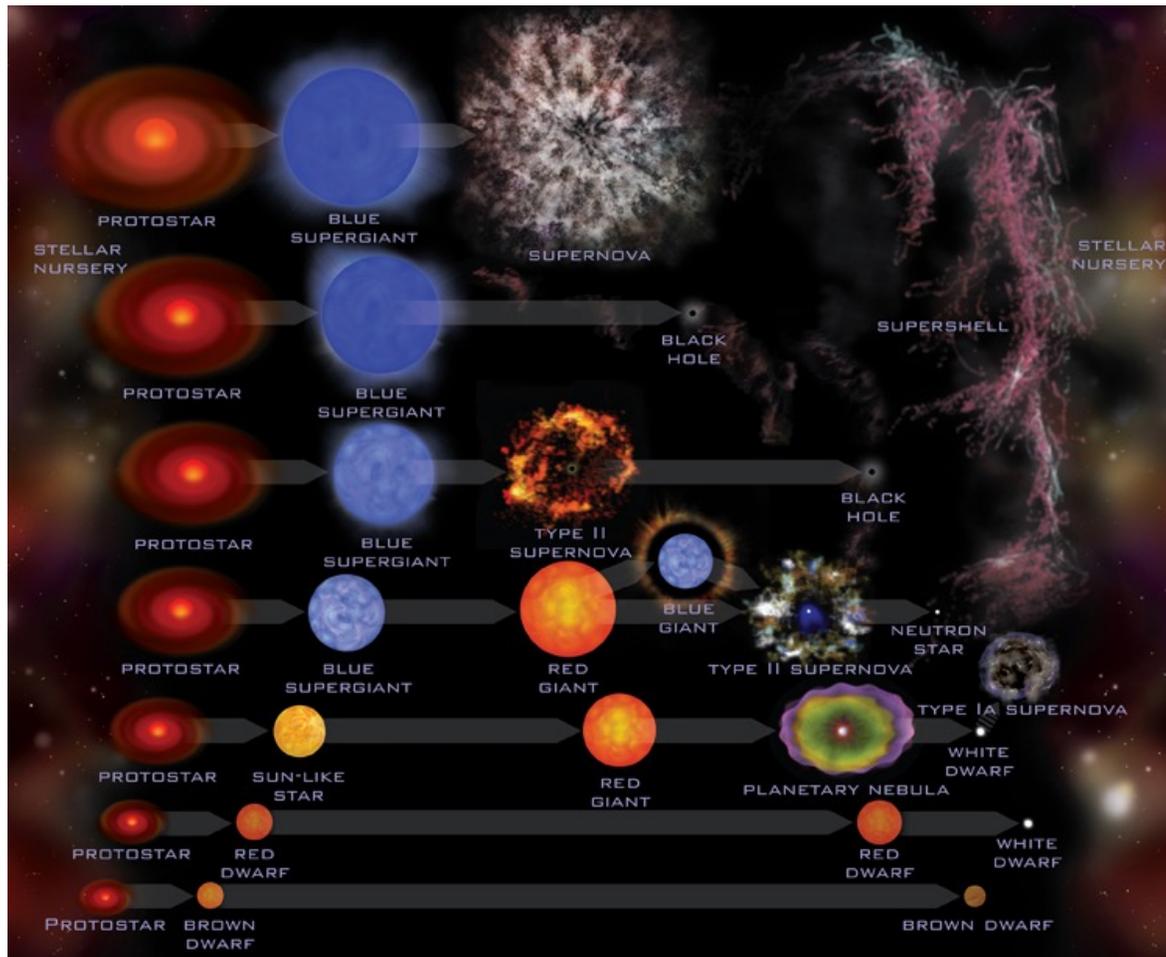


Astronomy 421



Lecture 17: Stellar Evolution

Outline

Width of MS – evolution and metallicity

MS scaling laws

Evolution of “low-mass” stars

Evolution of “high-mass” stars, including supernovae

Clusters

Stellar evolution

Stars have many properties:

