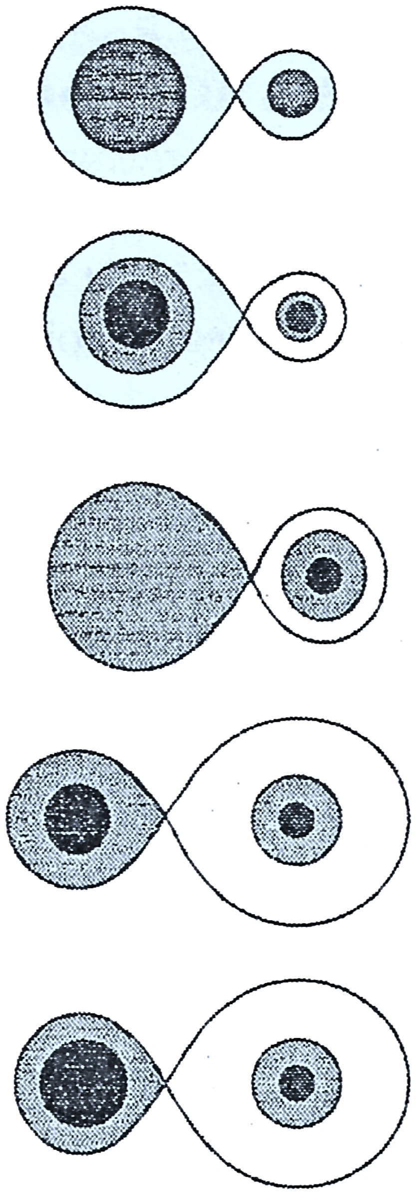
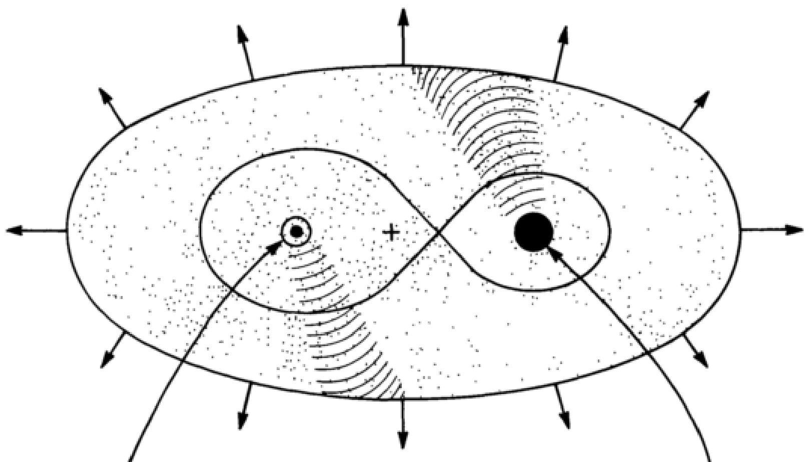


Image Credit: Hansen (2004)

- Roche Lobes
- Roche Lobe overflow, mass transfer

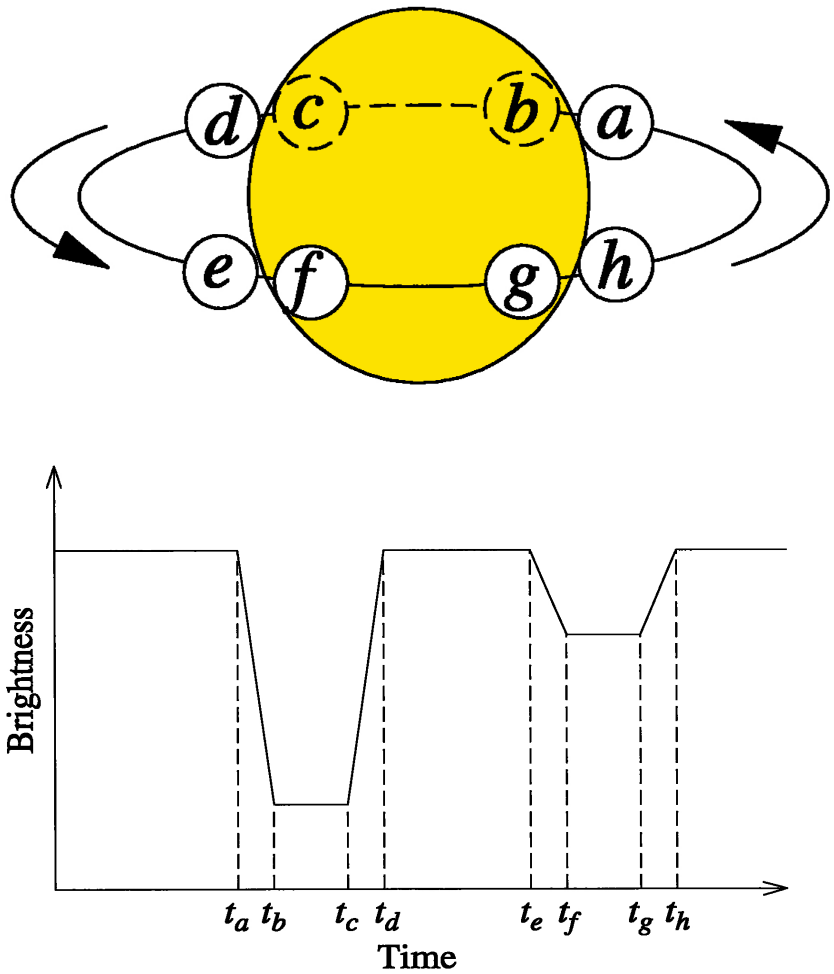
Binary Star Evolution

- Roche Lobes
- Roche Lobe overflow, mass transfer
- Common Envelope Phase



Common Envelope (Iben, 1991)

Binary Star Evolution



Eclipsing Binaries; Ostlie (1996)

- Roche Lobes
- Roche Lobe overflow, mass transfer
- Common Envelope Phase
- Observable Eclipses

