Writing a dissertation about epsilon Aurigae and experience with Citizen Sky

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Astro April Talks
Citizen Sky Webinar

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Background: Brian Thieme

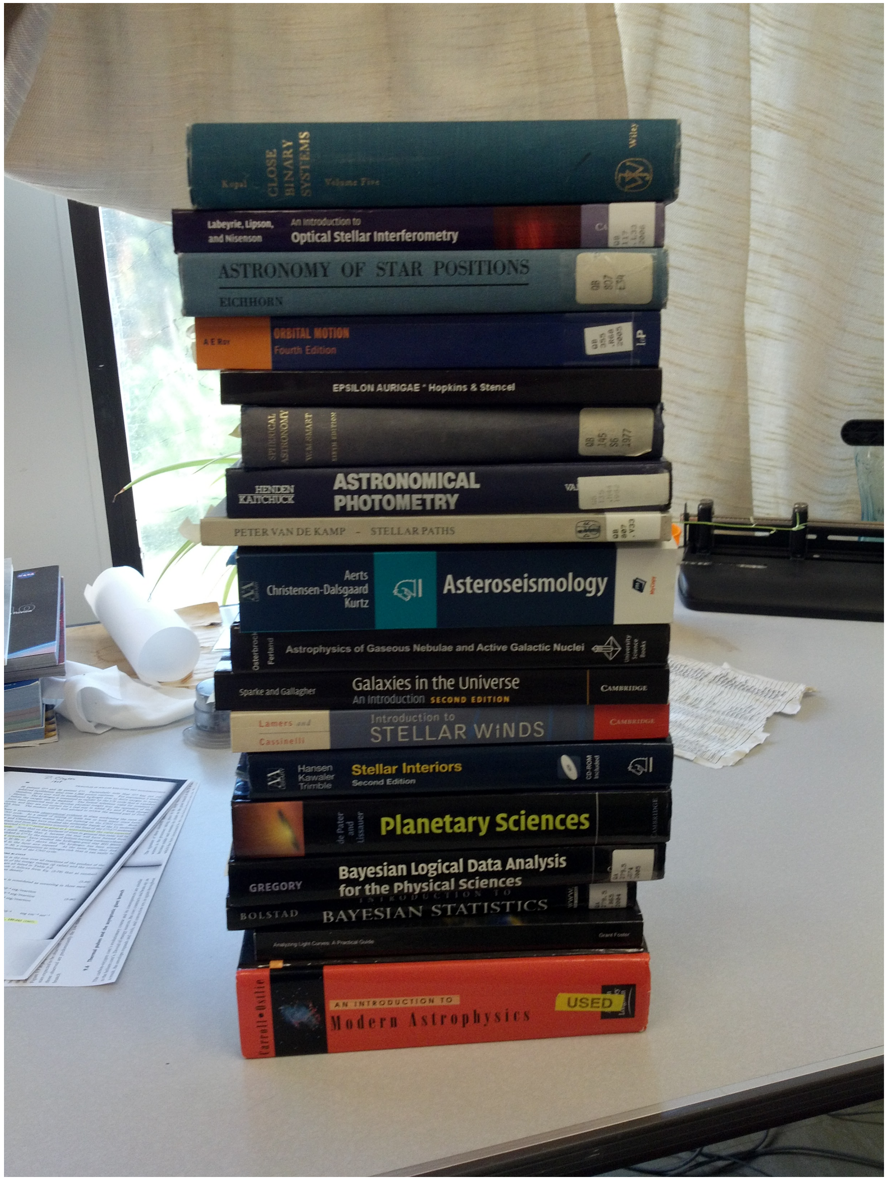
Writing a dissertation: Overview

- Background work, learning
- Formation of Hypothesis
  - What are you trying to show?
  - How are you going to show it?
- Conduct Research
  - Theory, observing,data reduction
- Write up results in document
- Submit work to committee
  - Limbo...
- Dissertation Defense
- Corrections and formatting
- Ph.D. ?

Background Work

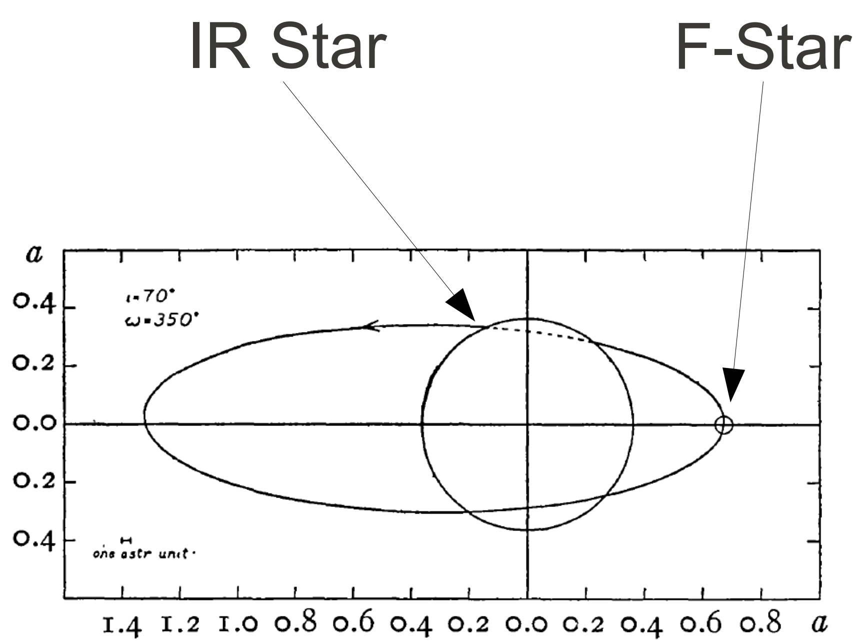
Reading

- 5 Astro texts
  - Stellar Interiors, Galaxy Evolution, Planetary Sciences, Nebulae and ISM, Stellar Winds
- 12+ Subject Specific Books
  - Interferometry (x2), Astrometry (x5), Asteroseismology, Bayesian Statistics (x2), Photometry, ???
- Software Documentation
- ~600 papers
  - ~250 eps Aur specific
    - Depth-first process



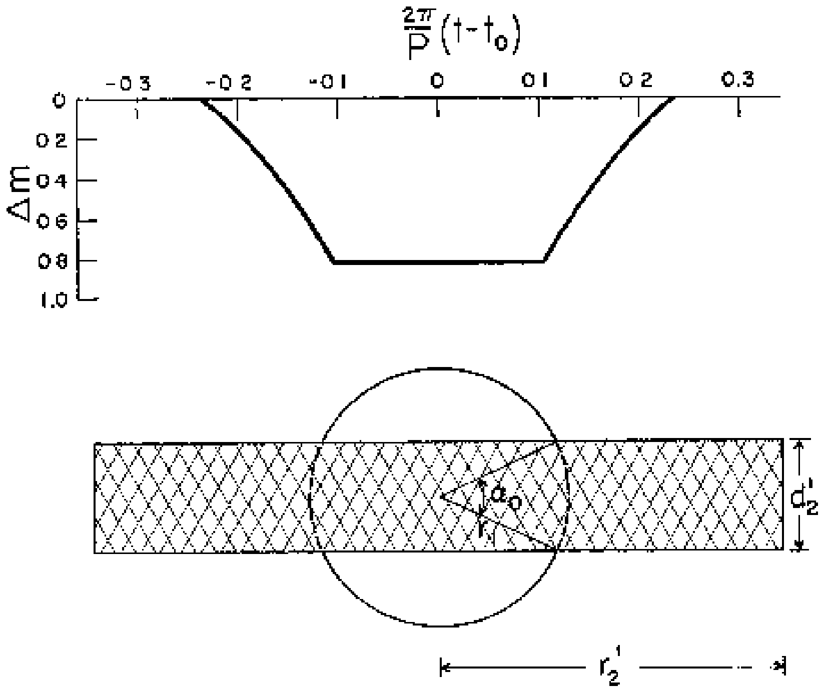
Background on eps Aur

- 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

- 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.



Background on eps Aur

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.

Background on eps Aur

- 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.

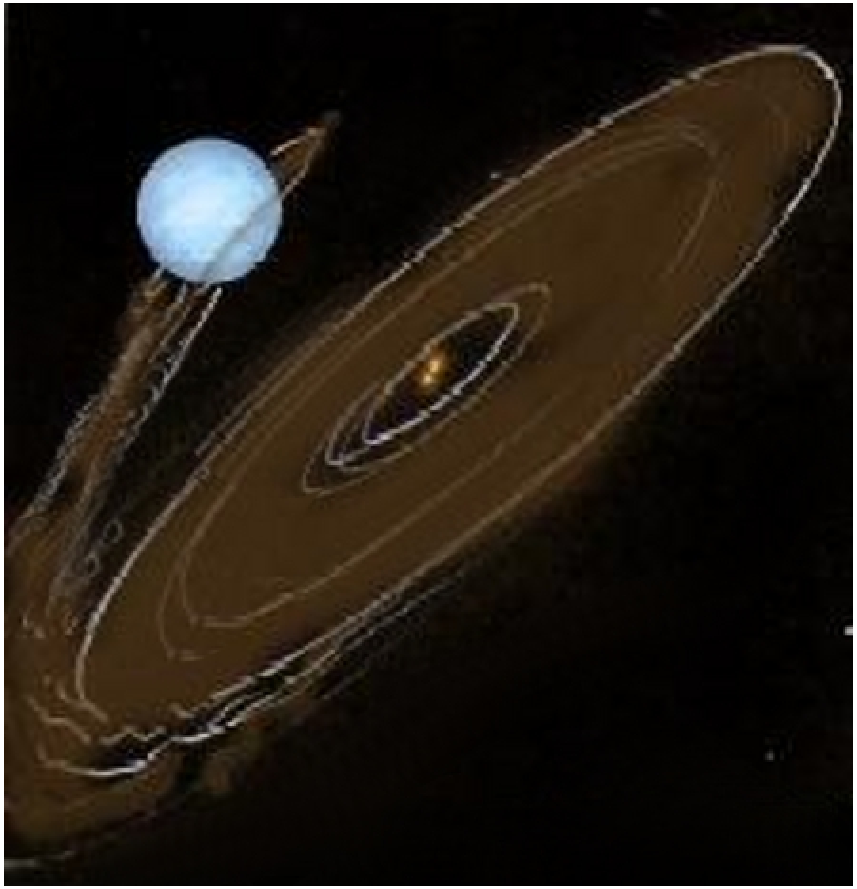
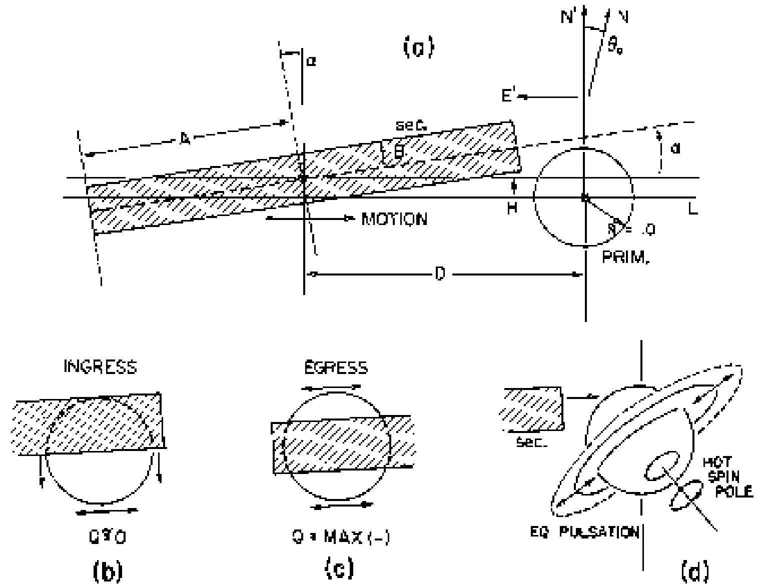
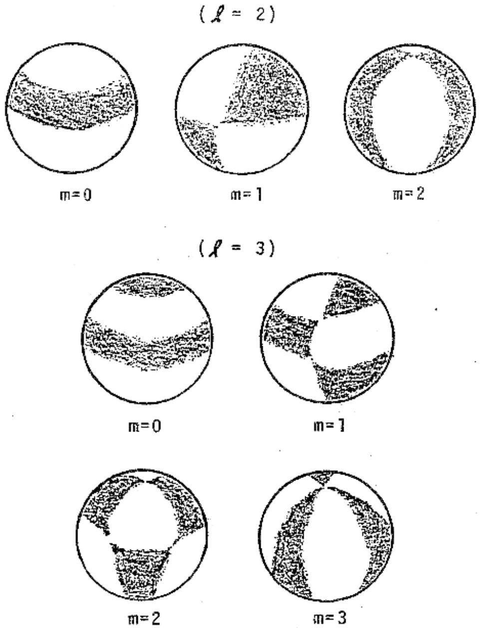