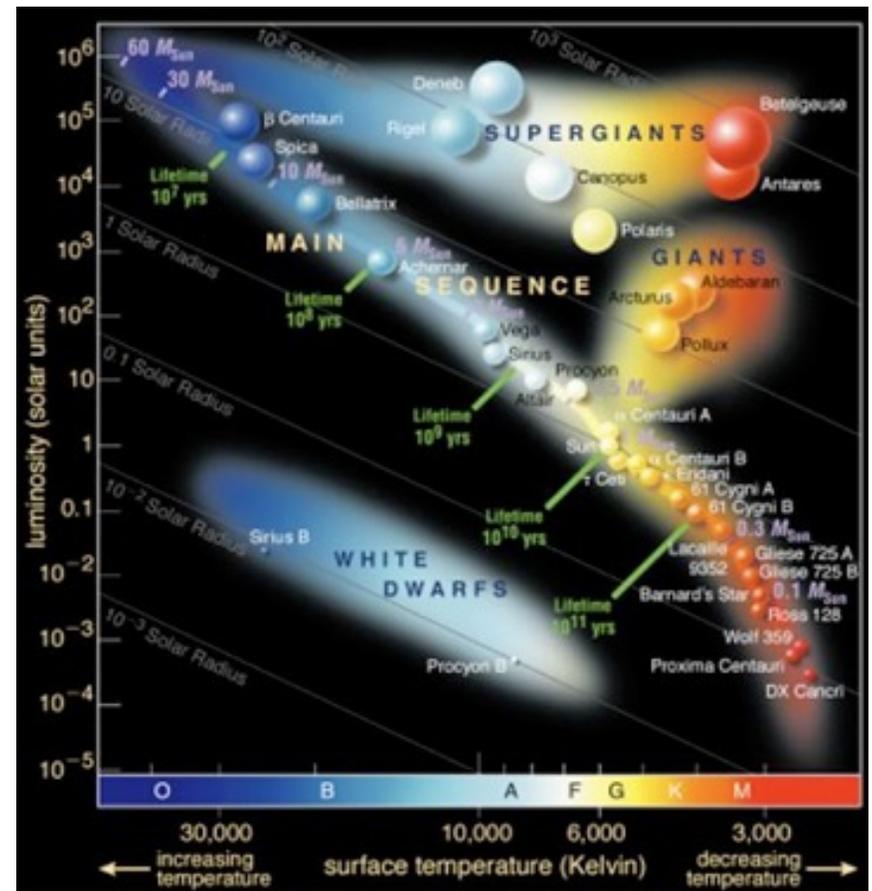
mass, luminosity, radius, chemical composition, surface temperature, core temperature, core density etc..

However, only two properties, the mass and initial chemical composition, dictate the other properties as well as the star's evolution (at least for isolated stars)

