Stellar Evolution

- Stars evolve (change over time) because of GRAVITY!
- A star passes through phases, grouped as
  - Pre-Main Seq (birth)
  - Main Seq (MS) (life)
  - Post-MS (demise)
- Stellar evolution is generally studied in terms of “tracks” in the HRD

Formation of Stars

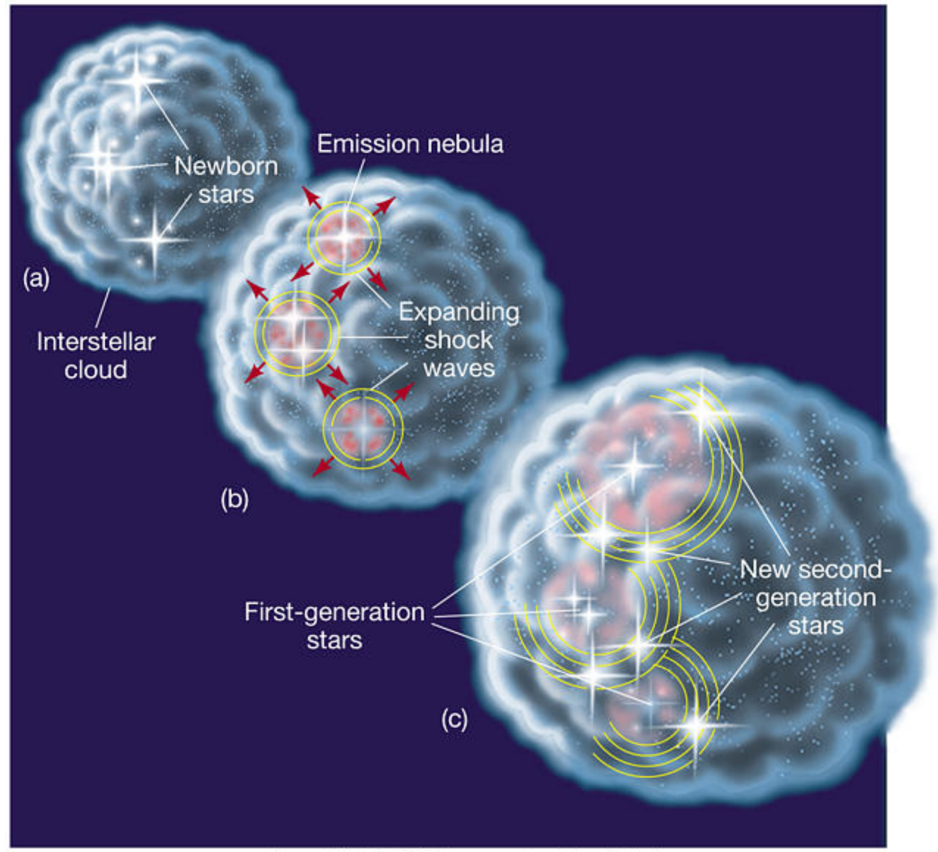
- In our Galaxy, most of the gas lies in a flattened disk structure
- We tend to find hot massive stars in clusters near big clouds of gas
- In these regions we also find stars with rapid rotation, disks, jets, and magnetic activity
- These stars are not on the Main Sequence (M.S.)

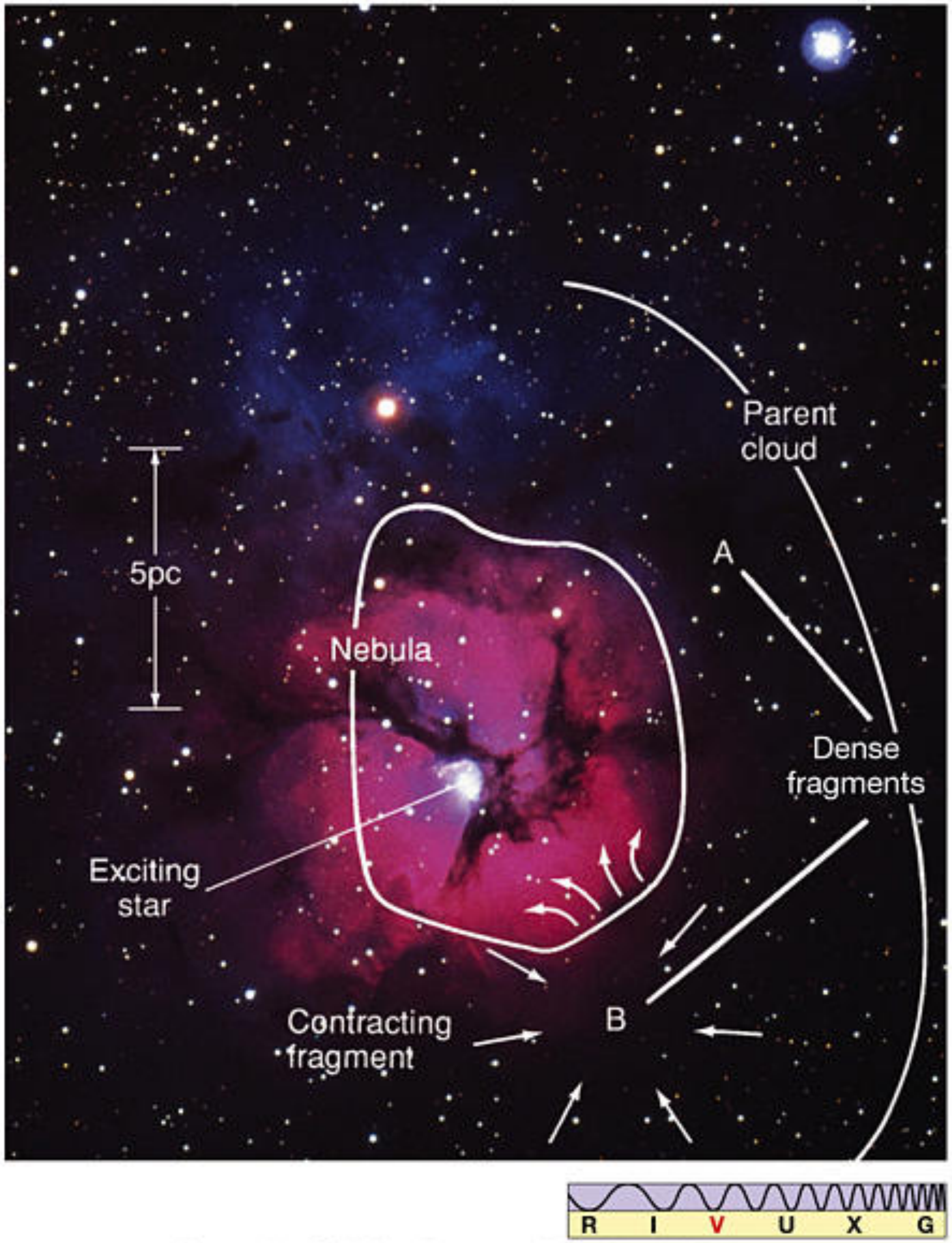
We think that big gas clouds collapse under gravity and fragment into "pieces" to make new stars

$$\text{Free-Fall Timescale:} \quad t_{ff} \approx 50 \text{ Myr} \times 1/\sqrt{n}$$

Stimulating Star Formation

How does star formation get going? There is more than one way, but certainly one is that "stars beget stars". Some stars explode, and these events "stir" and compress the gases of space to start new cloud collapse events.

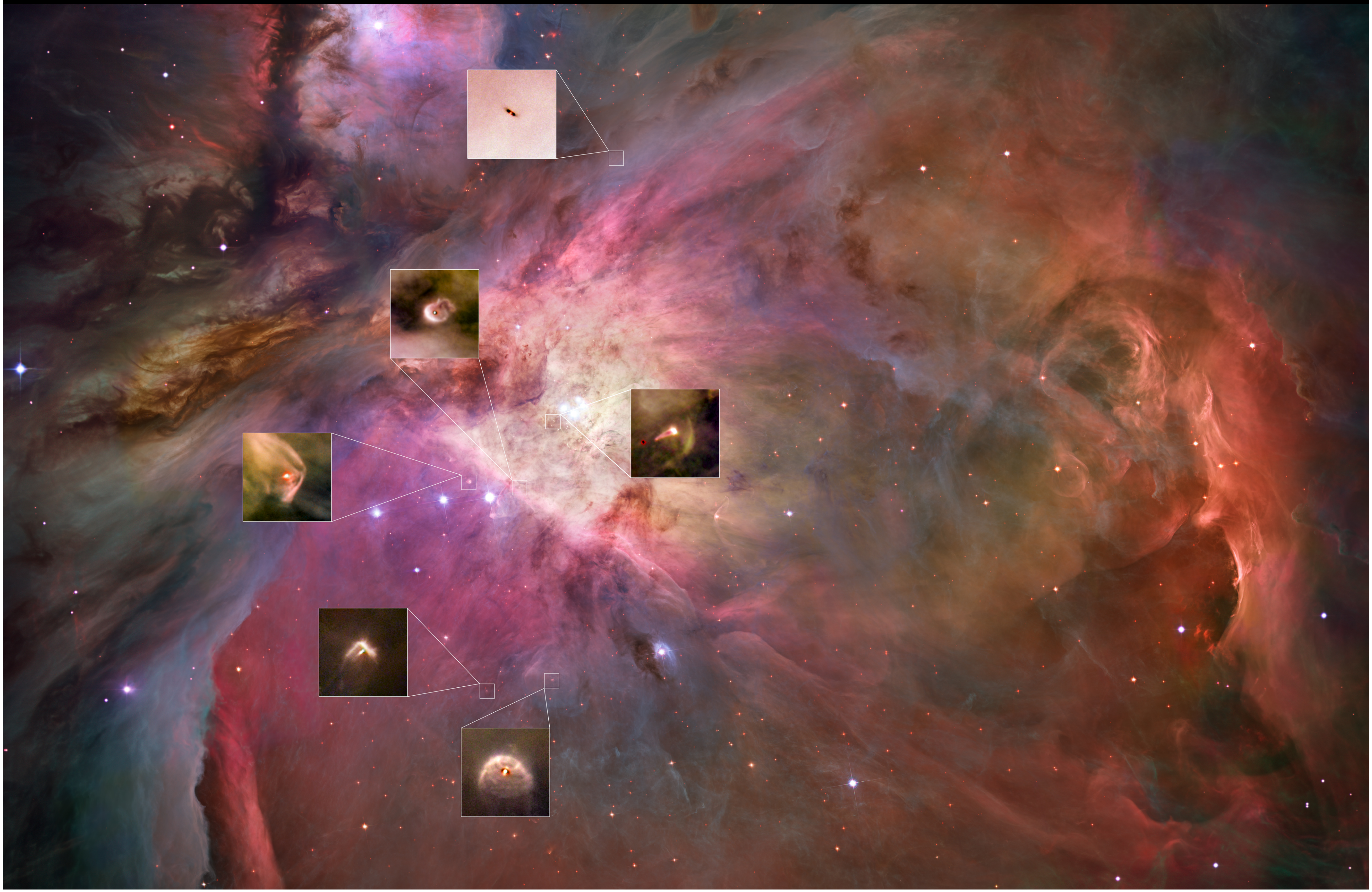




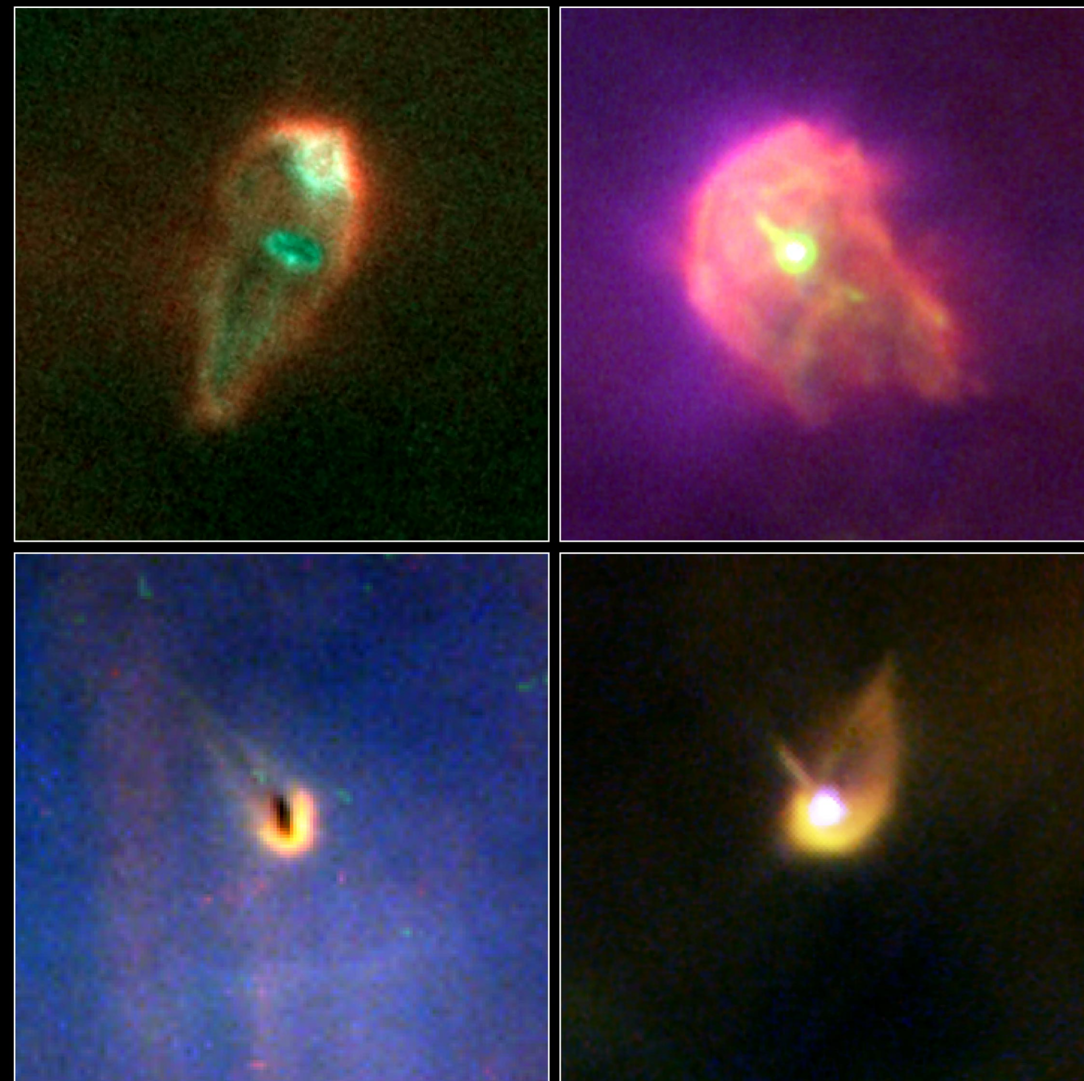
Example of a Star Forming Region in Action

Horsehead and Orion Nebulae

Forming Stars in Orion



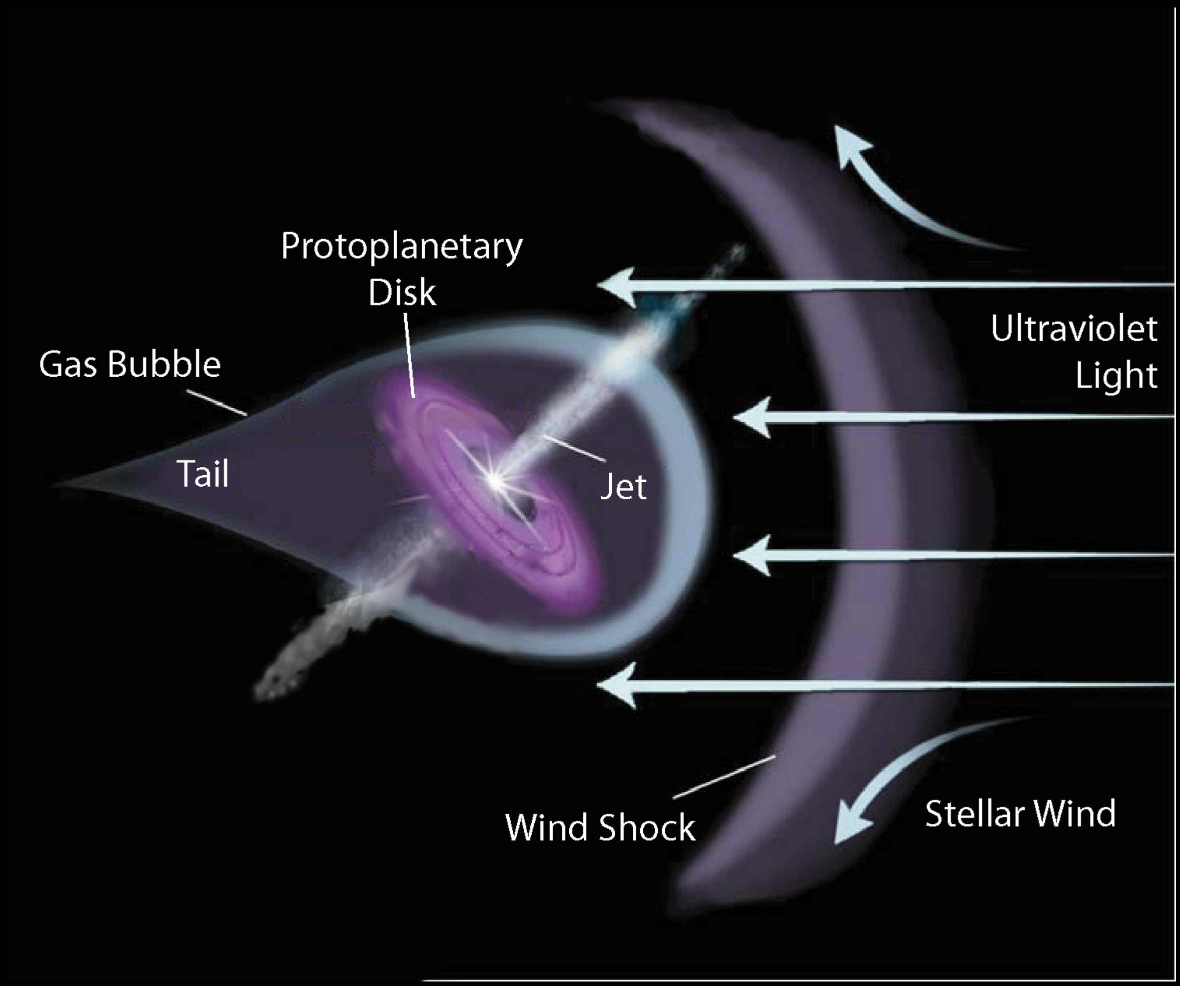
“Proplyds”