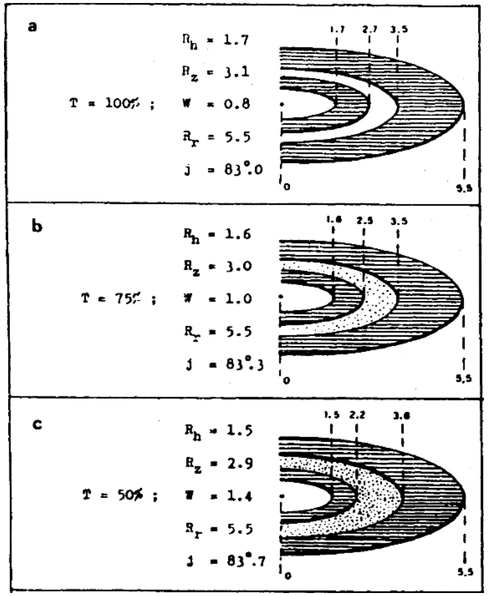
Image Credit: M. Carroll, R. Stencel (2008)

Background on eps Aur

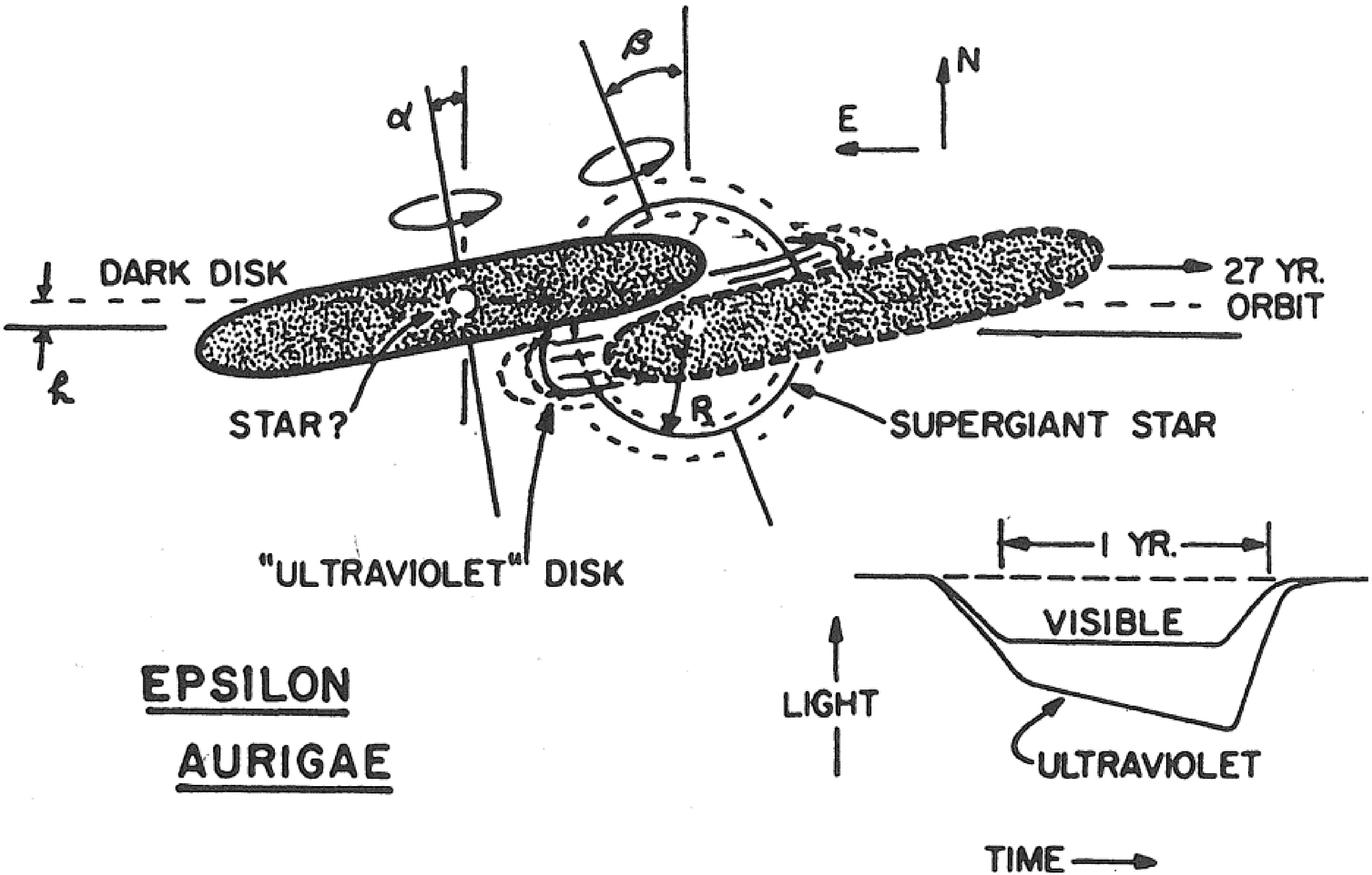
- 1986: Kemp
  - Obtained polarimetry during the 1983 eclipse, argued that the disk is inclined.
- 1989: Henson
  - F-star might be undergoing non-radial pulsation.
- 1990: Ferluga
  - Tweaked the Huang model, proposed the disk consisted of a series of rings.







2009 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

What do we (not) know?

- The system undergoes dimming every 27 years
  - Thought to be caused by a disk of material
- System could be in one of two evolutionary states
  - Supergiant
  - Post-AGB
- Data sources including
  - Photometry
  - Spectroscopy
  - Polarimetry
- Lots of random facts and odd things, e.g.
  - F-star undergoes 0.1 mag variations outside of eclipse

- But what is a supergiant or a post-AGB star?

HR Diagram

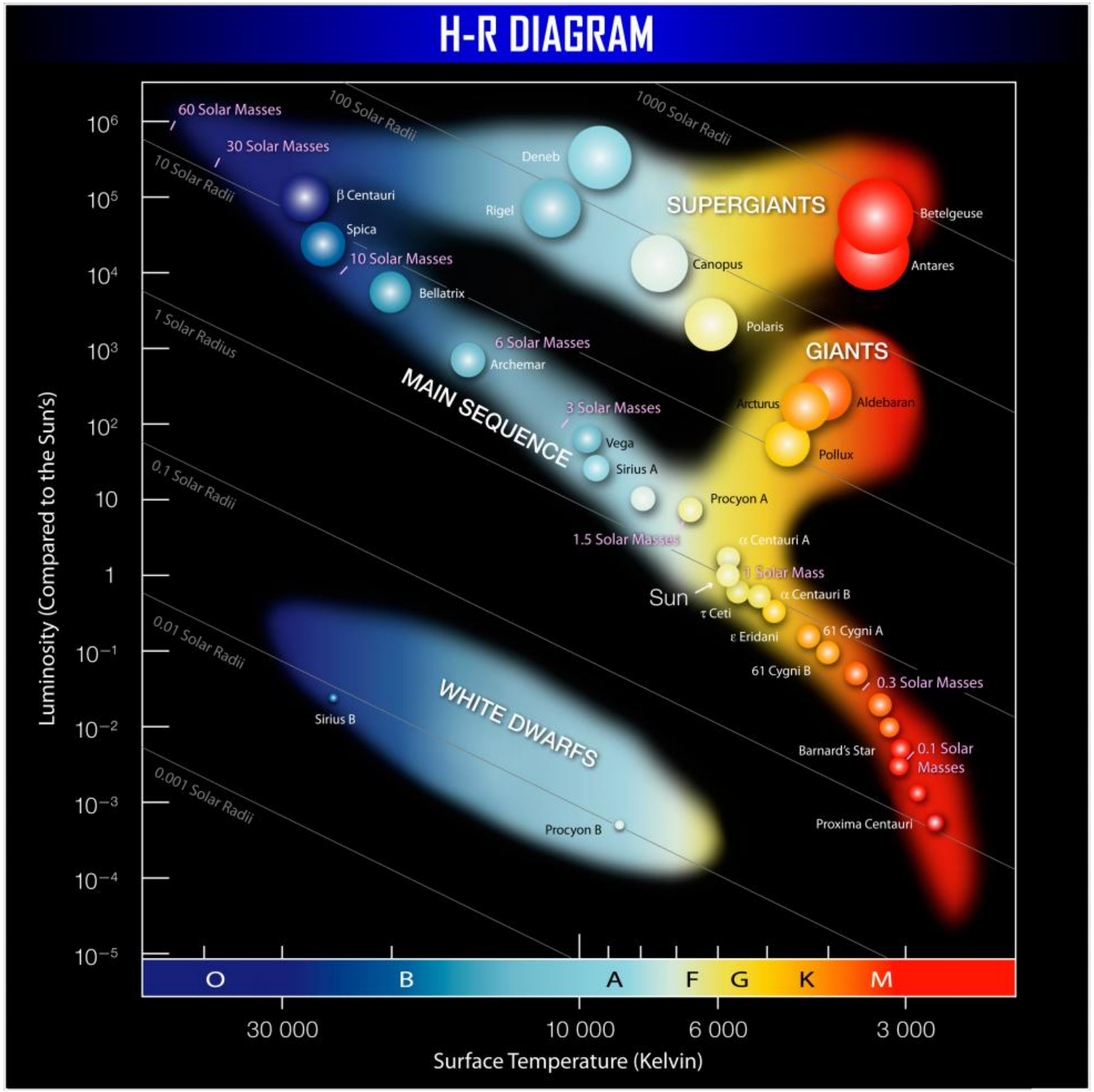
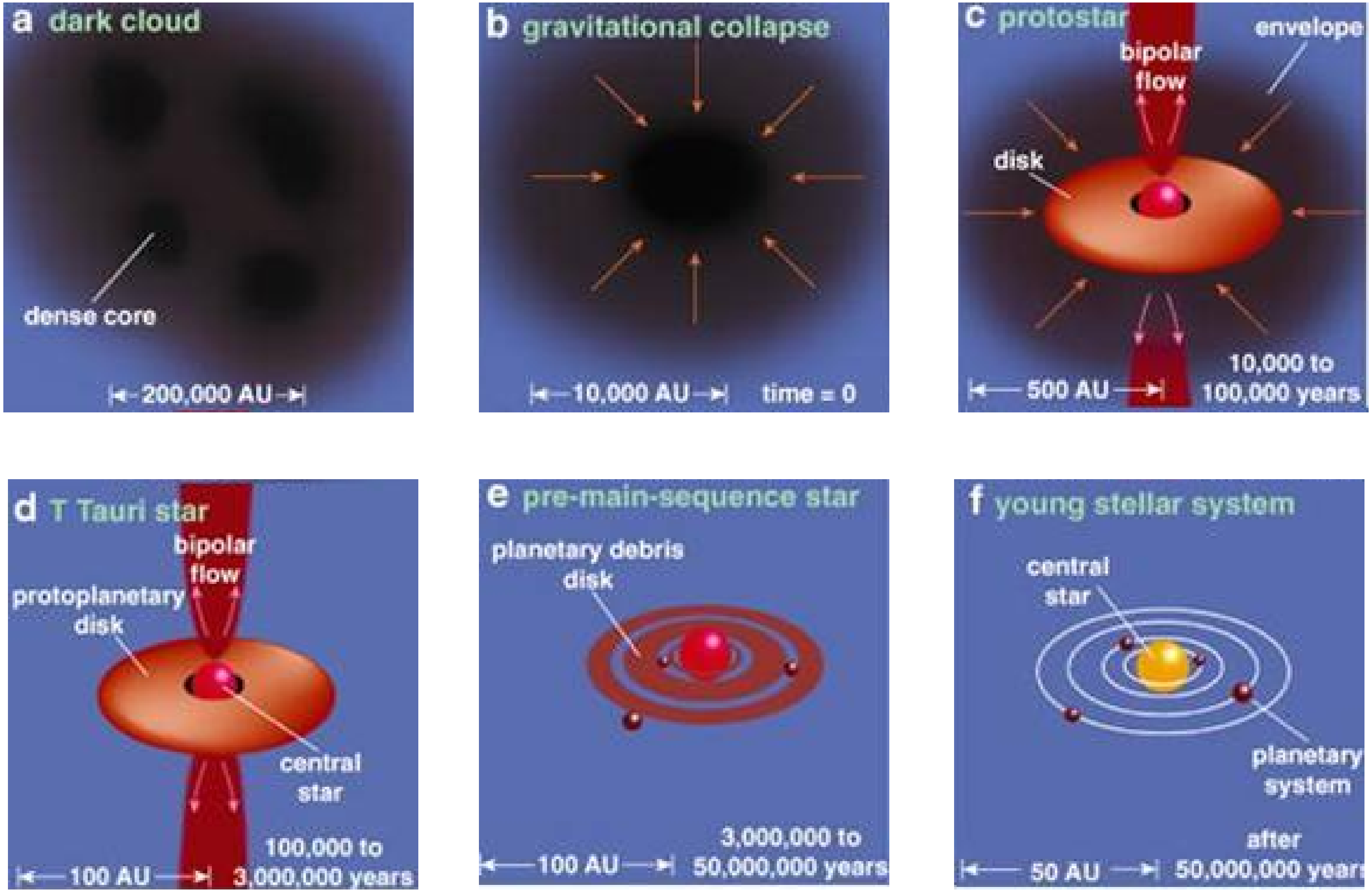