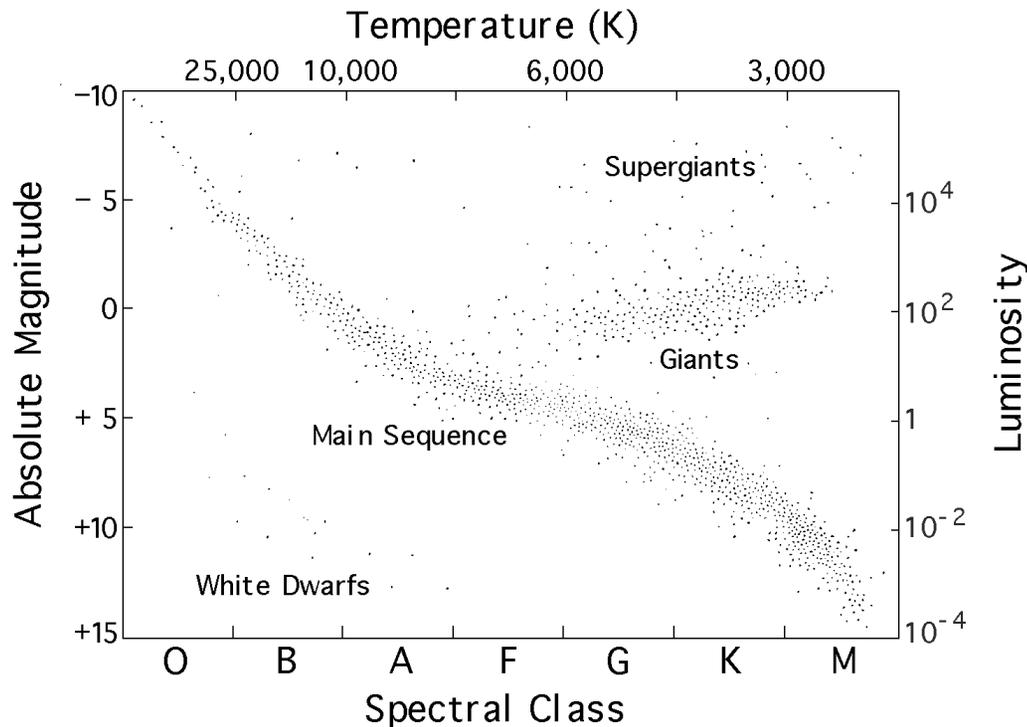
This is the Vogt-Russell “theorem”.

There is only one way to make a star with a given mass and chemical composition.

=> If we have a protostar with a given mass and composition, we can calculate how that star will evolve over its entire life.



MS evolution and MS width:



Why does MS have width?

During MS H burns into He. After 50% of H has been used, the number of particles in core has decreased by a factor 0.73 (assuming original 10% He). What are the implications?

As $H \Rightarrow He$, μ increases in core.