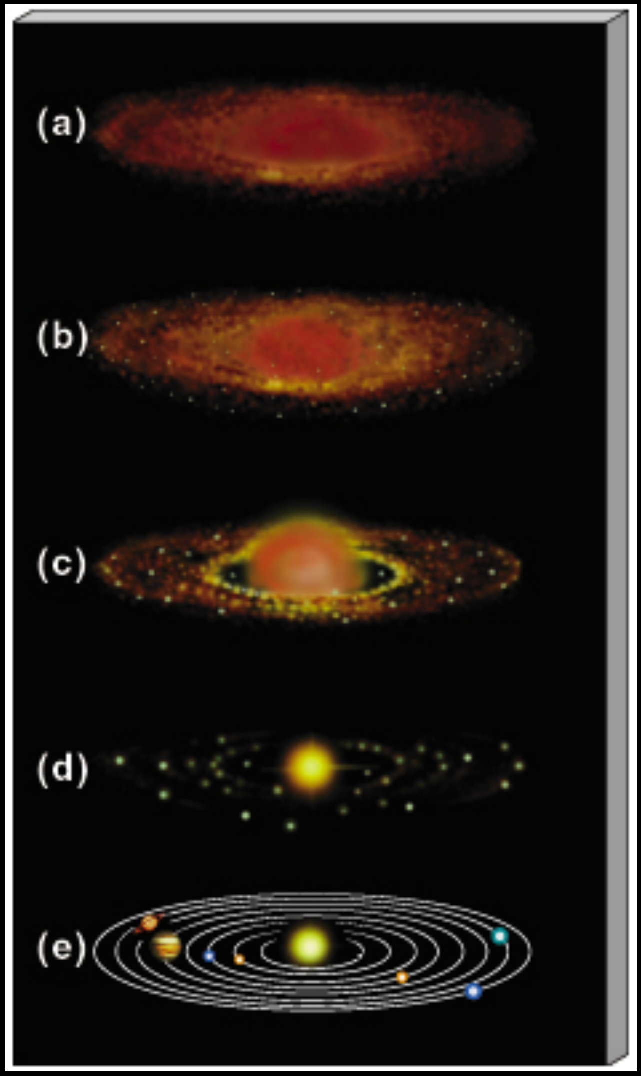


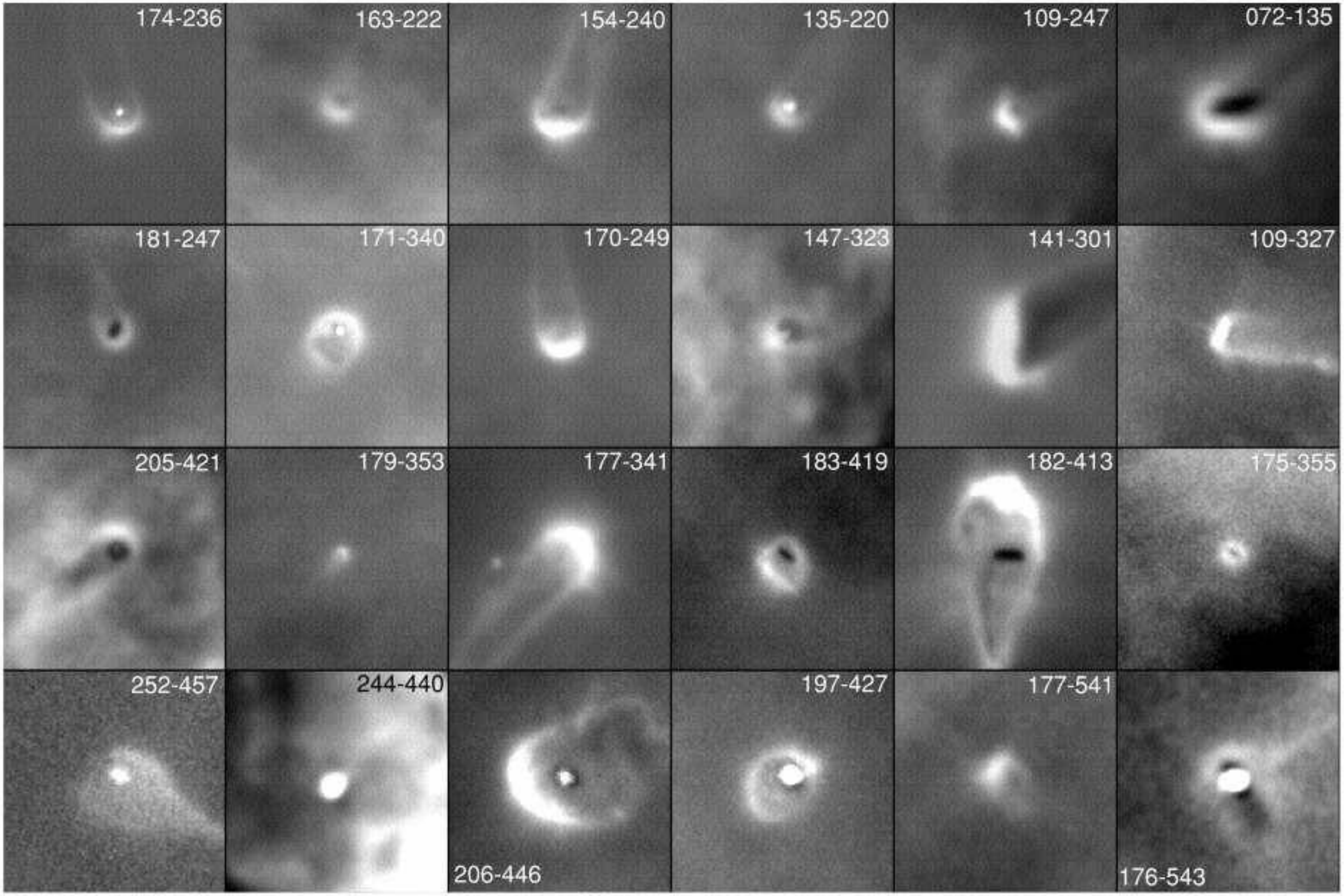
Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13

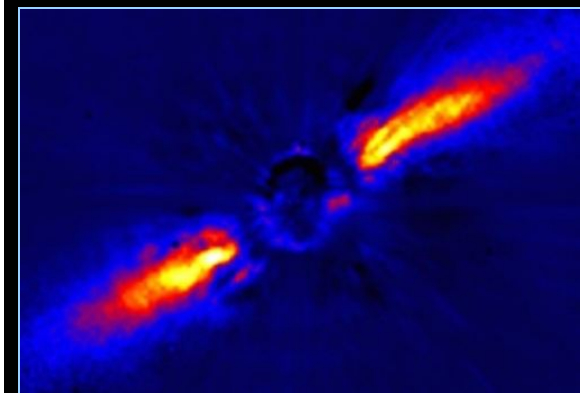
What's a Proplyd?

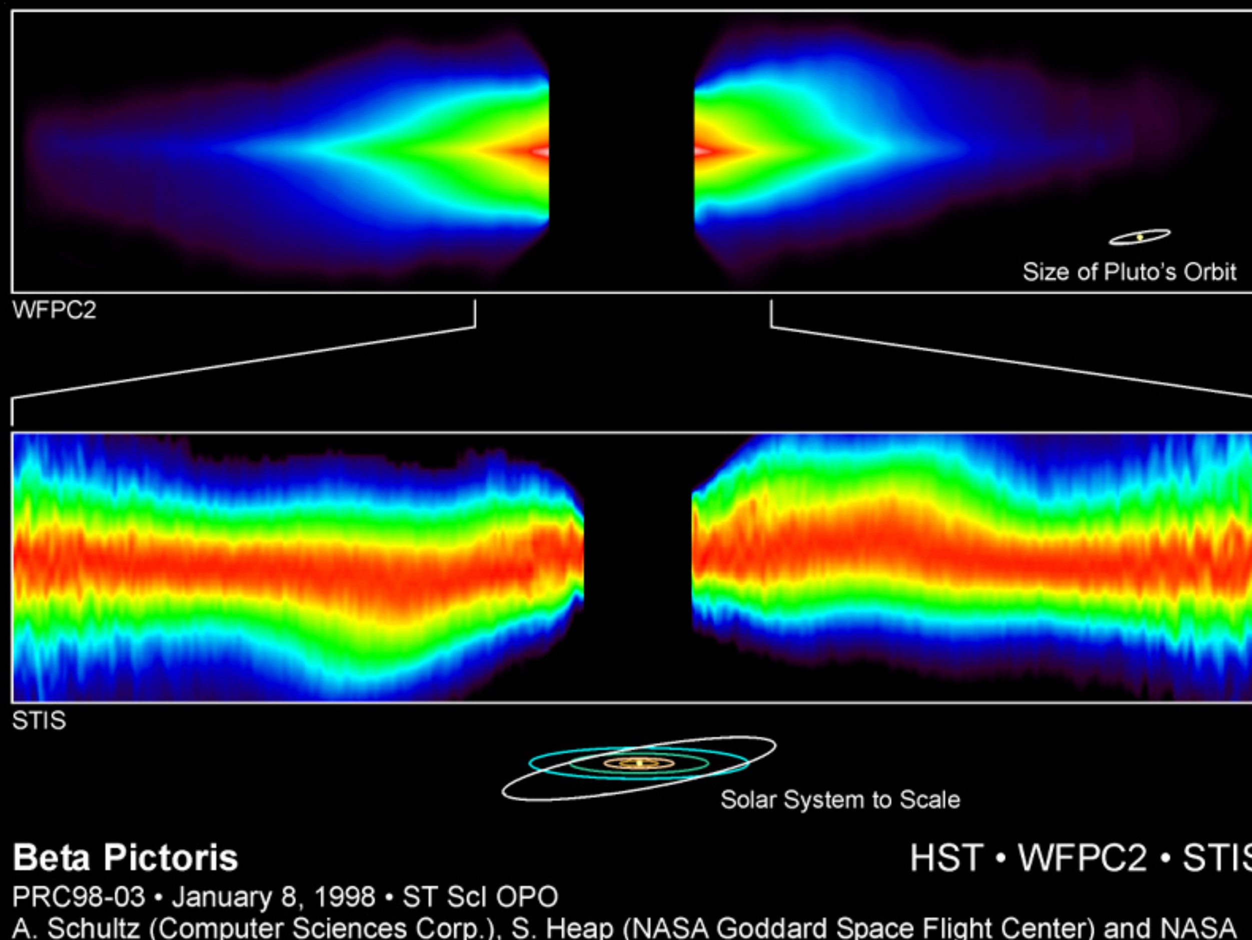




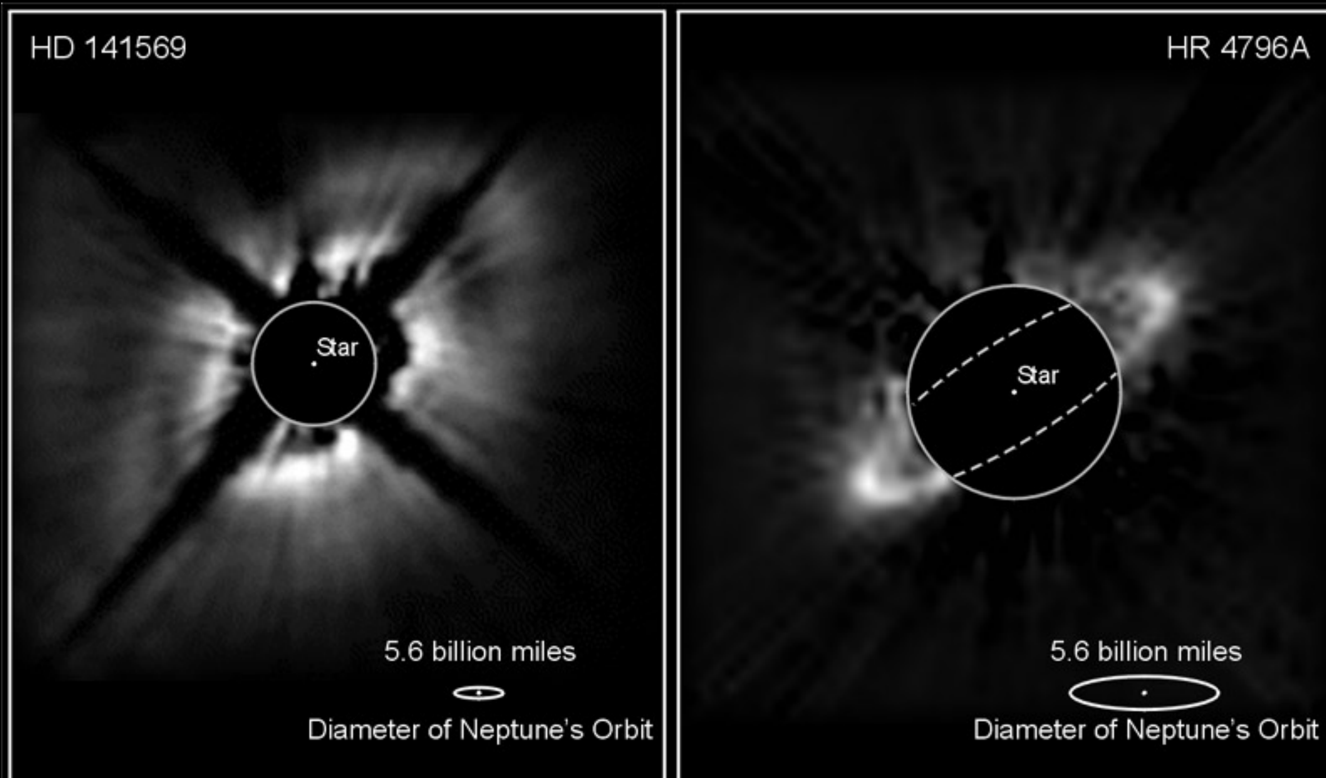

174-236
163-222
154-240
135-220
109-247
072-135
181-247
171-340
170-249
147-323
141-301
109-327
205-421
179-353
177-341
183-419
182-413
175-355
252-457
244-440
206-446
197-427
177-541
176-543

β Pictoris Disk





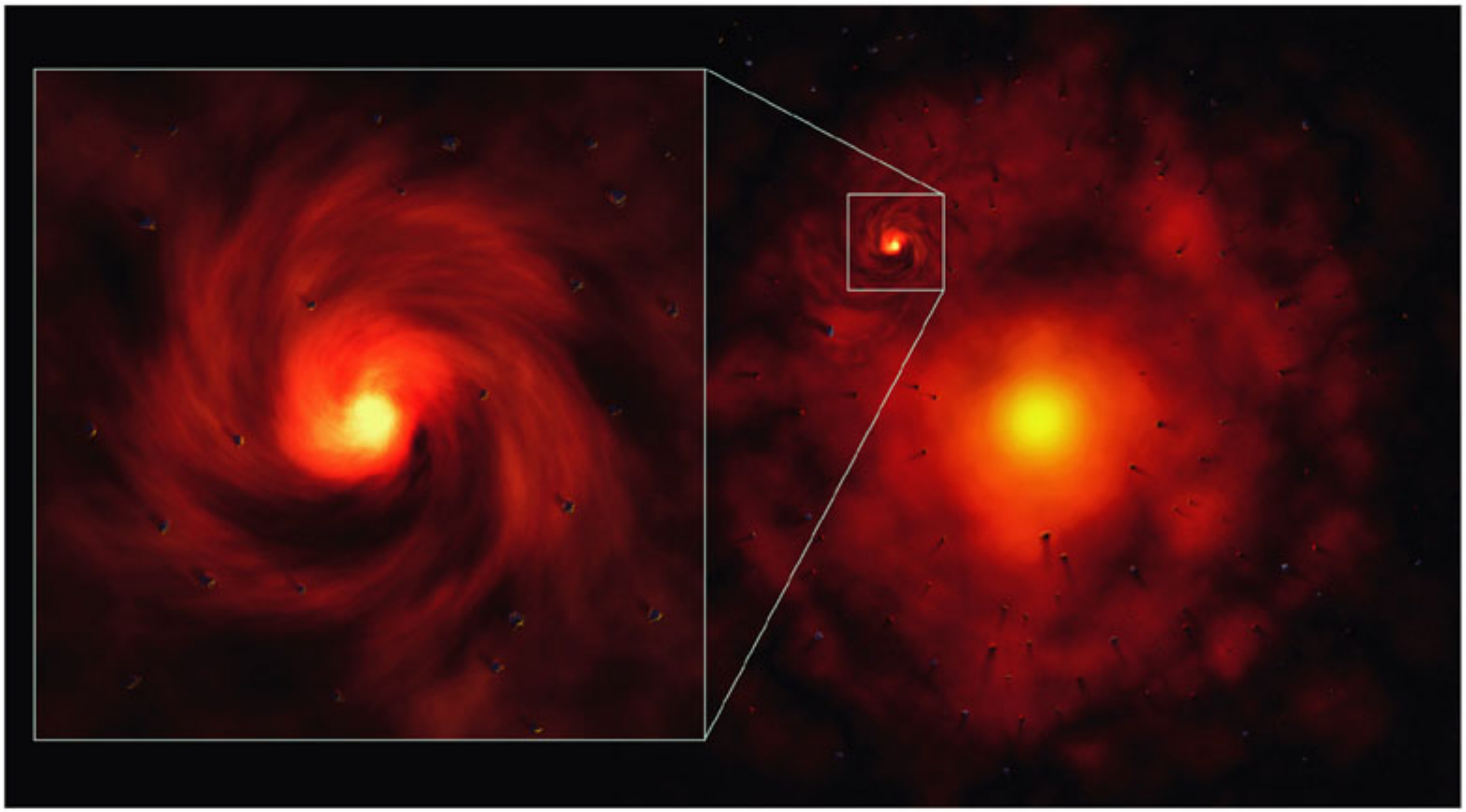
Dusty Circumstellar Disks



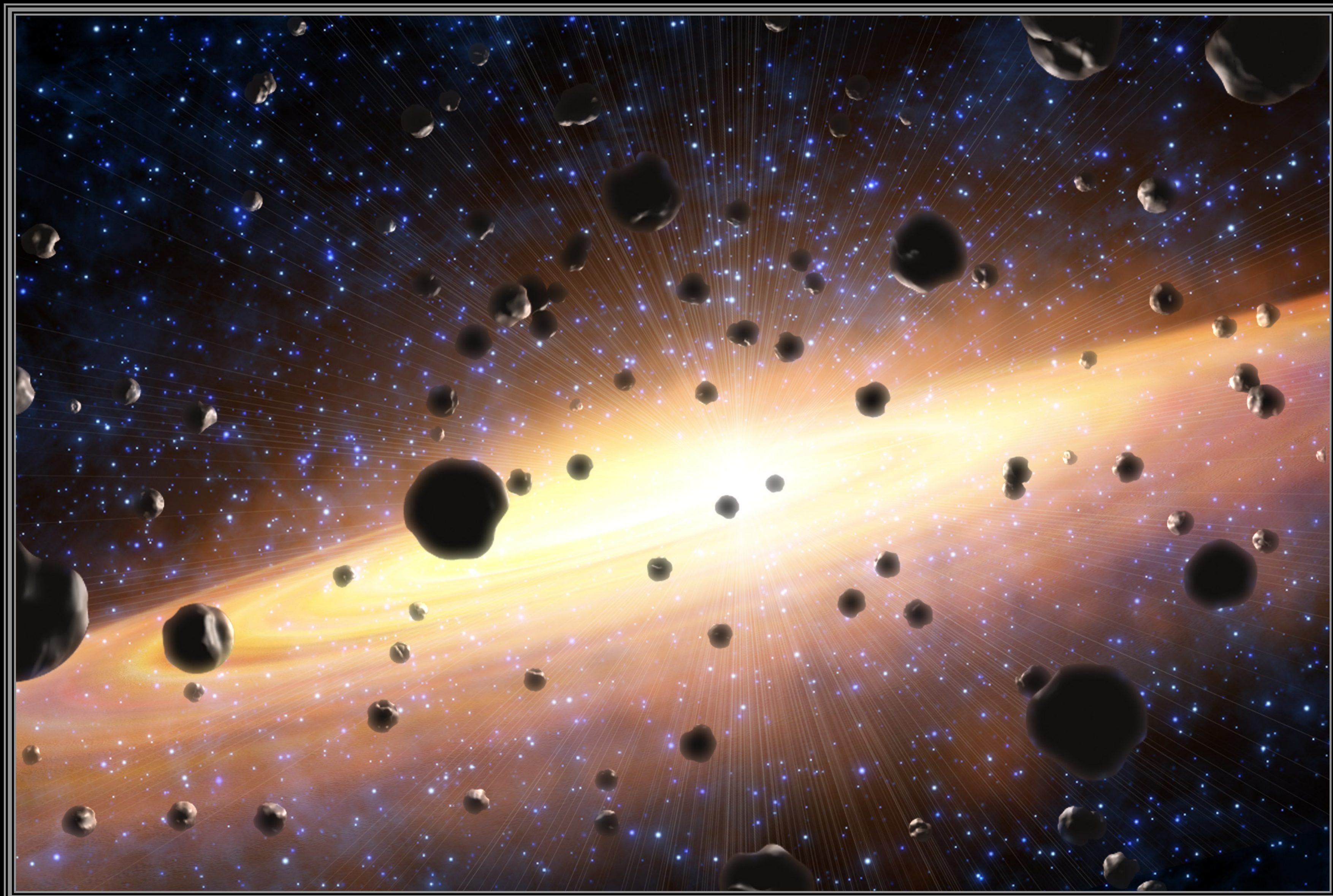
Dust Disks around Stars **HST • NICMOS**

PRC99-03 • STScI OPO • January 8, 1999
B. Smith (University of Hawaii), G. Schneider (University of Arizona),
E. Becklin and A. Weinberger (UCLA) and NASA

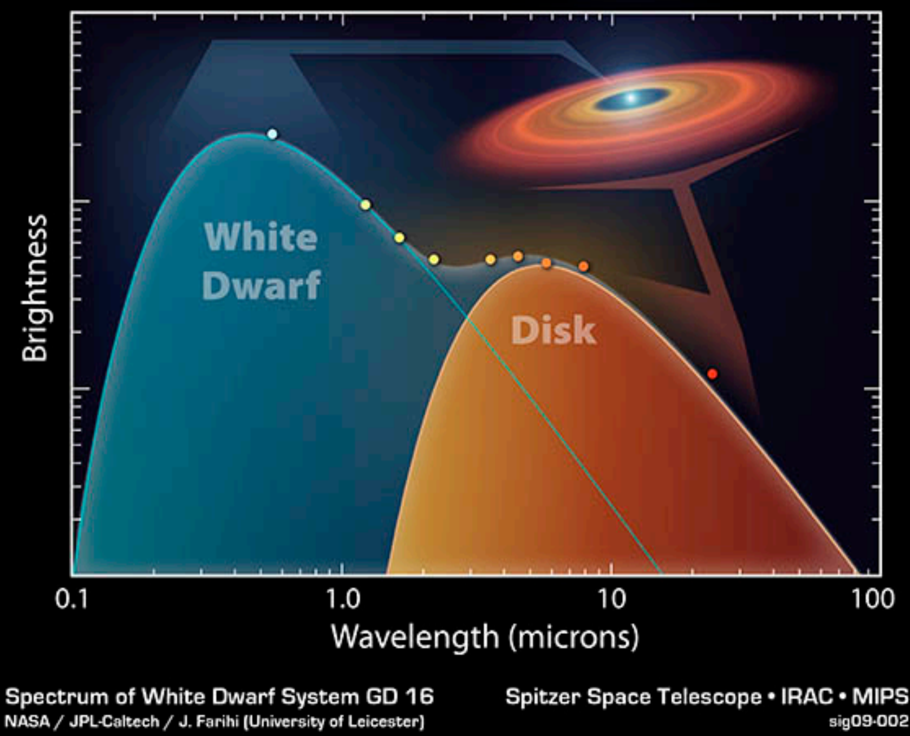
Accretion and "Sub-Accretion"