Other Stellar Evolution Concerns

Single Stars

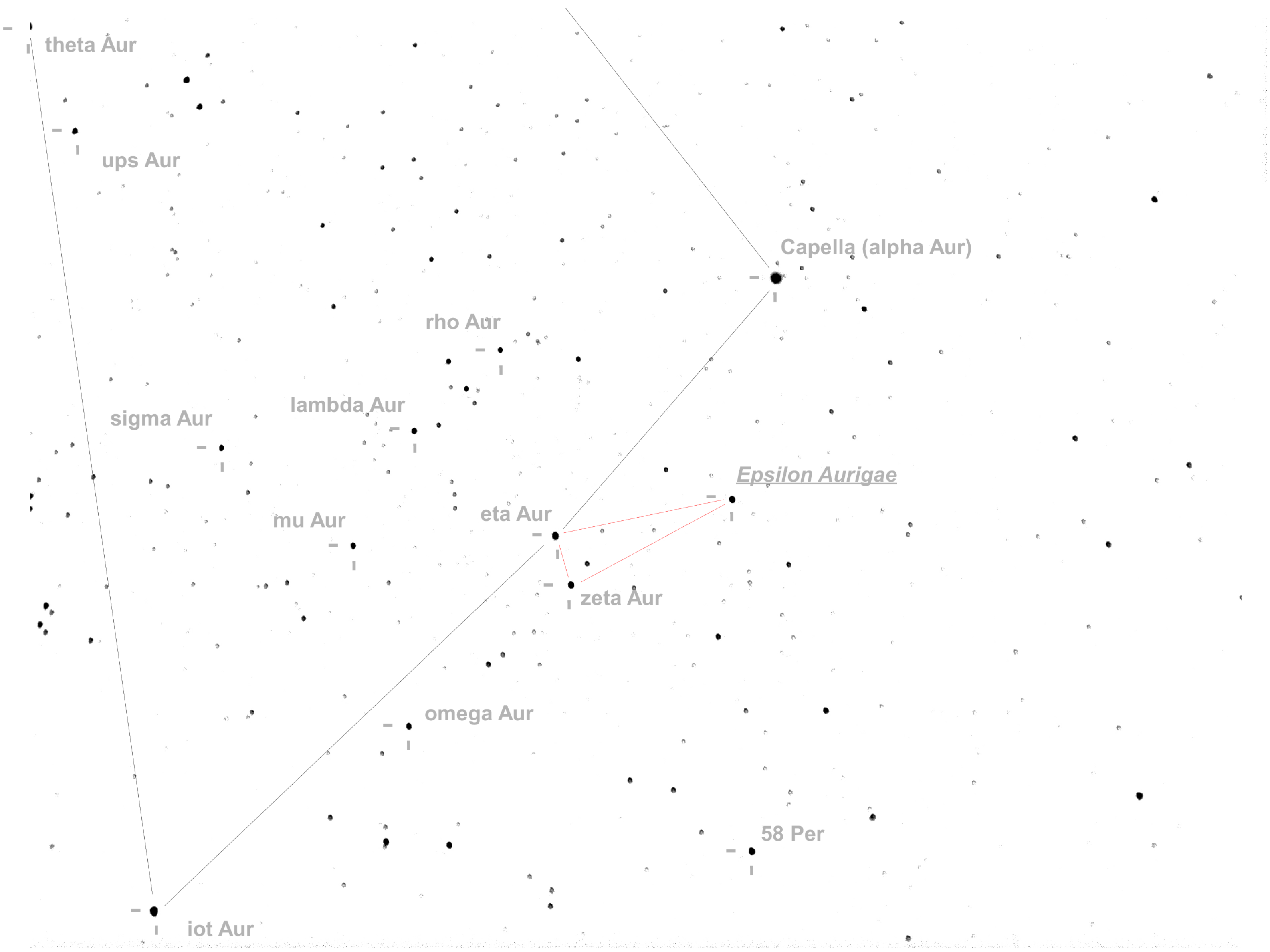
- Stellar Composition
- Rotation
- Mixing / Convection

Binary Stars

- Non-spherical cores
- Tidal interactions
  - Including tidal heating

Now on to Epsilon Aurigae!

Where to find eps Aur



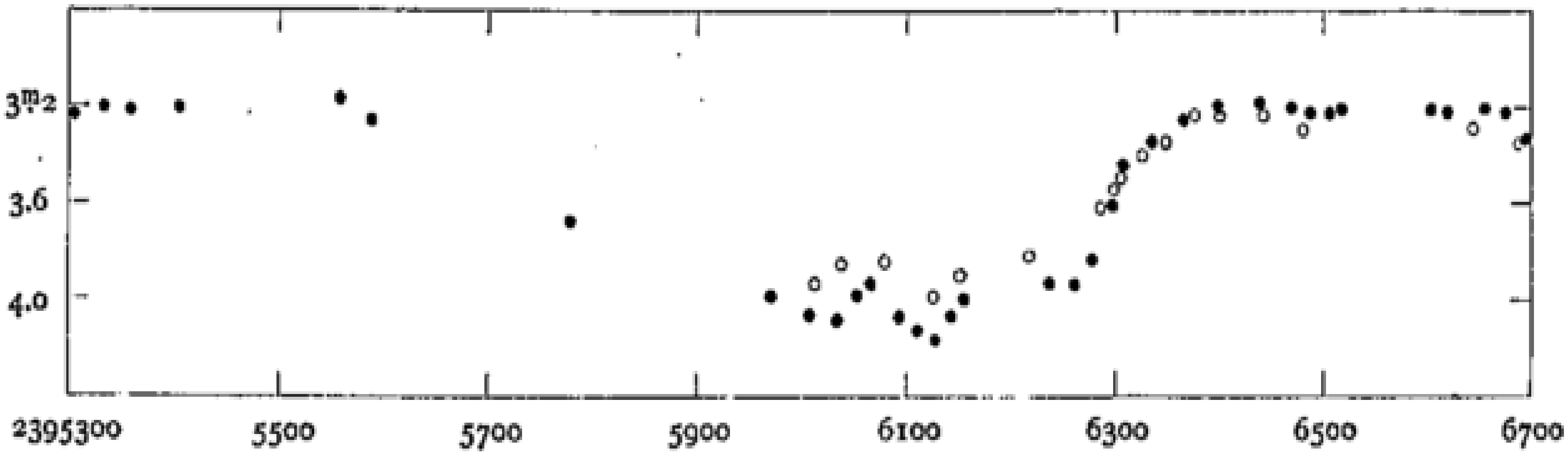
About eps Aur

- What is eps Aur?
  - Single line spectroscopic eclipsing binary star system
    - Single Line: only one star visible spectroscopically
    - Eclipsing: One object passes in front of the other
- What makes it so interesting?
  - ...

The Discovery

- 1821: High Minister Fritsch of Quedlinburg, Germany

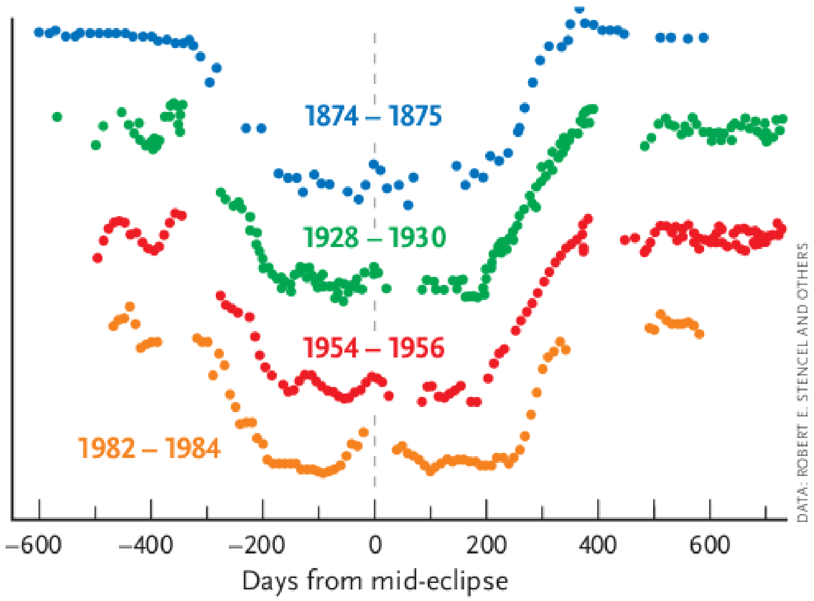
  "I saw the star epsilon Aurigae in the she-goat of the Charioteer [i.e. Auriga] frequently [to be] so dim compared with zeta and eta that it was barely to be recognized. Has [any]one [else] as yet observed this?"