$\Rightarrow P$ drops \Rightarrow core contracts

$\Rightarrow \rho, T$ rise $\Rightarrow P$ rises and new equilibrium established

$\Rightarrow \epsilon_{pp} \propto \rho X^2 T^4$ rises $\Rightarrow L$ rises

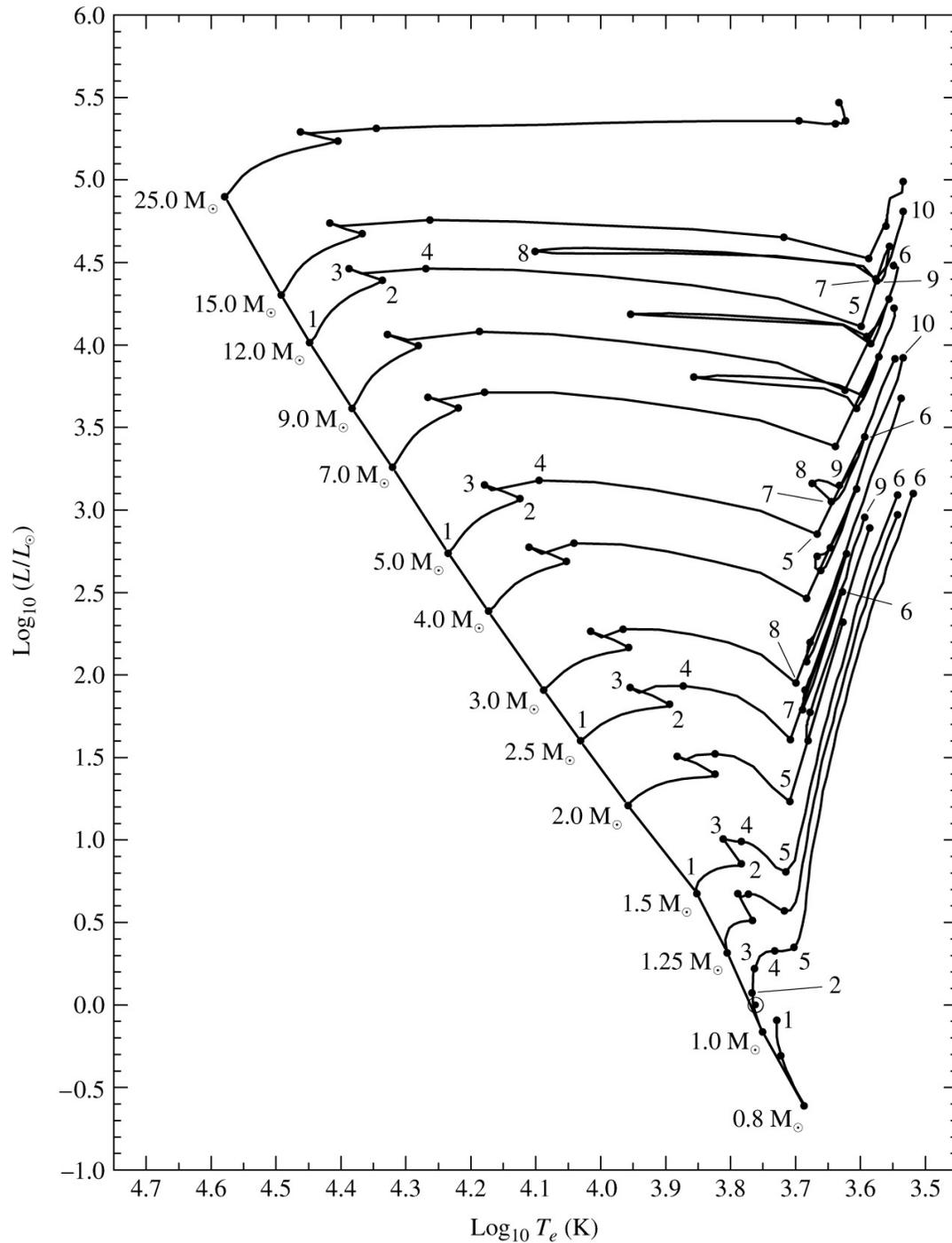
$$P = \frac{\rho k T}{\mu m_H}$$

Since its arrival on the MS, the Sun has become 30% more luminous. Stars of a given mass but different ages contribute to MS width.

Fig 13.1 from C+O.

ZAMS or Zero Age Main Sequence is at point 1.

Exhaustion of core H at point 2.



Metallicity and MS width:

Lower metal abundances

⇒ fewer free e^- in atmosphere (most e^- 's come from metals because of lower Ionization Potentials, despite lower abundances)