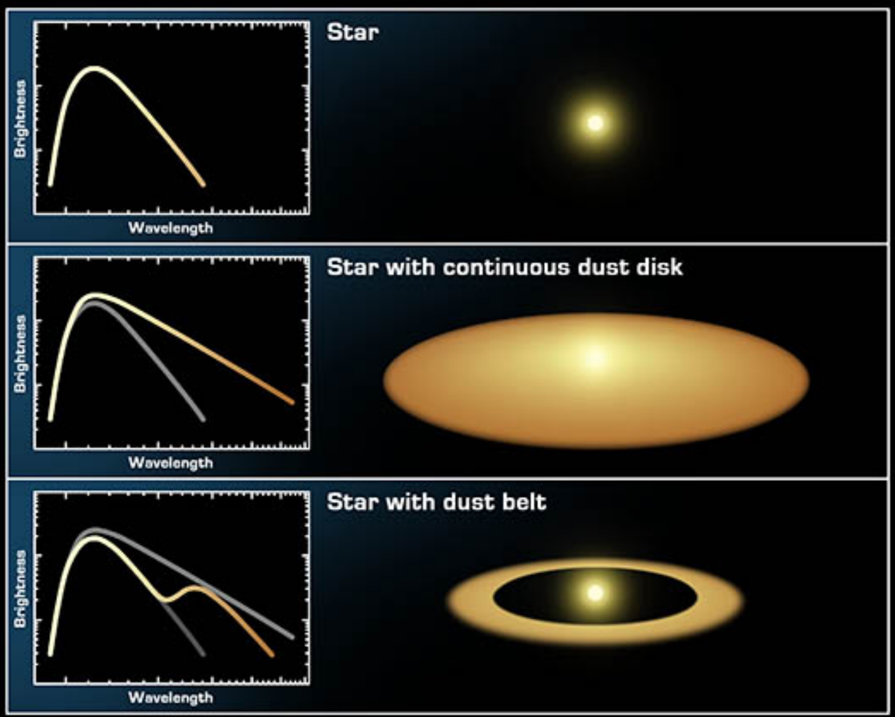


PLANET STAR



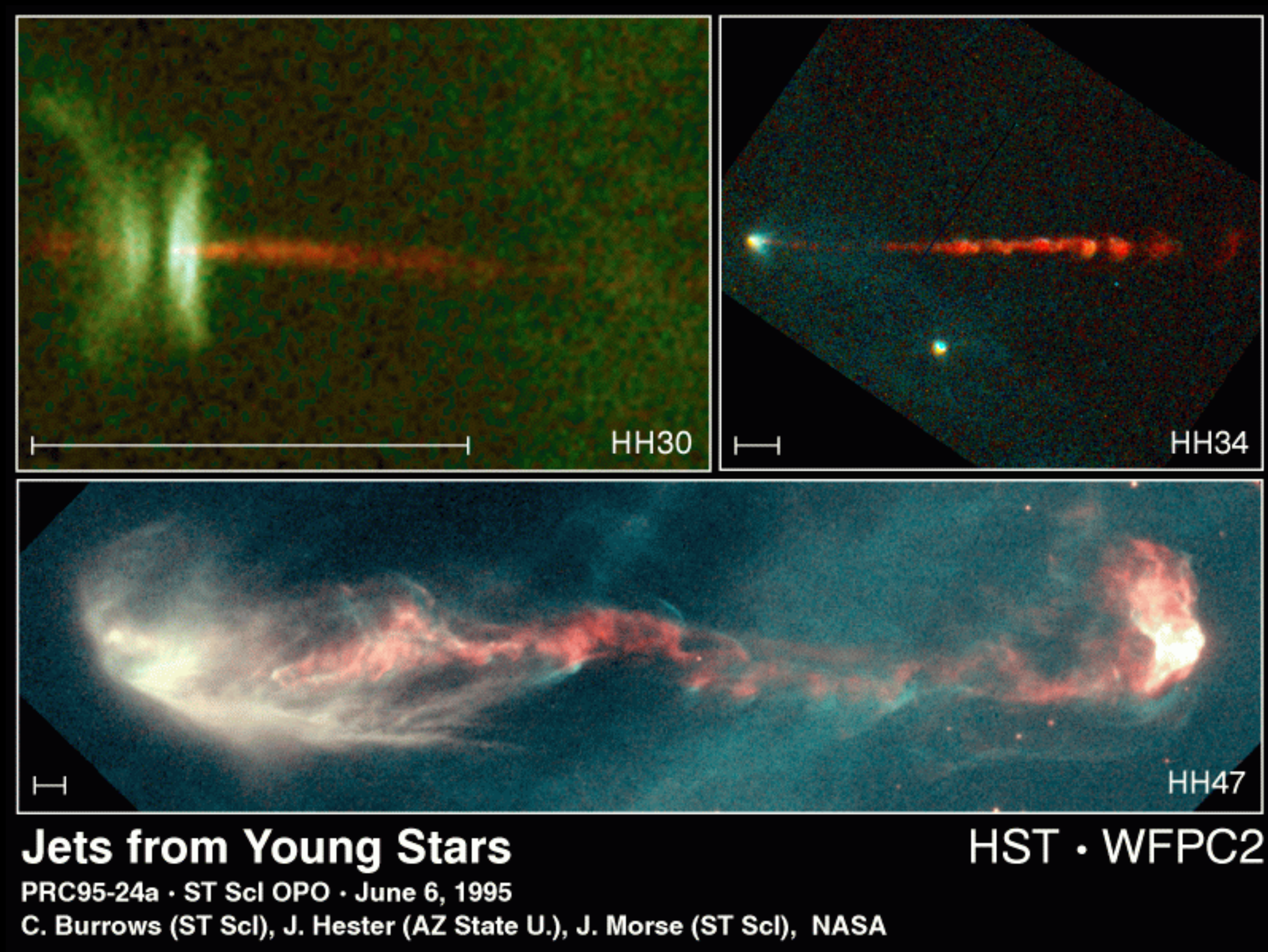
What about disks we cannot resolve? Right is an example of a star with a disk and the merged spectrum that they produce.

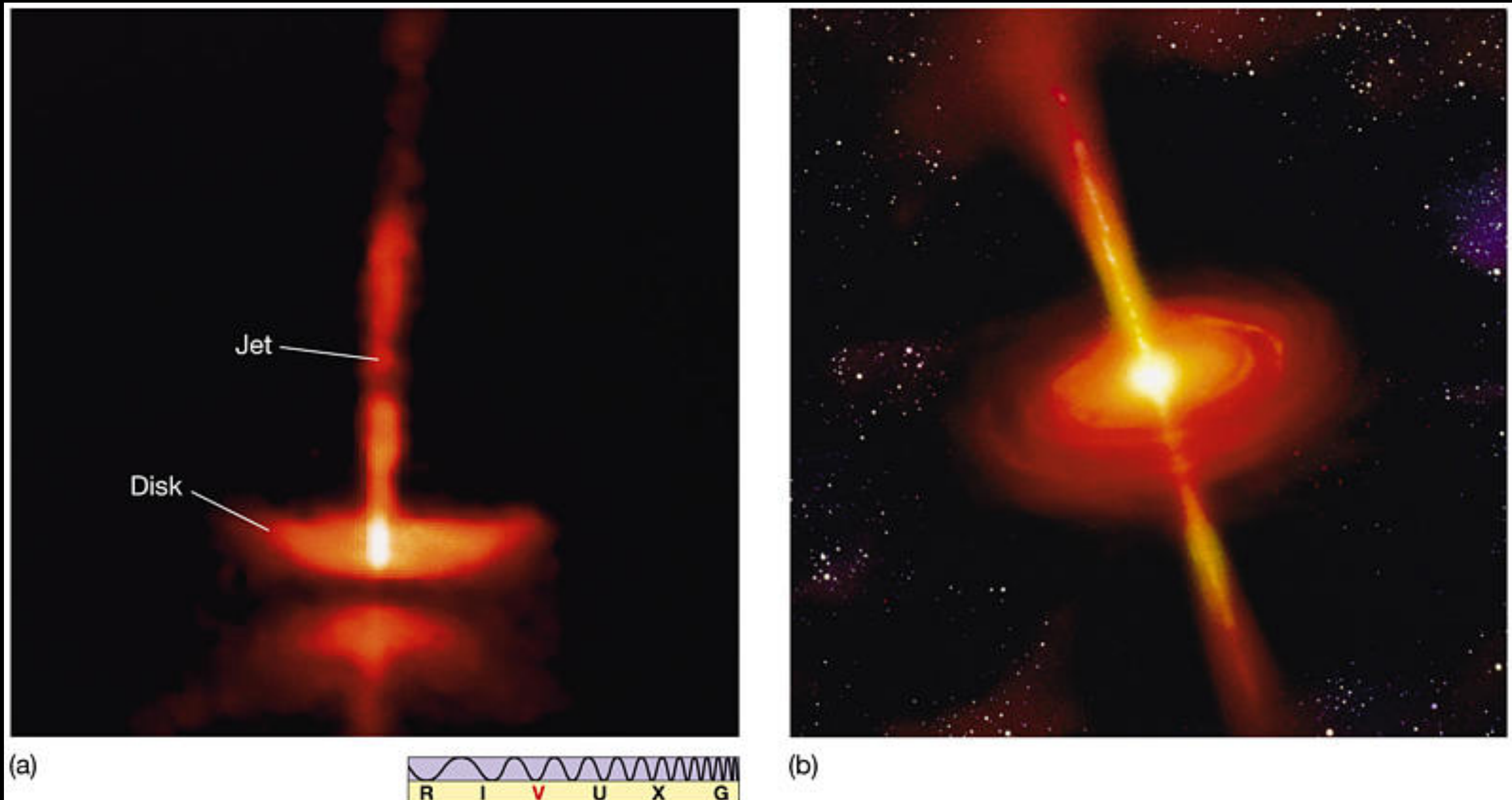




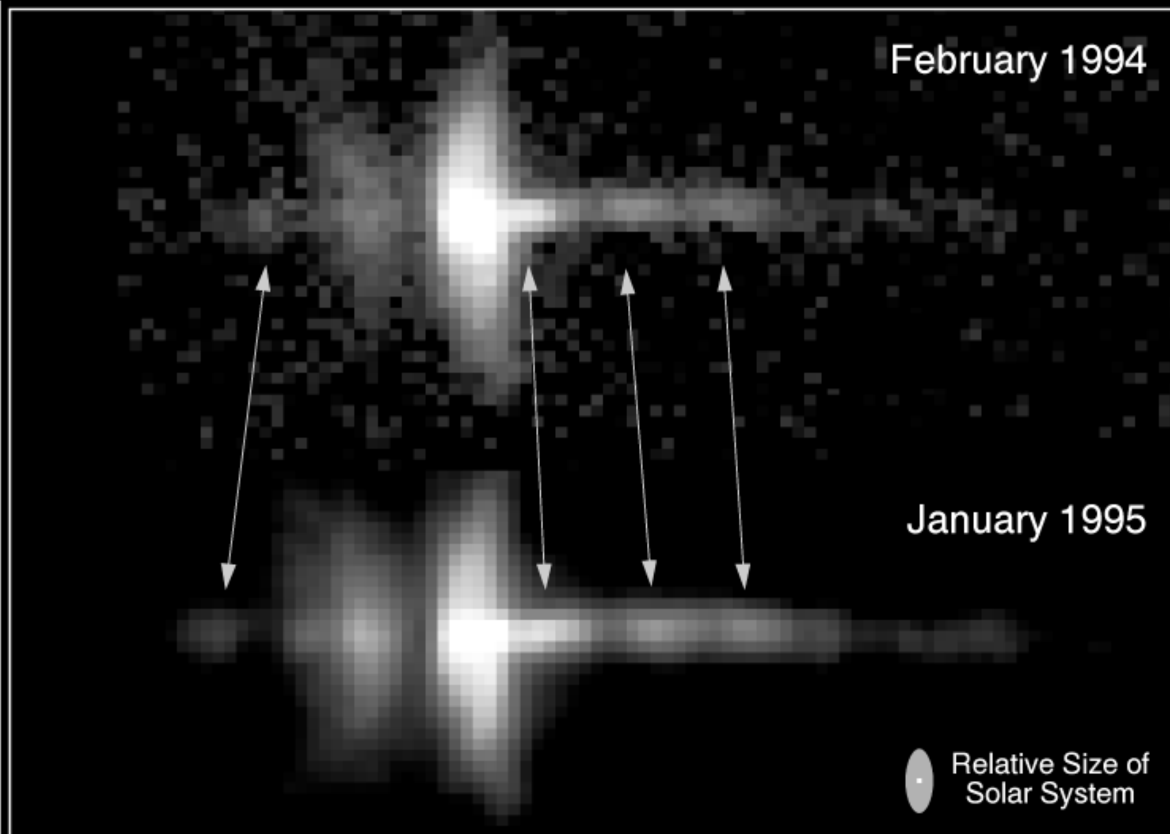
Left illustrates how spectra Can be used to infer the geometry of the disk. Middle is a continuous disk; bottom has a "gap" zone.

Jets Observed in Forming Stars




Jet
Disk
(a)
R I V U X G
(b)

