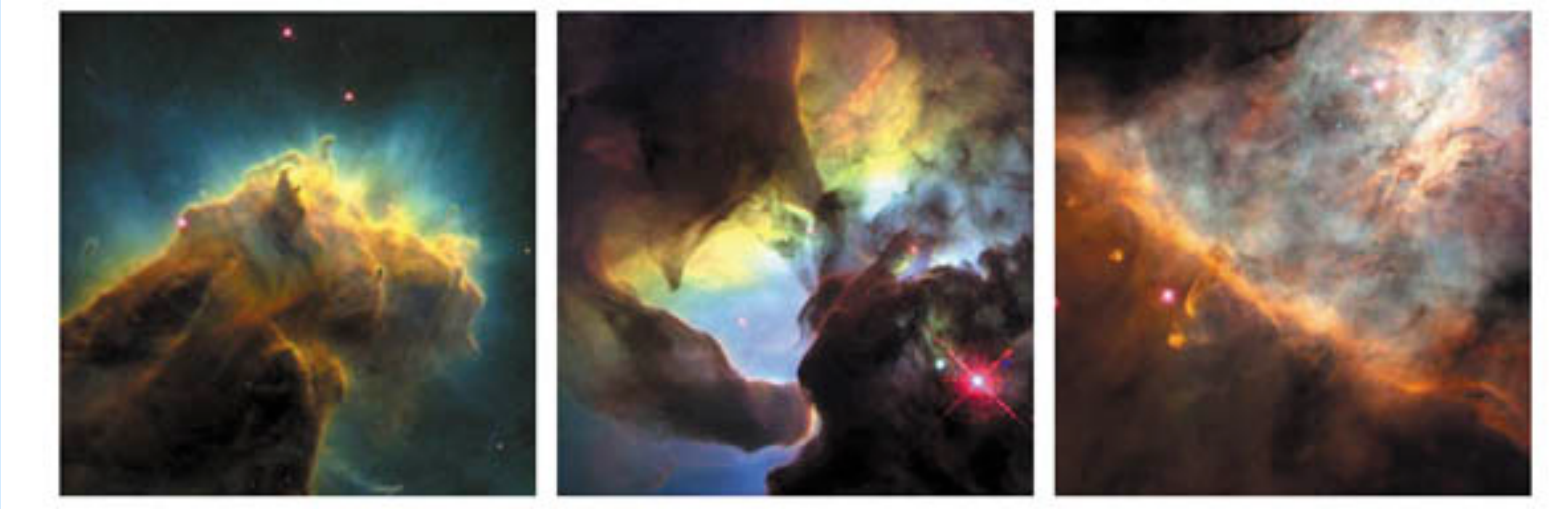
Star Formation



Eagle Nebula, Lagoon Nebula, and Orion Nebula

By the late 18th century astronomers understood that there were changes in the starry realm. Occasionally, new stars appeared, then faded away. The stars moved ever so slowly with respect to each other. Precession of the equinoxes altered the direction of the North Celestial Pole.

They also recognized that the time scale for stellar evolution of most stars was much longer than a human lifetime. How could it be possible to understand anything about it?

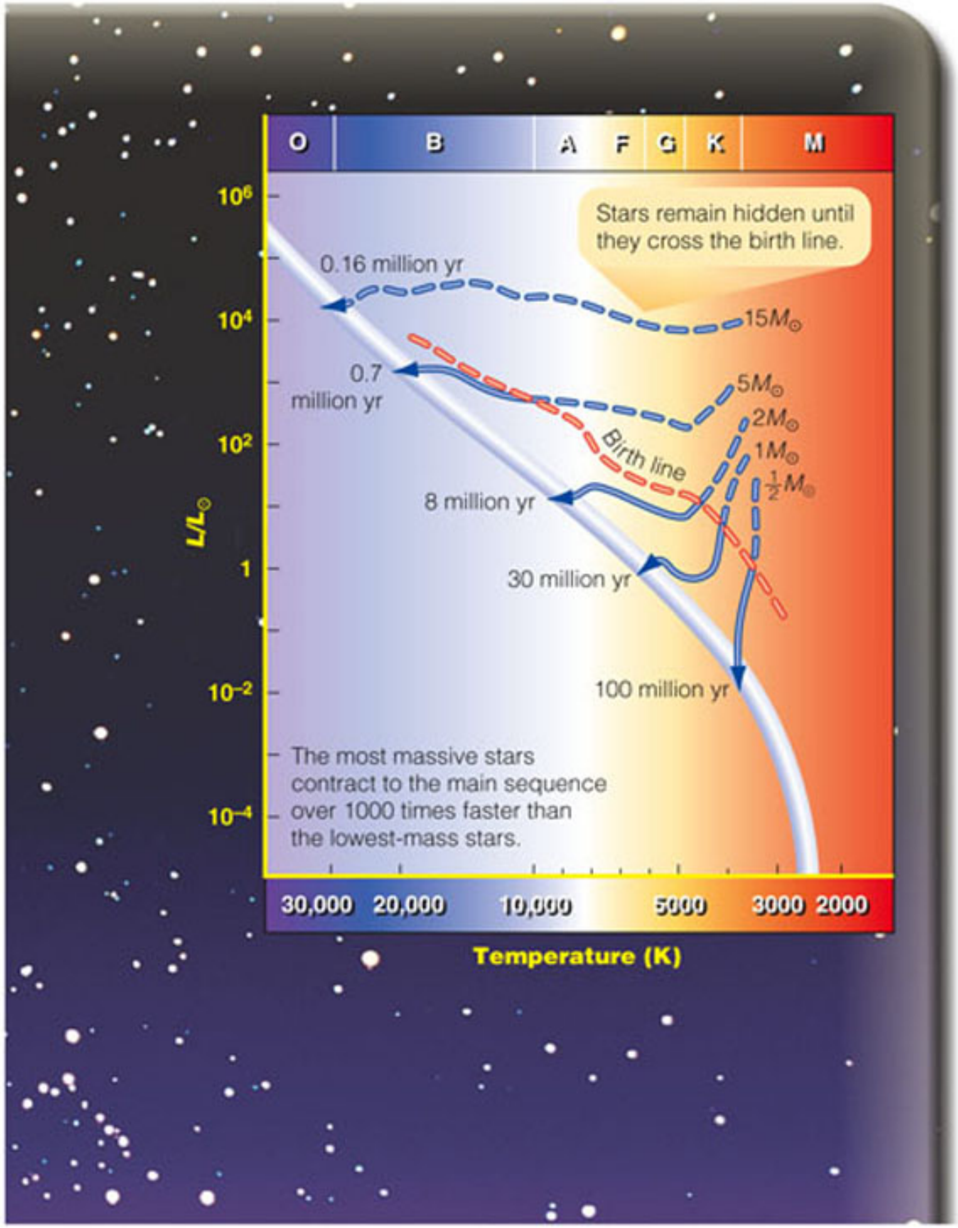
William Herschel suggested an analogy in1789:
“...is it not almost the same thing, whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?”

Our knowledge of stellar evolution comes from a combination of *data* on stars in clusters, plus theoretical *models* based on the physics of the properties of gas and nuclear reactions.

If interstellar gas is cold enough and dense enough, it will collapse under its own gravitational power to form stars. The “free fall” time of a spherical cloud is given by:

$$T_{ff} = [3\pi/(32\ G\ \rho_0)]^{1/2} \quad ,$$

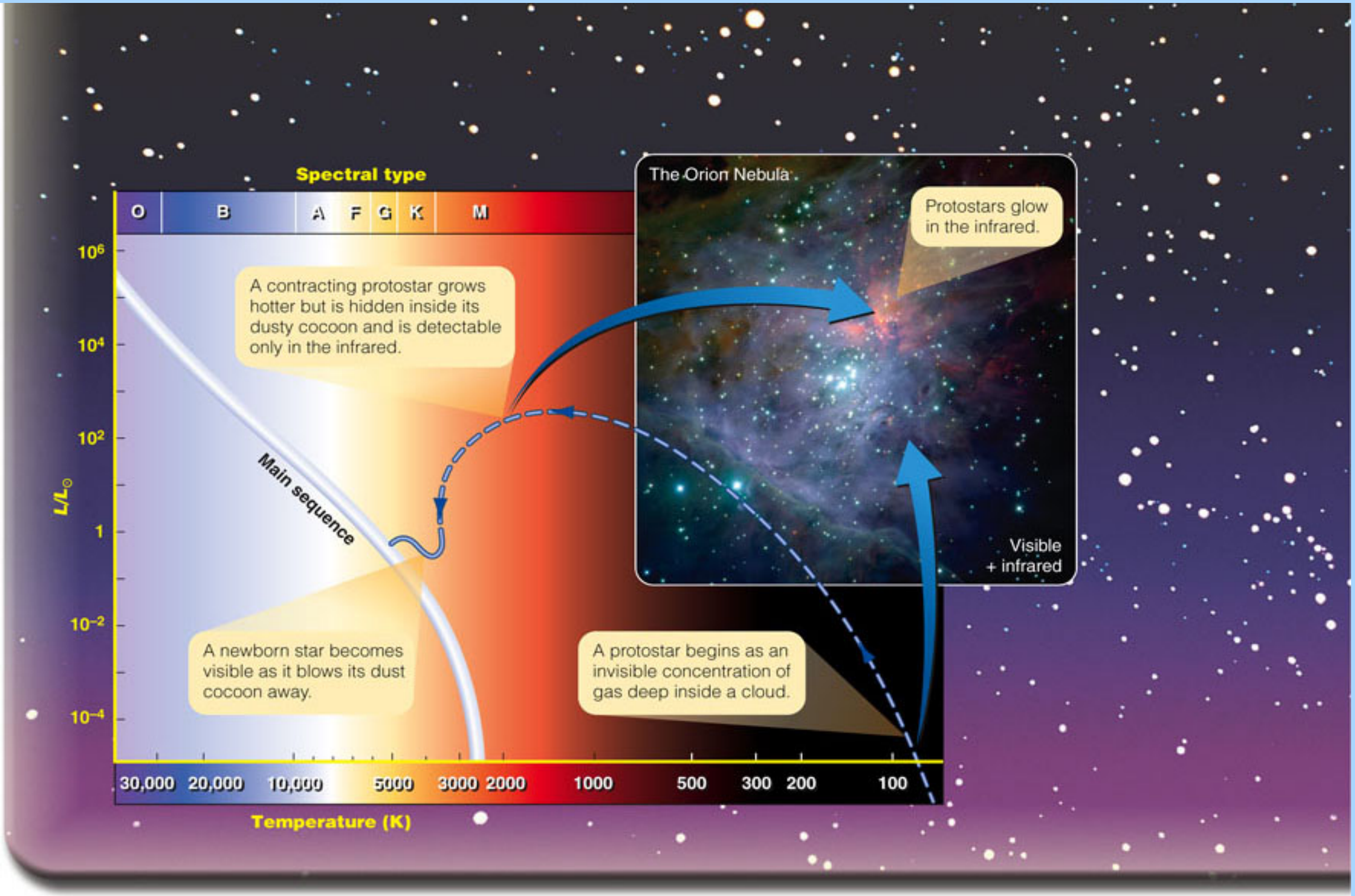
where G is Newton's gravitational constant and ρ_0 is the initial density of the cloud. If the density of a cloud is 100 hydrogen atoms per cubic cm and the radius of the cloud is 0.46 parsecs, the cloud contains 1 solar mass of material and the time scale for collapse is 5 million years.