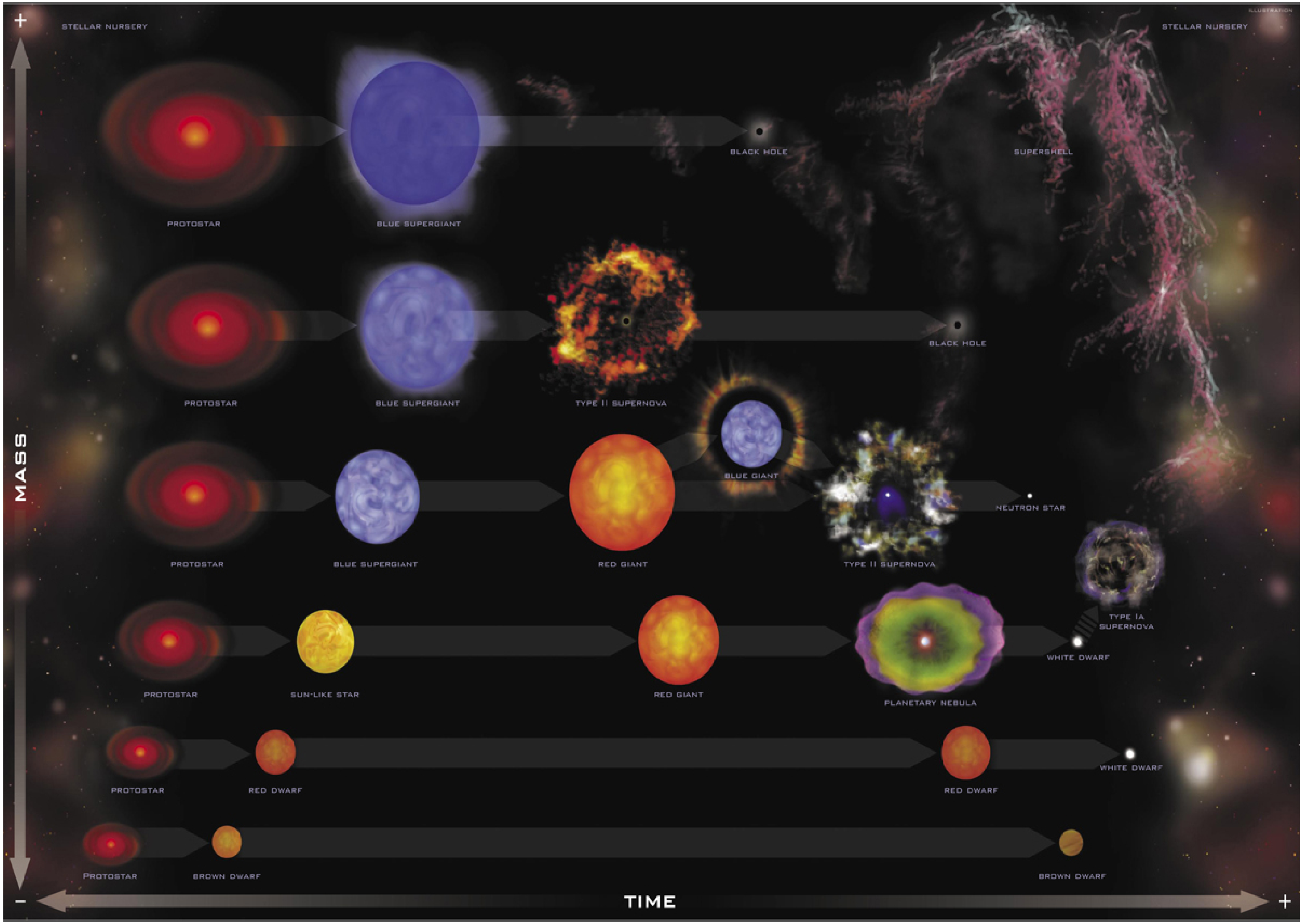
Image Courtesy of Museum of Flight

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

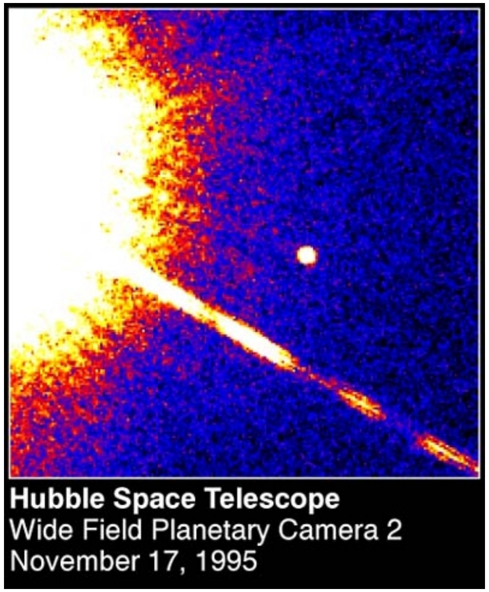
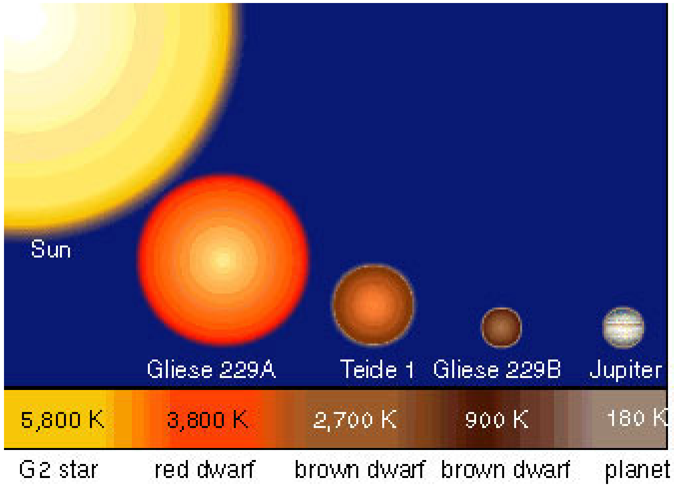


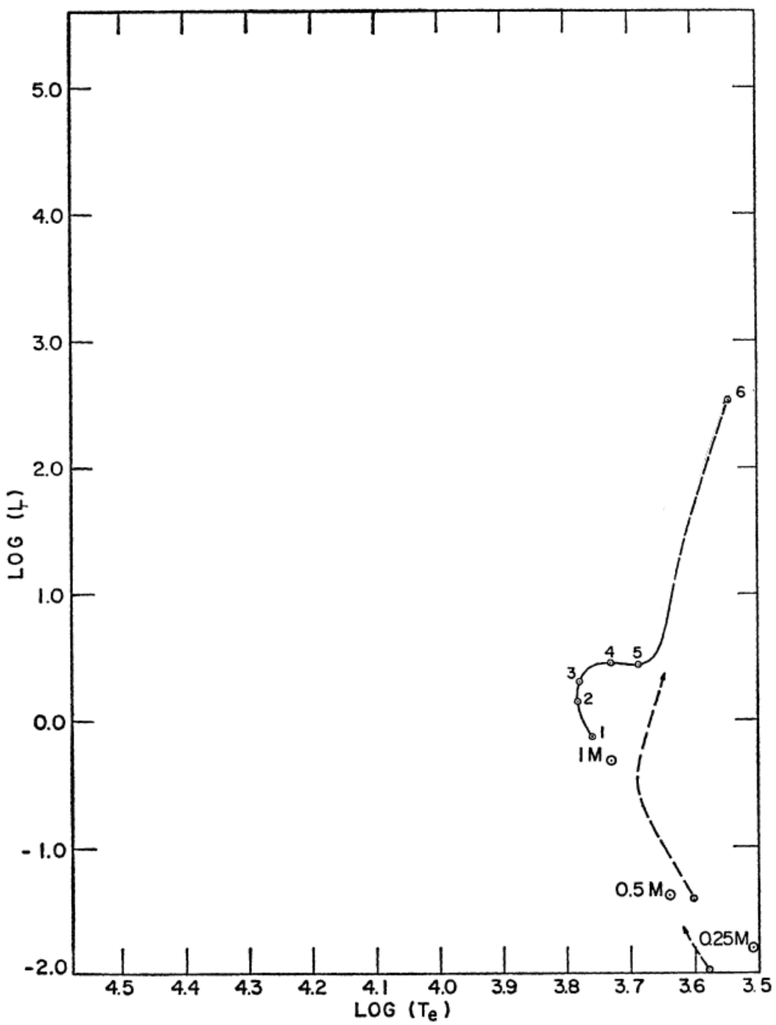
Image Courtesy of HST Gallery
PRC95-45 STSCI OPO