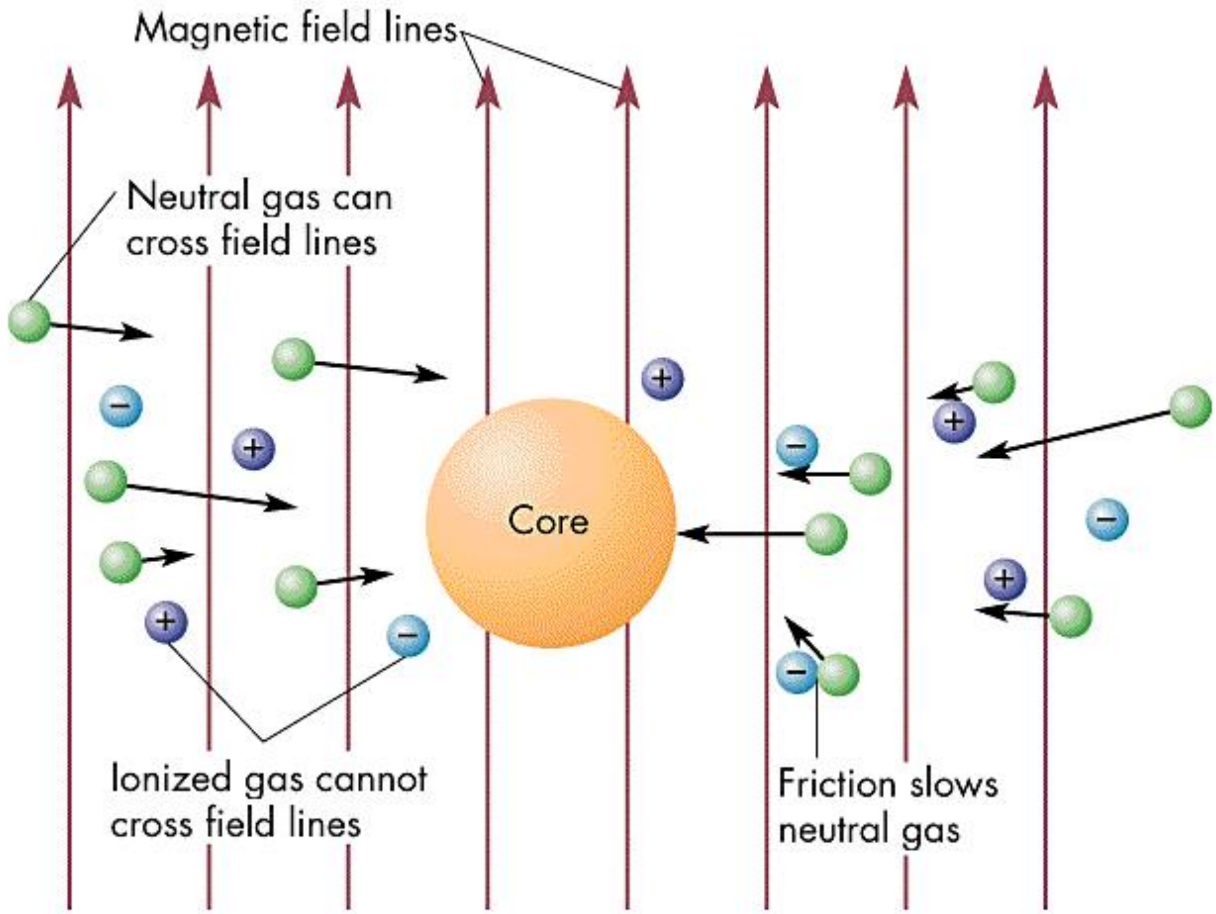
Motion in The HH30 Jet



Stellar Disk and Jet Motion · HH30 HST · WFPC2

PRC95-24b · ST ScI OPO · June 6, 1995 · C. Burrows (ST ScI), NASA

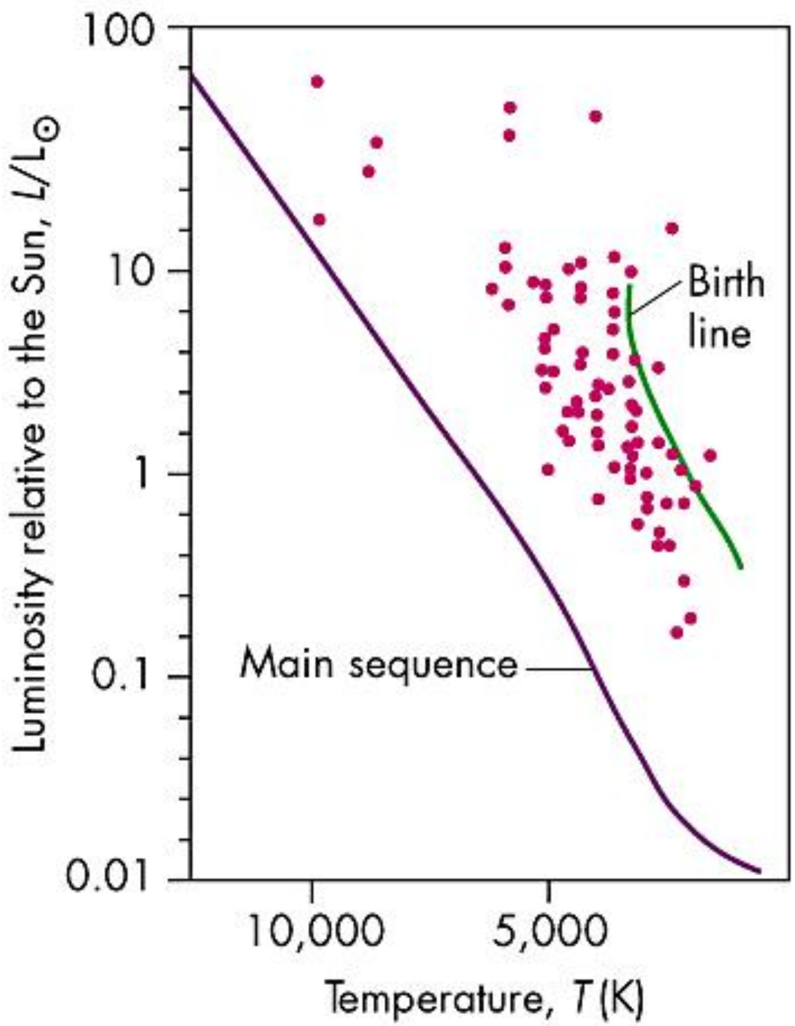
Magnetism Impedes Star Formation



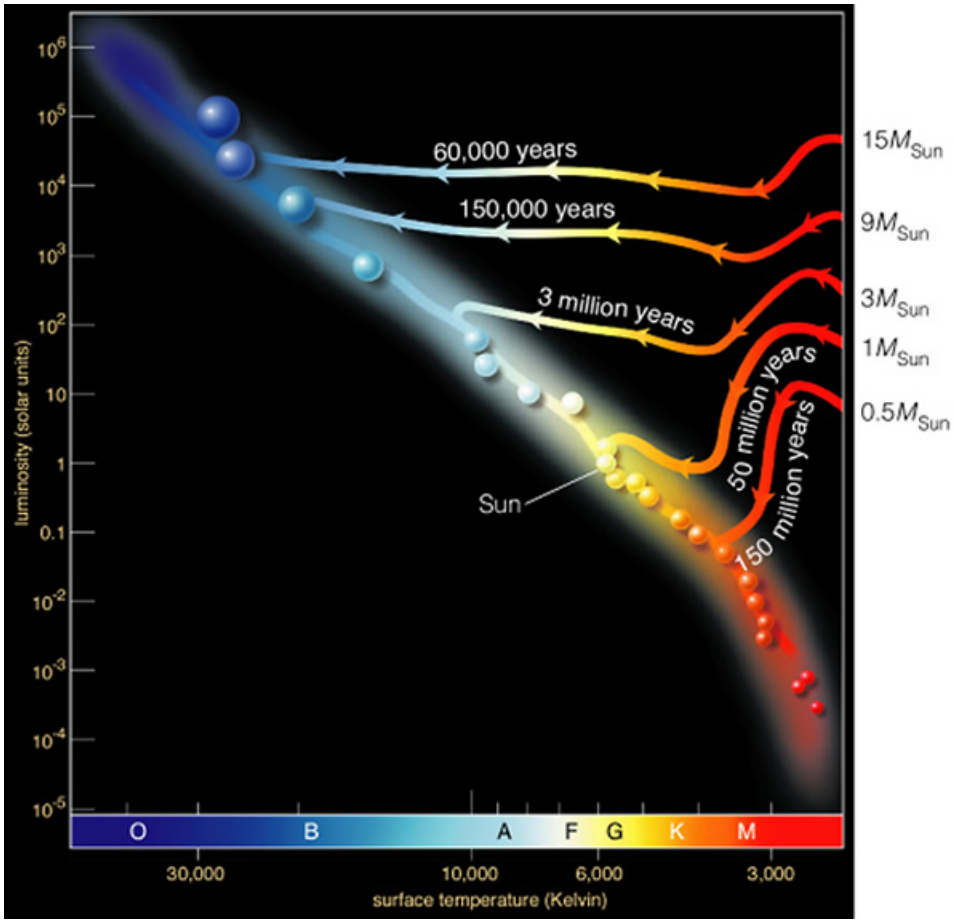
Contraction Phase

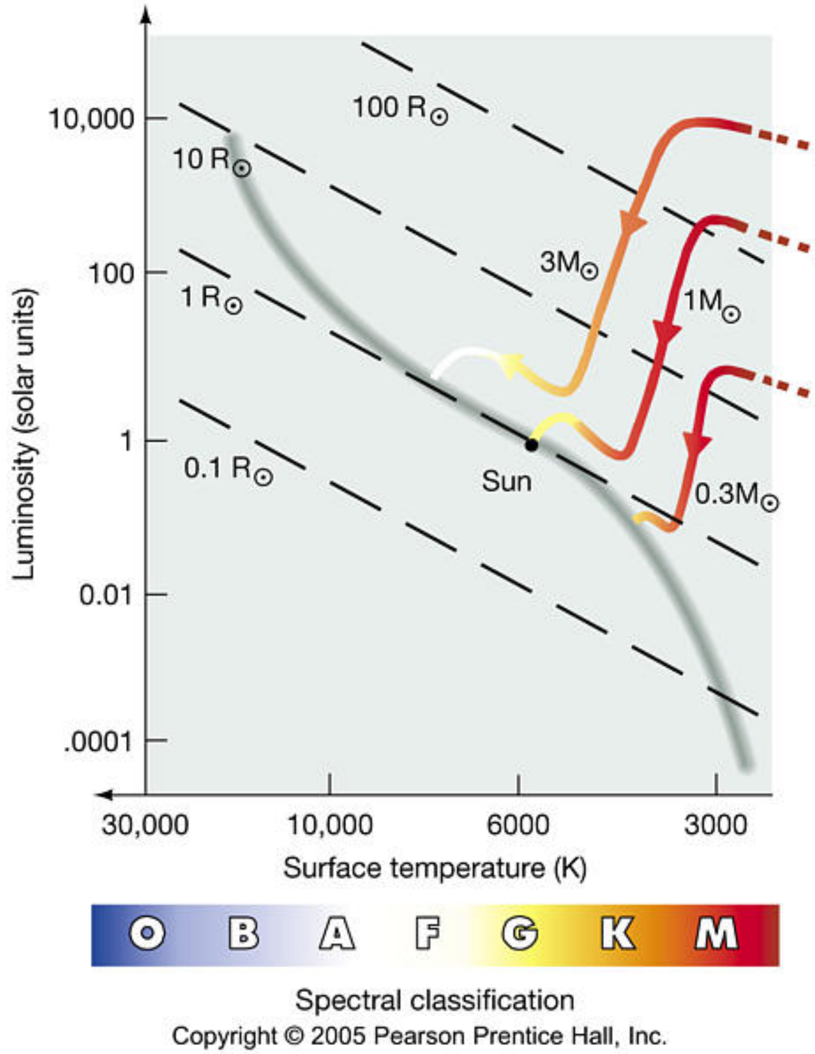
- As collapse proceeds, density increases and cloud becomes opaque. Radiation is trapped, hence temperature and pressure increase
- Gas pressure now acts to resist the collapse, resulting in a more gradual gravitational "contraction" called the *Kelvin-Helmholtz* phase
- The object now shines as a **protostar**, fueled by gravity (i.e., contraction leads to "jostling" resulting in heating and IR light)

The Stellar Birthline

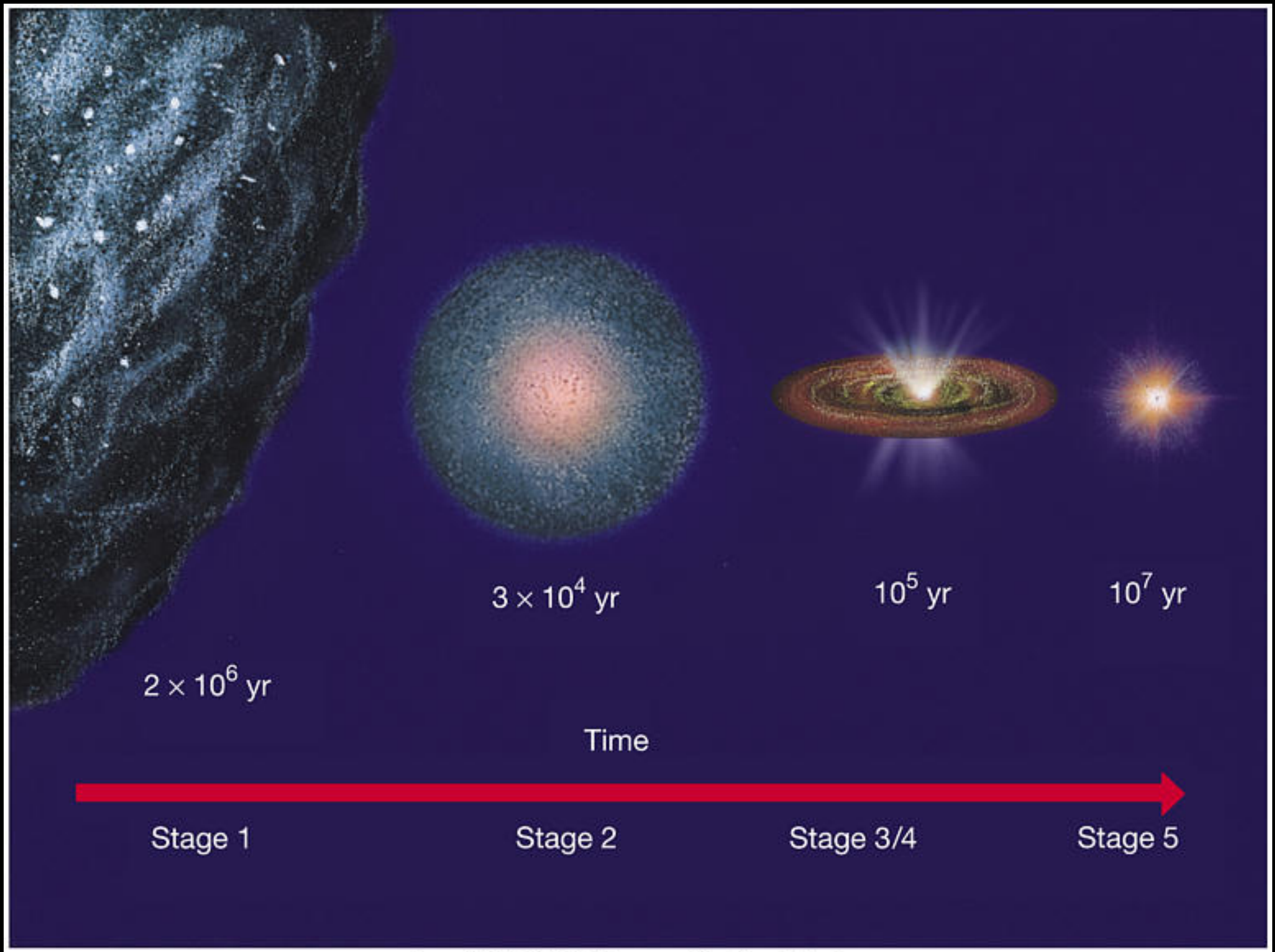


Pre-Main Sequence Tracks





Schematic of Star Formation



Kelvin-Helmholtz Timescale

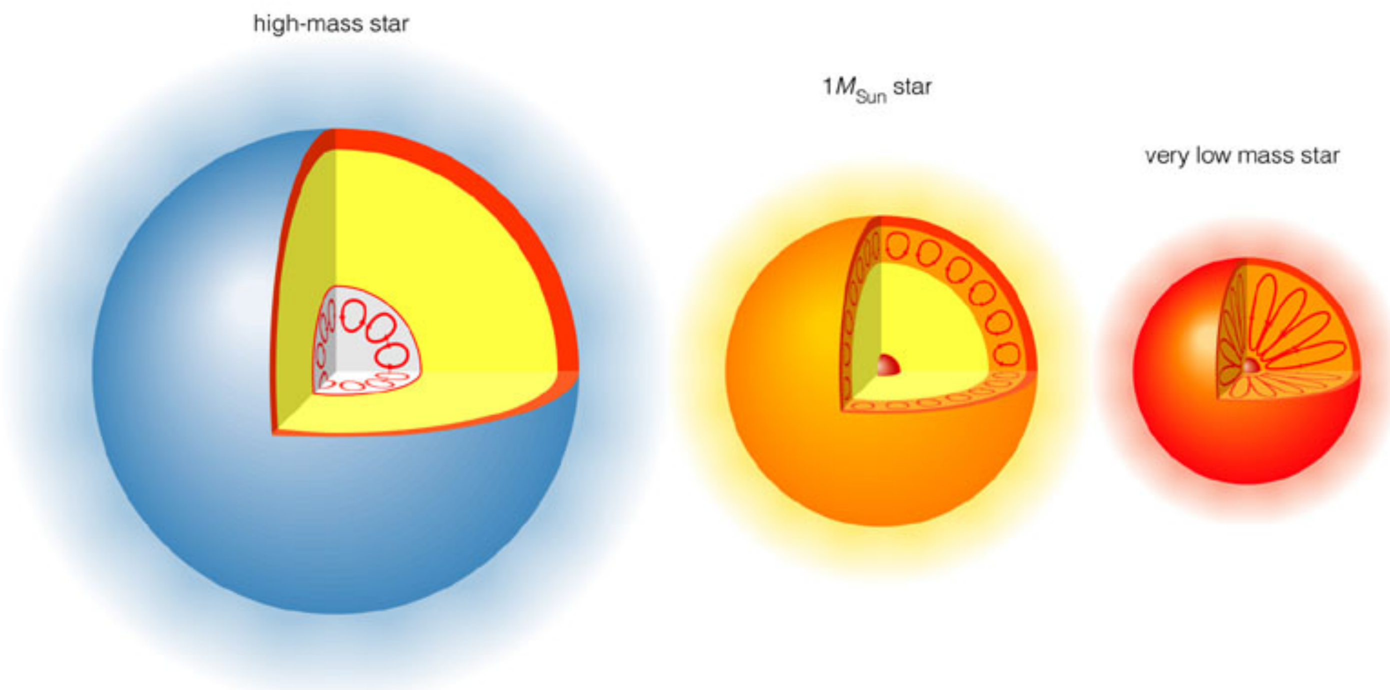
$$t_{KH} = \frac{\text{amount of fuel}}{\text{rate of consumption}}$$

$$\approx \frac{GM^2/R}{L}$$

$$\approx 30\ \text{Myr} \times \frac{M^2}{LR}\ \text{(in solar units)}$$

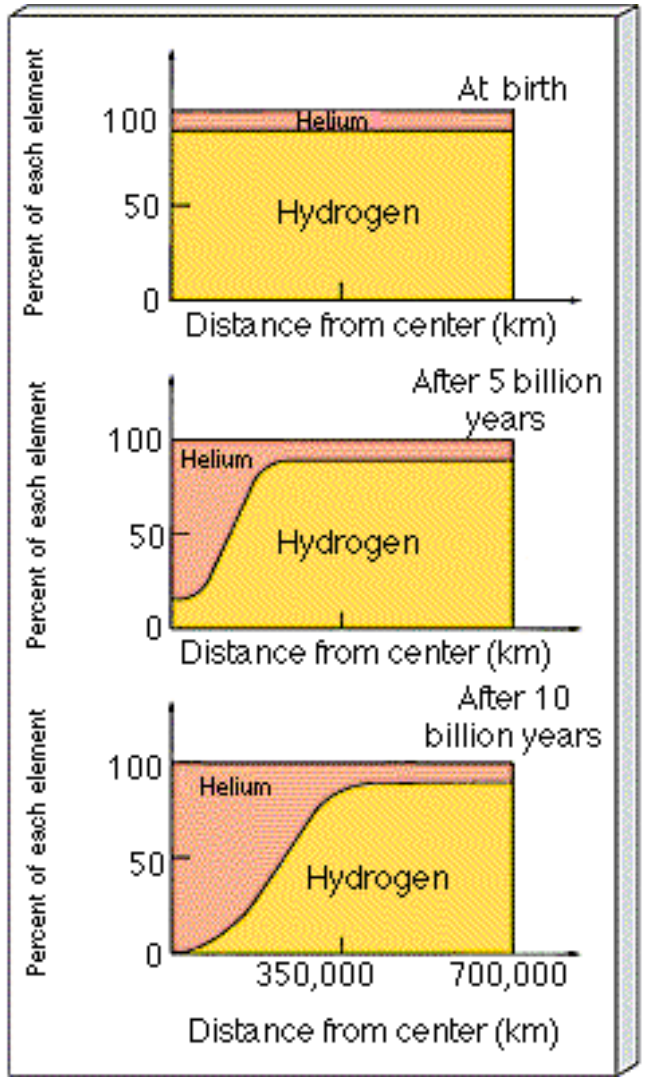
After this time, the core is hot enough to initiate H-fusion, and the star settles onto the MS in the H-R Diagram

Convection Along the Main Seq.

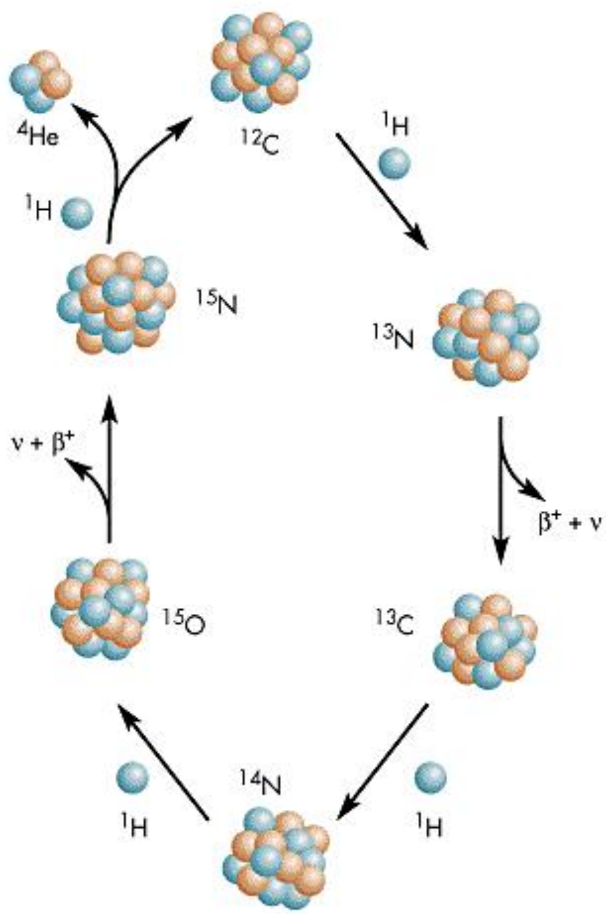


Convection is a "mixing" process. It moves gaseous material around. Convection transitions from being the outer region for low mass stars to central region for high mass ones. This results in more material available for fusion.

Changing Core Composition



The Carbon Cycle



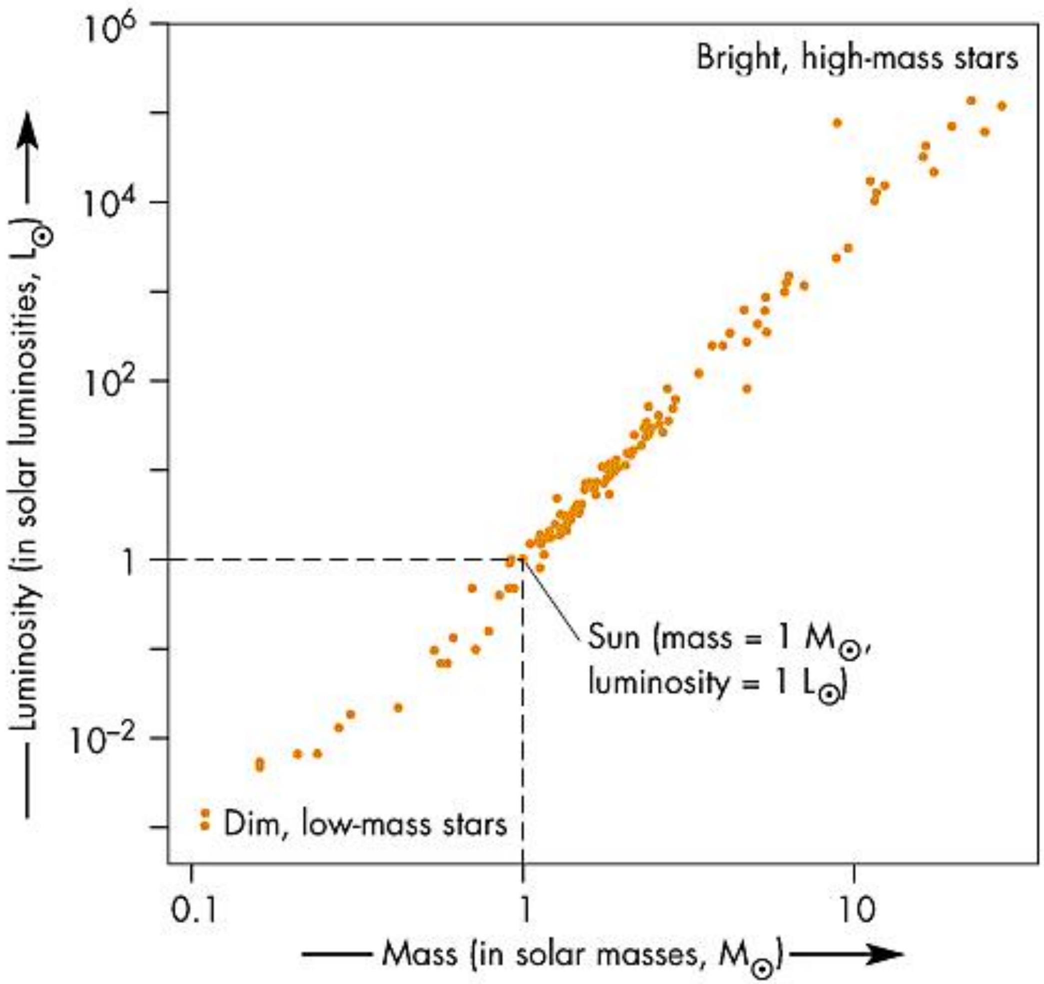
The protoon-proton is not the only way to convert H to He. Above about 8 solar masses, stars still convert 4 H's to 1 He to sustain their luminosity, but the cycle follows a new chain instead of the proton-proton chain