Stars remain hidden until they cross the birth line.

The most massive stars contract to the main sequence over 1000 times faster than the lowest-mass stars.

Stars, like people, spend a certain fraction of their history with negative lifetime.

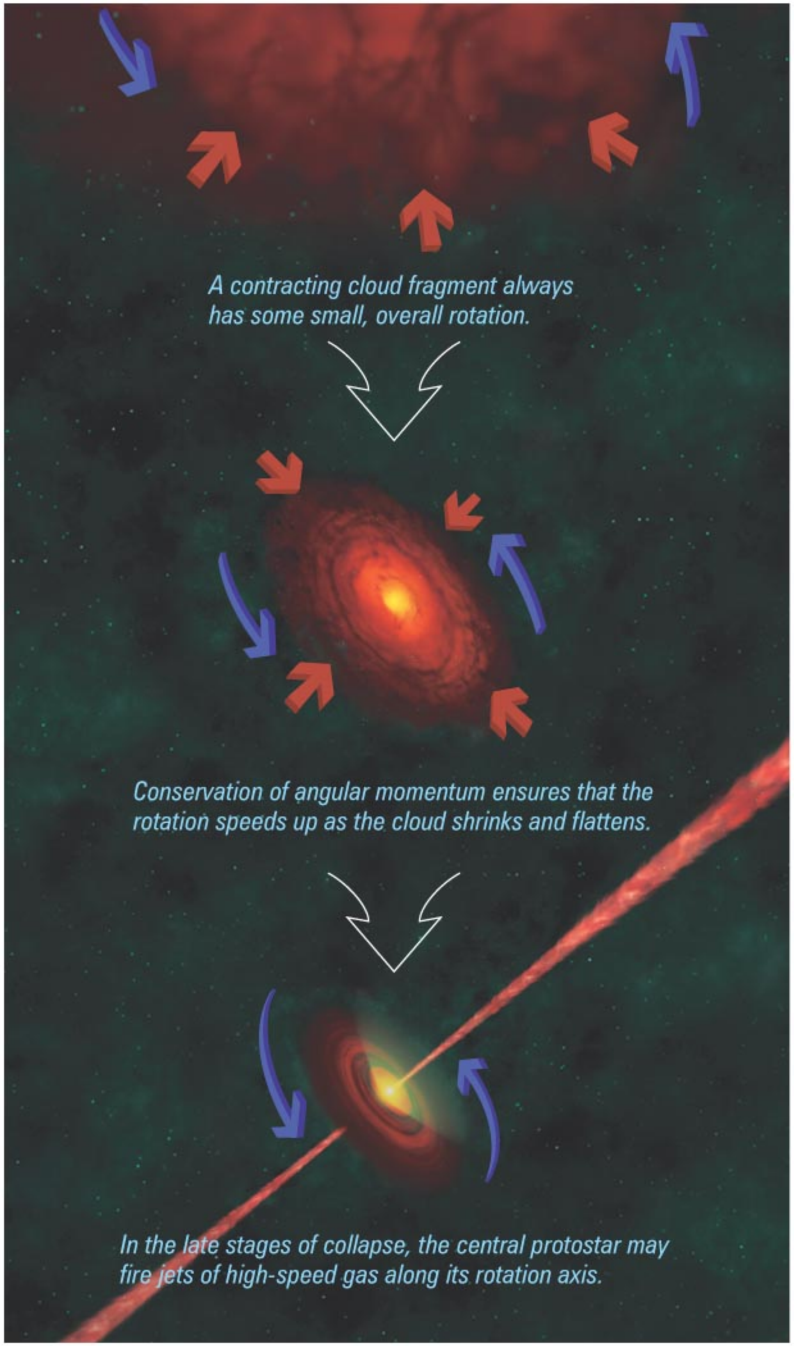


A contracting protostar grows hotter but is hidden inside its dusty cocoon and is detectable only in the infrared.

A newborn star becomes visible as it blows its dust cocoon away.

A protostar begins as an invisible concentration of gas deep inside a cloud.

Protostars glow in the infrared.



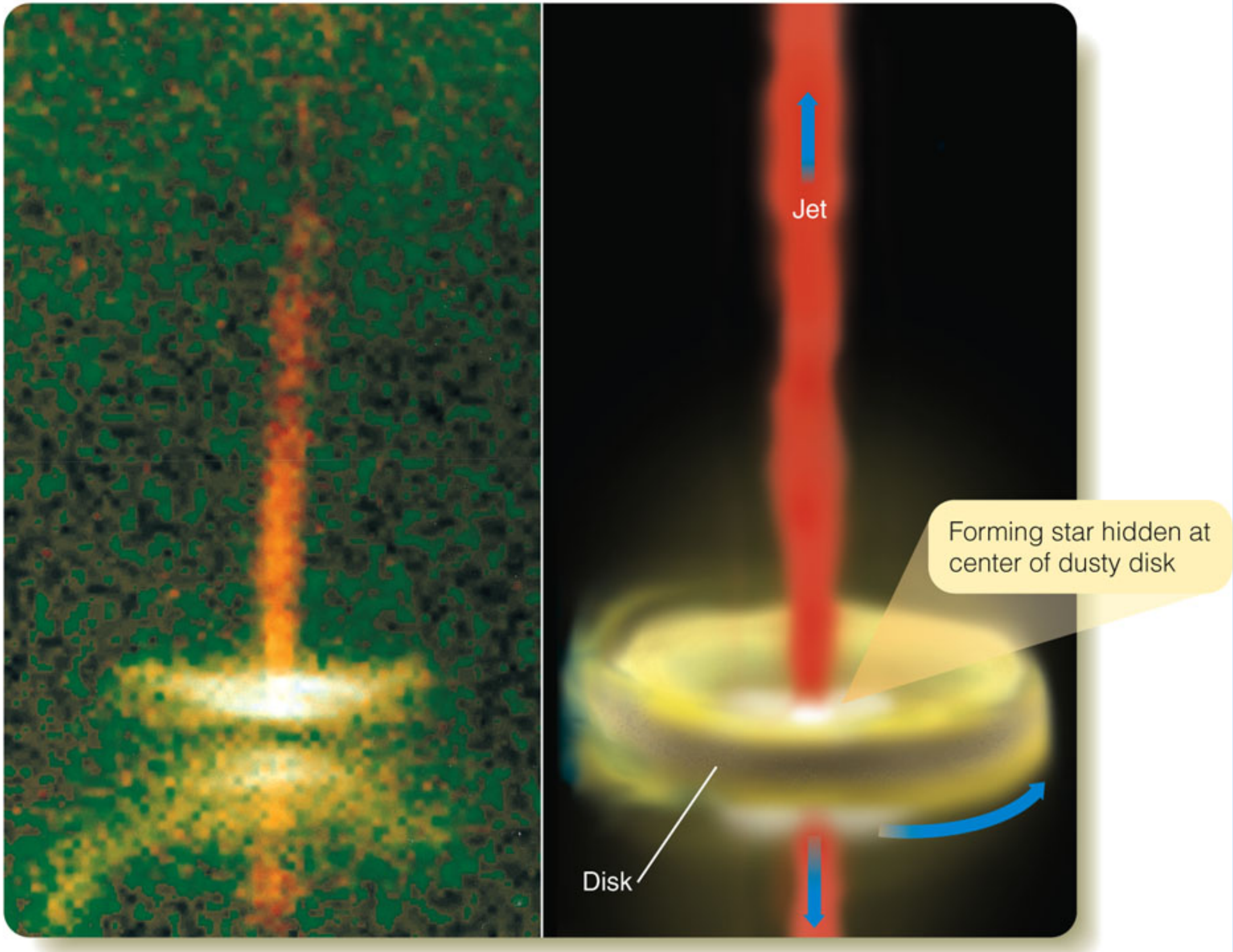
A contracting cloud fragment always has some small, overall rotation.

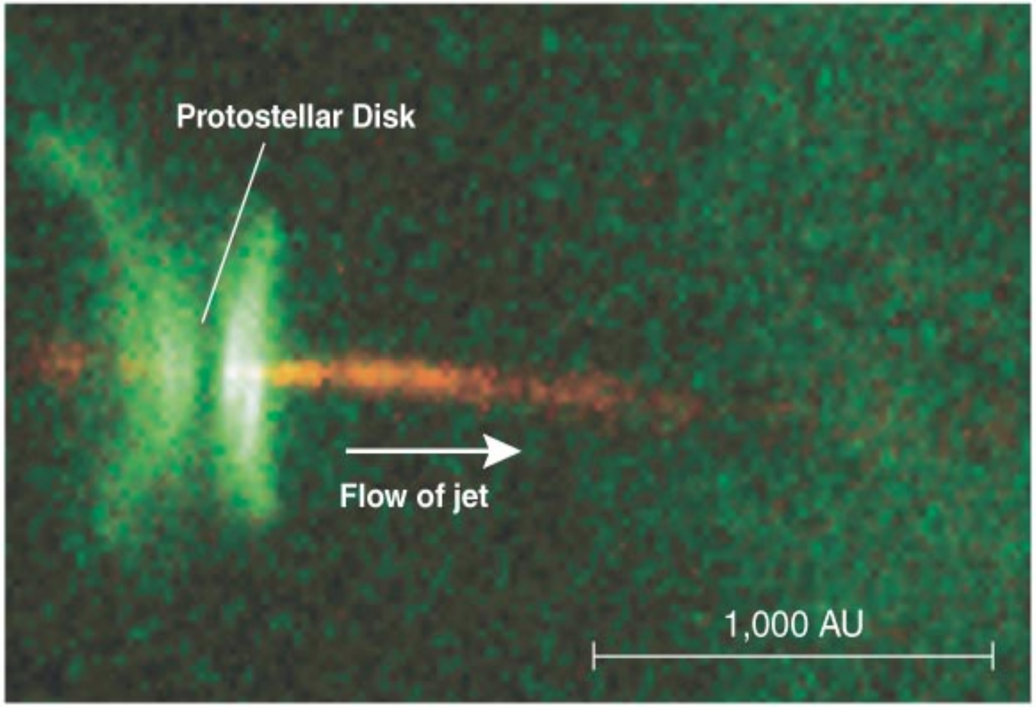
Conservation of angular momentum ensures that the rotation speeds up as the cloud shrinks and flattens.