1846 Eclipse of eps Aur; Gussow (1936)

82 Years Later...

- 1821-1936
  - 41 observers monitored eps Aur
- 1903 (Ludendorff)
  - 27-year period determined
- 1912 (Russel)
  - Analytical Model for binary star eclipses developed.
- 1915 (Shapley)
  - Found binary star theory didn't work on eps Aur.



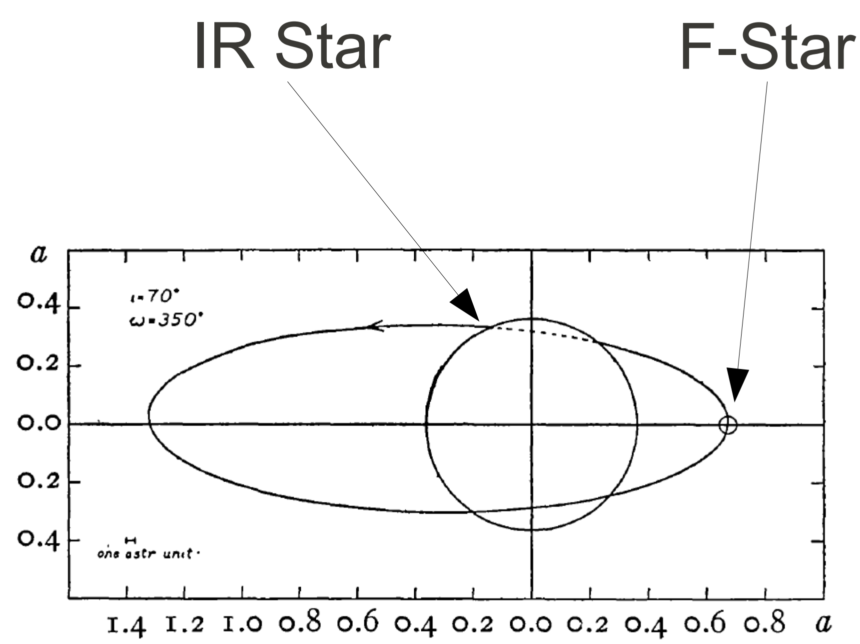
A Paradoxical Problem

- Binary Star Theory said companion was equally massive to the observable F-star, but yet unseen!

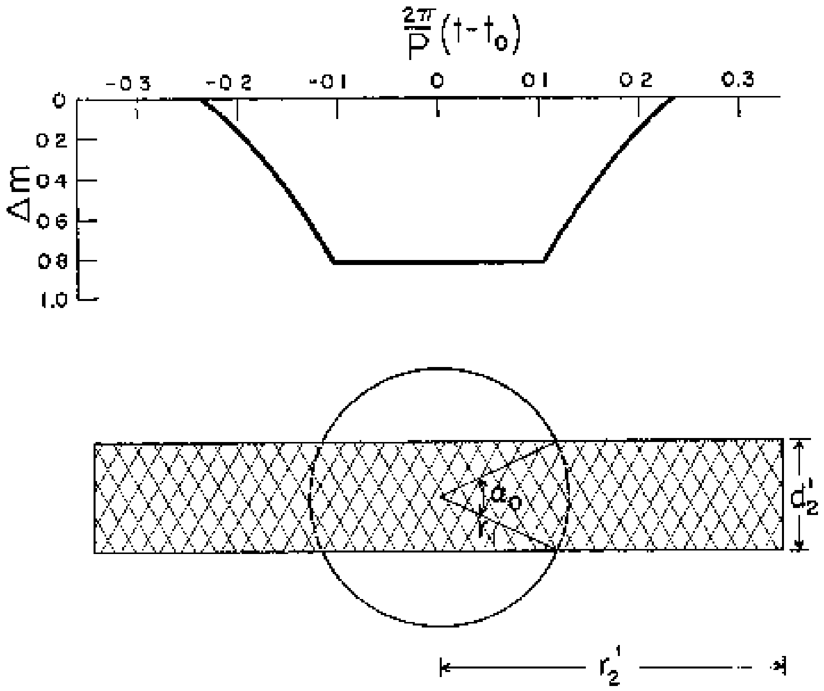
    Questions:
    - What is the companion?
    - Why is it so under-luminous?
    - Is it detectable at all?
    - How do these eclipses happen/work?

Explaining the Eclipse

- 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



Explaining the Eclipse



- 1954: Kopal
  - While refuting Struve's model, he claims it could just be a flat, semi-transparent ring of material composed of small 10-100 um particles.
- 1965: Huang
  - The first analytical model supporting a disk-like object as the cause of the eclipse.

Explaining the Eclipse

Image Credit: Dan Weeks

- 1971: Cameron
  - Agreed with Huang, but supposed a black hole was lurking at the center of the disk.
- 1971: Wilson
  - Simulated the eclipse on a computer and criticized the Huang model. Claimed the disk was physically thin, but optically thick.

Explaining the Eclipse

- 1985: Eggleton et al.
  - Proposed that the disk obscured two stars, rather than just one.
- 1985: Schmidtke
  - Explored the possibility that a gravitational lens could cause the mid-eclipse brightening.