⇒ less H^- forms

⇒ less continuum opacity

⇒ see deeper down

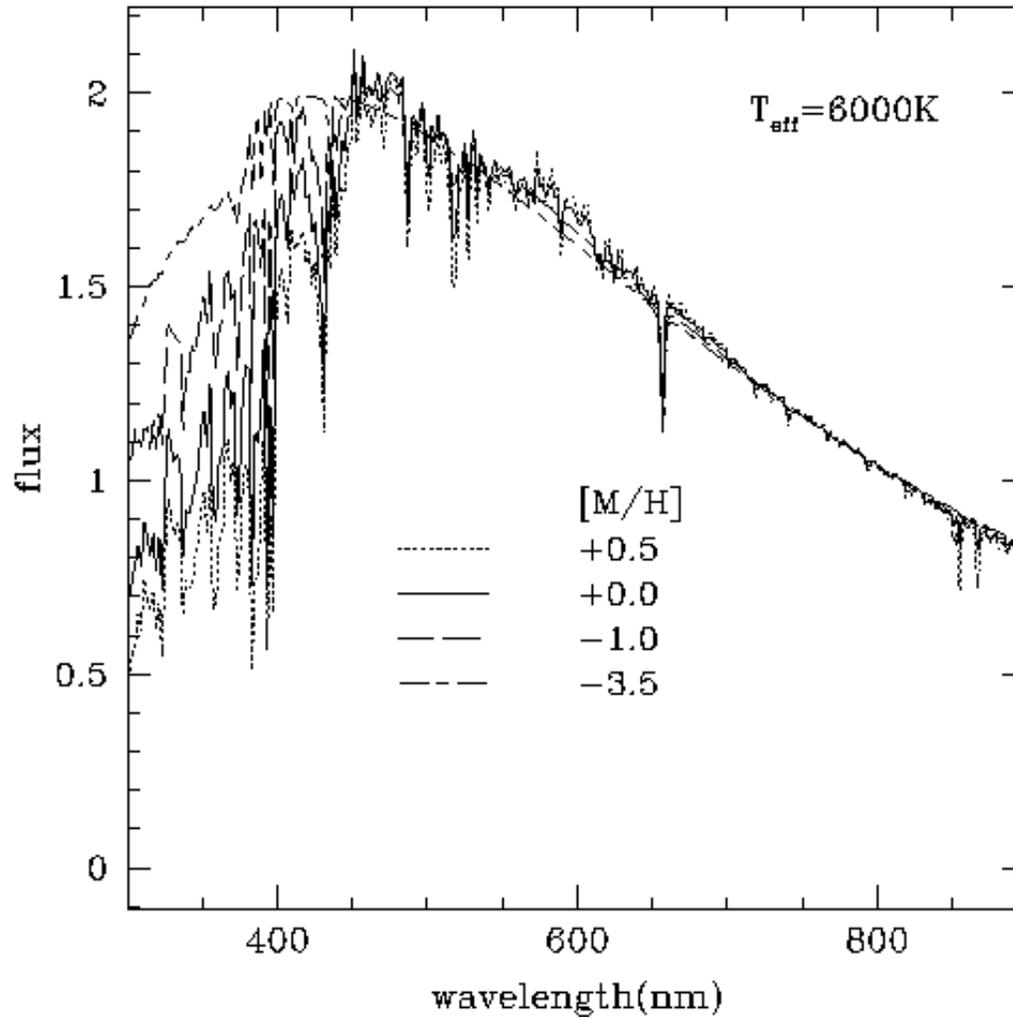
⇒ see higher atmospheric temperature.

Also, many metal absorption lines in blue, UV. "Line blanketing" - decrease in continuum due to many overlapping absorption lines.

Lower metals => more blue, UV, lower $B-V$.

Width on MS is due to both evolution as well as differences in chemical composition.

Examples of model stellar atmospheres with different “metallicities” showing effect of line blanketing on blue/UV light.



Main sequence relations:

$$\text{M - L:} \quad \log\left(\frac{L}{L_{\odot}}\right) = \beta + \alpha \log\left(\frac{M}{M_{\odot}}\right)$$

M	β	α

$M < 0.5M_{\odot}$	-0.15	2.85
$0.5M_{\odot} < M < 2.5M_{\odot}$	0.07	3.60
$M > 2.5M_{\odot}$	0.48	2.91

M - R:

$$\log\left(\frac{R}{R_{\odot}}\right) = \log\left(\frac{M}{M_{\odot}}\right) + 0.10 \quad (M \leq 0.4M_{\odot})$$

$$\log\left(\frac{R}{R_{\odot}}\right) = 0.73 \log\left(\frac{M}{M_{\odot}}\right) \quad (M \geq 0.4M_{\odot})$$

M - t_{MS} :
$$t_{\text{MS}} \propto \frac{M_{\text{core}}}{L} \propto \frac{M}{L} \propto M^{1-\alpha}$$