In the late stages of collapse, the central protostar may fire jets of high-speed gas along its rotation axis.

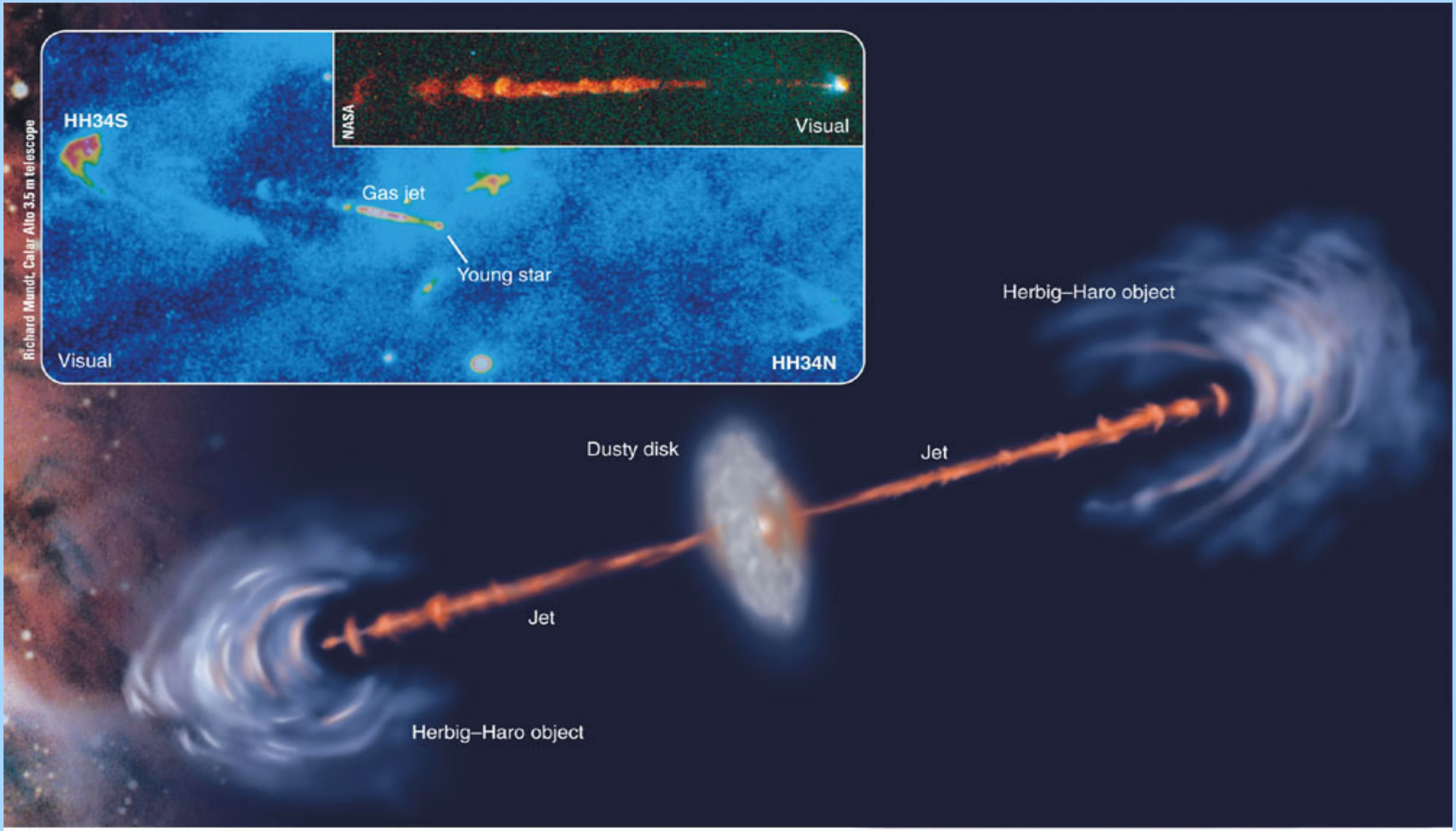
The disks that form around young stars give rise to observable jets of gas.

Later the disks provide the material for the formation of planets.


Jet
Forming star hidden at center of dusty disk
Disk



b This photograph shows a close-up view of jets (red) and a disk of gas (green) around a protostar. We are seeing the disk nearly edge-on. The top and bottom surfaces of the disk are glowing, but we cannot see the darker middle layers of the disk.

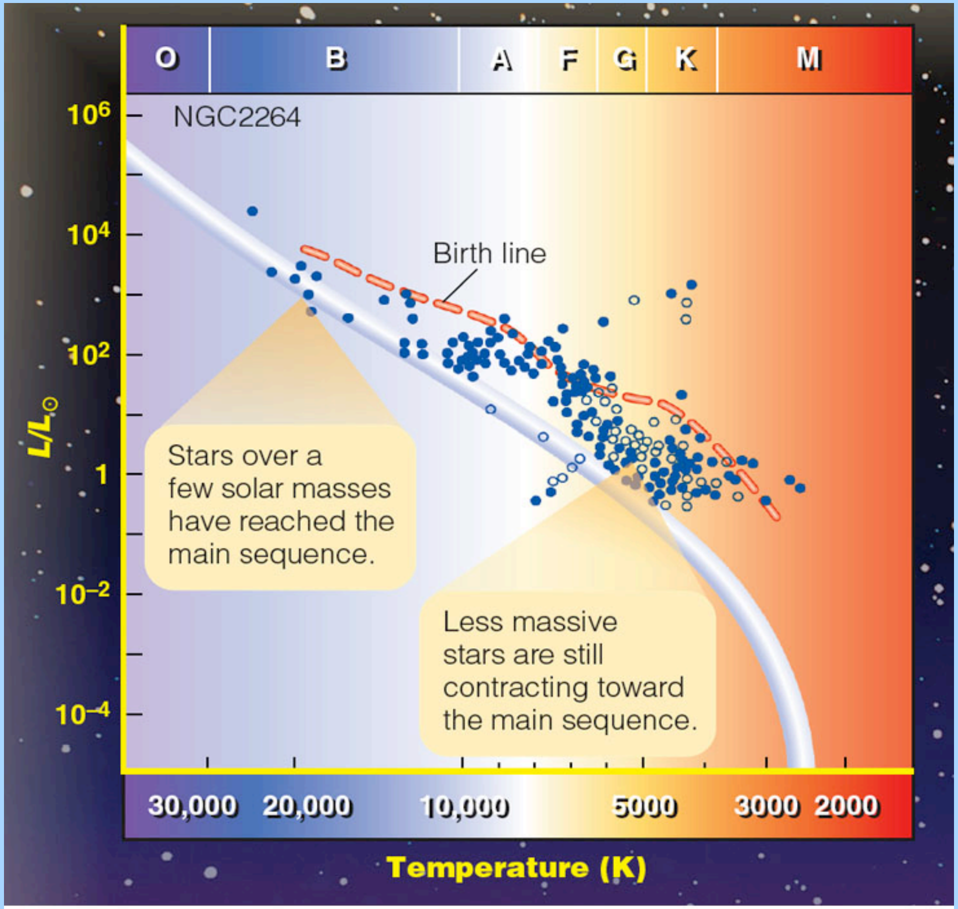


Richard Mundt, Calar Alto 3.5 m telescope

NASA

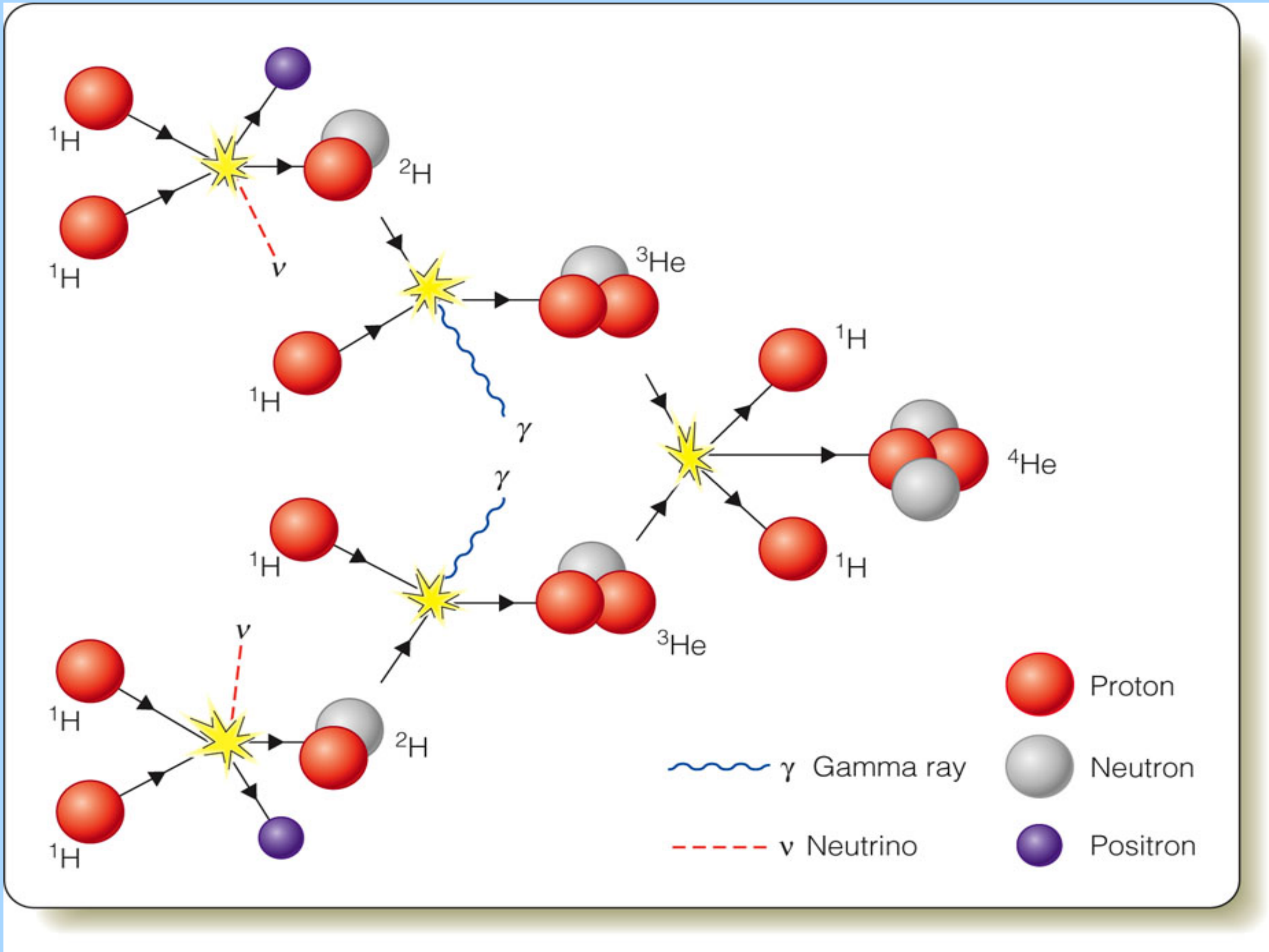
Where jets strike interstellar medium, they produce objects originally studied by G. Herbig and G. Haro.