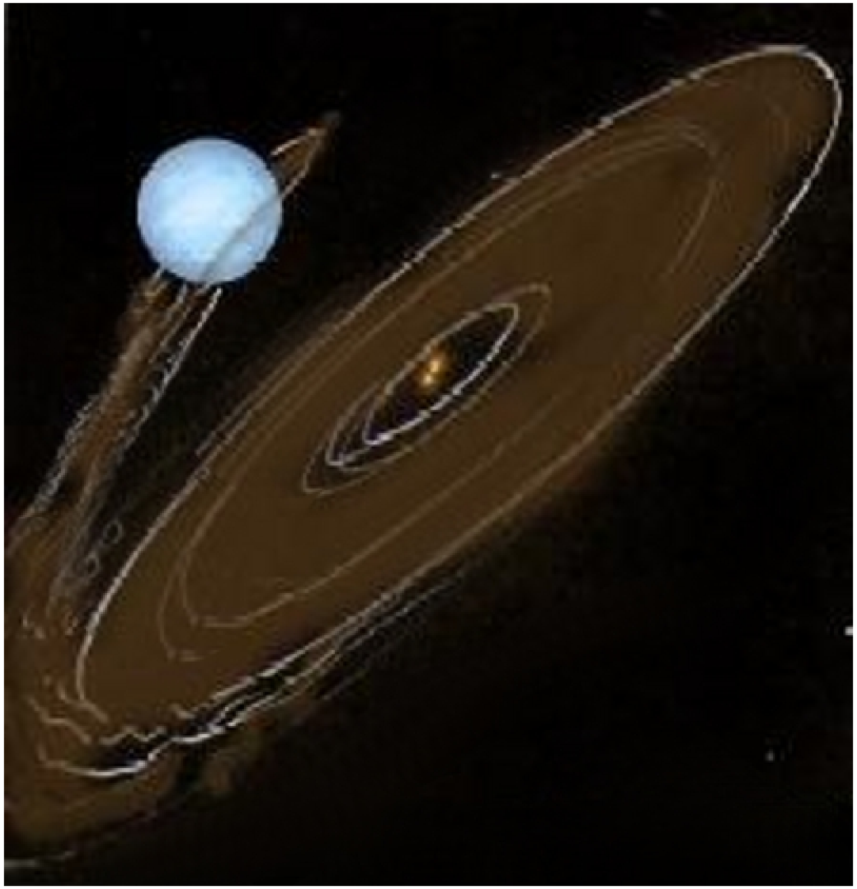
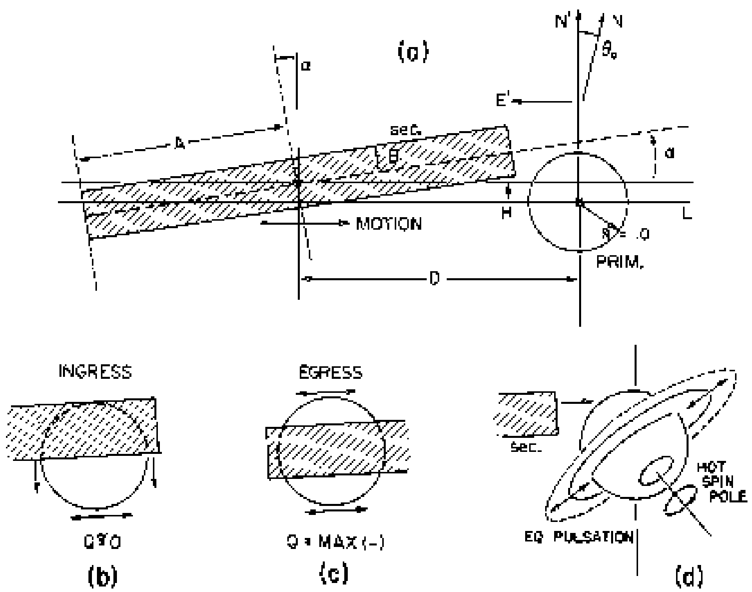
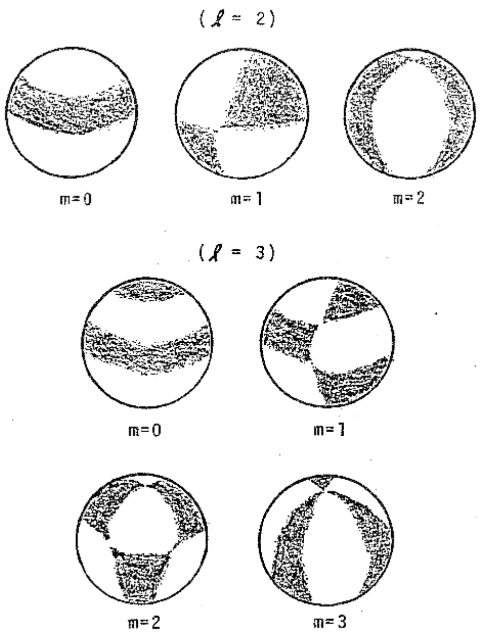


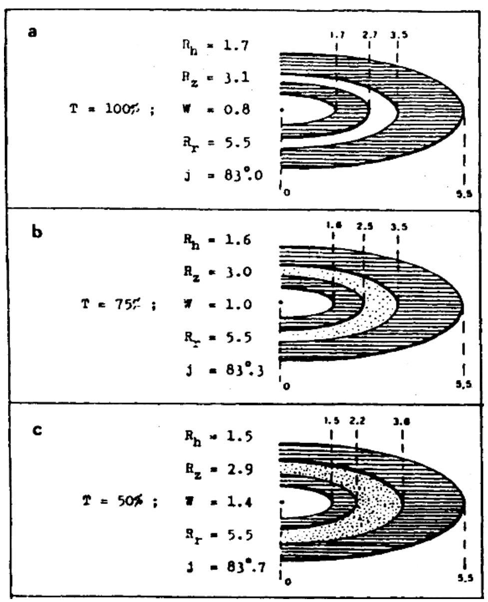
Image Credit: M. Carroll, R. Stencel (2008)

Explaining the Eclipse

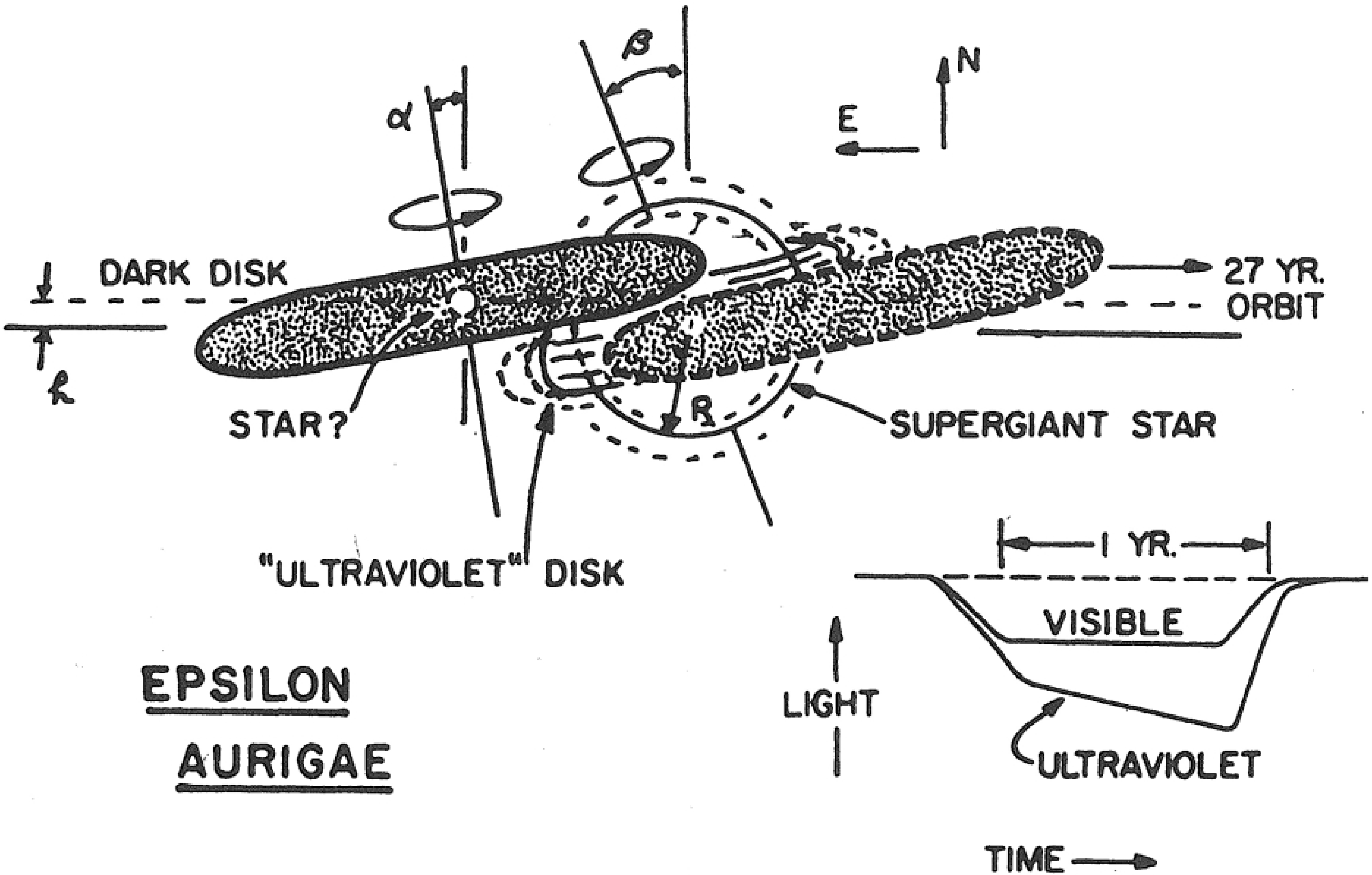
- 1986: Kemp
  - Obtained polarimetry during the 1983 eclipse, argued that the disk is inclined.
- 1989: Henson
  - F-star might be undergoing non-radial pulsation.
- 1990: Ferluga
  - Tweaked the Huang model, proposed the disk consisted of a series of rings.