$$t_{\text{MS}} \simeq t_0 \left(\frac{M}{M_{\odot}} \right)^{1-\alpha}$$

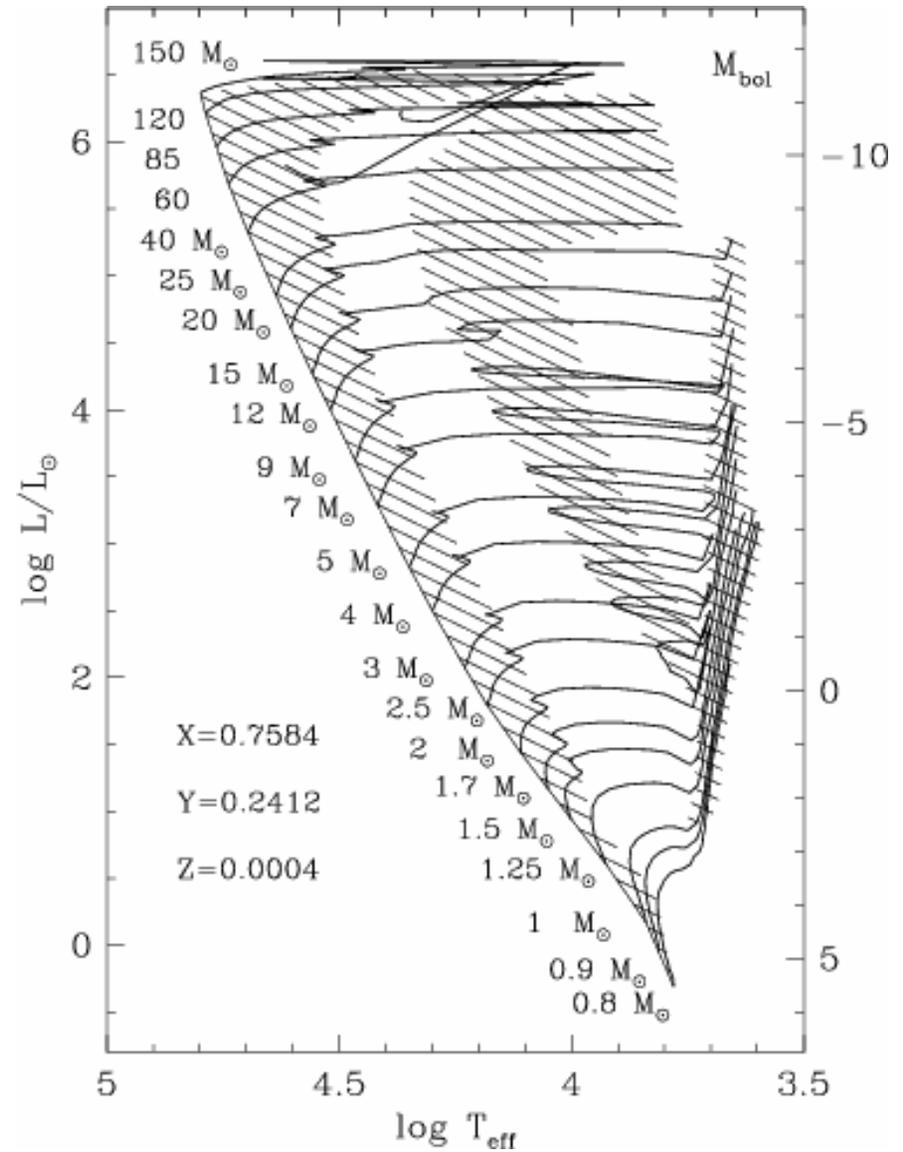
M	t_0 (10^{10} years)

$M < 0.5M_{\odot}$	1.55
$0.5M_{\odot} < M < 2.5M_{\odot}$	0.93
$M > 2.5M_{\odot}$	0.36

Geneva tracks

Right: *Geneva* tracks. Stellar modeling used to create evolutionary models of stars.

Done with complex computer code, based on physics we saw in Chapter 10.



Conditions for convection:

$$\frac{dT}{dr} = -\frac{3}{4} \frac{\bar{\kappa} \rho}{ac T^3} \frac{L_r}{4\pi r^2}$$

dT/dr increases when opacity or radiative flux increases. At some point convection takes over, being a more efficient way of transporting energy. This happens in layers with very high opacity, or when a large fraction of energy is released within a small volume.

Low mass stars: cores are fusing at lower rates by the p-p chain at a lower temperature. High opacity in outer layers due to, e.g. H⁻. Thus they have radiative cores and convective envelopes.

High mass stars: high fusion rate from CNO cycle leads to large core luminosity and steep temperature gradient. Opacity lower because most gas ionized. Hence convective cores and radiative envelopes.