How do we know that models of star formation are correct? Comparison with actual data.

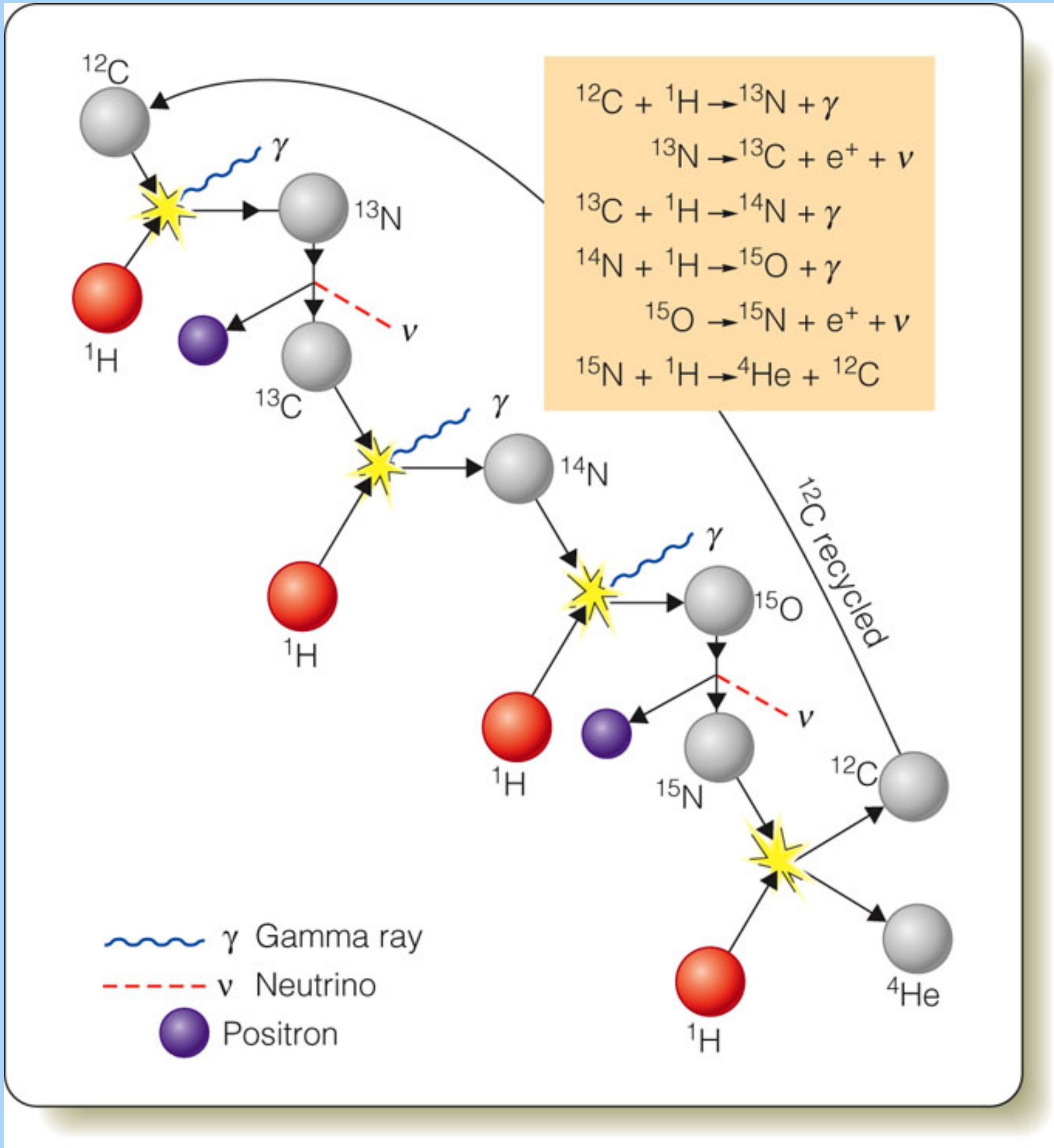


Stars over a few solar masses have reached the main sequence.

Less massive stars are still contracting toward the main sequence.



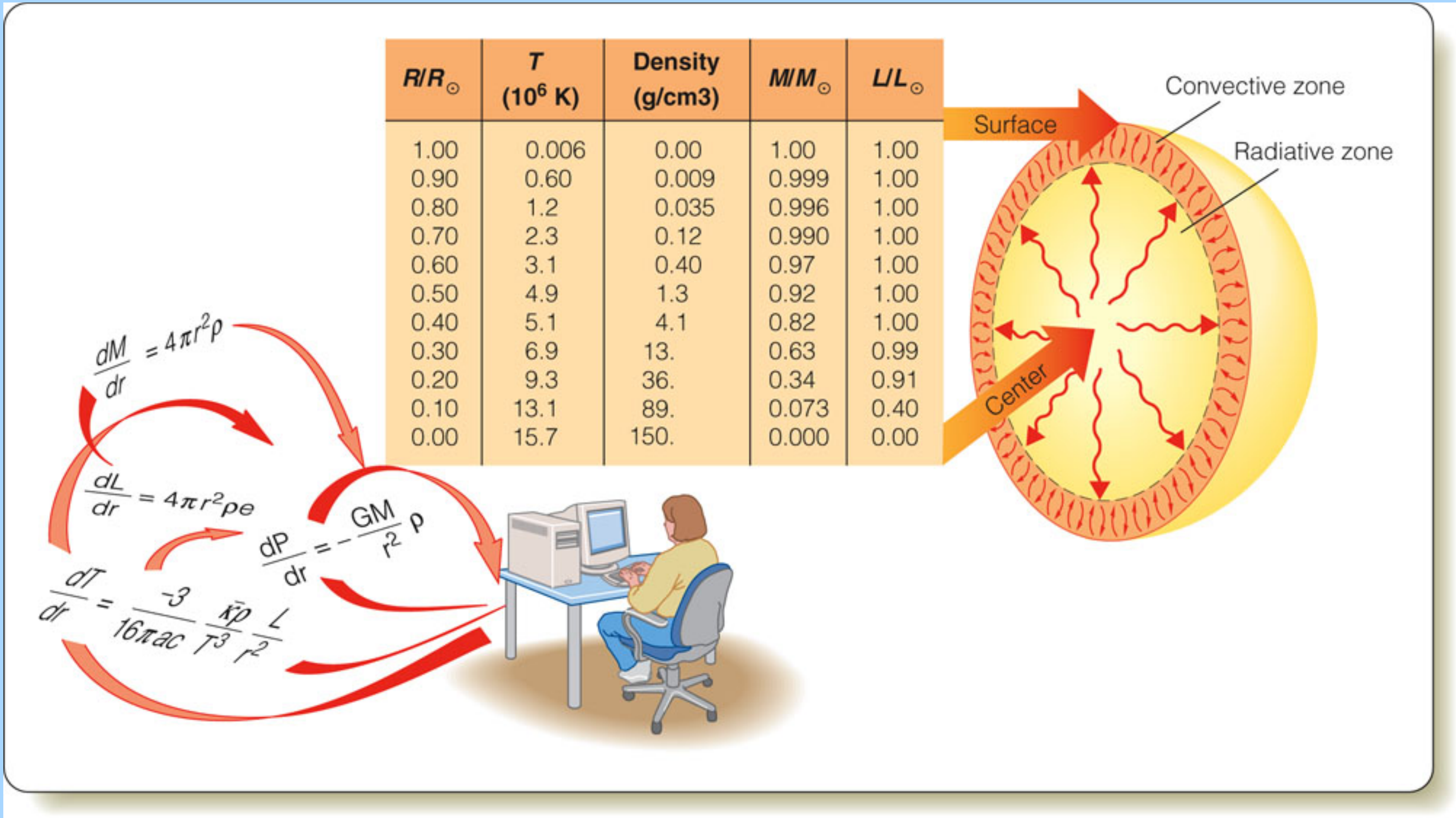
Principal energy generation for stars with 1.1 M_{sun} or less.



$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$
$$^{15}N + {}^{1}H \rightarrow {}^{4}He + {}^{12}C$$

For stars with more than 1.1 M_{sun} (giving hotter core temperatures), the CNO cycle is the primary energy generation mechanism.

The first generation of stars formed after the Big Bang had no carbon, nitrogen, or oxygen. Massive, single stars that explode as Type II supernovae very quickly changed the composition of the interstellar medium. Subsequent generations of stars start their main sequence phases with different initial compositions.



$R/R_\odot$	T (10^6 K)	Density (g/cm3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13.	0.63	0.99
0.20	9.3	36.	0.34	0.91
0.10	13.1	89.	0.073	0.40
0.00	15.7	150.	0.000	0.00