Current Model of eps Aur



Two Competing Theories

High Mass Scenario

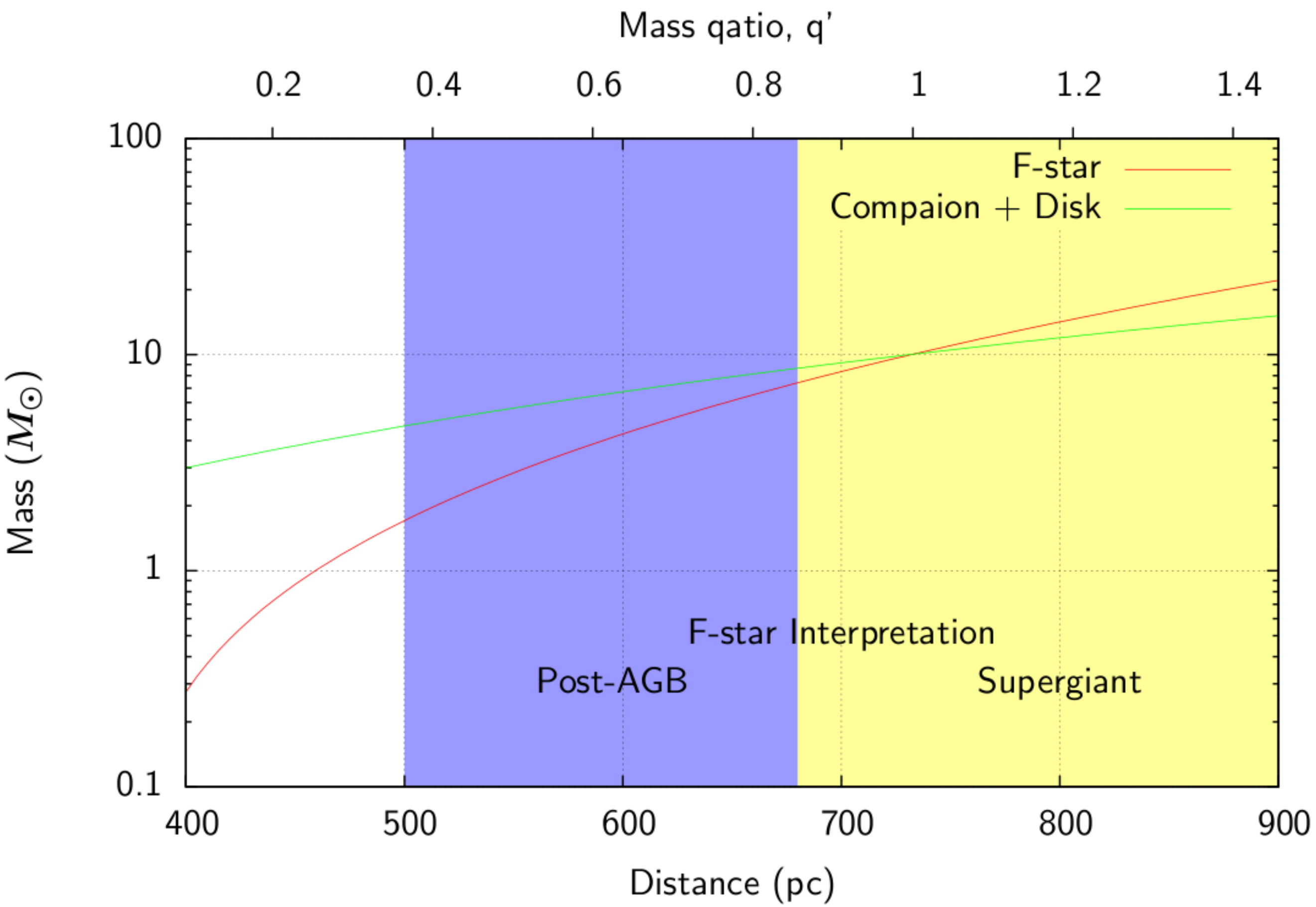
- F-star
  - Type: Superigant
  - $M_o \sim 15$
- Star + Disk
  - Young Stellar Object

Low Mass Scenario

- F-star
  - Type: Post-AGB
  - $M_o \sim 4$
- star + Disk
  - Main Sequence ~B5V
  - Disk is debris from mass overflow

But how to we tell which is right?

- Determine the Distance
  - Hipparcos: 653 +/- 551 pc
  - Astrometry + RV: 580 +/- 20 pc
  - Supergiant Stellar Evolution: 725 pc

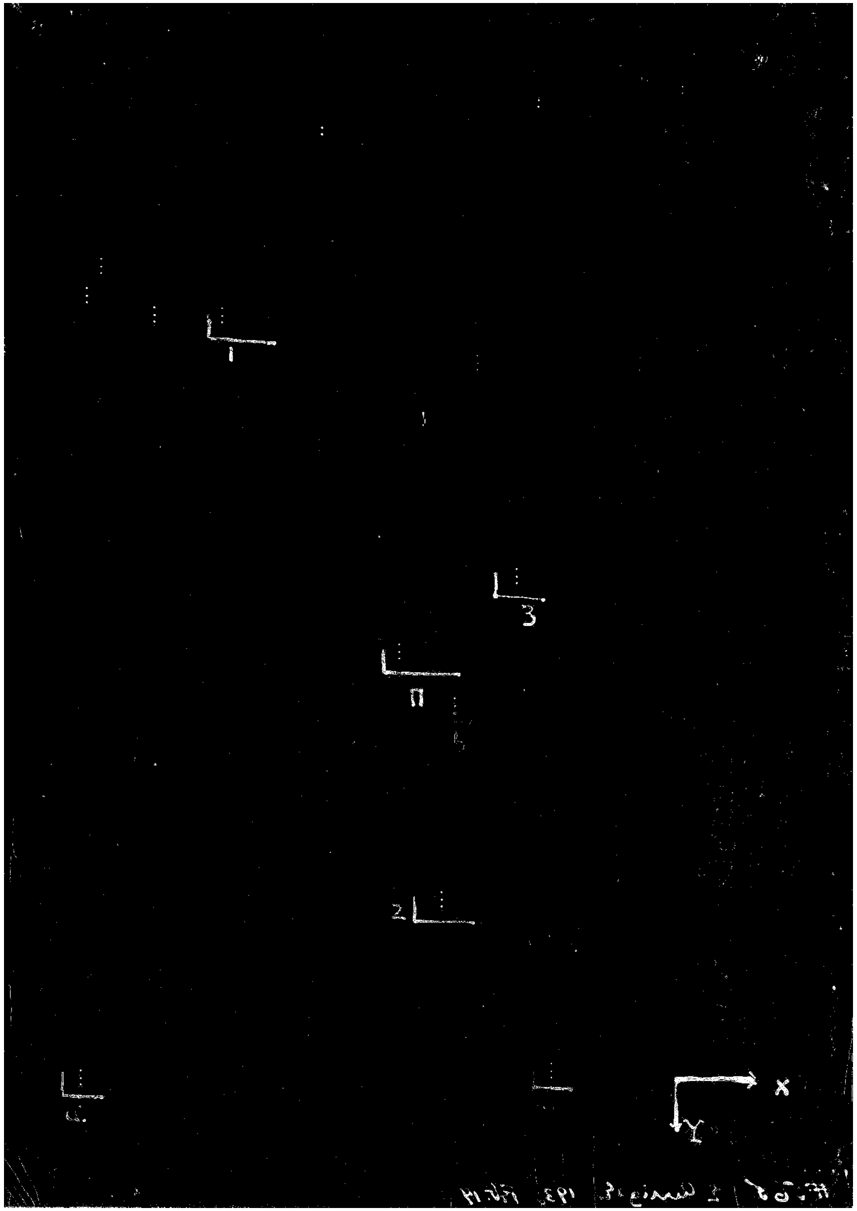


Problems Abound...