American Scientist/Linda Huff

- No Hydrogen Fusion
- Powered by gravitational collapse, Deuterium (^{2}H or ^{2}D) 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

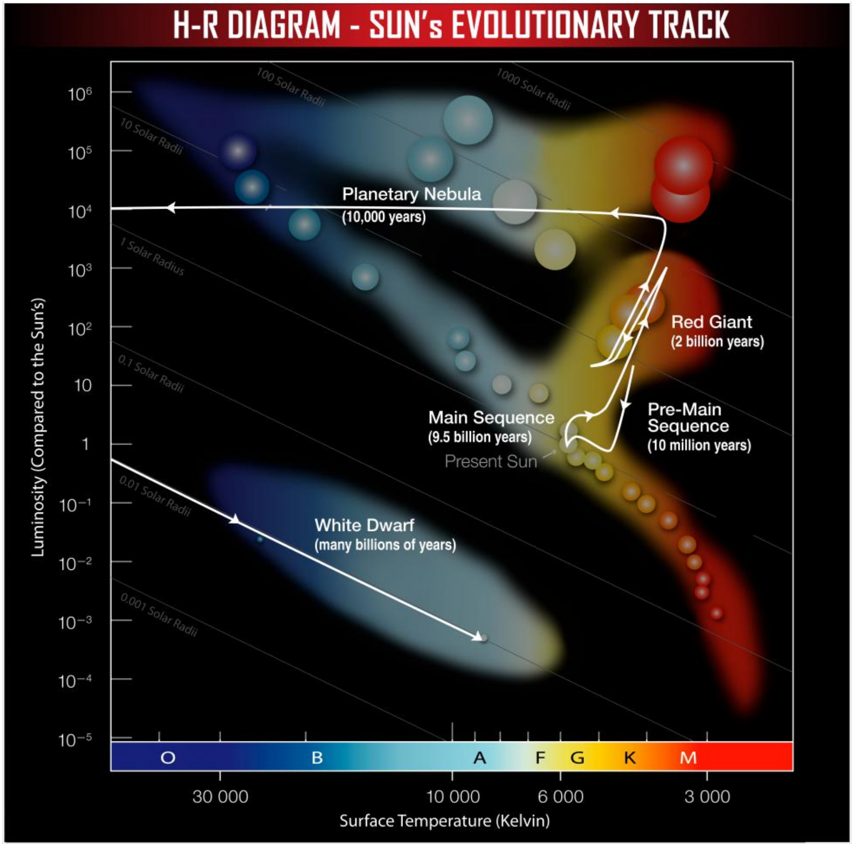
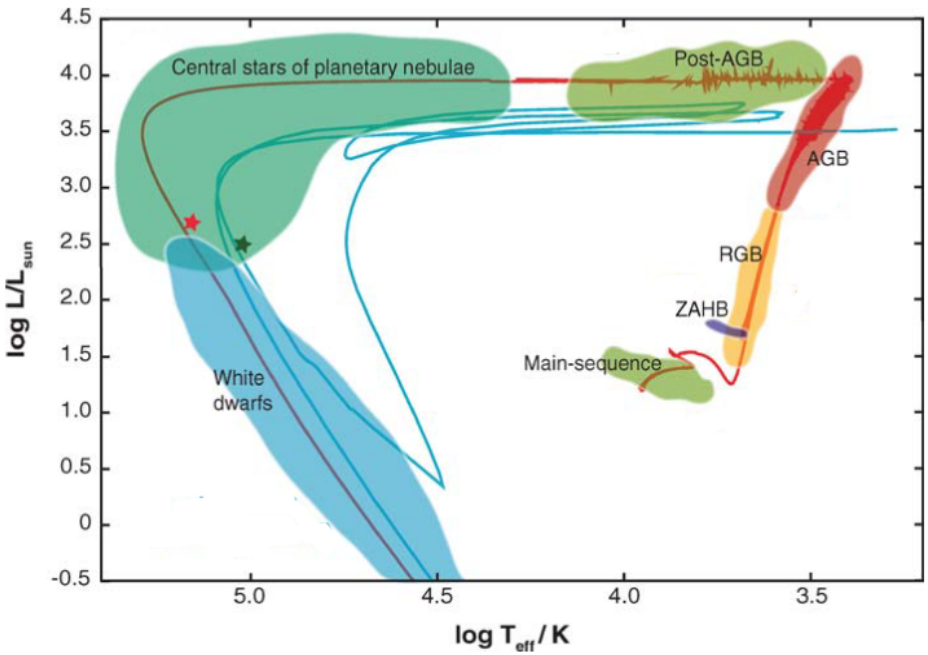


Image Courtesy of Museum of Flight

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

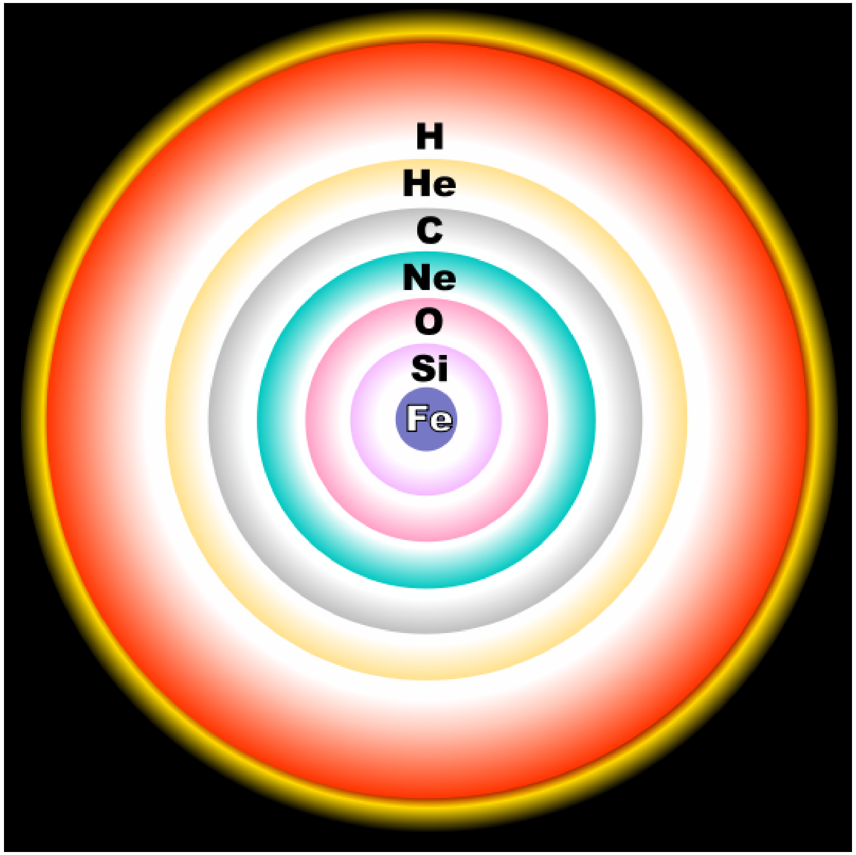
- $M > 10\ M_o$
- Burn Nuclear Fuel Quickly
- HR Diagram Becomes Mostly Useless
- Envelope cannot respond fast enough.

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

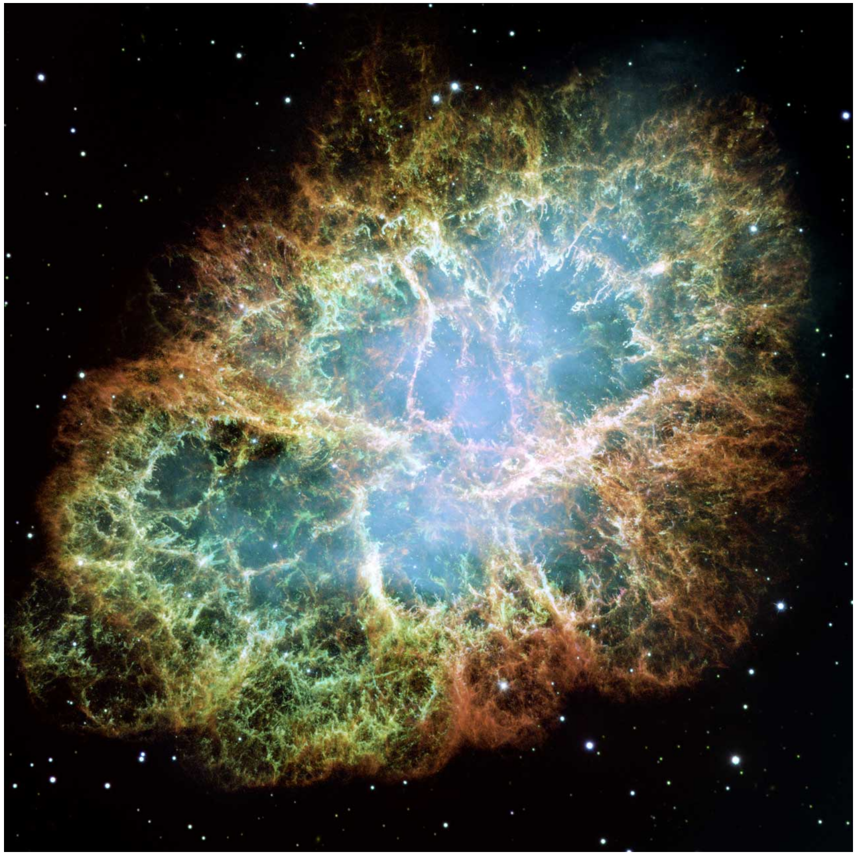


Image Credit: Hester (2005) via. HST

- Roche Lobes

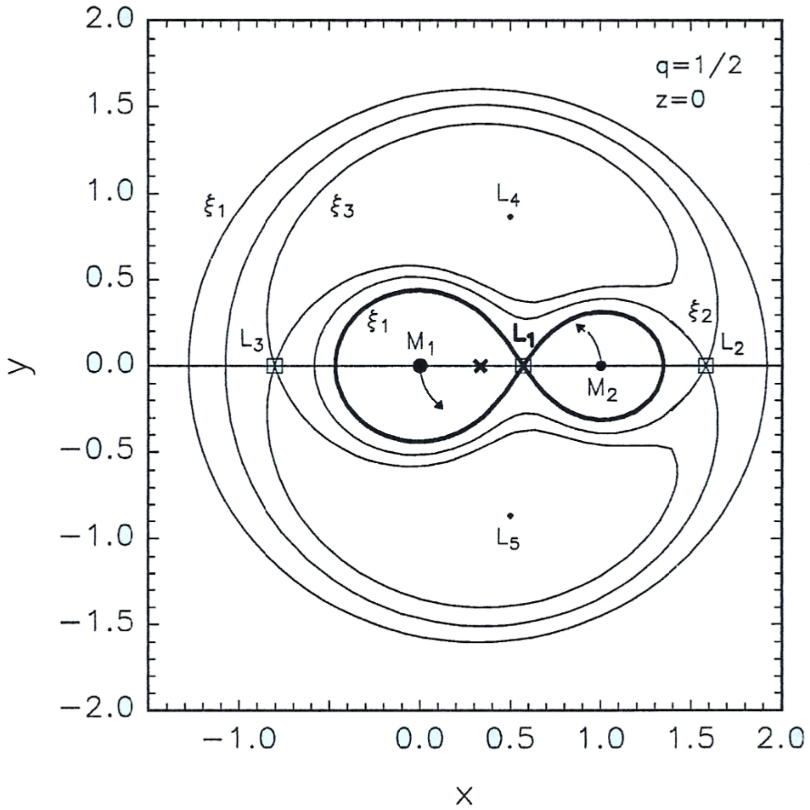


Image Credit: Hansen (2004)