Mass-Luminosity Relation

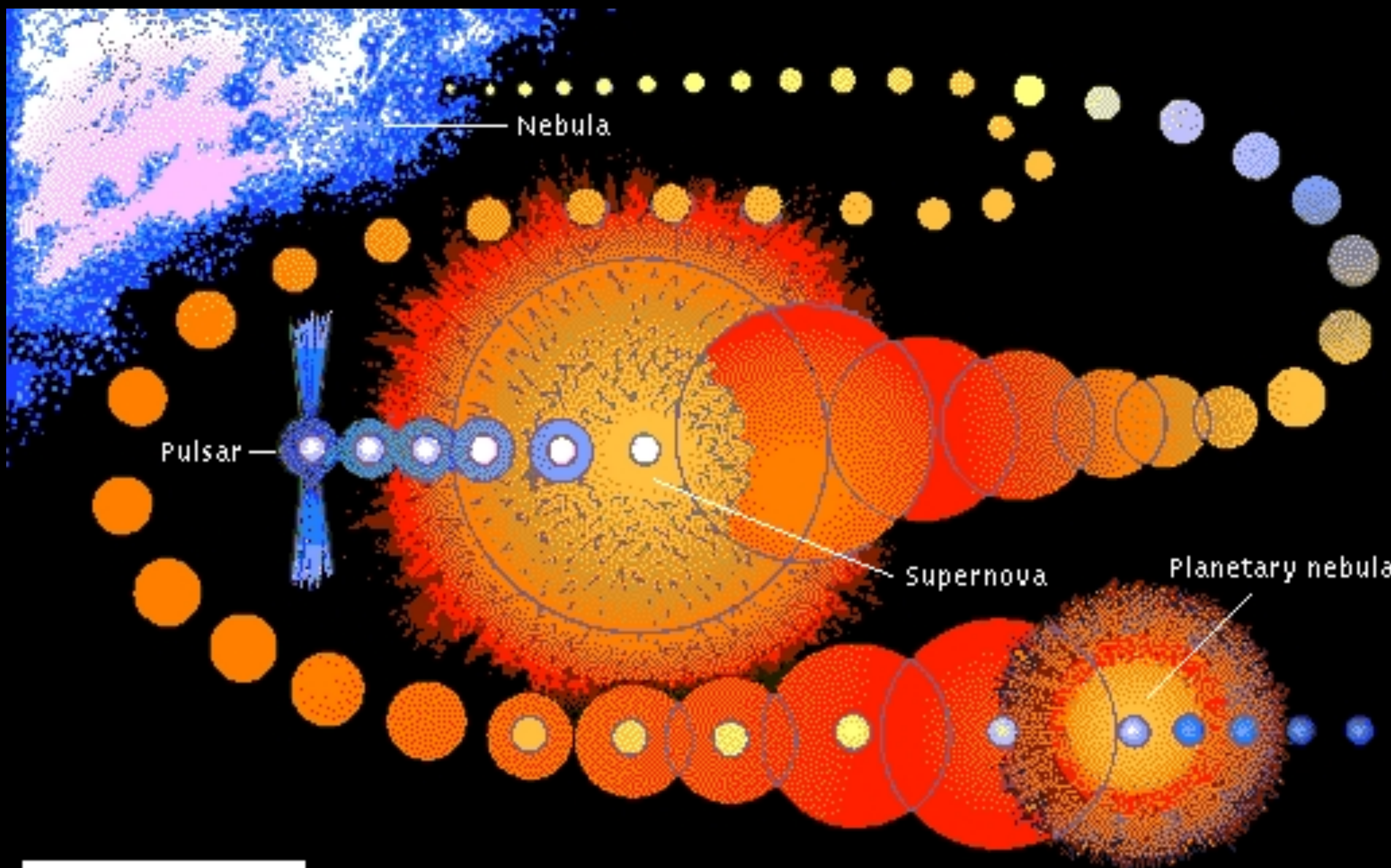
For Main Sequence Stars:

$$L/L_o \approx \left(M/M_o\right)^3$$

This is enormously important and emphasizes the central role of mass for how stars operate.

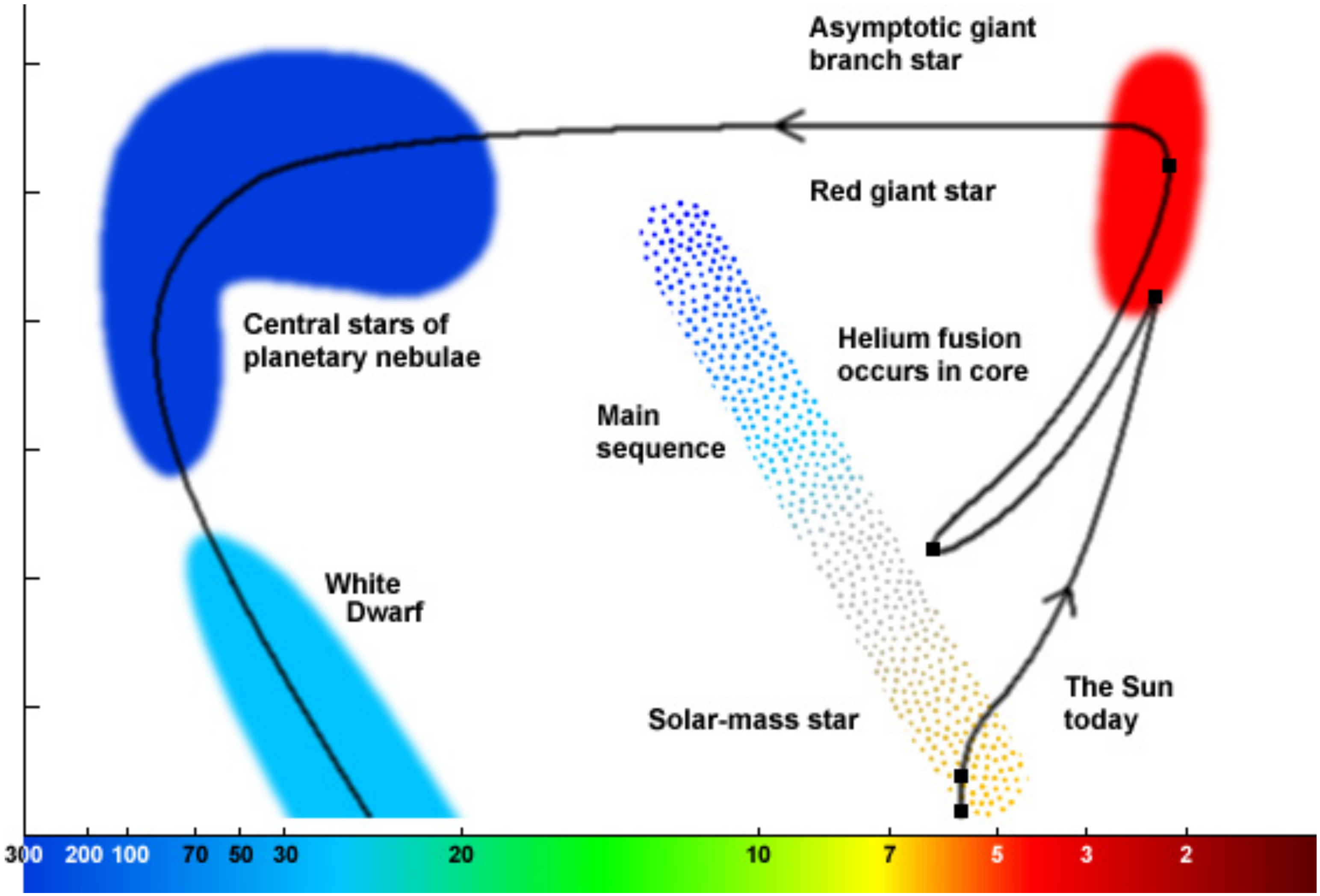


Long-Term Changes in the Sun



Microsoft Illustration

Temperature-Luminosity States



Main Sequence Timescale

On the MS, stars convert 4H's to He, plus energy production. Eventually the core hydrogen fuel is exhausted. How long does that take?

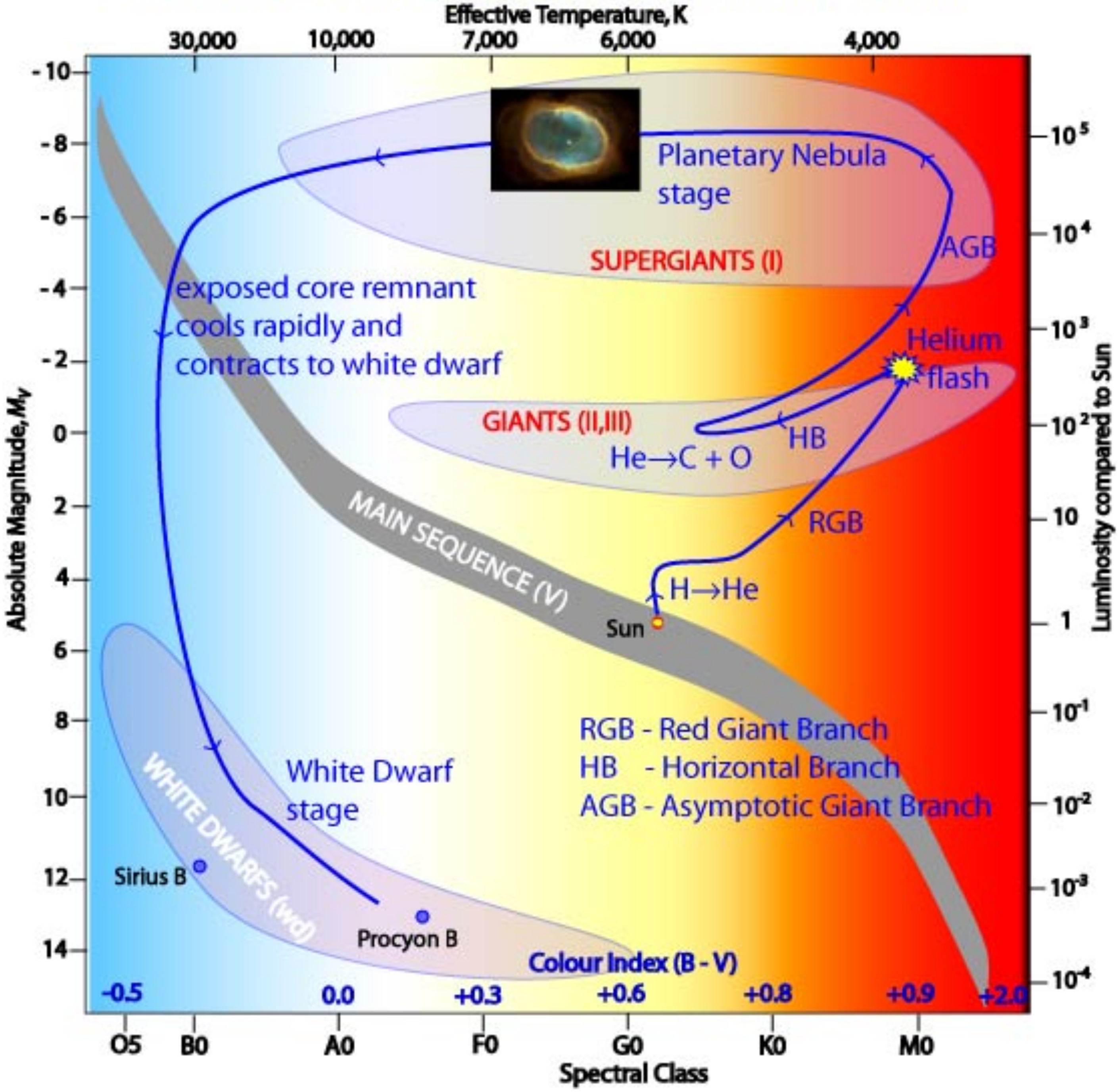
1. About ε = *10%* of the star's mass goes into H-fusion.
2. Every time a helium atom is made, a fraction *f = 0.7%* of the 4H's go into energy.
3. The fuel is *E=(mass x c*^{2}*)*, and the consumption rate is the luminosity *L*.

$$t_{MS} = \frac{\varepsilon \times f \times M_* c^2}{L_*} \approx 10 \text{ Gyr } \times \frac{M_*/M_\circ}{L_*/L_\circ}$$

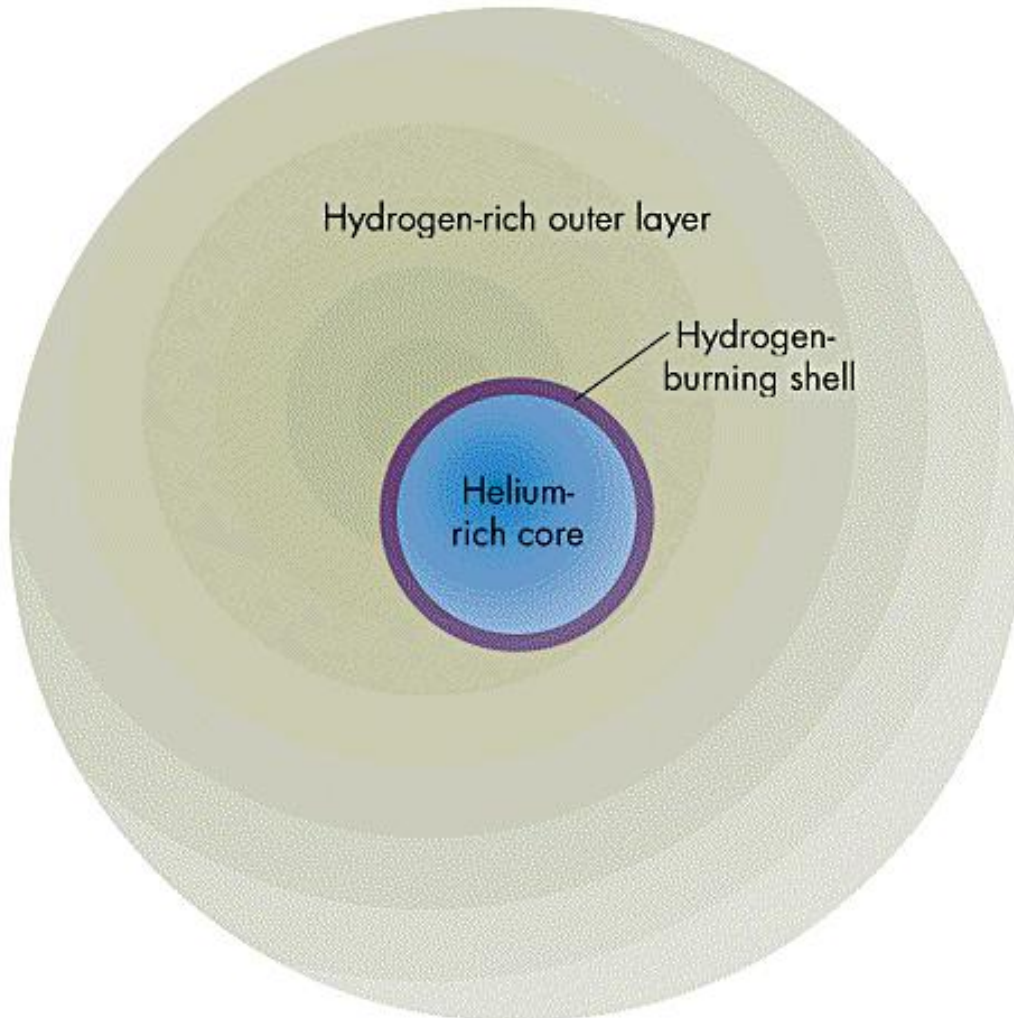
Using the mass-luminosity relation:

$$t_{MS} \approx 10 \text{ Gyr } \times \frac{1}{(M_*/M_\circ)^2}$$

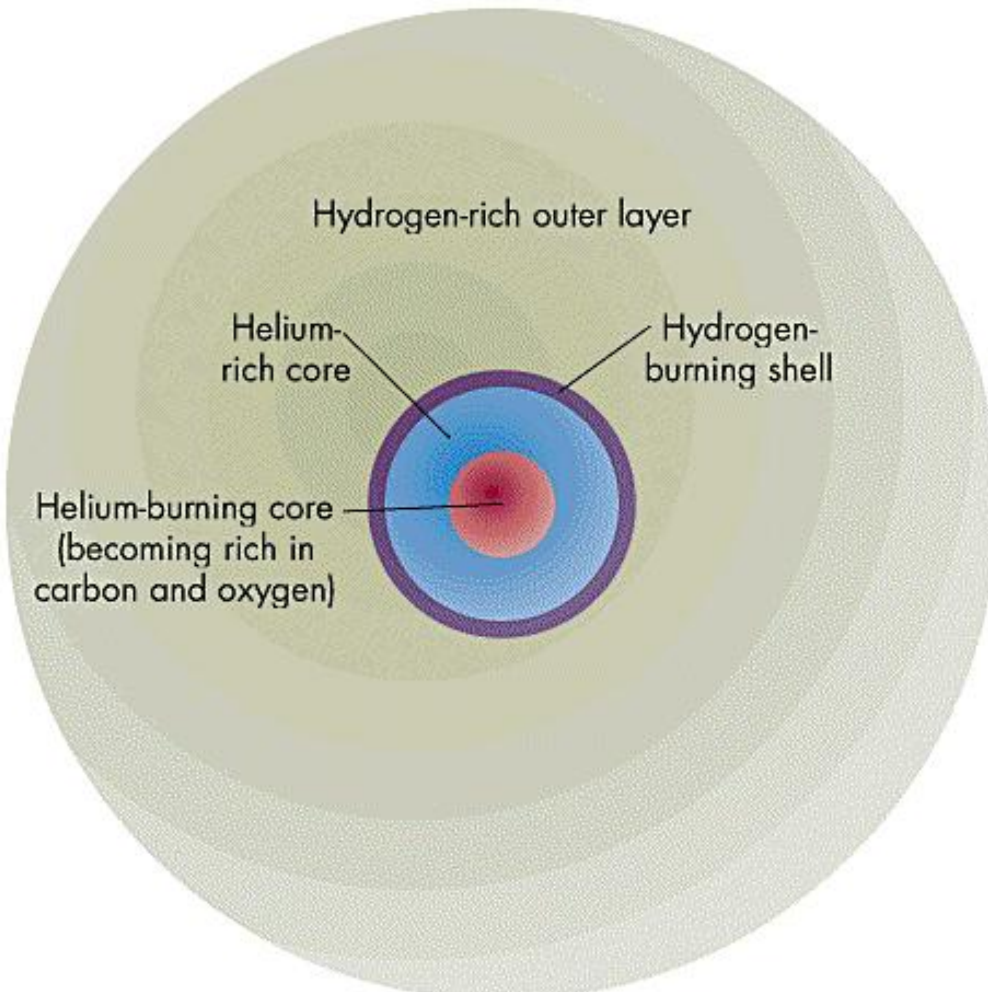
Sun's Post-Main Sequence Evolutionary Track

