Evolutionary Status of Epsilon Aurigae

Brian Kloppenborg

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1 Background Material
   - Why we care about stellar evolution
   - The HR Diagram

2 Stellar Evolution in 10 Minutes
   - Single Star Formation and Evolution
   - Binary Star Evolution

3 The Evolutionary Status of $\epsilon$ Aur
Why we care about evolutionary state

- 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
Background Material
Stellar Evolution in 10 Minutes
The Evolutionary Status of $\epsilon$ Aur

**HR Diagram**

![HR Diagram](Image Courtesy of the Museum of Flight)

**Image Courtesy of the Museum of Flight**

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Evolutionary Status of Epsilon Aurigae
Single Star Formation

1. Cloud of gas and dust

Images Courtesy of SSC IR Compendium
Single Star Formation

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Single Star Formation and Evolution

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Evolutionary Status of Epsilon Aurigae

Cloud of gas and dust
Gravitational collapse

Images Courtesy of SSC IR Compendium
Single Star Formation

1. Cloud of gas and dust
2. Gravitational collapse
3. Conservation of angular momentum and collisions cause disk to form.

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4. Envelope has dissipated or collapsed into the disk.
Single Star Formation

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5. Collisions inside disk cause planetesimal for form, clearing the disk of debris.

Images Courtesy of SSC IR Compendium
Single Star Formation

1. Cloud of gas and dust
2. Gravitational collapse
3. Conservation of angular momentum and collisions cause disk to form.
4. Envelope has dissipated or collapsed into the disk.
5. Collisions inside disk cause planetesimal for form, clearing the disk of debris.
6. Star ignites hydrogen in its core.

Images Courtesy of SSC IR Compendium
Mass Dictates Evolution*

Images Courtesy of CHANDRA EPO

* Composition changes evolution too, but it’s a far second compared to mass.
Substellar objects

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

Brown Dwarf Gliese 229B

Image Courtesy of HST Gallery, PRC95-45 STSCI OPO

American Scientist/Linda Huff
Low-mass Stellar Evolution

- \( M < 0.3 \, M_\odot \) remains on MS for more than \( \tau_{\text{Hubble}} \)

Evolutionary Tracks, adapted from Iben (1967)
Low-mass Stellar Evolution

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

Evolutionary Tracks, adapted from Iben (1967)
Intermediate Mass Stars

- $0.4 < M < 6-10 \, M_\odot$ Degeneracy is lifted (He flash)

![H-R Diagram: Sun's Evolutionary Track](image)

Image Courtesy of the Museum of Flight
Intermediate Mass Stars

- $0.4 < M < 6 - 10 \, M_\odot$: Degeneracy is lifted (He flash)
- Core expands, H-burning damped, star contracts

Image Courtesy of the Museum of Flight
Intermediate Mass Stars

- $0.4 < M < 6-10 \, M_\odot$: Degeneracy is lifted (He flash)
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- Star moves into horizontal branch

Image Courtesy of the Museum of Flight
Intermediate Mass Stars

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- 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 the Museum of Flight
Intermediate-Mass Phase: Post-AGB

- Low to intermediate initial mass (1 - 8 \( M_\odot \)) transitioning between AGB and PN
- Not very well understood
- Fairly short lived \((10^2 - 10^3 \text{ yr})\)
- 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
- Good AAVSO Observing opportunity

Evolution of a 2\( M_\odot \) star (Herwig, 2005)
Massive Stars

- $M > 10 \, M_\odot$
Massive Stars

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

<table>
<thead>
<tr>
<th>Dominant fuel</th>
<th>$T_e$</th>
<th>Duration</th>
<th>Important products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>$5 \times 10^8$ K</td>
<td>$10^3$–$10^4$ yr</td>
<td>Ne, Na</td>
</tr>
<tr>
<td>Neon</td>
<td>$8 \times 10^8$ K</td>
<td>$10^2$–$10^3$ yr</td>
<td>Mg, some O</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$1 \times 10^9$ K</td>
<td>&lt; 1 yr</td>
<td>Si, some S, etc.</td>
</tr>
<tr>
<td>Silicon</td>
<td>$3 \times 10^9$ K</td>
<td>days</td>
<td>$^{56}$Ni</td>
</tr>
</tbody>
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Stellar Timescales (Hansen, 2004)
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- Stars Become Highly Layered
**Massive Stars**

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- Core Collapse

Layering in Highly Evolved Stars
(Wikipedia Commons)

Layering in Highly Evolved Stars
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Image Credit: Hester (2005) via. HST
Binary Star Evolution
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- Roche Lobes

Roche Lobes (Hansen, 2004)
Binary Star Evolution

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- Roche Lobe overflow, mass transfer

Roche Lobe Overflow (Hansen, 2004)
Binary Star Evolution

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- Common Envelope Phase

Common Envelope (Iben, 1991)
Other Stellar Evolution Concerns

Single Stars:
- Stellar Composition
- Rotation
- Mixing/Convection

Binary Stars:
- Non-spherical cores
- Tidal Interactions (including Tidal Heating)
The Evolutionary Status of $\epsilon$ Aur on the HR diagram
ε Aurigae F-star
Stats:

- Temperature: 7750 K
- Radius: 135 R$_\odot$
- Luminosity: $> 10^4$

Image Courtesy of the Museum of Flight
The Evolutionary Status of $\epsilon$ Aur

Summarizing Webbink’s 1985 Review of the Evolutionary State:

- **High-Mass**: Massive star in the post-main sequence star burning Helium in a shell
- **Low-Mass**: Star is contracting towards white dwarf (post-AGB)
F-star Stats

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Masses: $3.6 \pm 0.7$ (Kloppenborg et al. 2010), $2.2 \pm 0.9$ (Hoard et al. 2010)
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*Appears to support the low-mass, post-AGB model*
Problems with this interpretation

Problems:
- post-AGB stars often have:
  - Circumbinary disks
  - Period/temperature changes (your observations help here)
  - Molecular and/or crystalline emission lines
- Spectral analysis shows oddities, could be non-LTE?
Remaining Work

- Need a modern spectroscopic analysis
- Look for changing Period and Temperature in/from historical and CS observational data
Acknowledgements

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