Binary Star Evolution

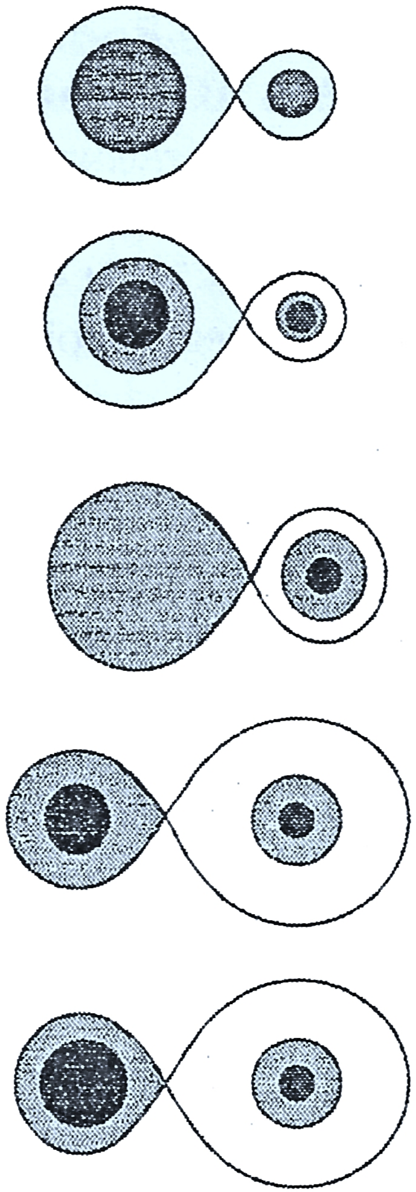
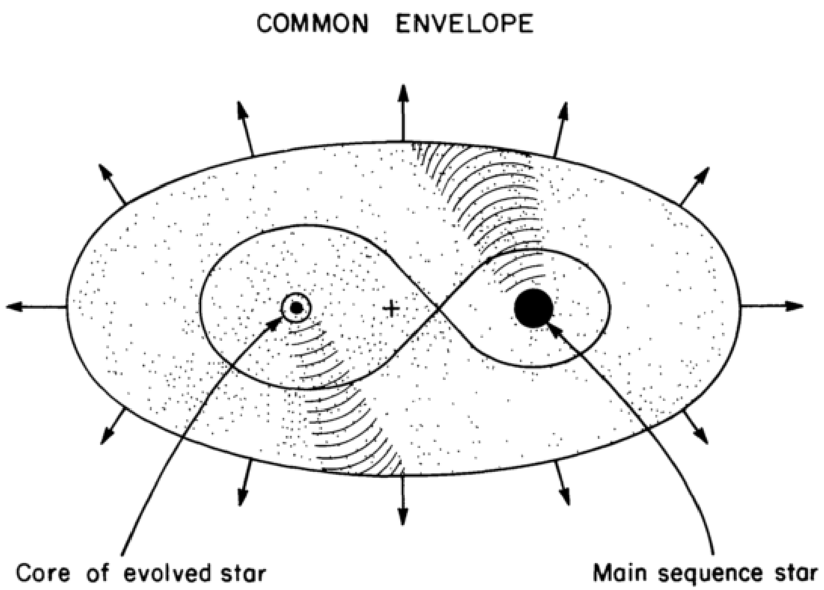


Image Credit: Hansen (2004)

- Roche Lobes
- Roche Lobe overflow, mass transfer

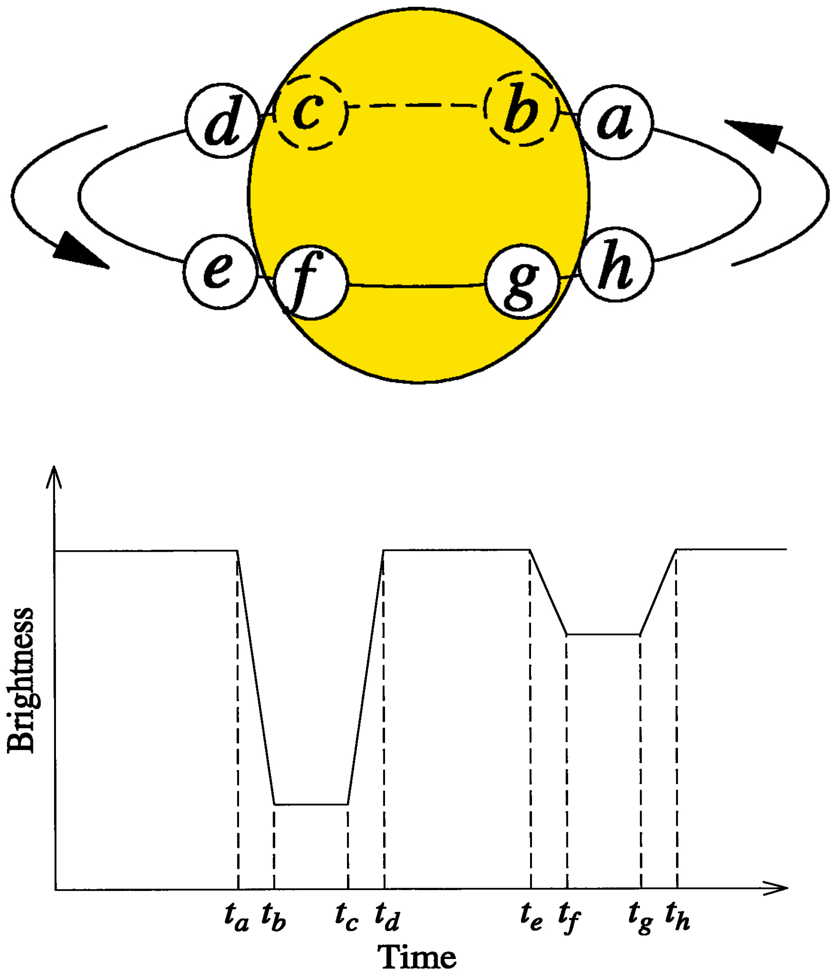
Binary Star Evolution

- 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

Forming a hypothesis

- Take what you know and make an educated inference

- My hypothesis

  The F-star is not a massive supergiant as classically assumed, but instead a lower-mass post-AGB star that has recently (in the evolutionary sense) lost a few solar masses of material which has largely ended up in and around the B-type companion and in a circumbinary disk.

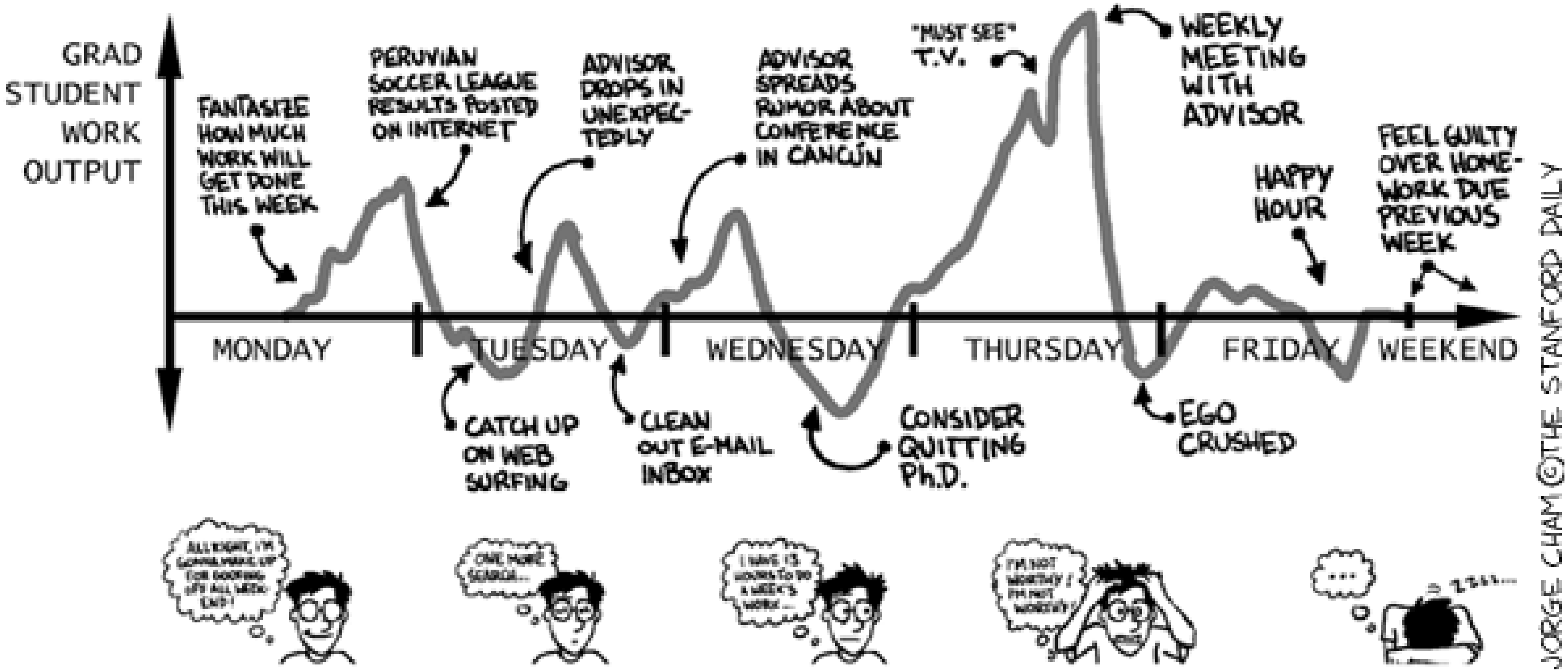
Break it down

- What key questions can you use to test your hypothesis?
- For me:
  - What is the nature of the photometric variability observed outside of eclipse and how does it relate to supergiant and post-AGB behavior?
  - Is there really a disk in the system and, if so, what are its geometric and optical properties? Is the disk typical of YSO or other disk objects?
  - What is the evolutionary state of the system?