- Hipparcos Error Bars 2-3x bigger than field stars
- Astrometric Orbit doesn't match up with other data

Possible Cause/Solutions:

- Spots on F-star corrupt Hipparcos solution. Characterize spots.
- Incorrect PM used for astrometric ref. stars. Redo solution.



1938 Photograph of eps Aur and field stars. Sproul Observatory.

Spectra, Looking for Signatures

- If F-star is post-AGB it should have spectral signatures.
  - Enhancements of s-process elements
    - Y, Zr, Ba
  - Elevation of ^{13}C
- Any signs of the companion?

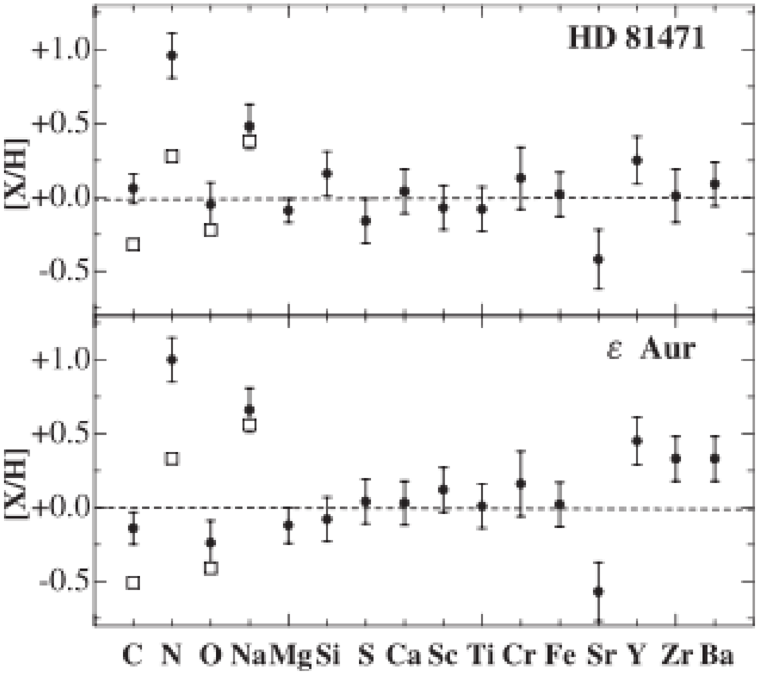
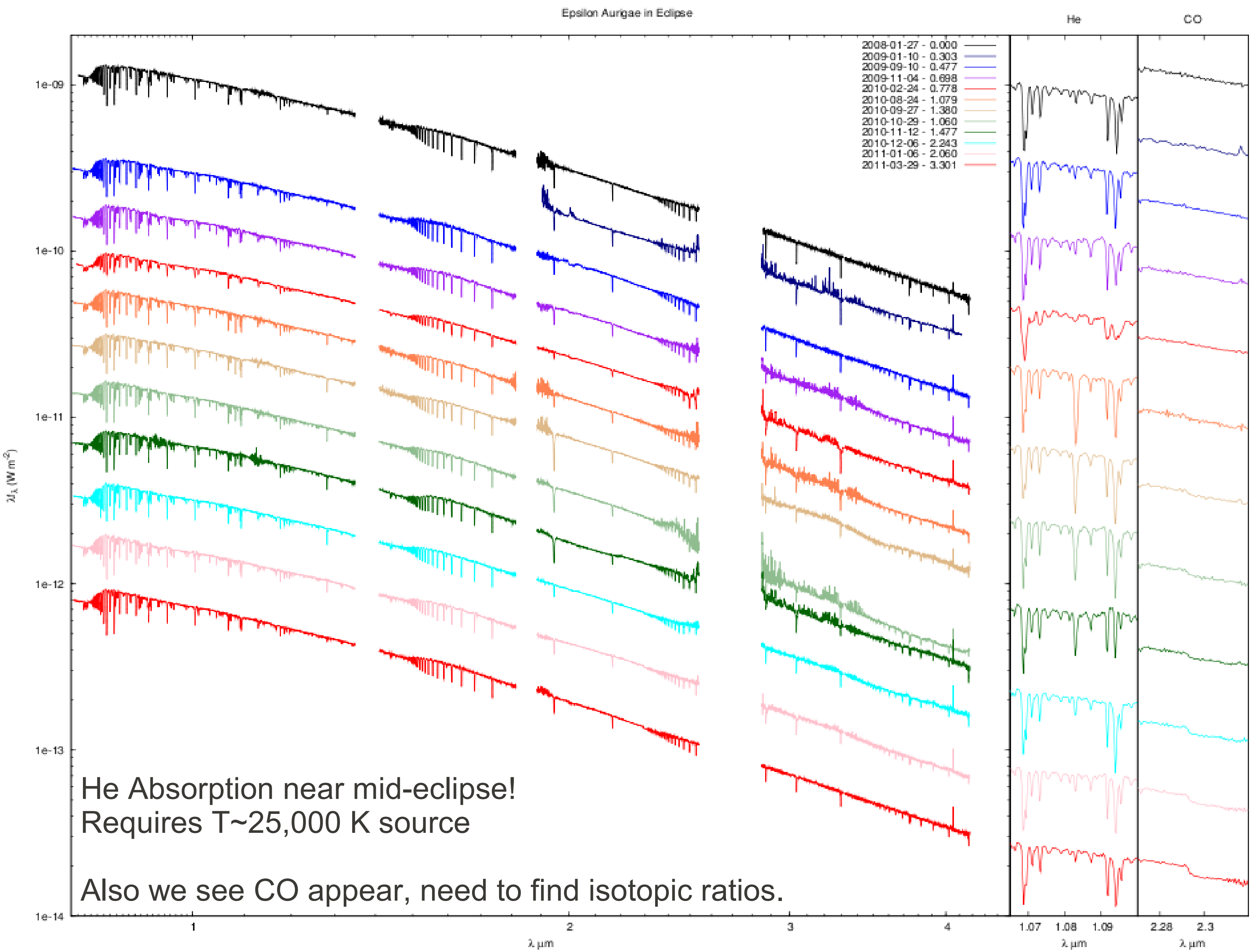


Image: Sadakane (2010)