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

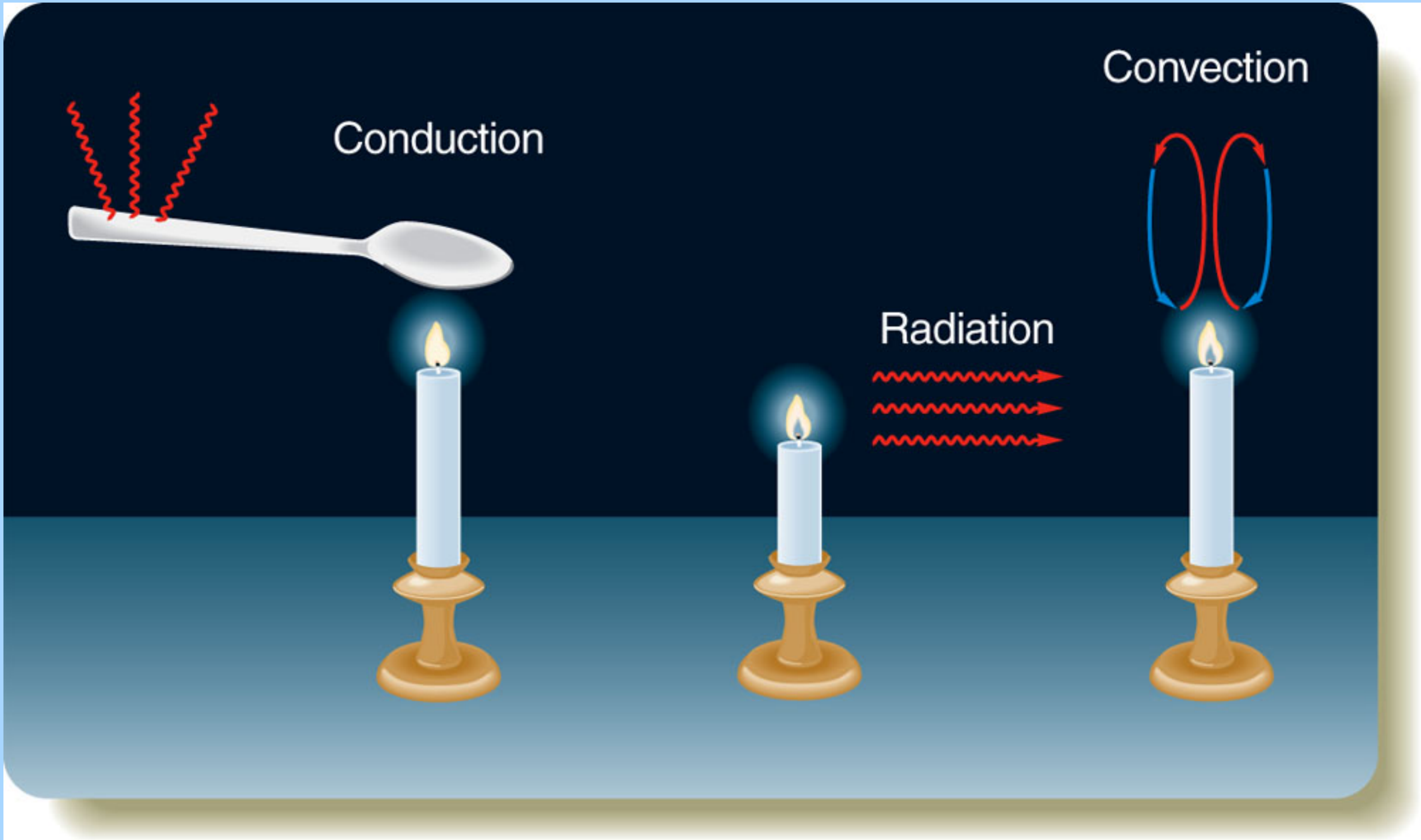
$$\frac{dL}{dr} = 4\pi r^2 \rho \epsilon$$

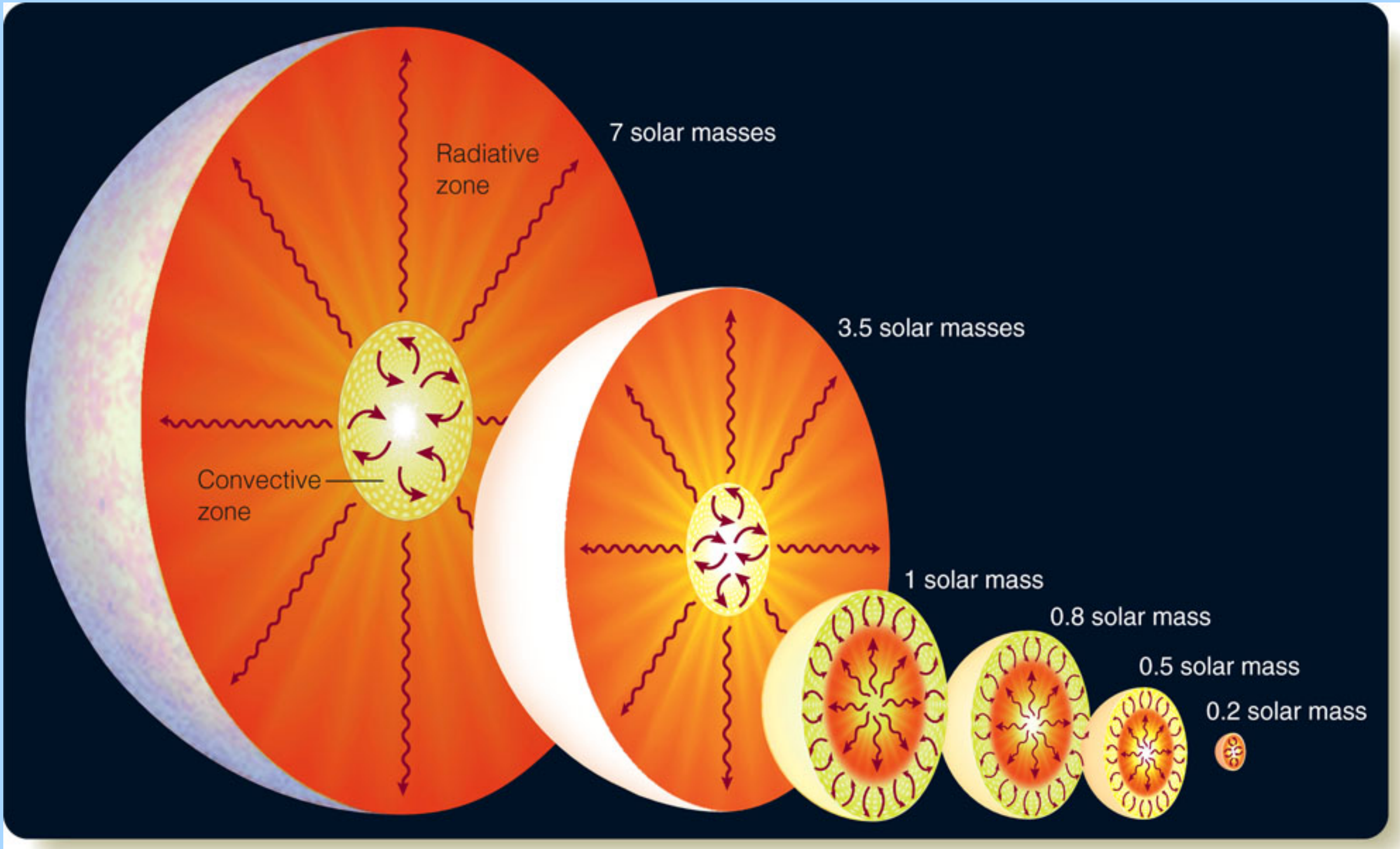
$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho$$

$$\frac{dT}{dr} = \frac{-3}{16\pi ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L}{r^2}$$

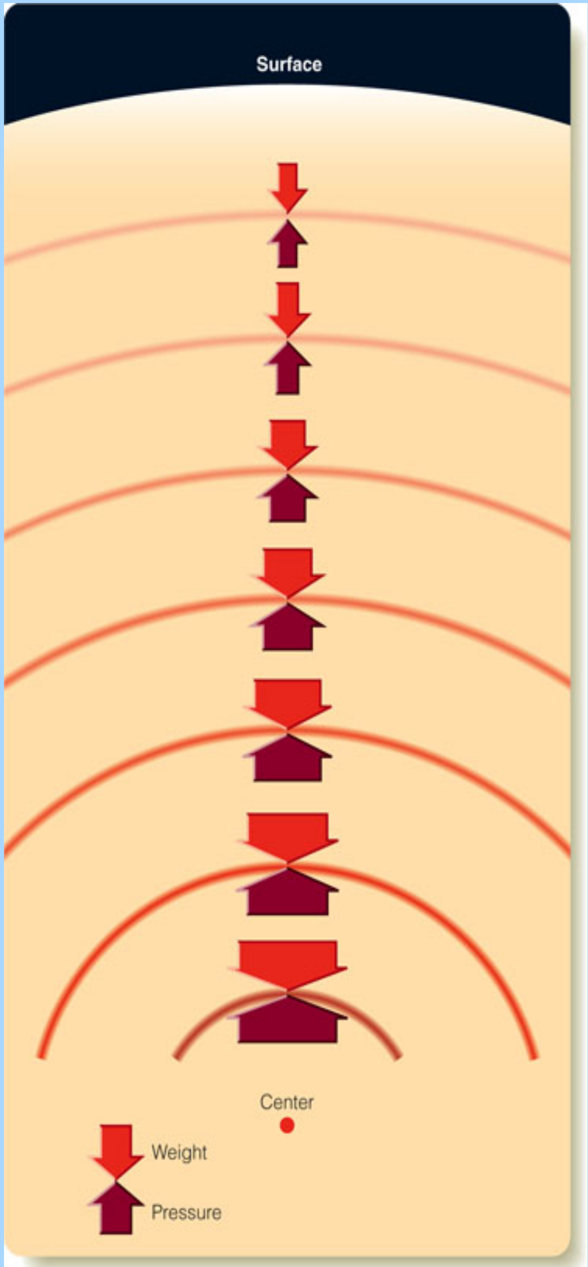
Model of a 1 solar mass star.

Energy in stars flows in three different ways:



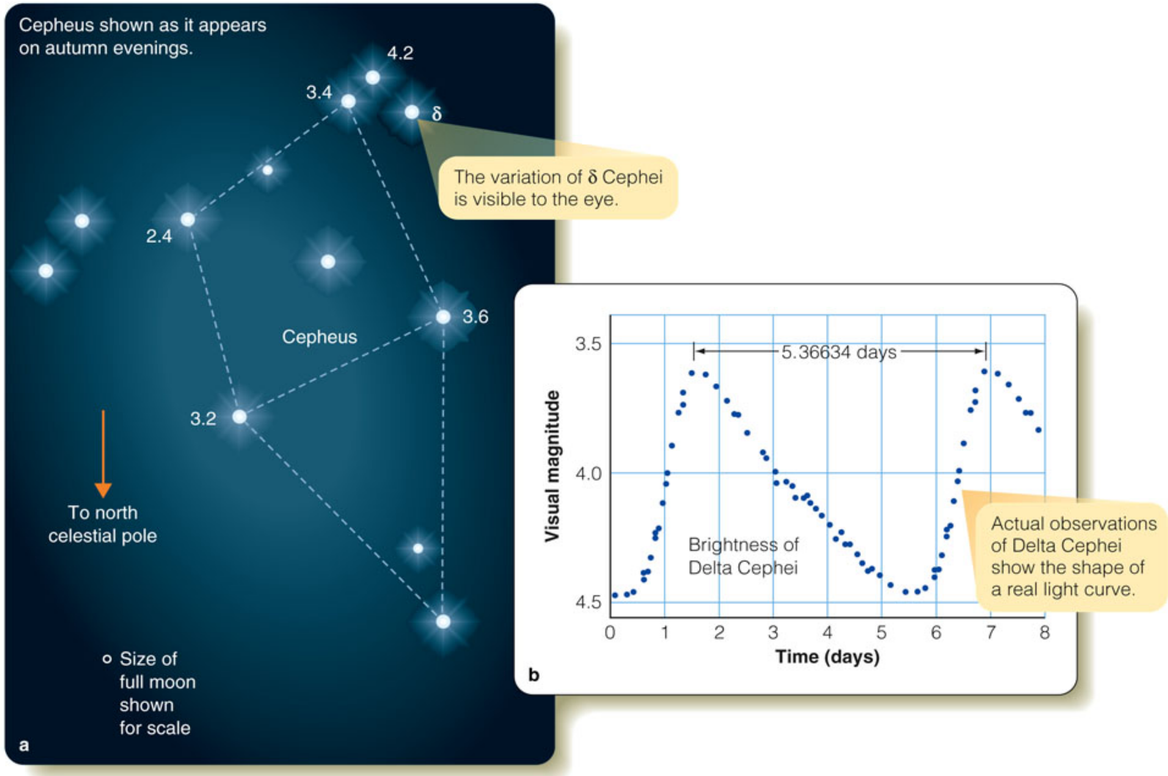

7 solar masses
Radiative zone
Convective zone
3.5 solar masses
1 solar mass
0.8 solar mass
0.5 solar mass
0.2 solar mass

If the lowest layer of this configuration cannot hold up the upper layers, the whole structure collapses. The same idea holds for the internal structure of a star.