Testing the hypothesis

- Devise a method by which it can be tested
- For Me:
  - Analyze the photometric behavior of the F-star, look for periods or some trends in the data.
  - Observe the disk with high resolution imaging (interferometry, initiated by Dr. Stencel)
  - Determine the mass of the components in the system

RESEARCH!

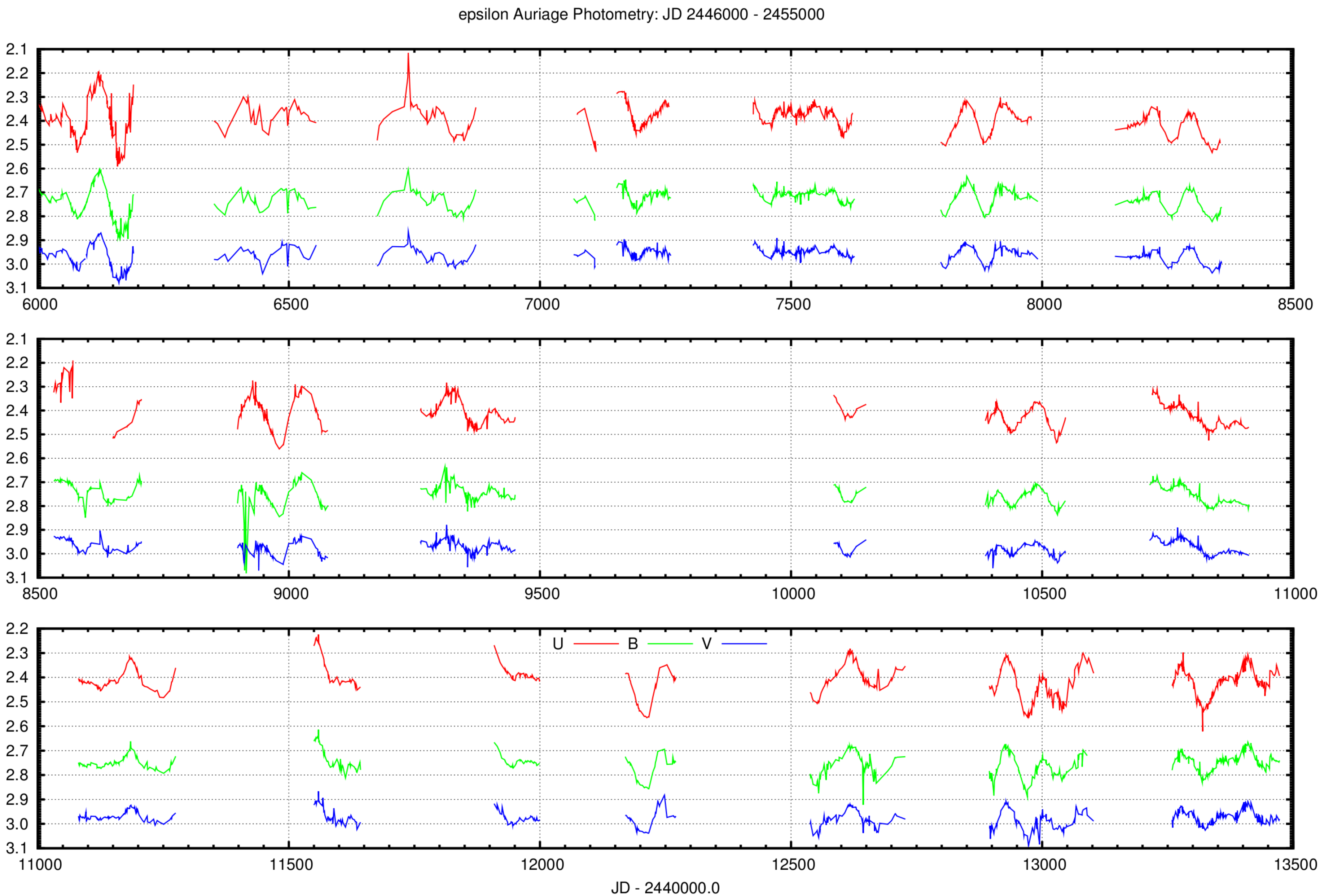


http://www.phdcomics.com/comics/archive.php?comicid=124

Skipping ahead two to three years....

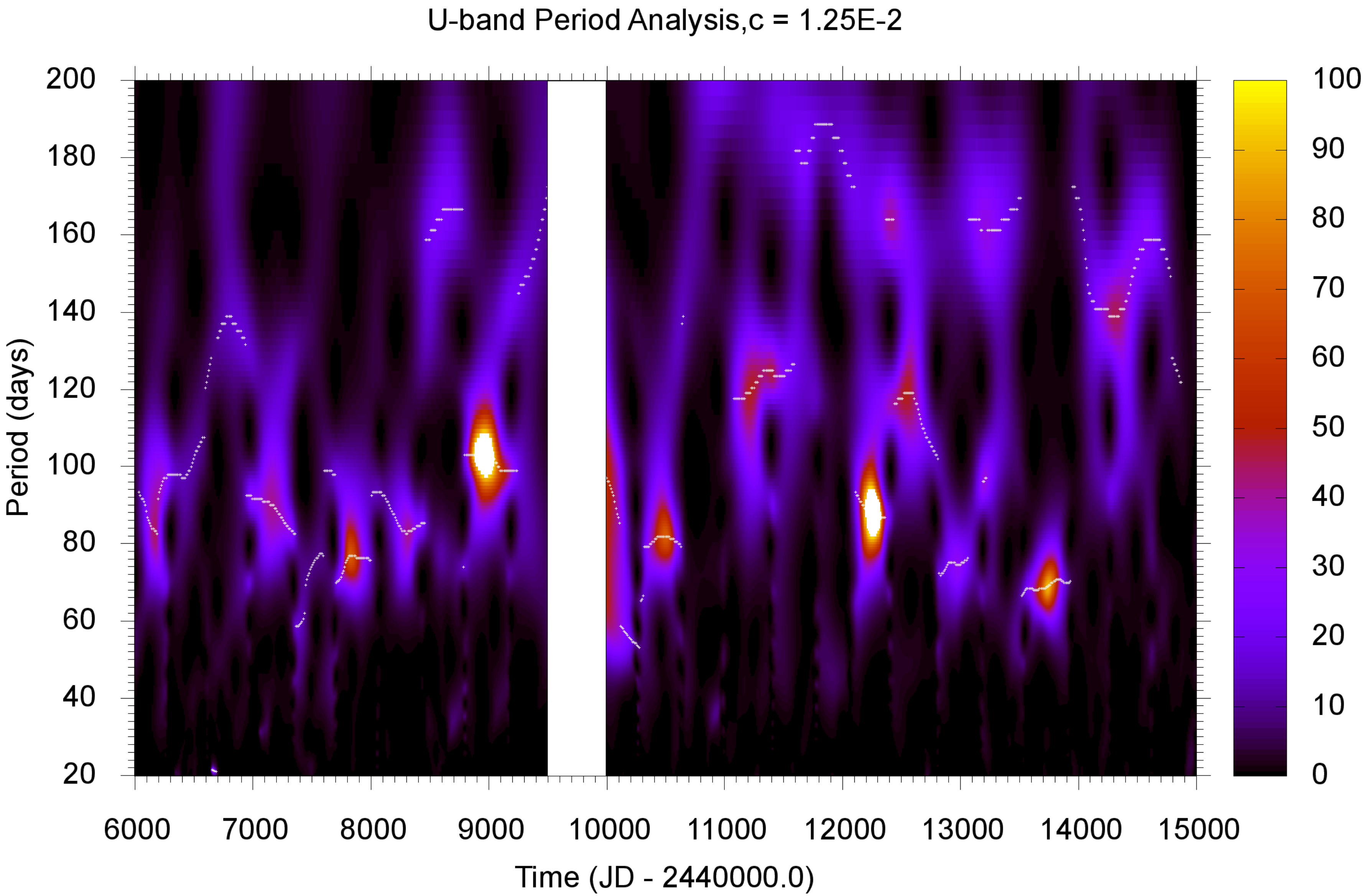
Results!

Photometry



27 years of data from Jeffrey Hopkins and Louis Boyd

U-band WWZ (wavelet) period analysis



Results

- F-star shows stable pulsations:
  - Exist in an upper and lower tracks
  - At 1/3 orbital periods (every 3382 days)
  - Periods
    - Upper: 102d, 87d
    - Lower: 90d, 82d, 68d
  - Shows Period Evolution

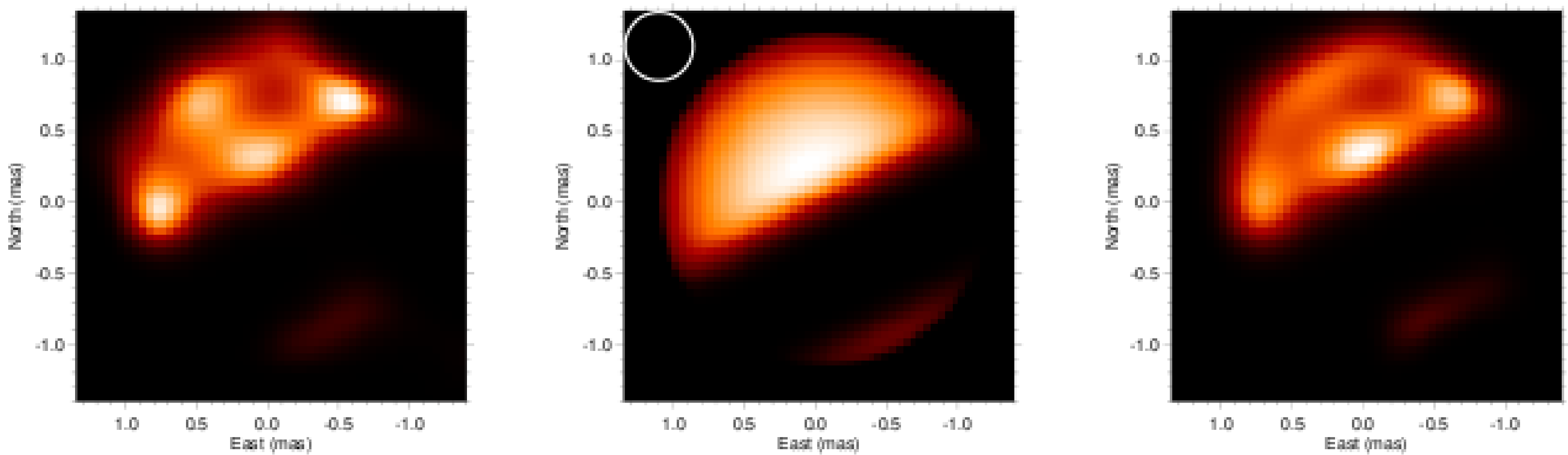
- A Post-AGB star of 7500 K should have ~45d period
- Supergiants have periods in ~100d range