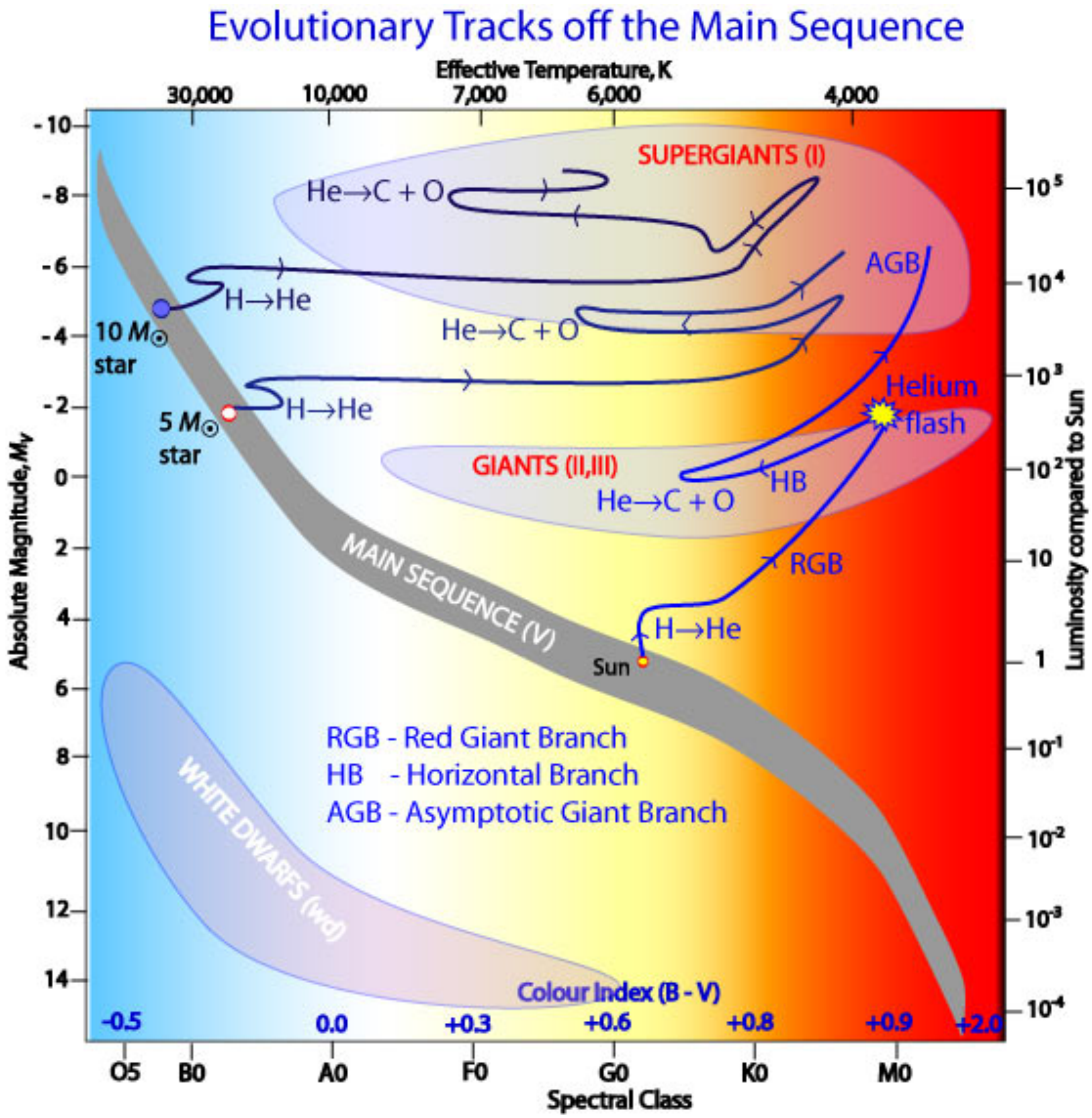


Hydrogen Shell Burning Phase



Core Helium Burning Phase





Evolutionary Tracks off the Main Sequence
Effective Temperature, K
30,000
10,000
7,000
6,000
4,000
SUPERGIANTS (I)
He→C + O
H→He
10 $M_\odot$ star
He→C + O
AGB
5 $M_\odot$ star
H→He
Helium flash
GIANTS (II,III)
HB
He→C + O
RGB
MAIN SEQUENCE (V)
H→He
Sun
RGB - Red Giant Branch
HB - Horizontal Branch
AGB - Asymptotic Giant Branch
WHITE DWARFS (wd)
Colour Index (B - V)
-0.5
0.0
+0.3
+0.6
+0.8
+0.9
+2.0
O5
B0
A0
F0
G0
K0
M0
Spectral Class
Absolute Magnitude, M_V
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
Luminosity compared to Sun
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Post-MS ($M<8M_{\odot}$)

1. After H in core exhausted, left with He ash. H-fusion continues in a "shell".
2. Atmosphere expands – the *Red Giant Star*, a phase lasting for about 10% of t_{MS}
3. Core heats up until He burning begins via the triple alpha process

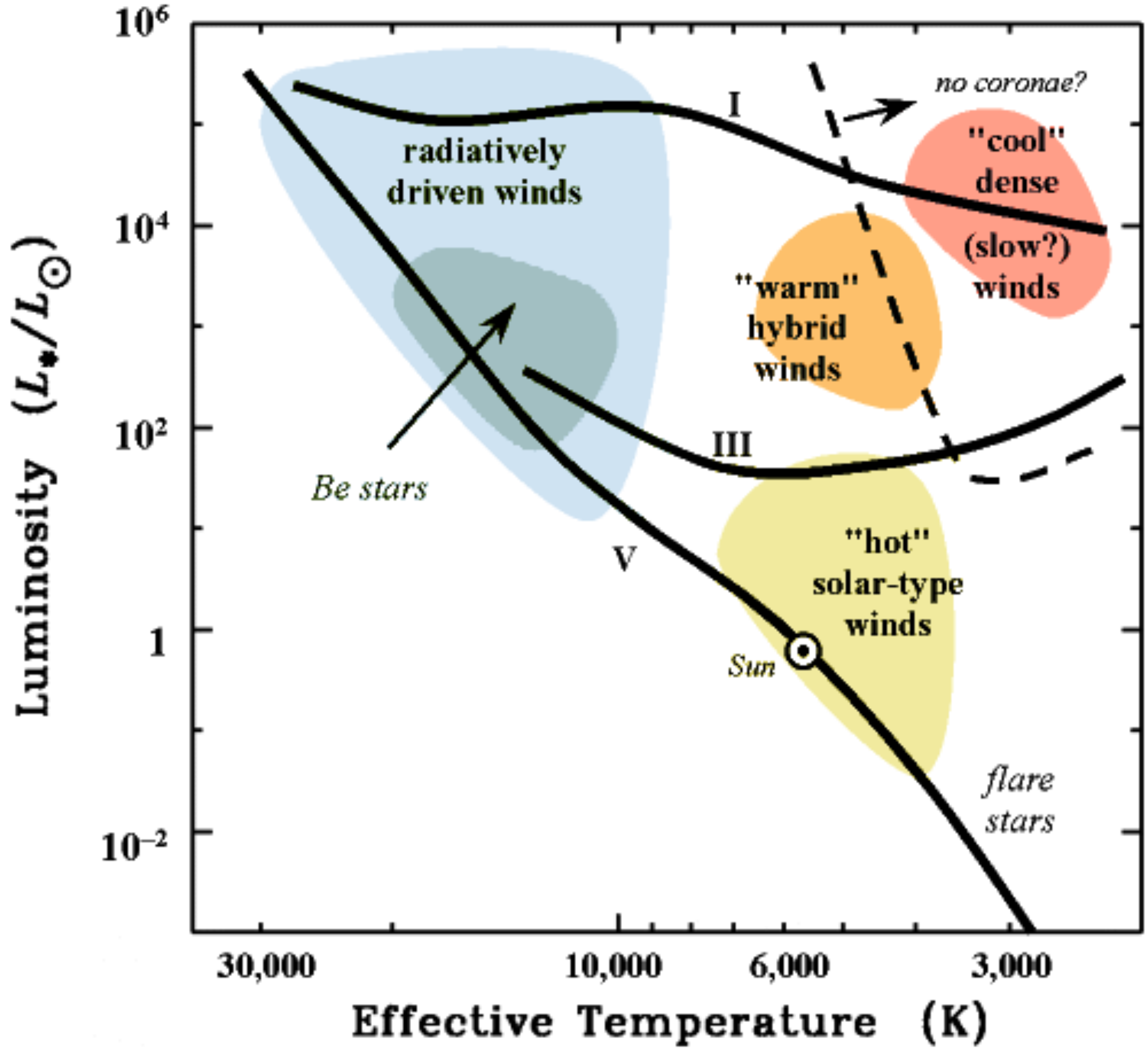
   3 ^{4}He converts to 1 ^{12}C, occurring at $T \sim 100 \times 10^6 K$
4. Becomes a *Horizontal Branch Star*
5. He core changes to C. He shell burning begins, and star climbs the *Asymptotic Giant Branch*
6. AGB star suffers mass loss; becomes a *Planetary Nebula*; dies a *White Dwarf Star*

Comment on Stellar Winds

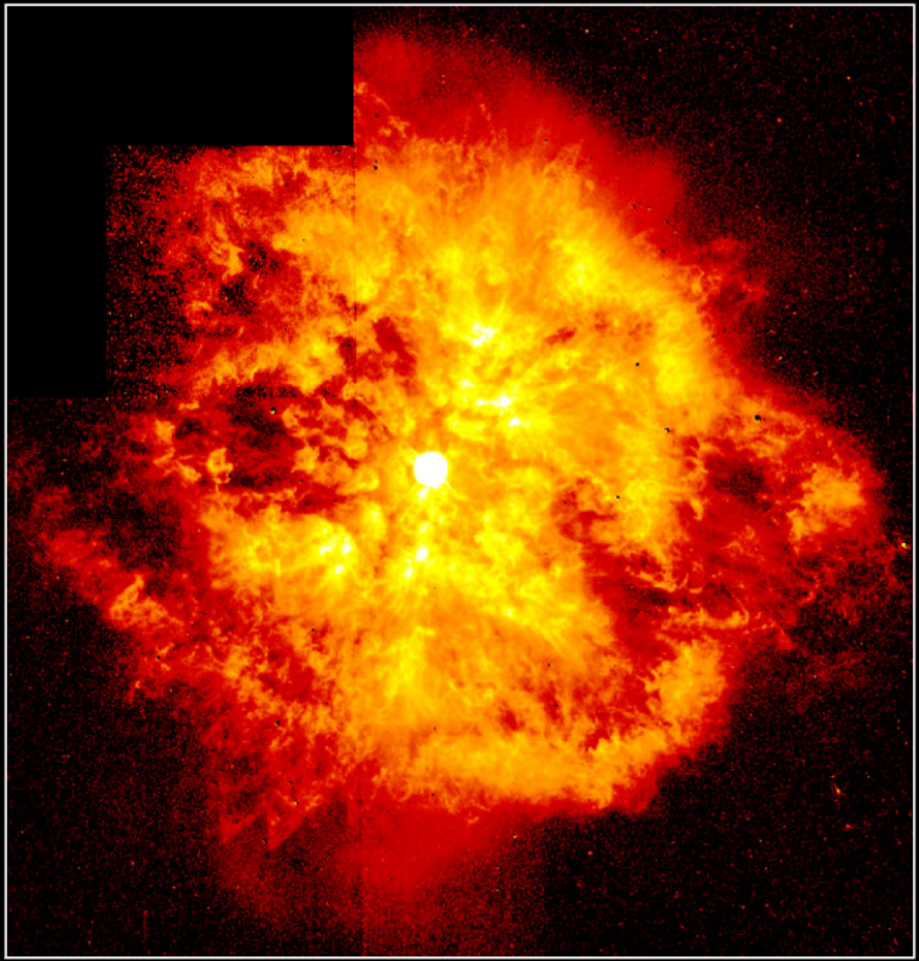
- All stars have mass loss
  1. Low Mass MS Stars: (e.g., Sun) thermal winds, hot corona "boils" away

     Very wimpy, losing only 10^{-14} M_o/year
  2. Cool Evolved Stars: (RG, AGB, RSG) usually higher mass loss, some have "superwind" that are dust-driven at 10^{-5} M_o/year
  3. Hot Stars: (OB stars) winds driven by high luminosities, ranging from 10^{-10} to 10^{-4} M_o/year
- Winds are important for determining stellar evolution and as a cosmic recycling process

Winds in the HRD



Stellar Recycling by Winds

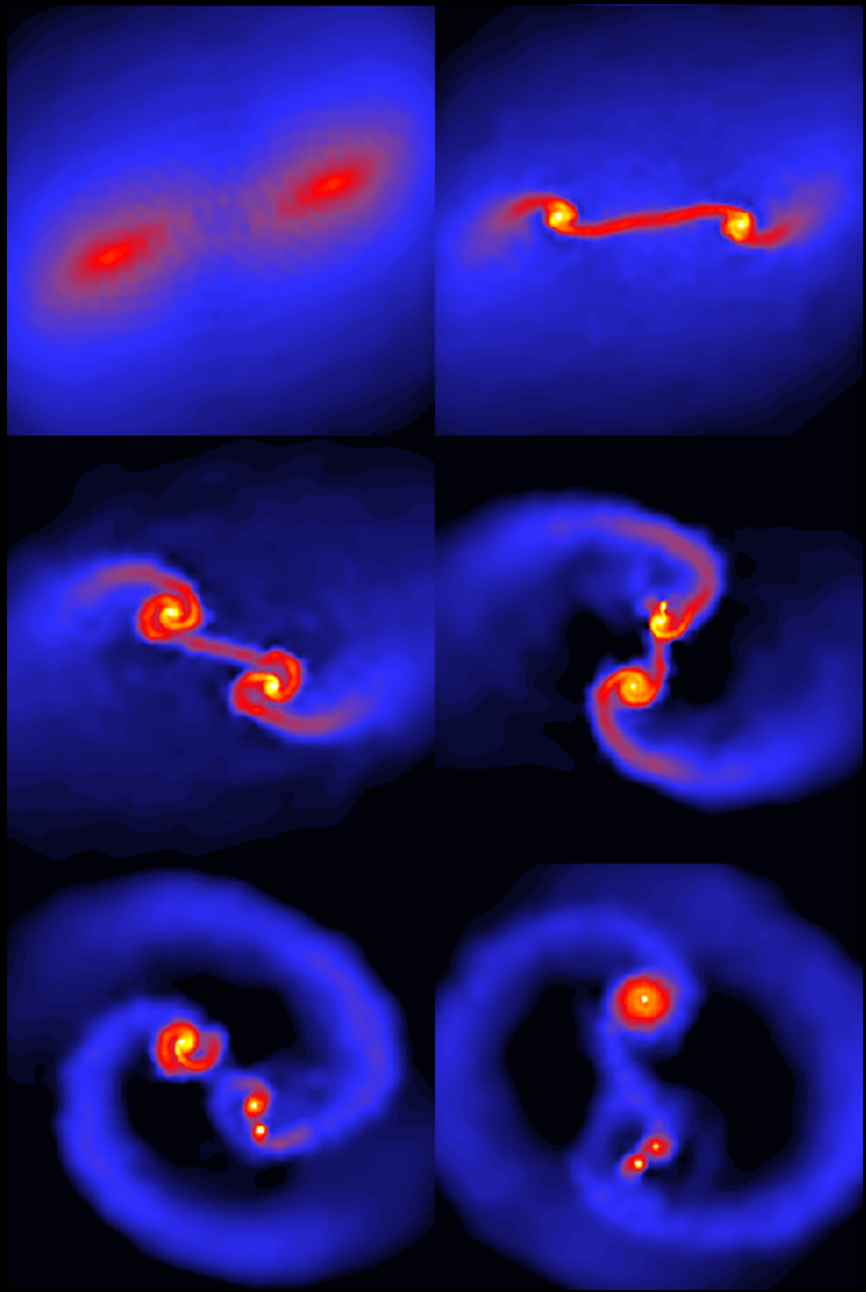


Nebula M1-67 around Star WR124 **HST • WFPC2**
PRC98-38 • STScI OPO • November 5, 1998
Y. Grosdidier and A. Moffat (University of Montreal) and NASA

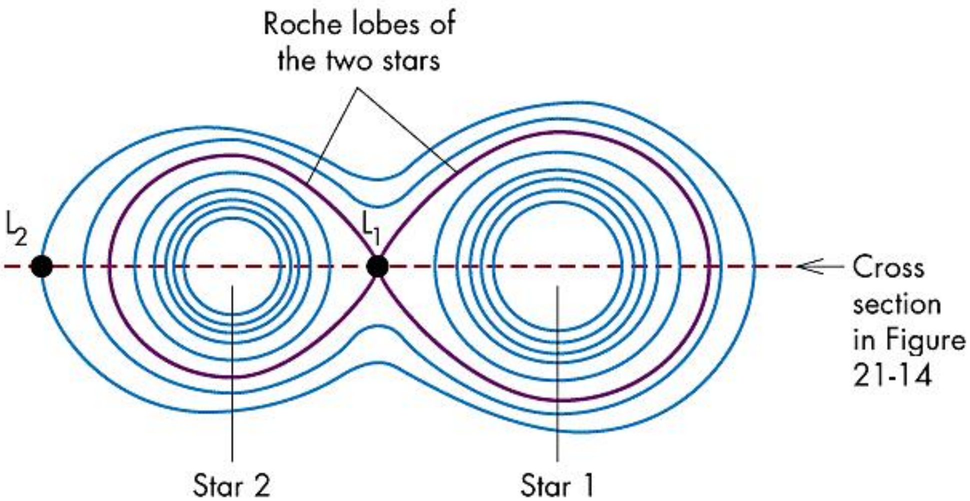
Evolution of Binaries

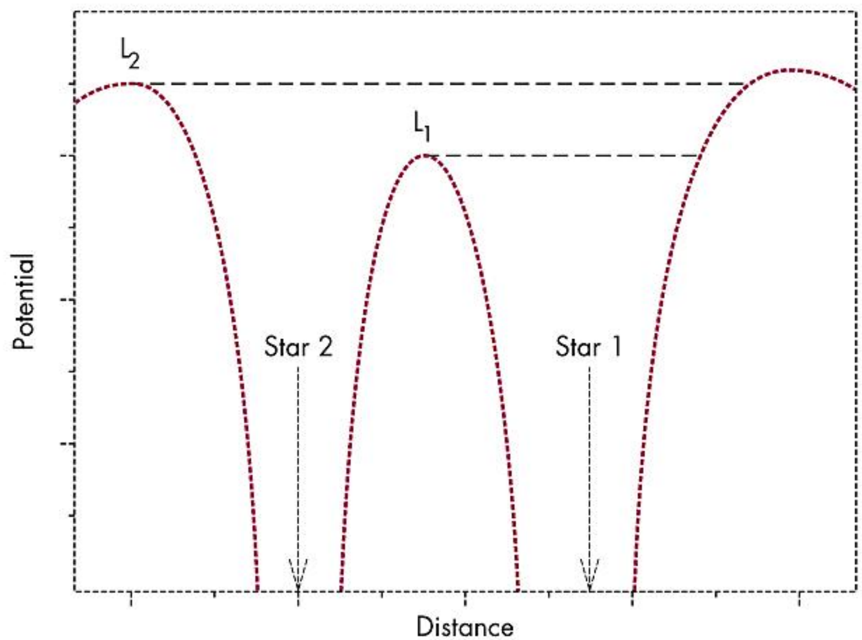
- Important issue, since about half of all stars are in binaries
- Primary rules:
  1. More massive star evolves faster
  2. Binaries can transfer mass if close, so less massive star can become more massive in some cases
  3. Angular momentum is ultimately conserved (relevant to how orbit can change)

Computer simulation of how a binary star system could form

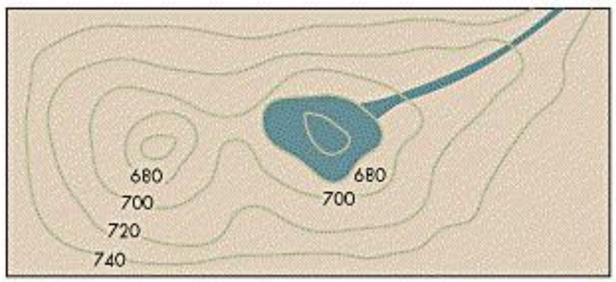


The Roche Lobe

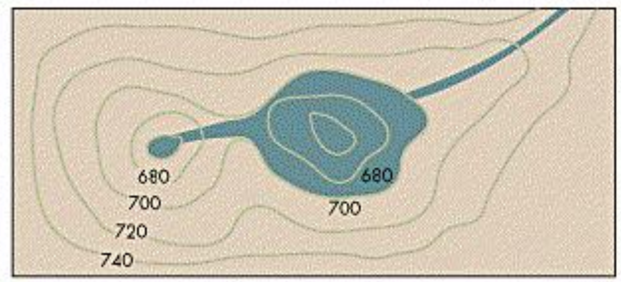




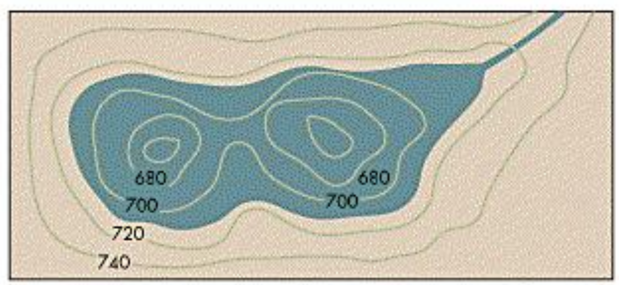
The Contour Map Analogy



A Water fills one depression first



B Water spills over into the second depression



C Water level rises as a single pond

Binary Evolution (cont.)