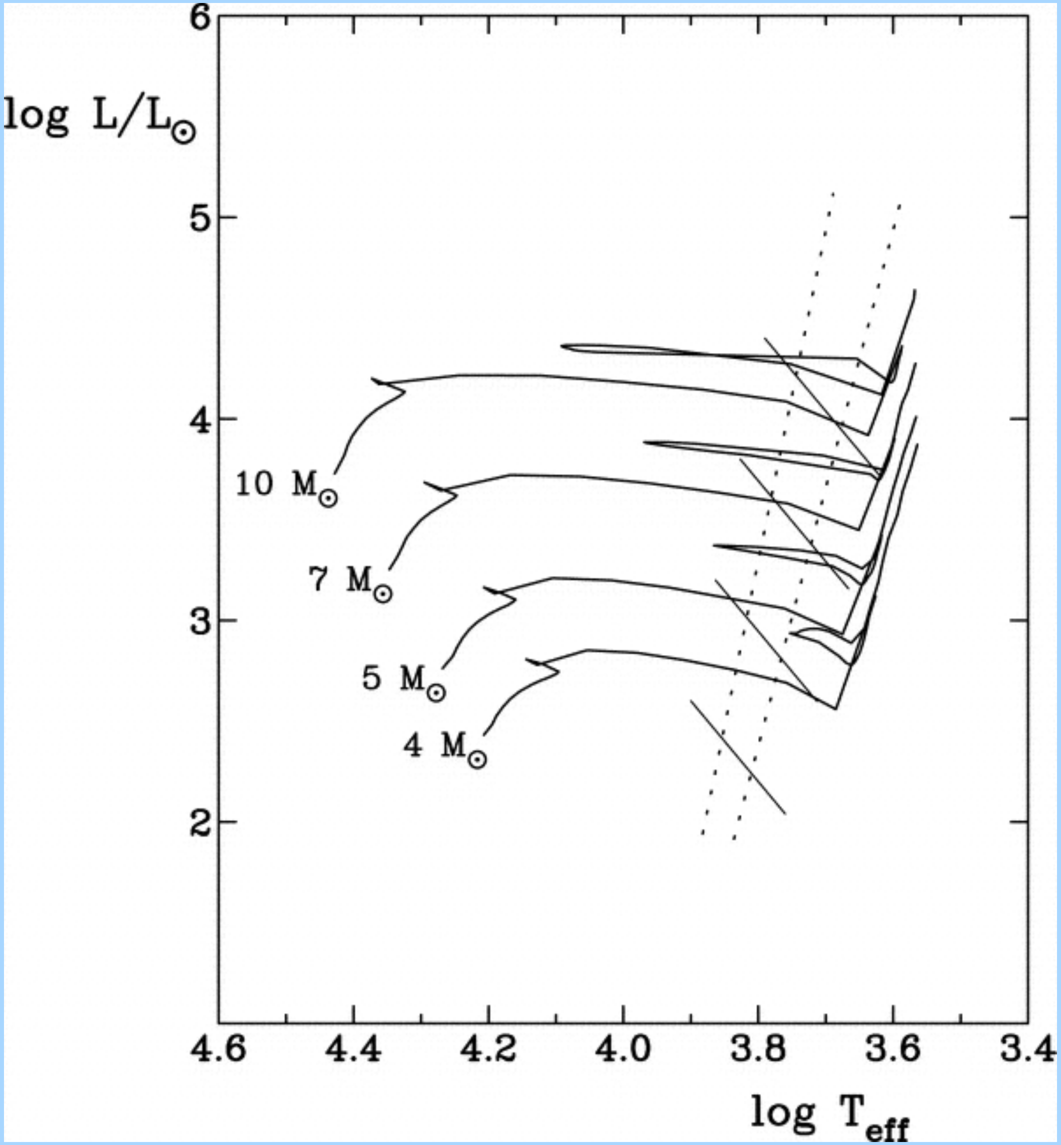


Stable stars are balanced.

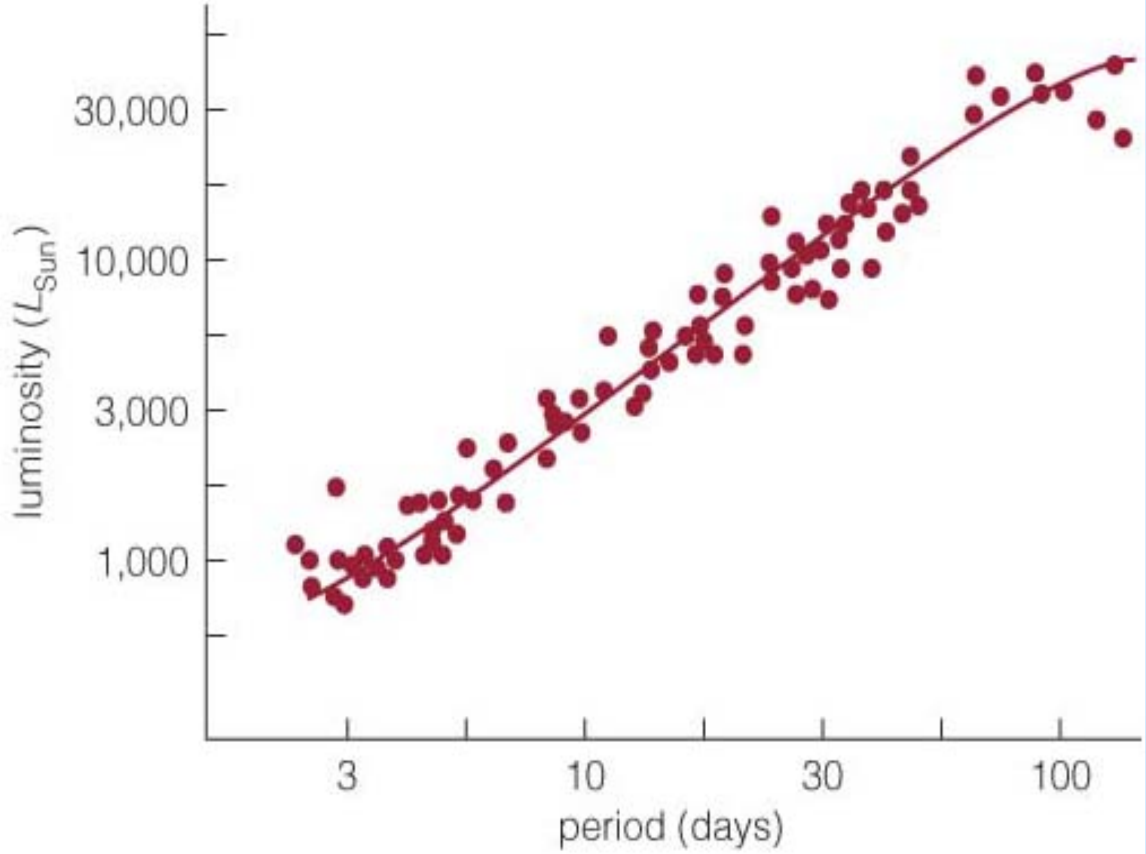
If nuclear reactions made too much energy, the extra energy would cause the star to expand. The expansion would lower the central temperature and density and slow the nuclear reactions.
If the nuclear reactions made too little energy, the star would contract, increasing the central temperature, increasing the reaction rates.



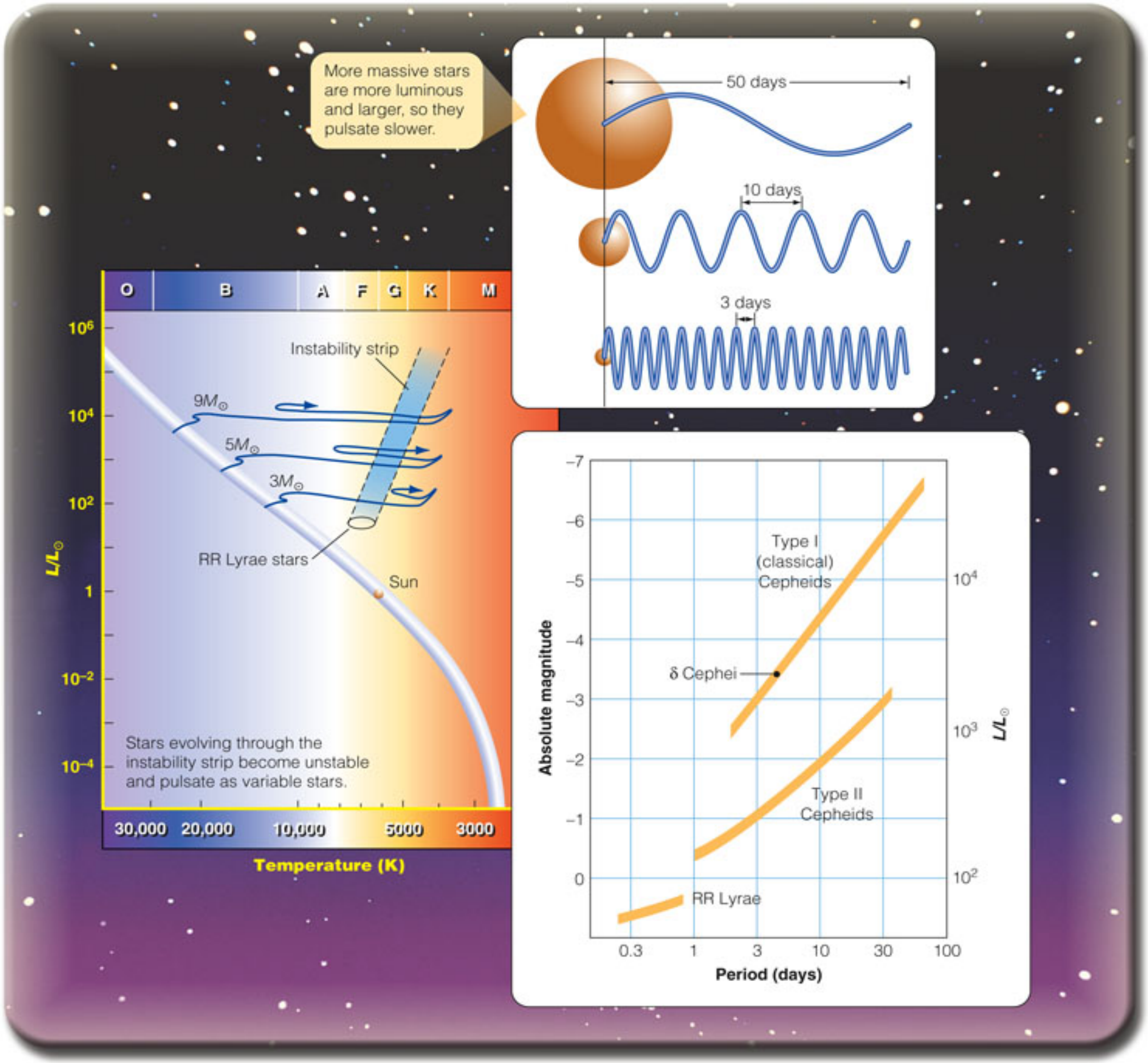
If there is an imbalance between the pressure of the layers in the star and the energy transport, the star can *pulsate*. For certain combinations of temperature and luminosity, this is common behavior.