- Pulsation more characteristic of supergiant behavior

CHARA Interferometer

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

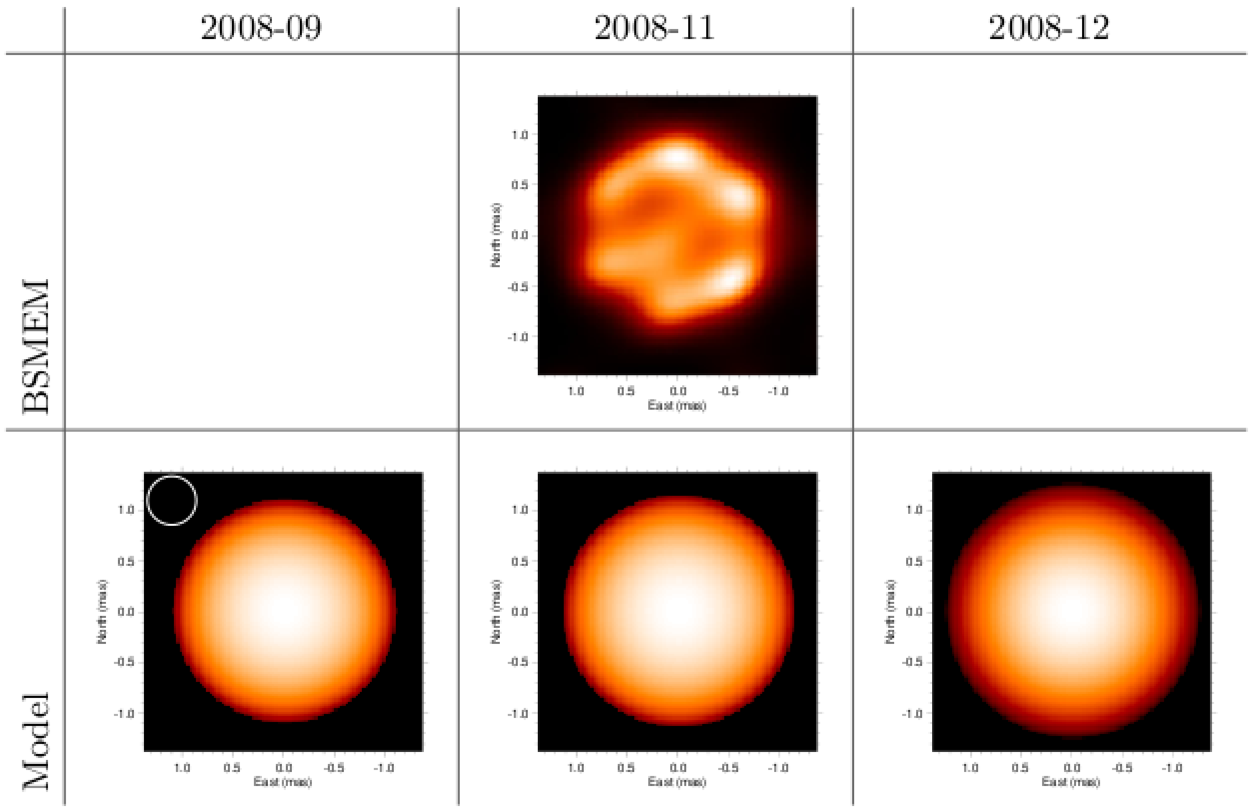
Image Reconstruction Artifacts



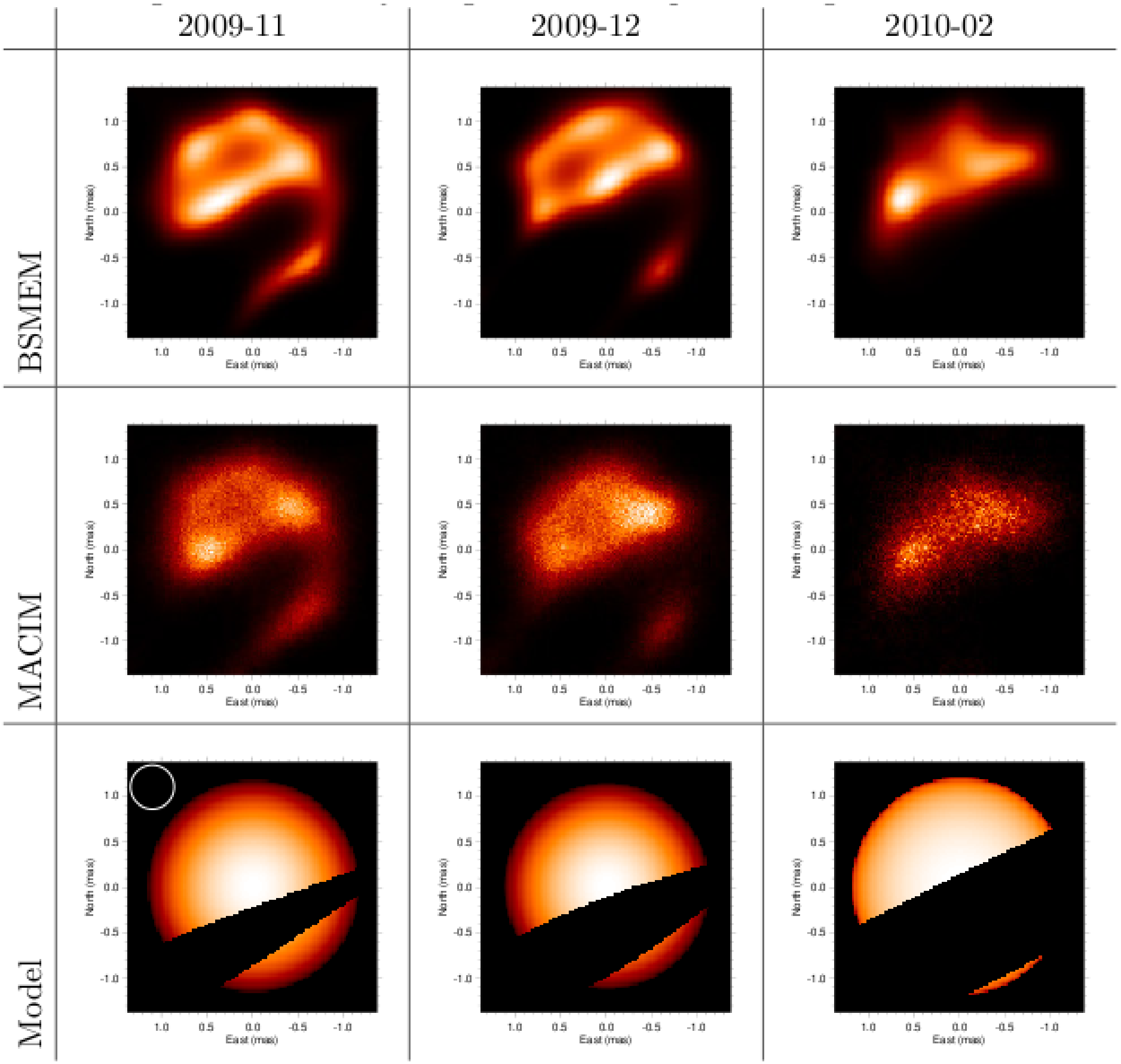
(a) Real Image (b) Model (c) Simulated Image

- Likely artifacts:
  - Bright / dark features in northern hemisphere
- Maybe artifacts
  - Flat edges on the star
- Not artifacts
  - The eclipse itself
  - Southern pole being visible