- *Low Mass Binaries:*

  One star can engulf another and they share a common envelope

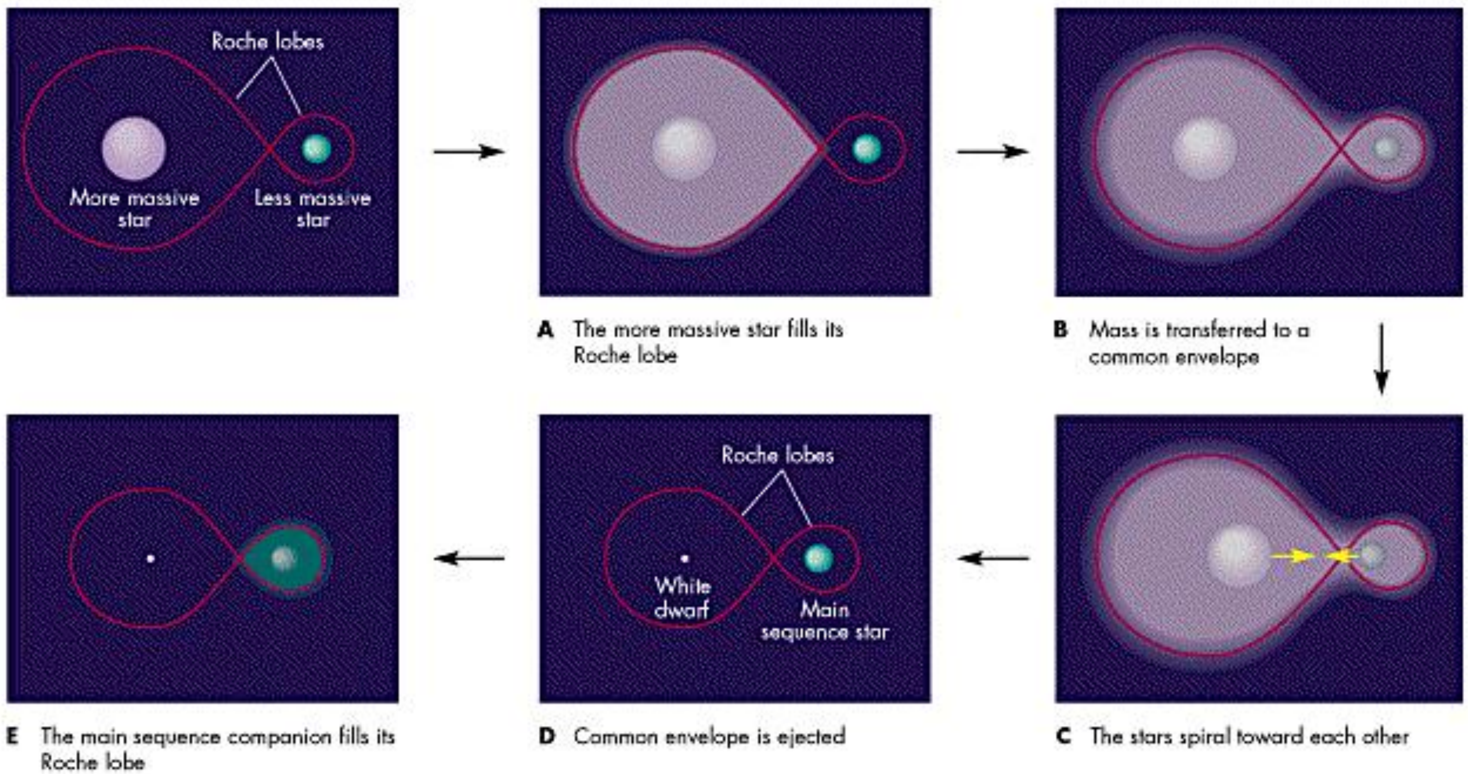
- *High Mass Binaries:*

  Main differences are that,

  a) massive stars have strong winds

  b) massive stars go SN

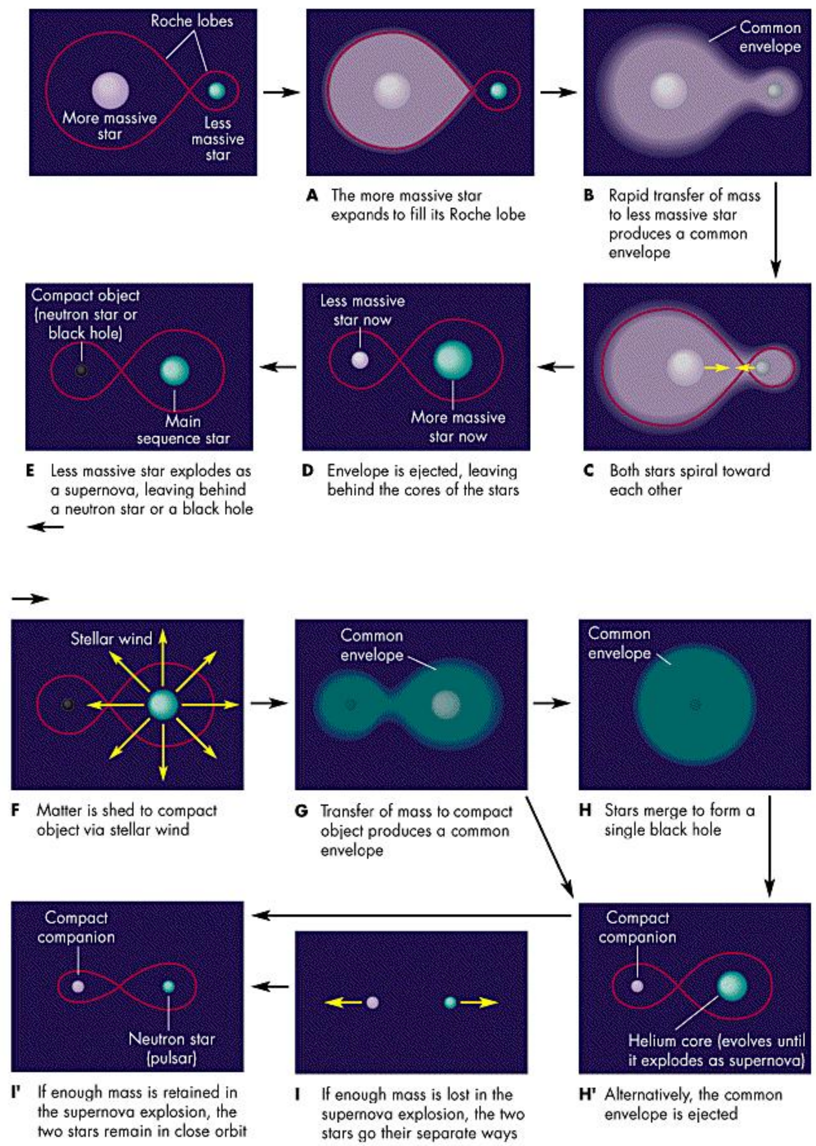
Evolution of Low Mass Binaries



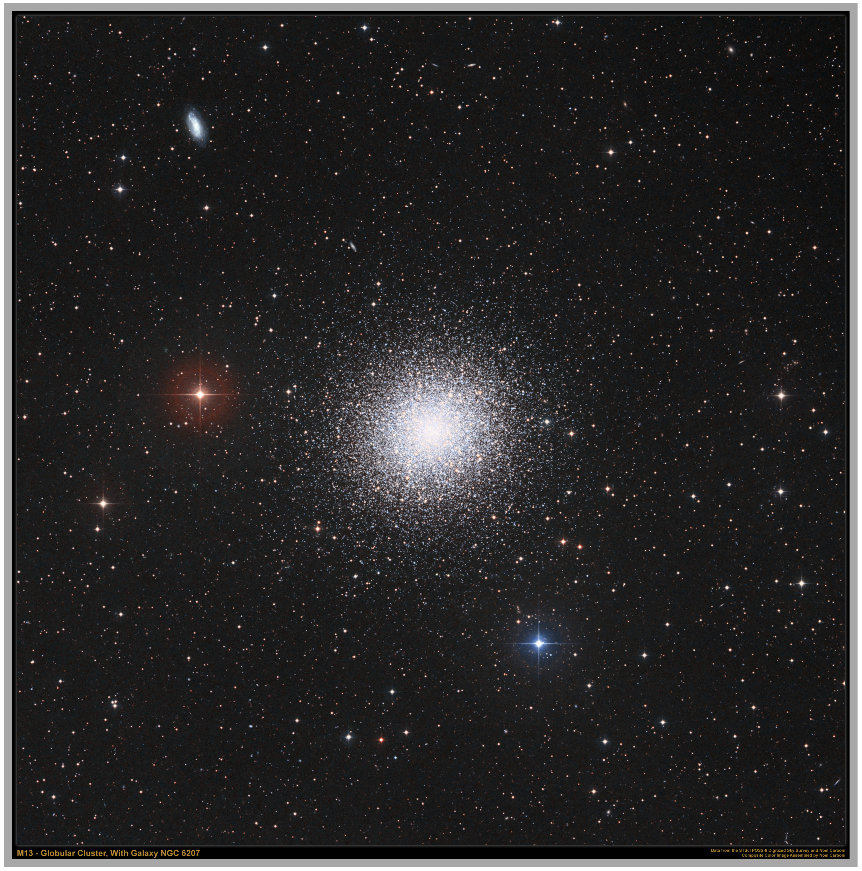
In low mass binaries, the more massive star will eventually become a white dwarf before the secondary.

Evolution of High Mass Binaries

- High mass binaries involve stars will explode as SN
- Many possible outcomes for endstates:
  - NS + NS
  - BH + NS
  - BH + BH
  - Merger of stars
  - Runaway stars



<u>Star Clusters</u>



How can we test theories of star evolution?

- Binaries help, because one can get mass so that theories can be tested
- But stars change so *slowly*, it is impossible to test theories by watching just one star move through phases
- Fortunately, there are 10^{11} stars in our Galaxy, all with a range of masses and ages!
- Conveniently, many stars are found in **clusters**

Star Clusters (cont.)

A star cluster is a collection of stars in roughly the same location having formed at about the same time. Two main kinds:

- *Galactic (or open) Clusters:*

  In galactic lane where there is gas. Tend to have some hot massive stars.

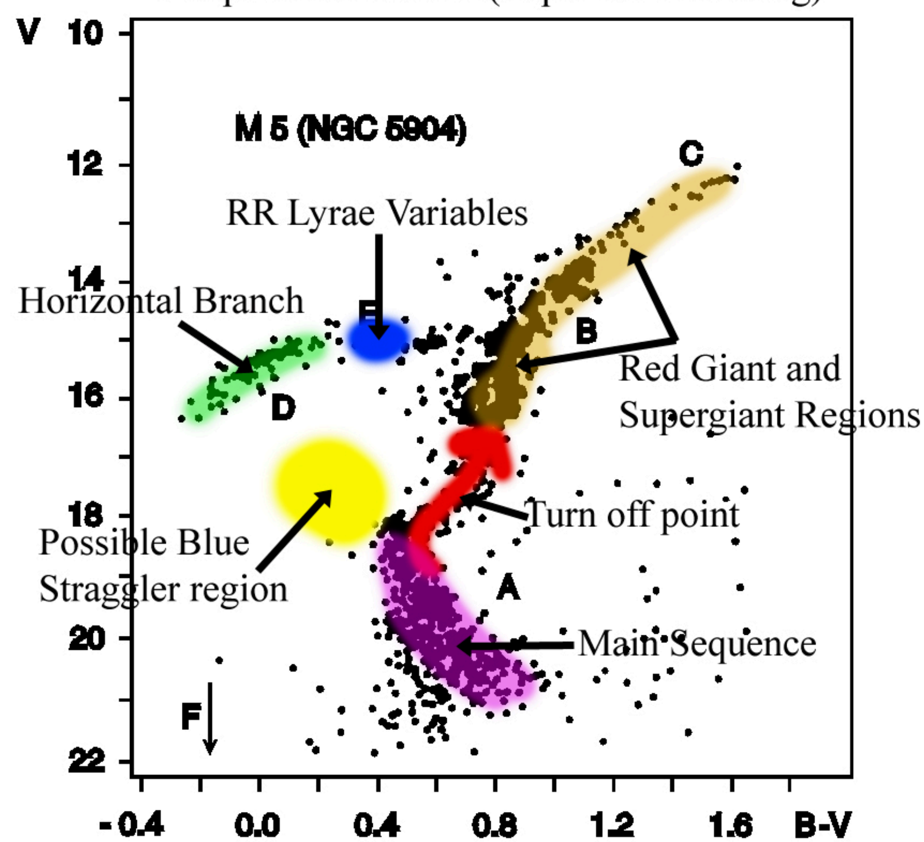
- *Globular Clusters:*

  Tend to possess older stars. No massive stars and little gas. Not in plane of Galaxy.

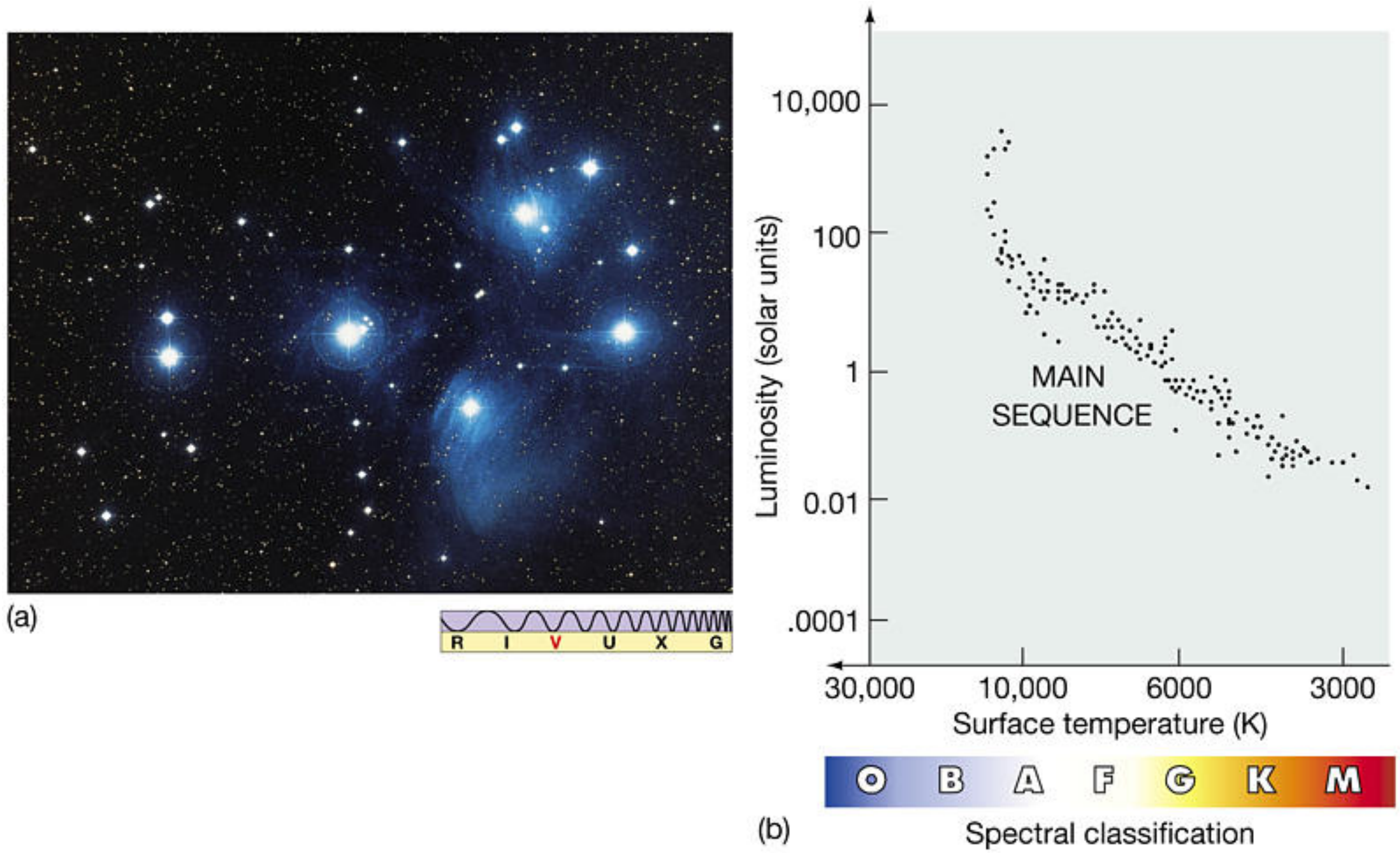
Key to Clusters

1. The more massive the star, the earlier it leaves the MS
2. HRD of a cluster will show stars tracing evolutionary tracks as determined by individual masses
3. The *MS turn-off point* indicates the cluster age
4. Can test details, like number of stars as Red Giants or on the Horizontal Branch

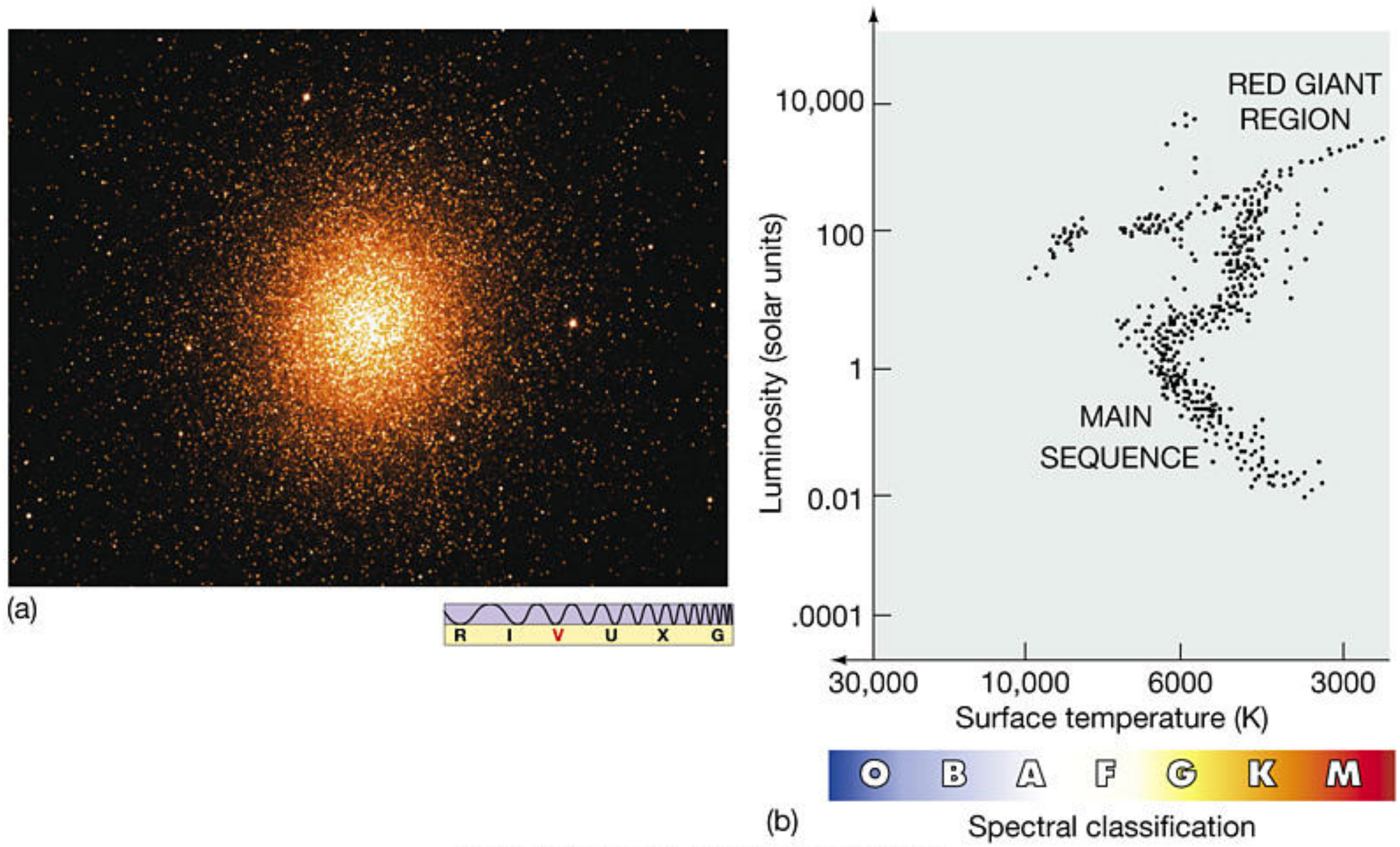
Adapted from SEDS (http://www.seds.org)