IR Spectroscopy

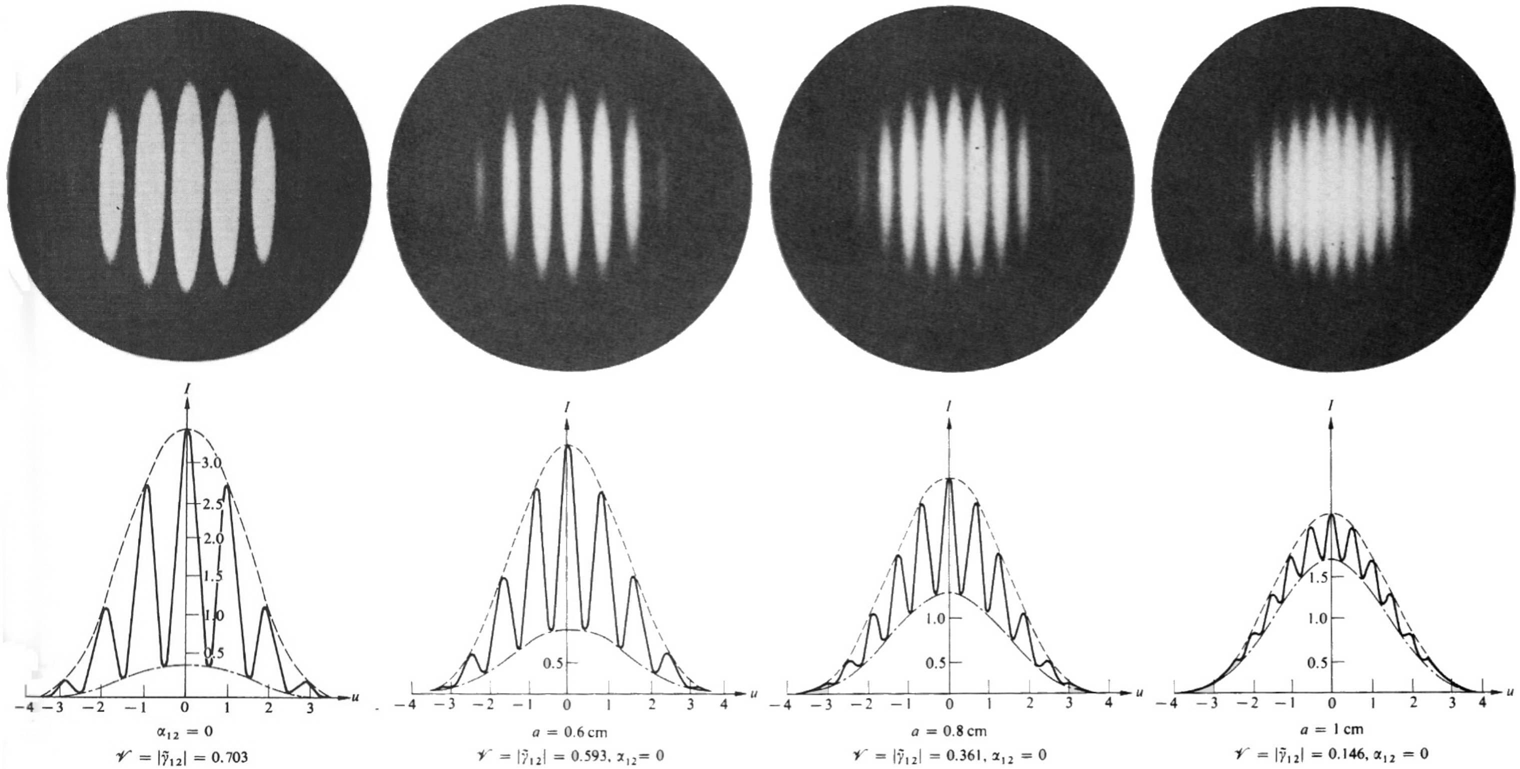


He Absorption near mid-eclipse!
Requires T~25,000 K source

Also we see CO appear, need to find isotopic ratios.

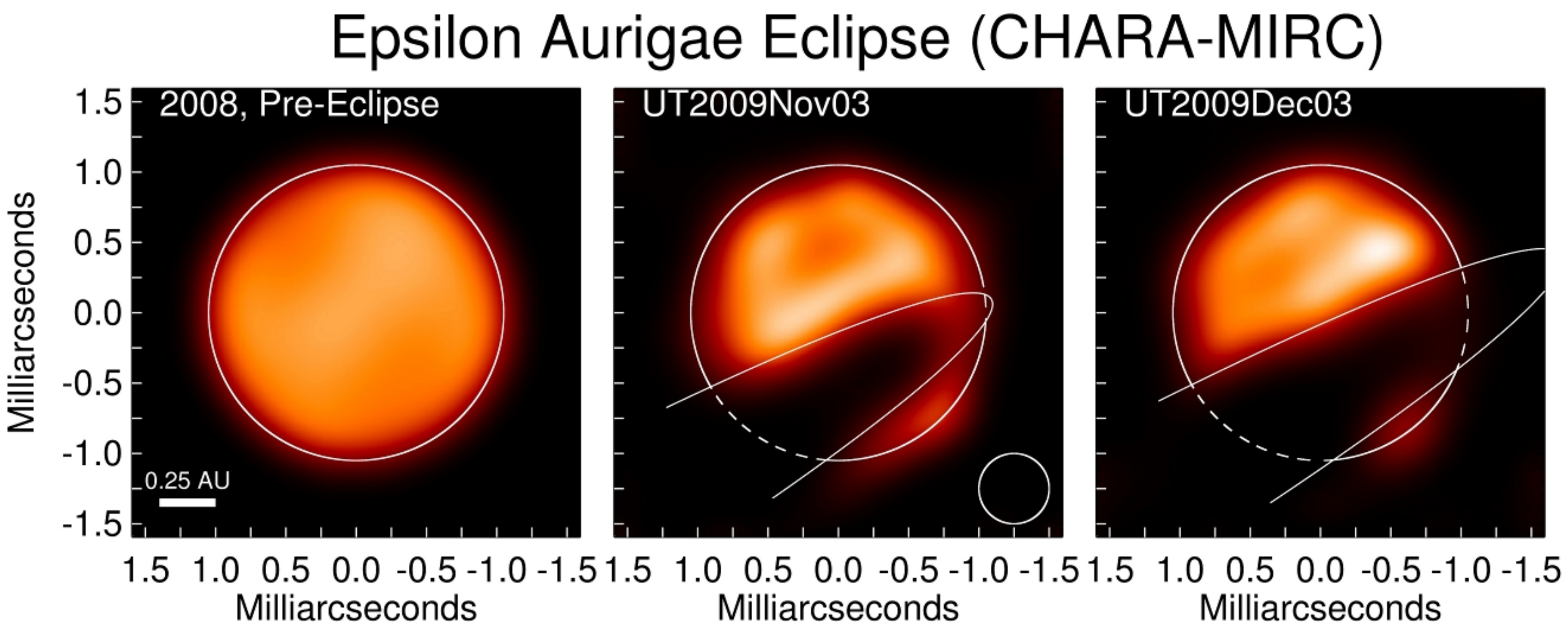
CHARA Interferometer

- Located on Mount Wilson, CA
- Six 1m Telescopes
- Maximum baseline 331m = 0.5 mas resolution in H-band