Interferometry



Interferometry



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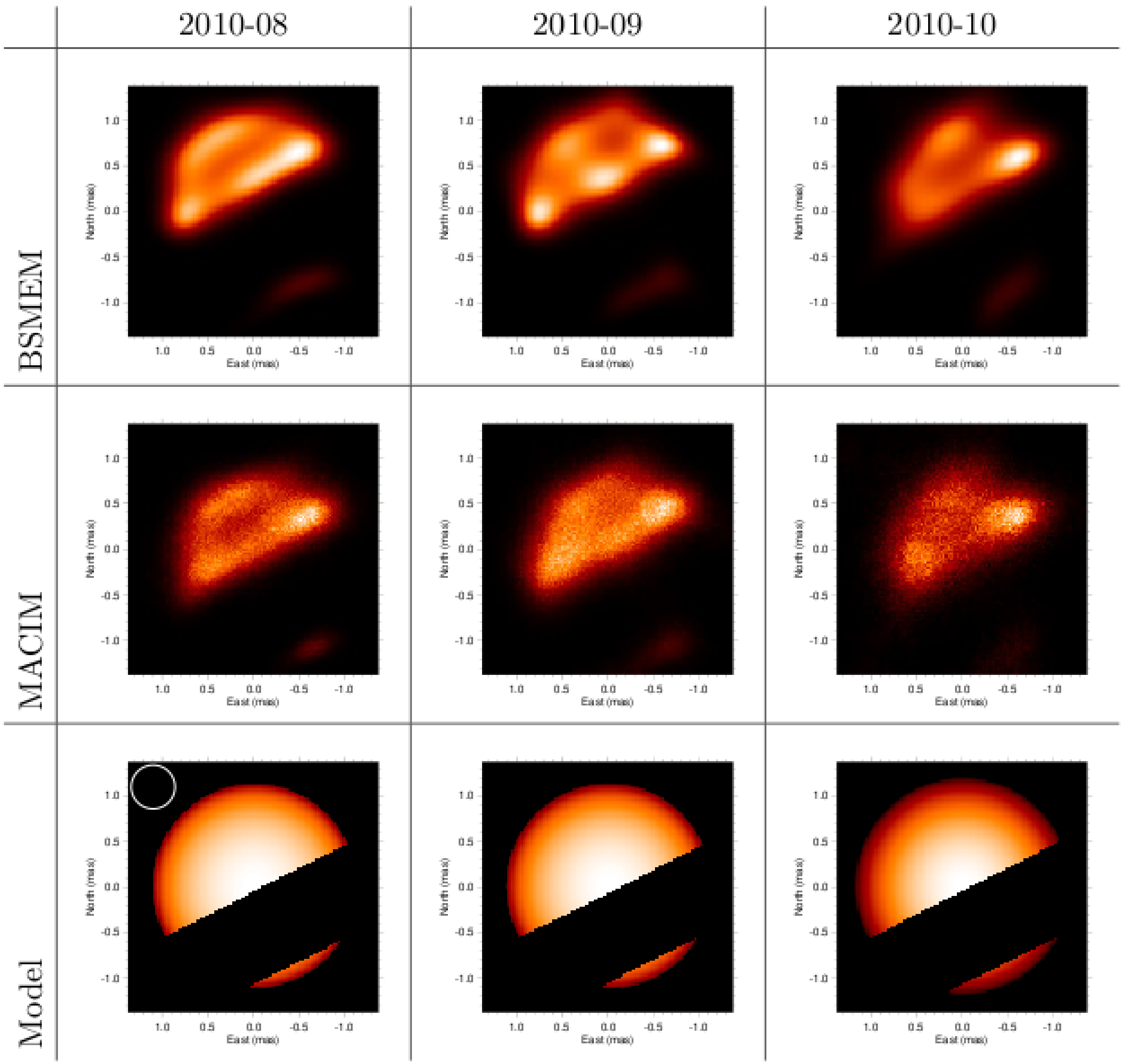
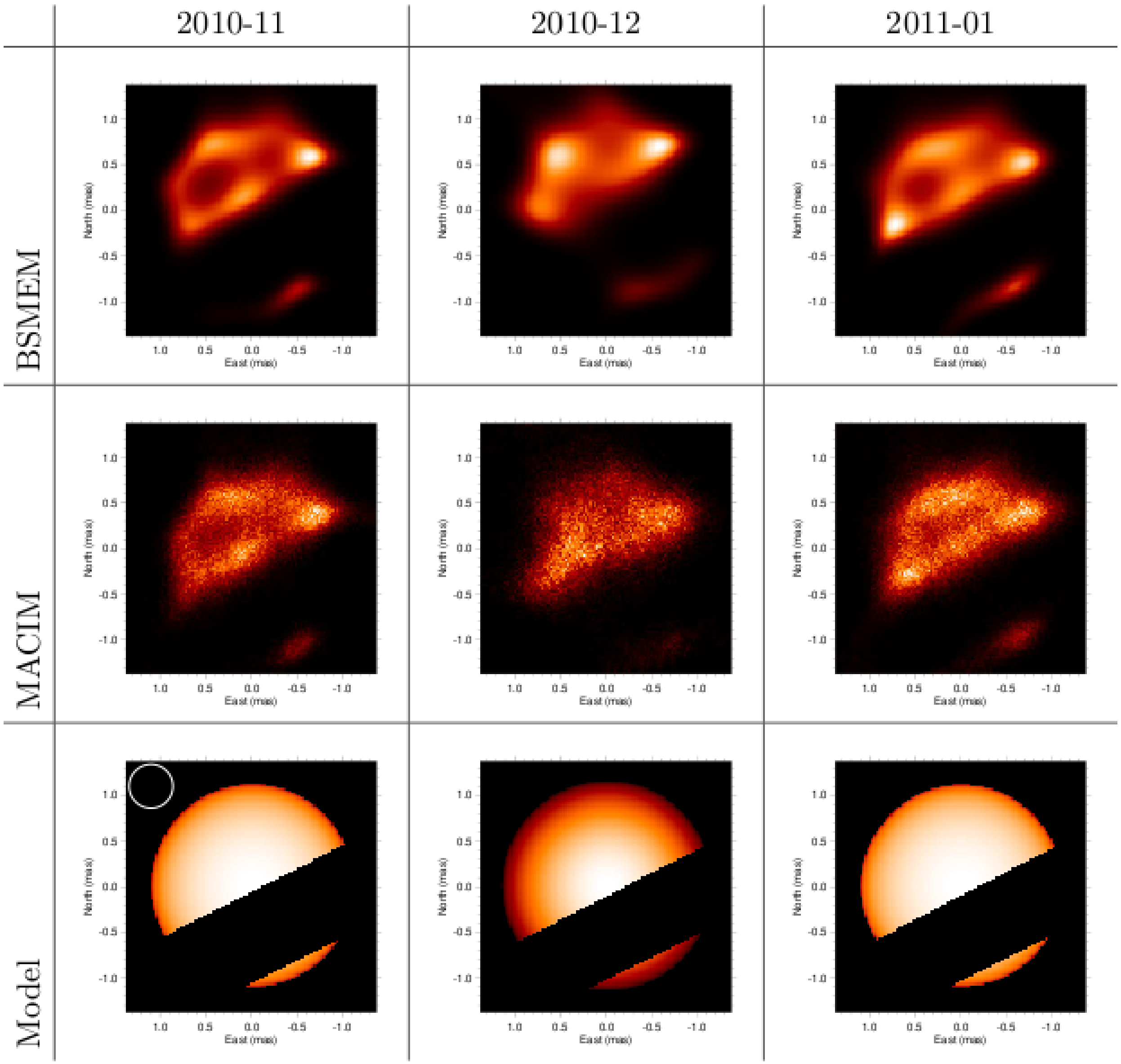
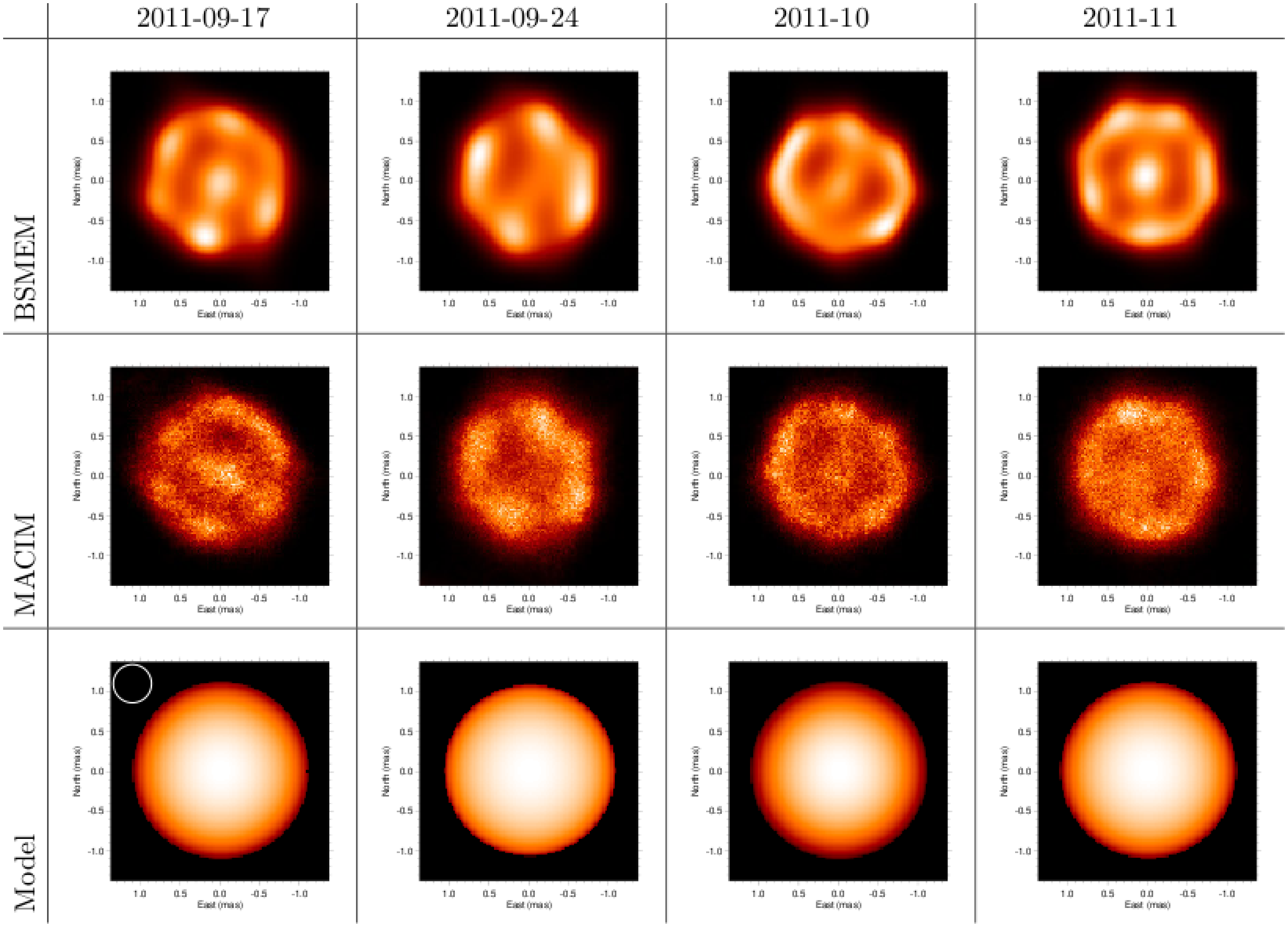


Interferometry



Interferometry



Results

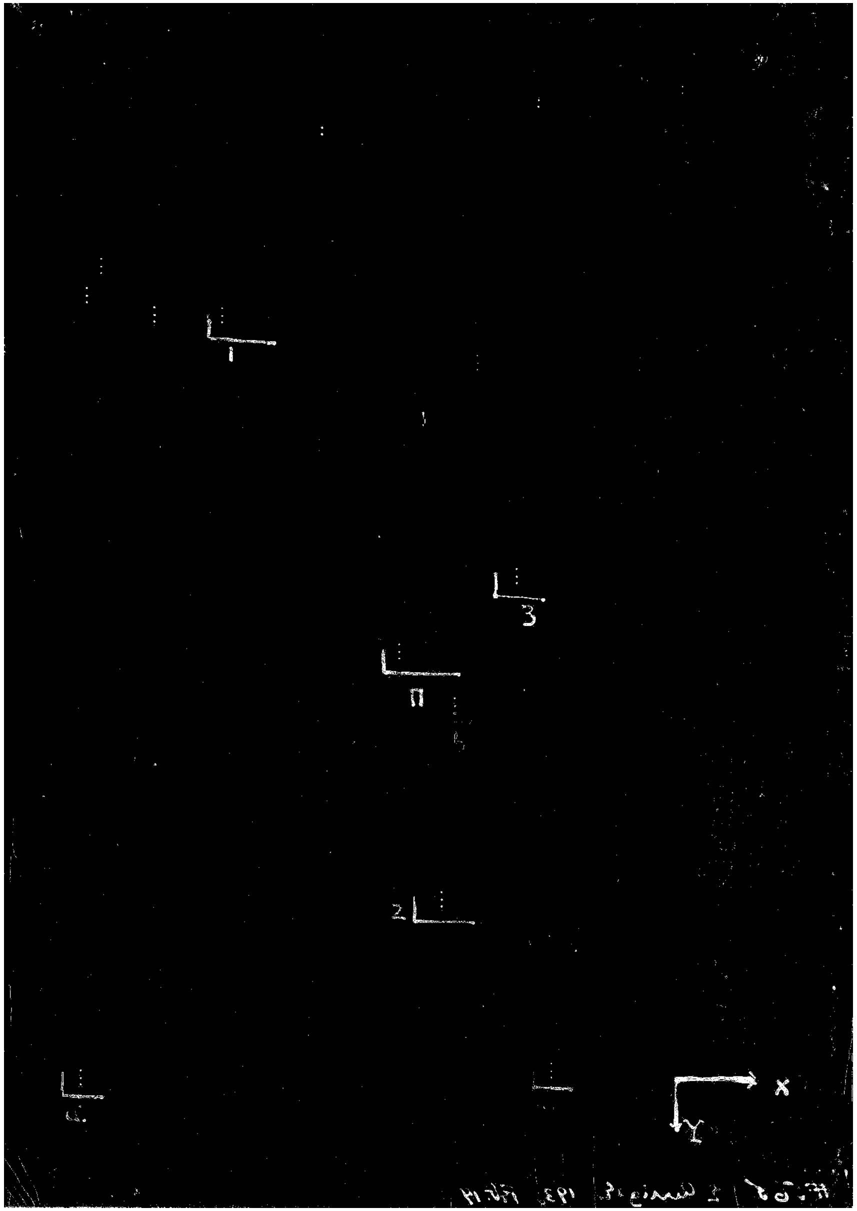
- Interferometry
  - Eclipse is caused by a disk
  - Disk dimensions now well characterized
  - Some evidence (although weak) that the F-star is shrinking by 0.3 mas / year (~1% / year)
  - Remainders from modeling imply there may be surface features on the star itself.
    - Spots, non-radial pulsation?

Astrometry

- 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.



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

Results

- Astrometry
  - New orbital solution
  - Newly determined distance

- Interferometry + Astrometry
  - Mass of F-star either 13 or 24 M_o
  - Disk + Star 11 or 15 M_o

- Evolutionary Scenario:
  - Classic Supergiant “high mass” case

The Remaining Work

- Dissertation Defense:
  - Present research to committee, defend work against inquires
- Corrections, Formatting
- Ph.Done?