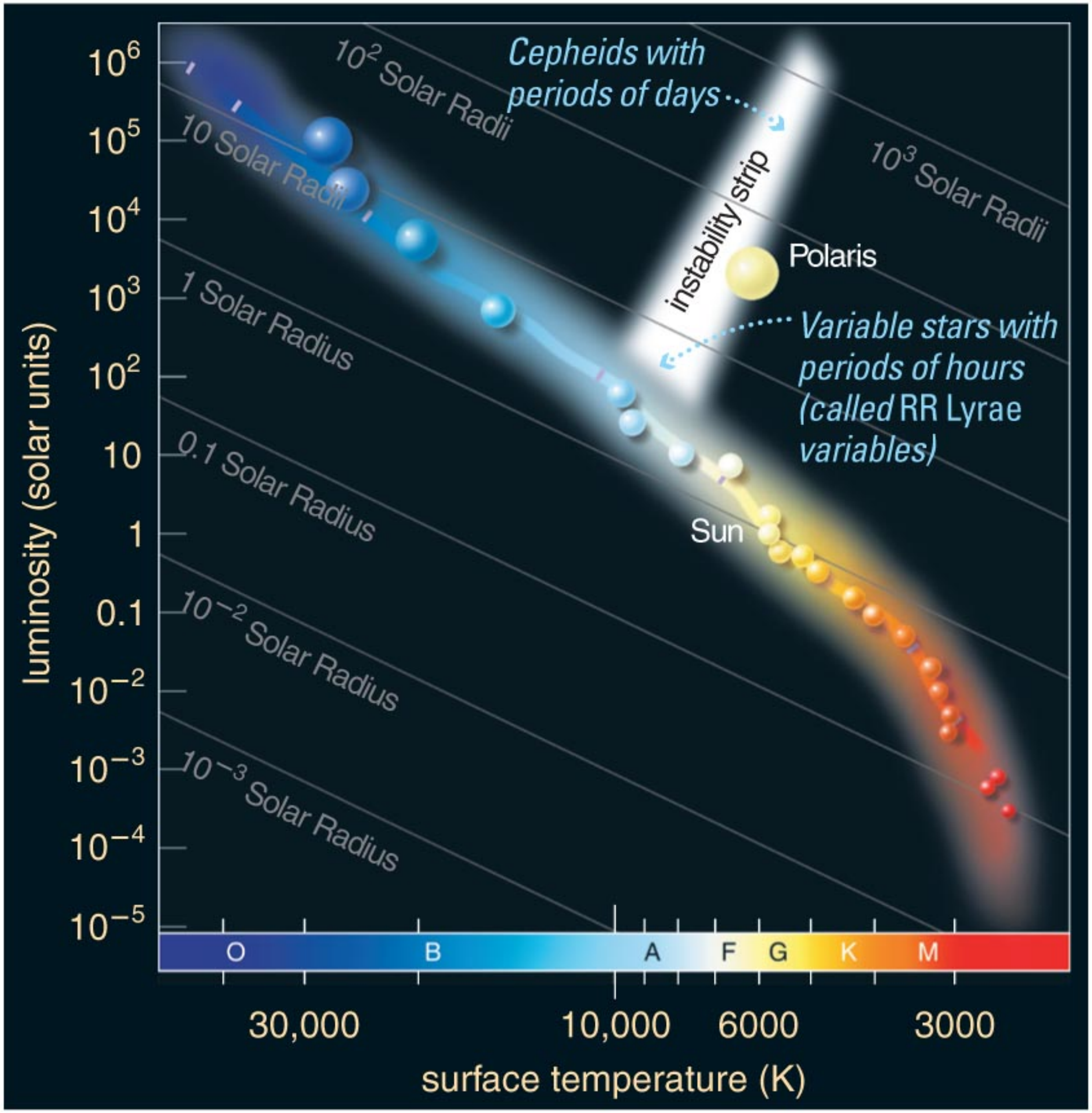
A giant star will pulsate as a Cepheid if the blue loop (as it evolves) extends into the instability strip.



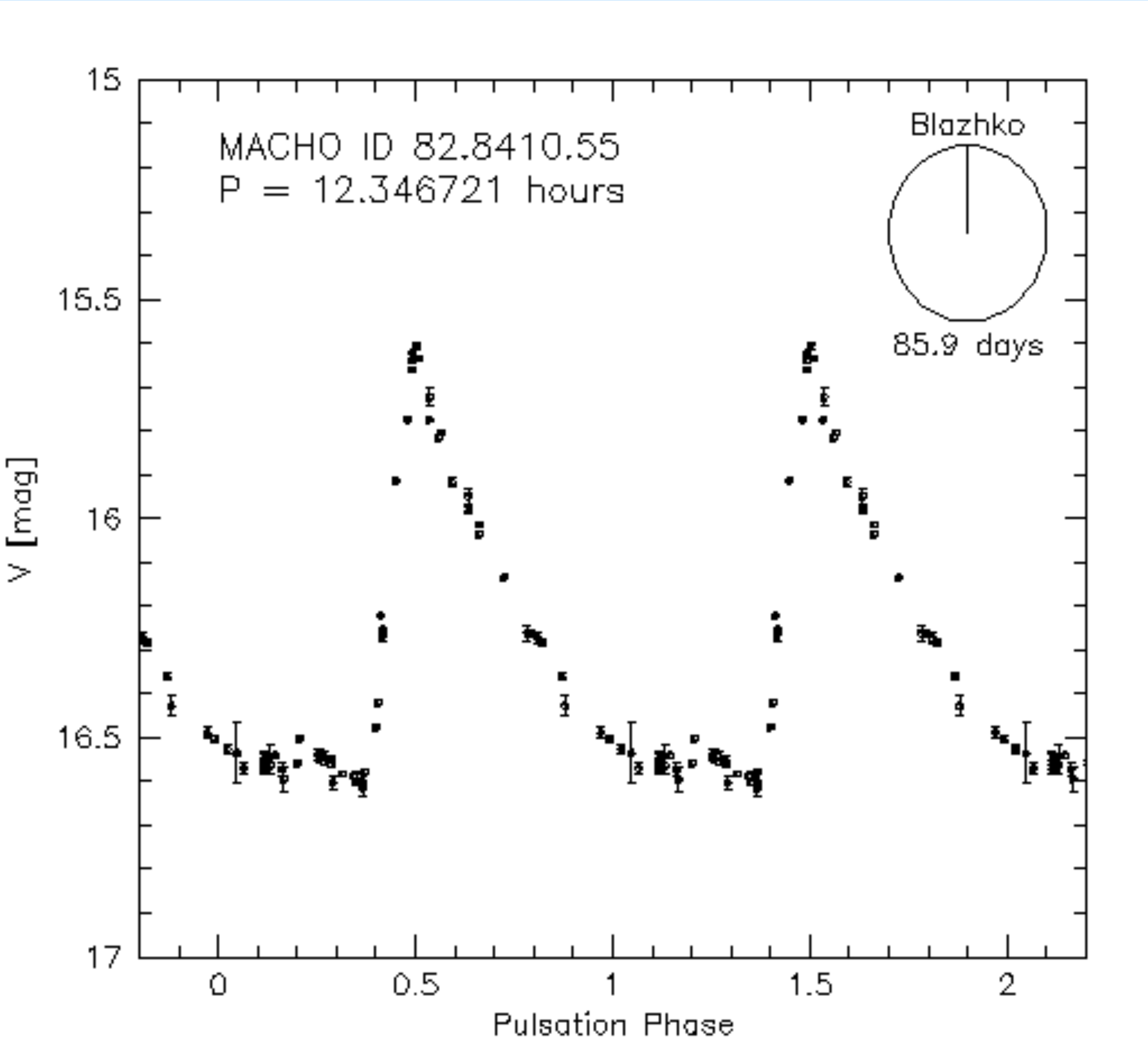
A Cepheid variable star with a period of 30 days is 10,000 times more luminous than the Sun. So its absolute visual magnitude is about -5.



Cepheids are found in the HR Diagram in the “instability strip”.