Young Cluster

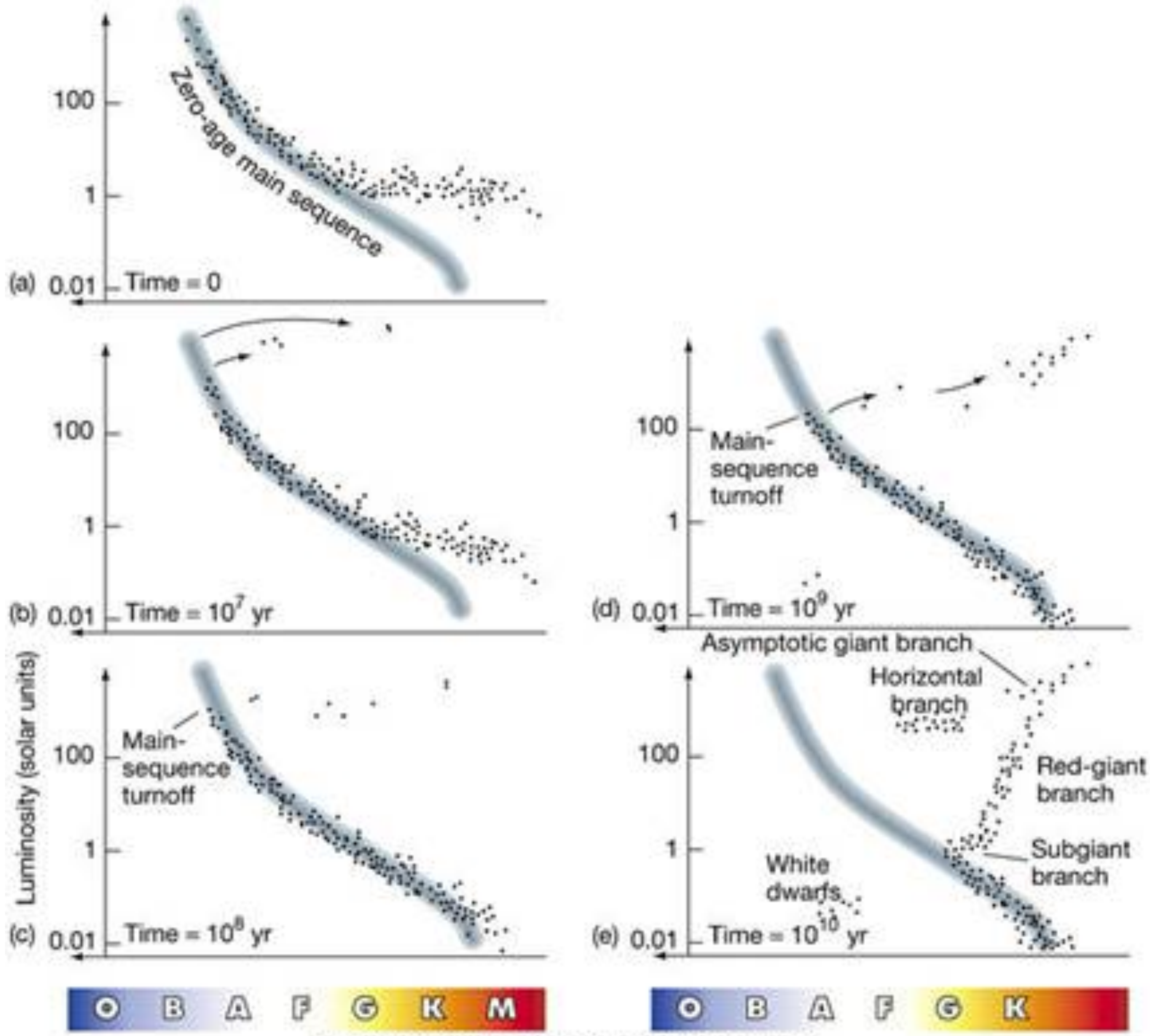


Old Cluster

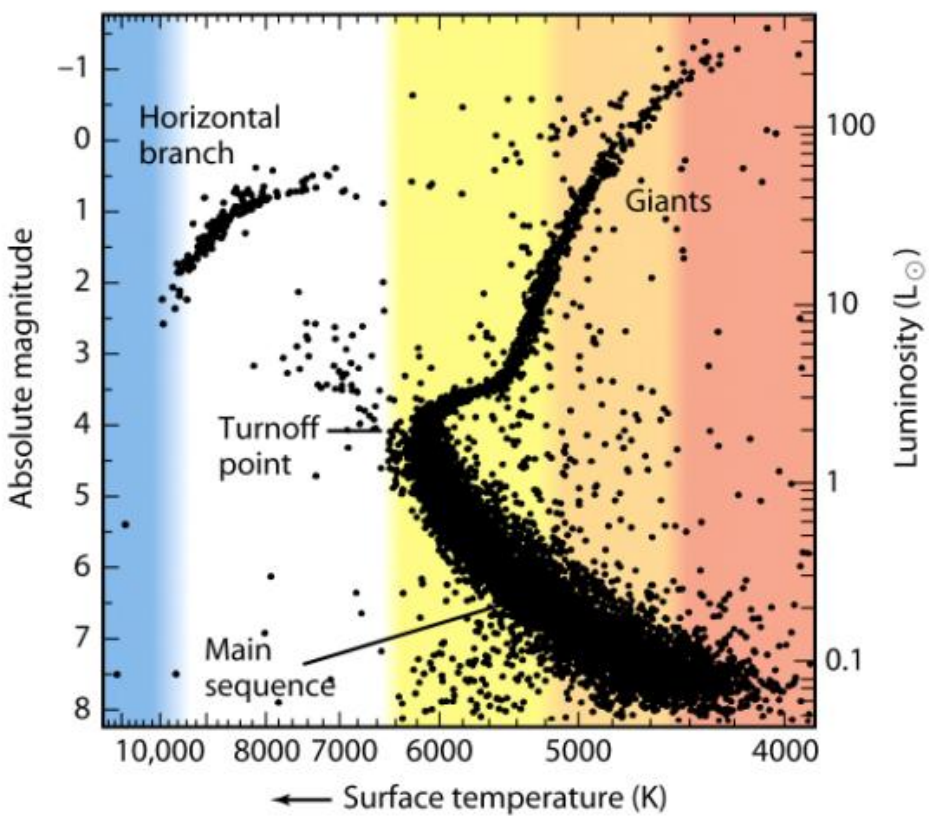


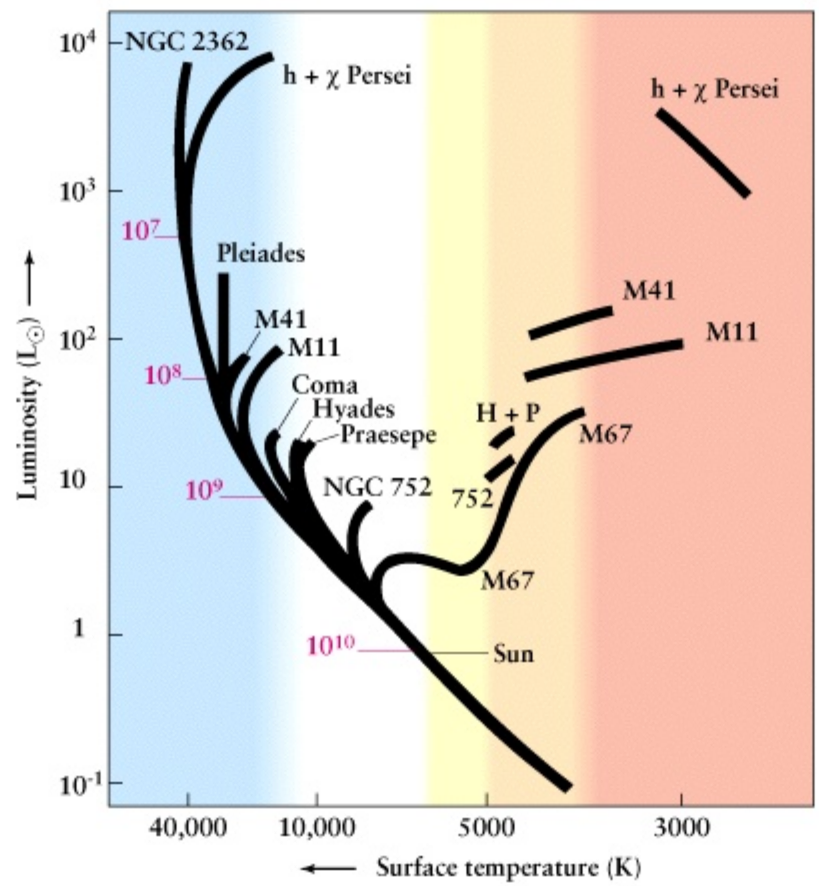
(a)
R I V U X G
RED GIANT REGION
MAIN SEQUENCE
10,000
100
1
0.01
.0001
Luminosity (solar units)
30,000
10,000
6000
3000
Surface temperature (K)
O B A F G K M
(b)
Spectral classification

Cluster Evolution



Turn-Off Point

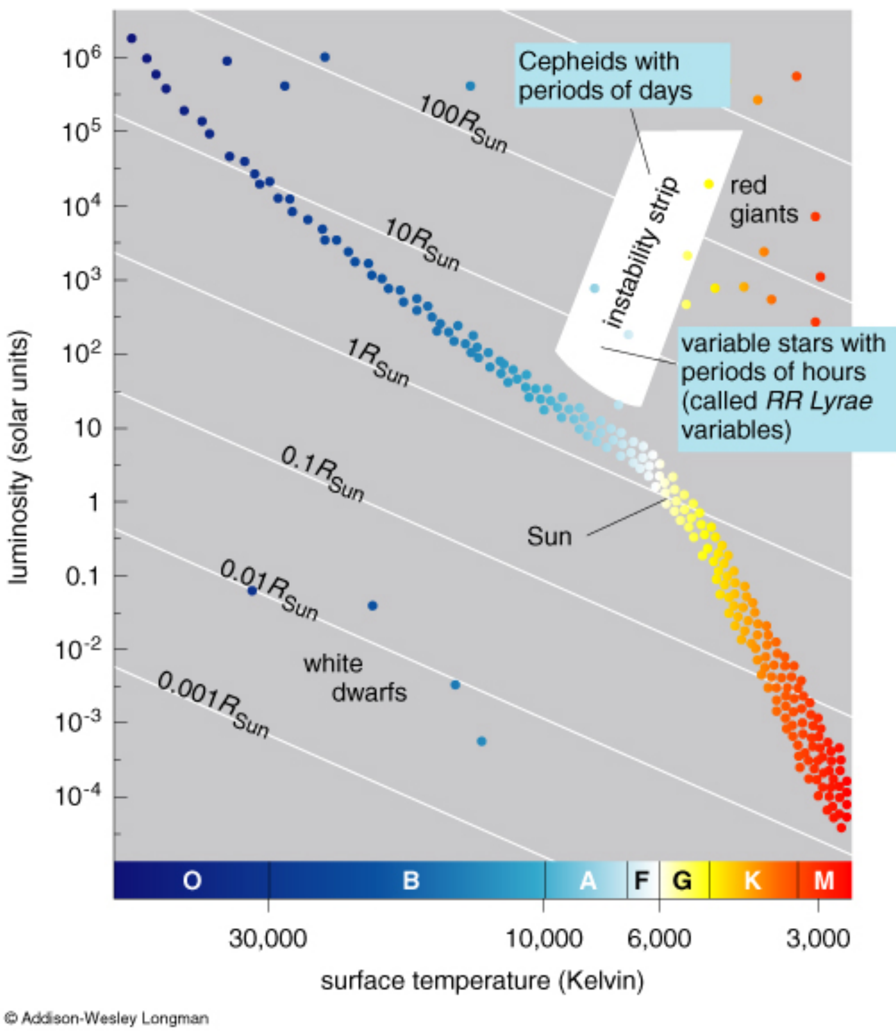


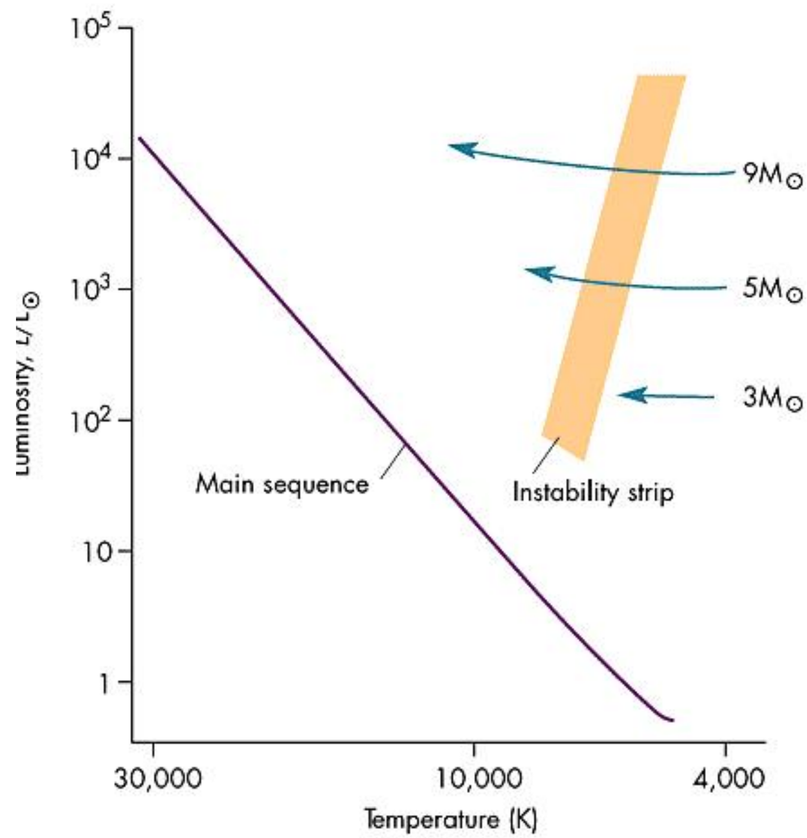


Instability Strip

- Some stars pulsate, often to be found in the "instability strip" in the HRD
- Two major classes of pulsators:
  - Cepheids – periods of 1-100 days with L ~10^3-$10^4 L_o$
  - RR Lyraes – periods of 1.5^h to 1^d and only ~10^2 L_o; these are Horizontal Branch stars

The Instability Strip in the HRD





Pulsations in δ Cephei

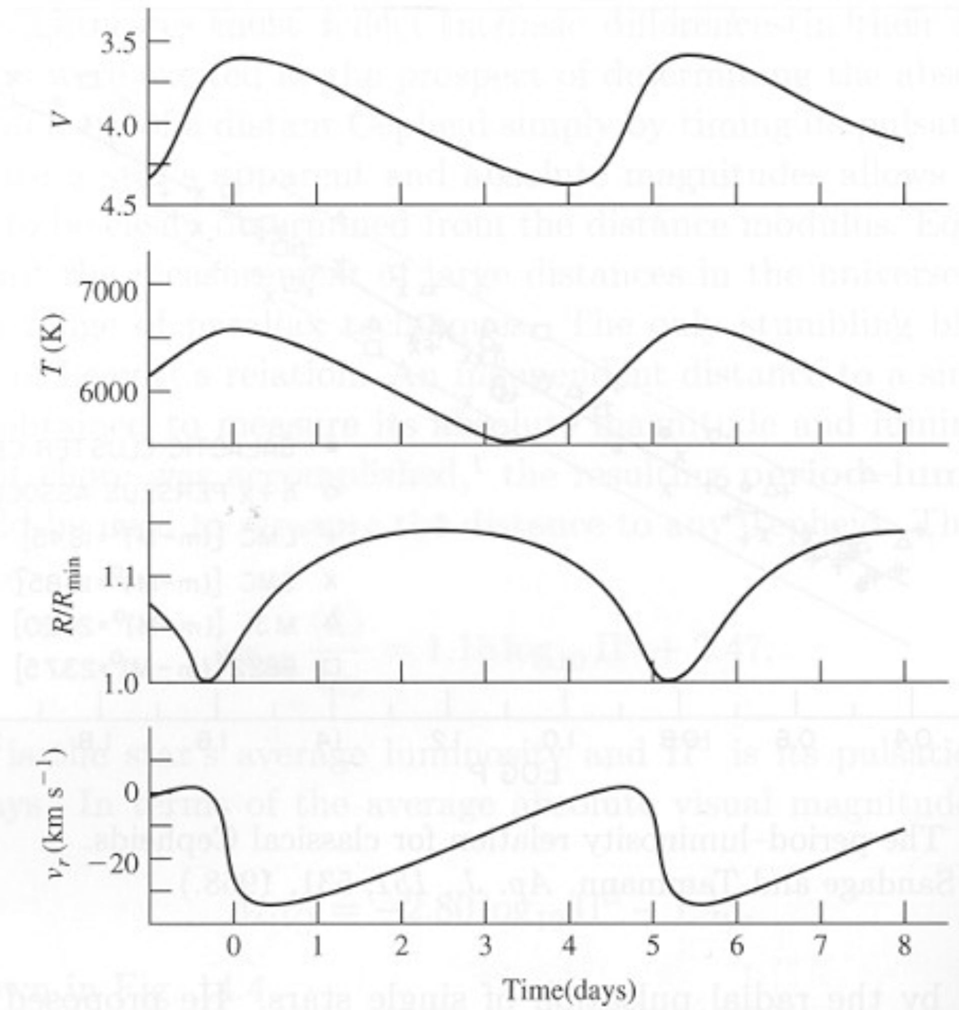


Figure 14.5 Observed pulsation properties of δ Cephei.

Period-Luminosity Relation

Figure 14.2 Henrietta Swan Leavitt (1868–1921). (Courtesy of Harvard College Observatory.)

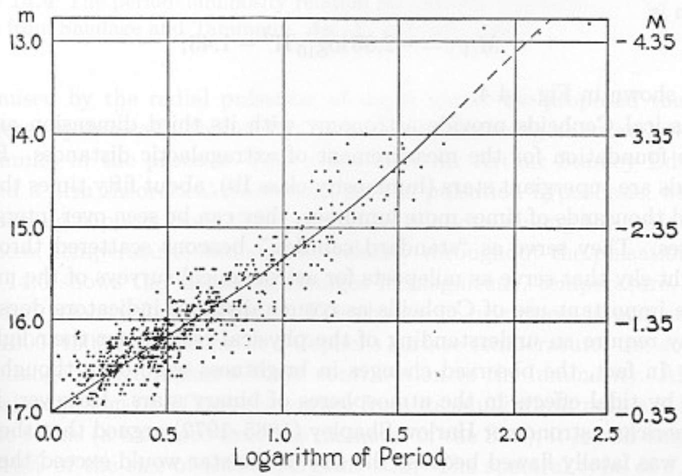
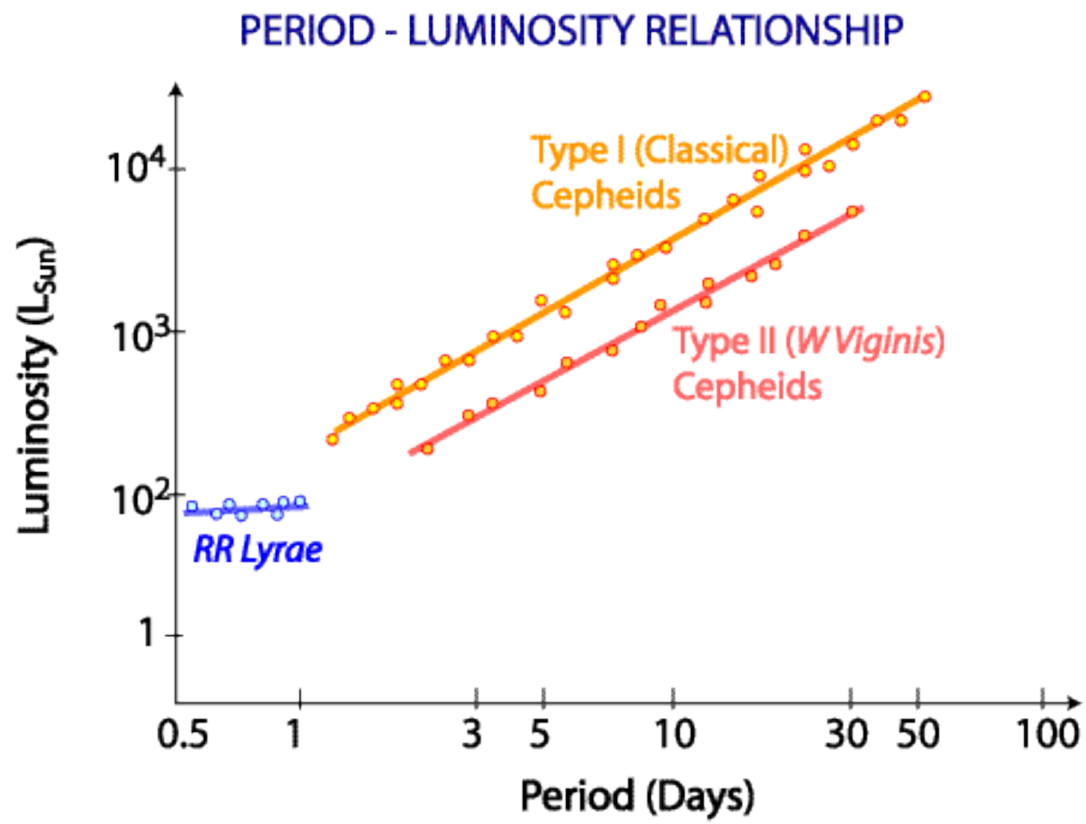


Figure 14.3 Classical Cepheids in the Small Magellanic Cloud, with the period in units of days. (Figure from Shapley, *Galaxies*, Harvard University Press, Cambridge, MA, 1961.)



Cepheids as Standard Candles