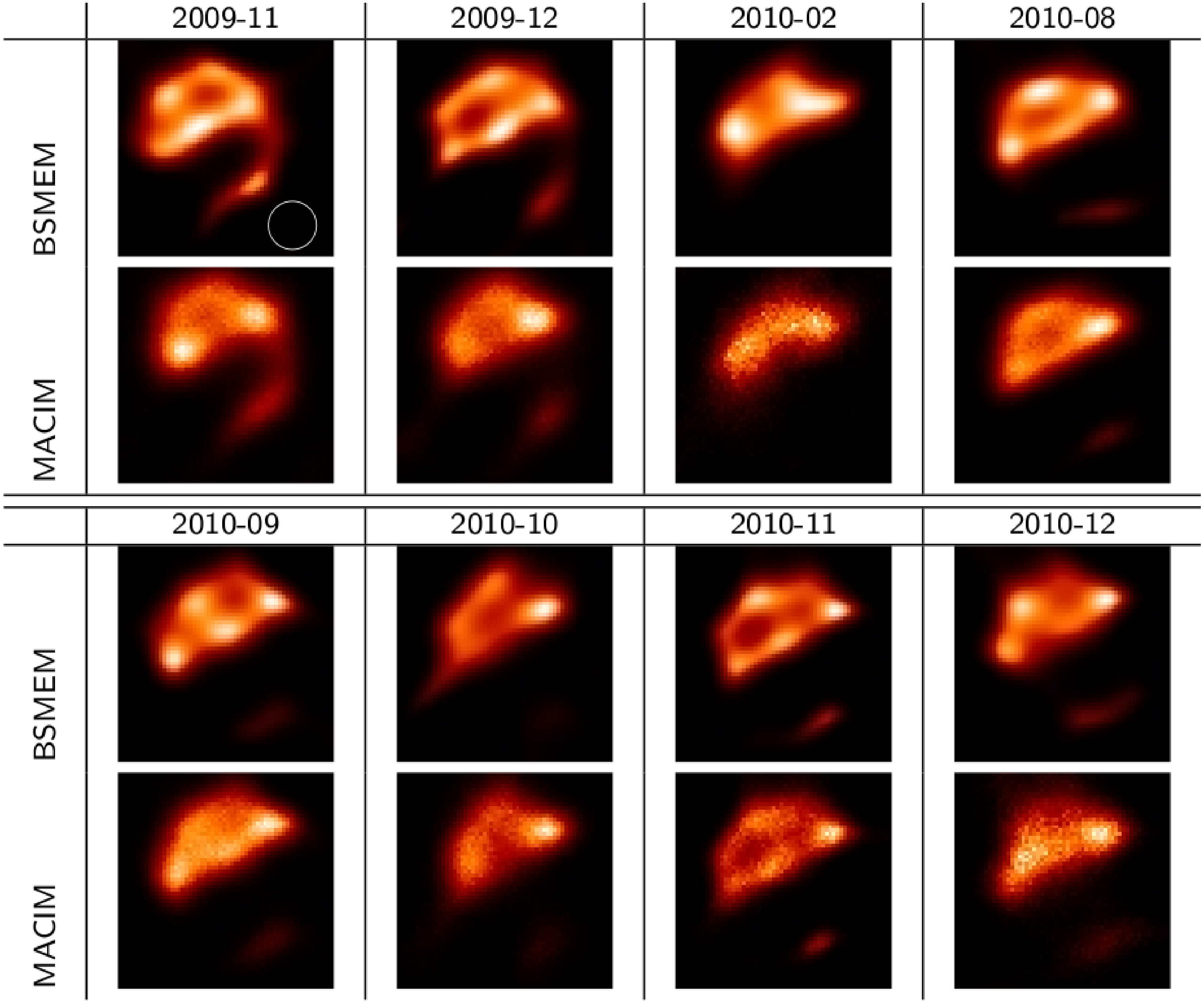


- Interferometers don't take pictures, they get fringes.

eps Aur Interferometric Images

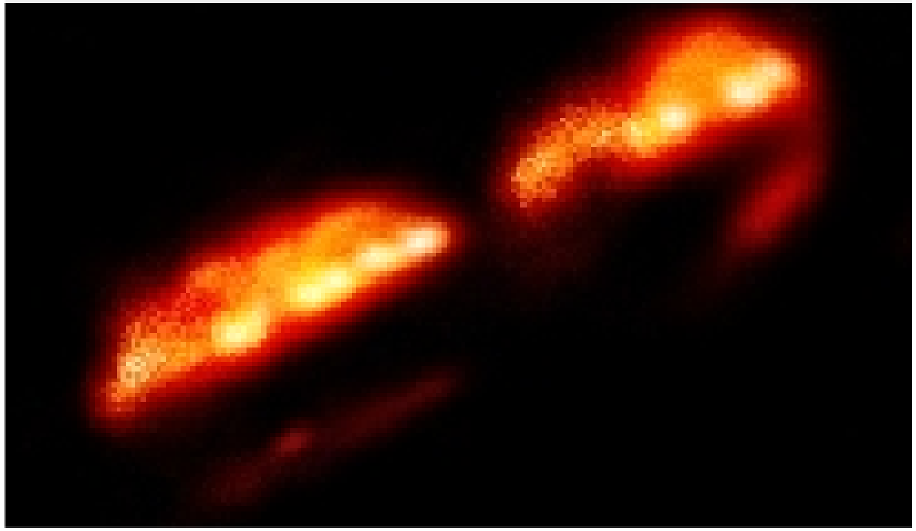


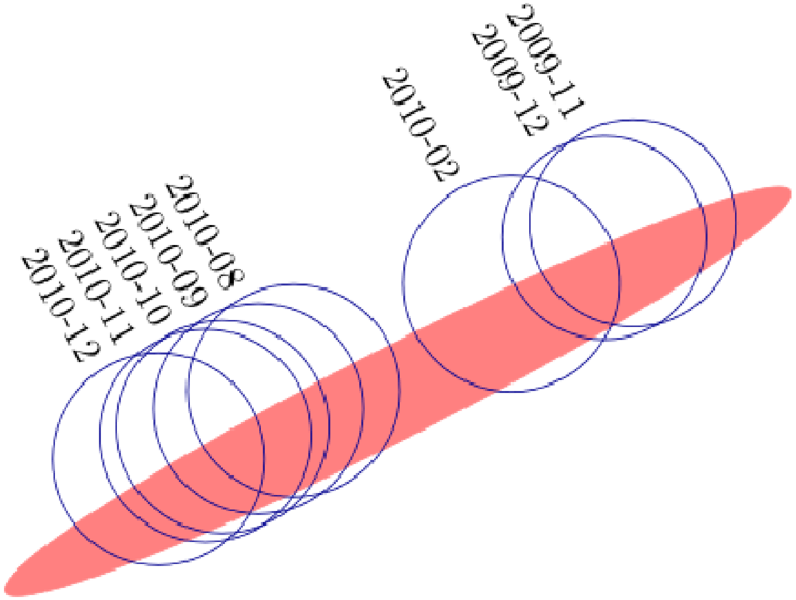
eps Aur Interferometric Images



From Kloppenborg (2011), Scale in 2009-11 image = 0.5 mas

First view of the Disk





Citizen Sky

- Citizen Science Effort focusing on epsilon Auriage
- Pro-Am collaboration through teams
- Blogs, Chats, Forums
- Photometry with DSLR cameras!!

- For more information:
  - http://www.citizensky.org