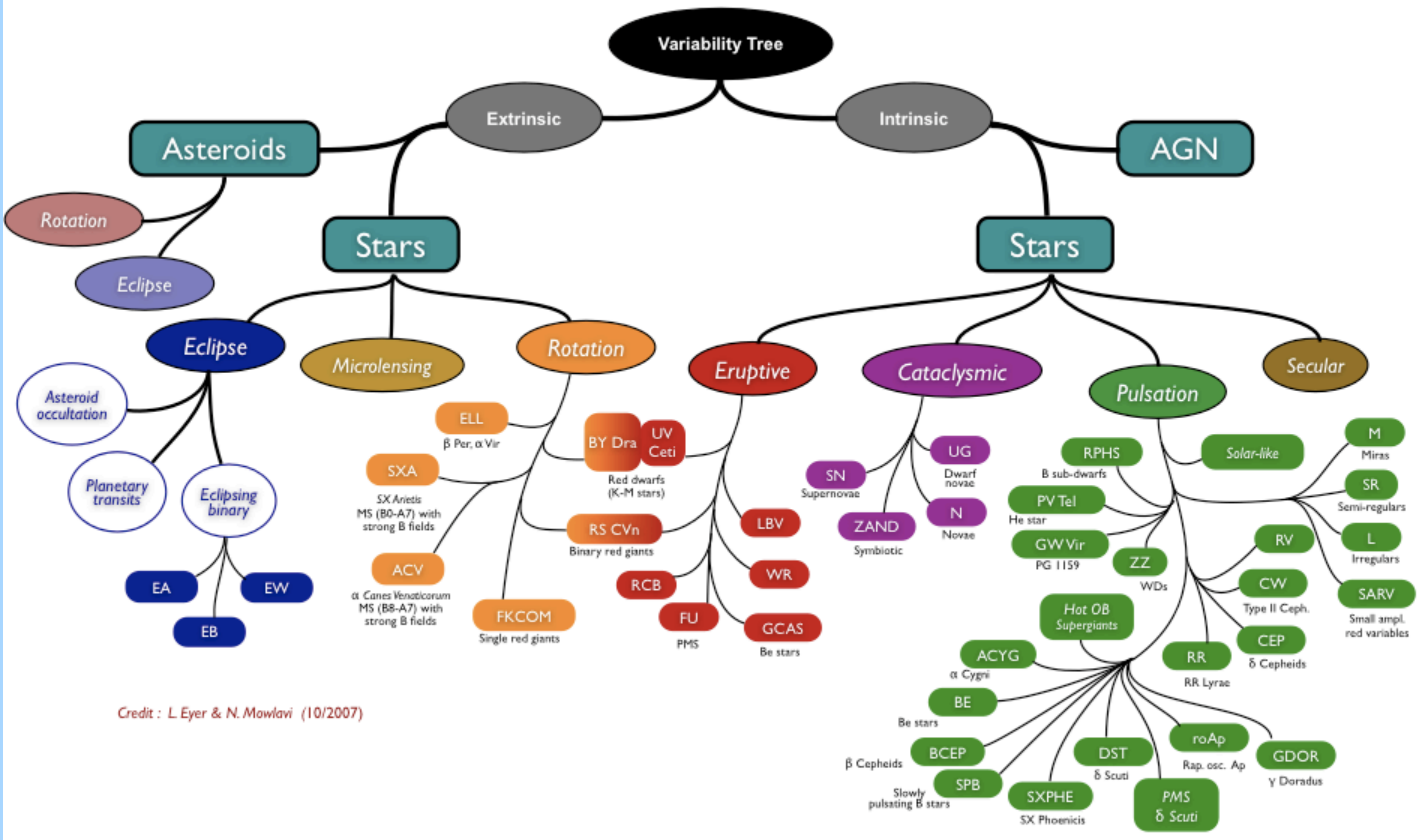
Cepheids with periods of days
instability strip
Polaris
Variable stars with periods of hours (called RR Lyrae variables)
Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6000
3000
surface temperature (K)



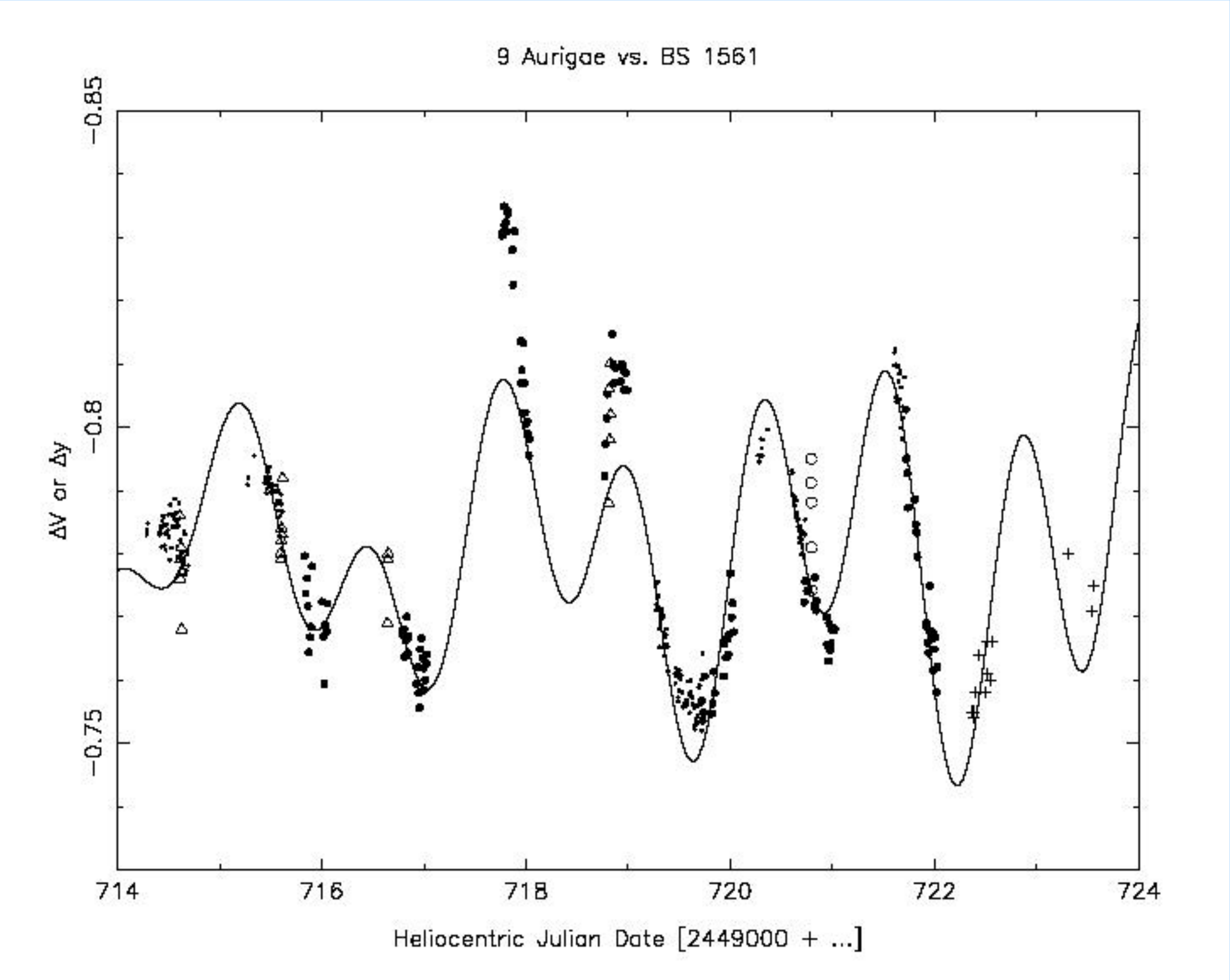
An RR Lyr star of variable amplitude

The instability strip actually extends down through the main sequence and into the region of the Hertzsprung-Russell Diagram occupied by white dwarf stars. The densest stars (white dwarfs) pulsate the fastest, with time scales of minutes, while the least dense stars in the instability strip (K giants) pulsate most slowly, with time scales up to 100 days.

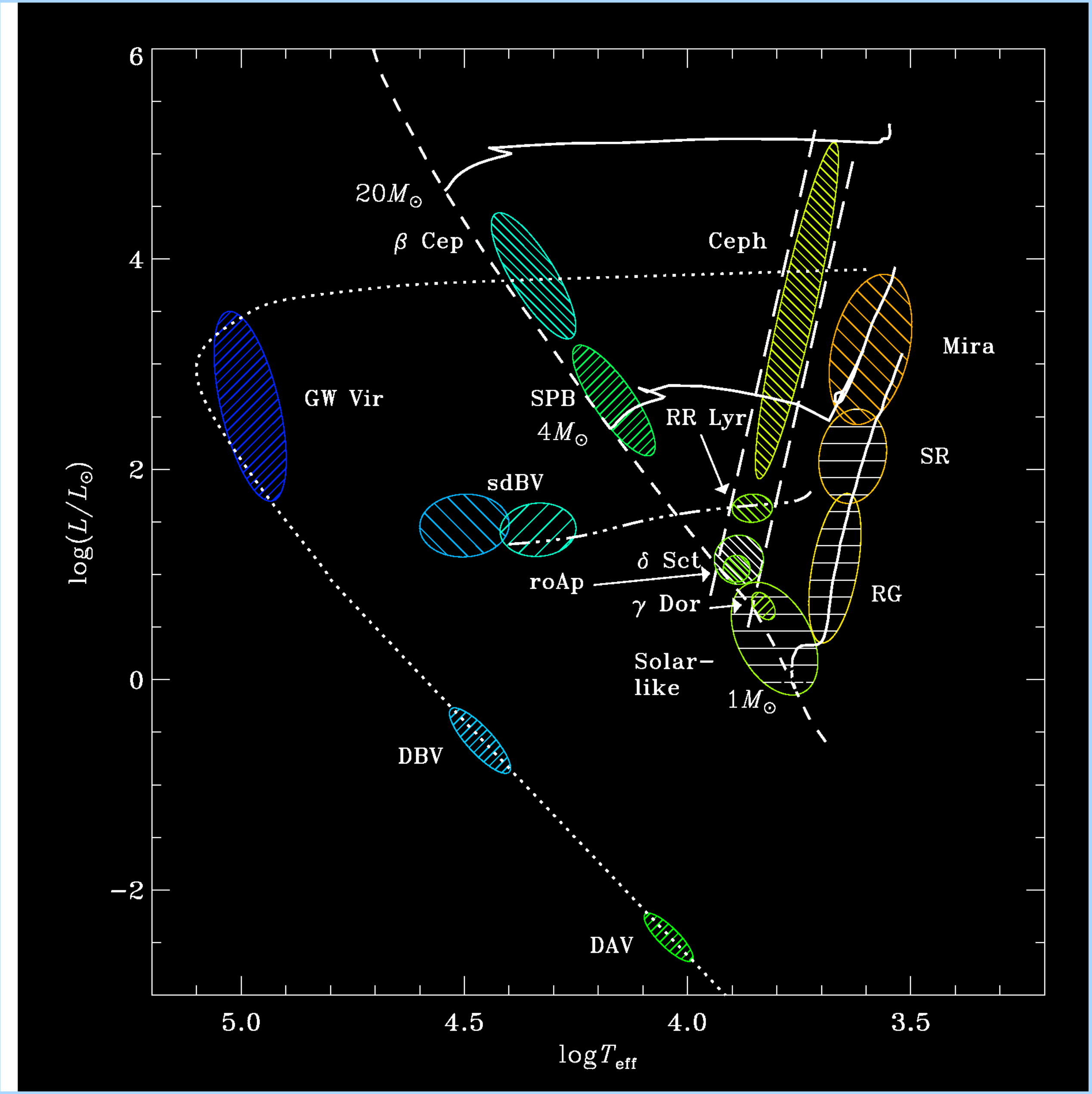
Different kinds of variable stars



Credit : L Eyer & N. Mowlavi (10/2007)



Light curve of a γ Doradus star. Data from Lithuania, Spain, New Mexico, Arizona, and Hawaii.



Locations of various pulsating stars in the HR diagram.

Consider a star whose mass is 4.0 solar masses.
How long is it a main sequence star?

a. 4 times as long as the Sun’s main sequence lifetime
b. 1 billion years
c. 312 million years
d. 3 million years