HII regions

- Hot stars emit vast amounts of UV radiation as MS stars => ionizes surrounding gas => HII regions.
- Balance between ionization of H and recombination. We see Balmer lines (reddish because of Balmer -alpha line).
- In large star formation regions, the UV radiation from massive stars may be strong enough to stop formation of light stars before they have fully collapsed.



The part in balance between ionization and recombination is called a *Strömgren sphere*. Size can be estimated, assuming no photons escape so that all end up ionizing an H atom.

Thus the total ionization rate equals production rate of ionizing photons by central star, N .

Recombination rate per H ion, R_p proportional to the interaction probability (determined from quantum mechanics) α and the density of free electrons, n_e .

Total recombination rate $R_{tot} =$ recombination rate per H ion times number of H ions. $R_p = \alpha n_e$

$$R_{tot} = R_p n_p \frac{4\pi r^3}{3} = \alpha n_e^2 \frac{4\pi r^3}{3}$$

If equilibrium, $R_{tot} = N$. Thus:

$$\Rightarrow r = \left(\frac{3N}{4\pi\alpha n_e^2} \right)^{1/3}$$

Example sizes of Strömngren spheres:

Assume typical values $\alpha \simeq 3 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ $n_e \simeq 10 \text{ cm}^{-3}$

G2V star $N = 10^{39} \text{ s}^{-1}$, $r \simeq 2 \times 10^{16} \text{ cm} \simeq 0.007 \text{ pc}$

B0V star $N = 4 \times 10^{46} \text{ s}^{-1}$, $r \simeq 6 \times 10^{18} \text{ cm} \simeq 2 \text{ pc}$

O5V star $N = 3 \times 10^{49} \text{ s}^{-1}$, $r \simeq 6 \times 10^{19} \text{ cm} \simeq 20 \text{ pc}$

Massive O stars can evaporate gas cloud in which they were formed.

In practice, the HII region will be overpressured wrt surrounding gas and thus expand, further destroying stellar birth place.

How bright can a star be? The Eddington Limit for stars

There is a physical limit to how bright a star can be. Recall total pressure is the sum of ideal gas pressure and radiation pressure:

$$P = \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4$$

For high T , low ρ , radiation pressure can dominate. In this case, the pressure gradient is:

$$\frac{dP_{rad}}{dr} = -\frac{\bar{\kappa}\rho}{c} F_{rad}$$

Worksheet: Assuming that radiation pressure dominates over thermal pressure (a good assumption for the outer layers of high mass stars), derive the Eddington Luminosity:

$L_{edd} = 38,000 L_{sun} (M/M_{sun})$. Compare your results to what the Mass-Luminosity relation predicts for a 10 solar mass star and for a 100 solar mass star.

How bright can a star be?

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For high T , low ρ , radiation pressure can dominate. In this case, the pressure gradient is:

$$\frac{dP_{rad}}{dr} = -\frac{\bar{\kappa}\rho}{c} F_{rad}$$
$$\Rightarrow \frac{dP}{dr} = -\frac{\bar{\kappa}\rho}{c} \frac{L}{4\pi r^2}$$

To remain in hydrostatic equilibrium:

$$\frac{dP}{dr} = -g\rho = -G\frac{M\rho}{r^2}$$

This leads to maximum radiative luminosity a star can have and be stable, the *Eddington Limit*

$$L_{edd} = \frac{4\pi Gc}{\bar{\kappa}} M$$

Observations: massive stars tend to have L near L_{edd} . What happens if $L > L_{edd}$?

If $L > L_{edd}$, pressure gradient greater than hydrostatic equilibrium case => radiation drives wind.

For massive stars, opacity is from e^- scattering (why?)

$$\bar{\kappa} = \overline{\kappa_{es}} = 0.02 (1 + X) \text{ m}^2 \text{ kg}^{-1}$$

For $X=0.7$

$$L_{edd} \simeq 1.5 \times 10^{31} \frac{M}{M_{\odot}} \text{ W}$$

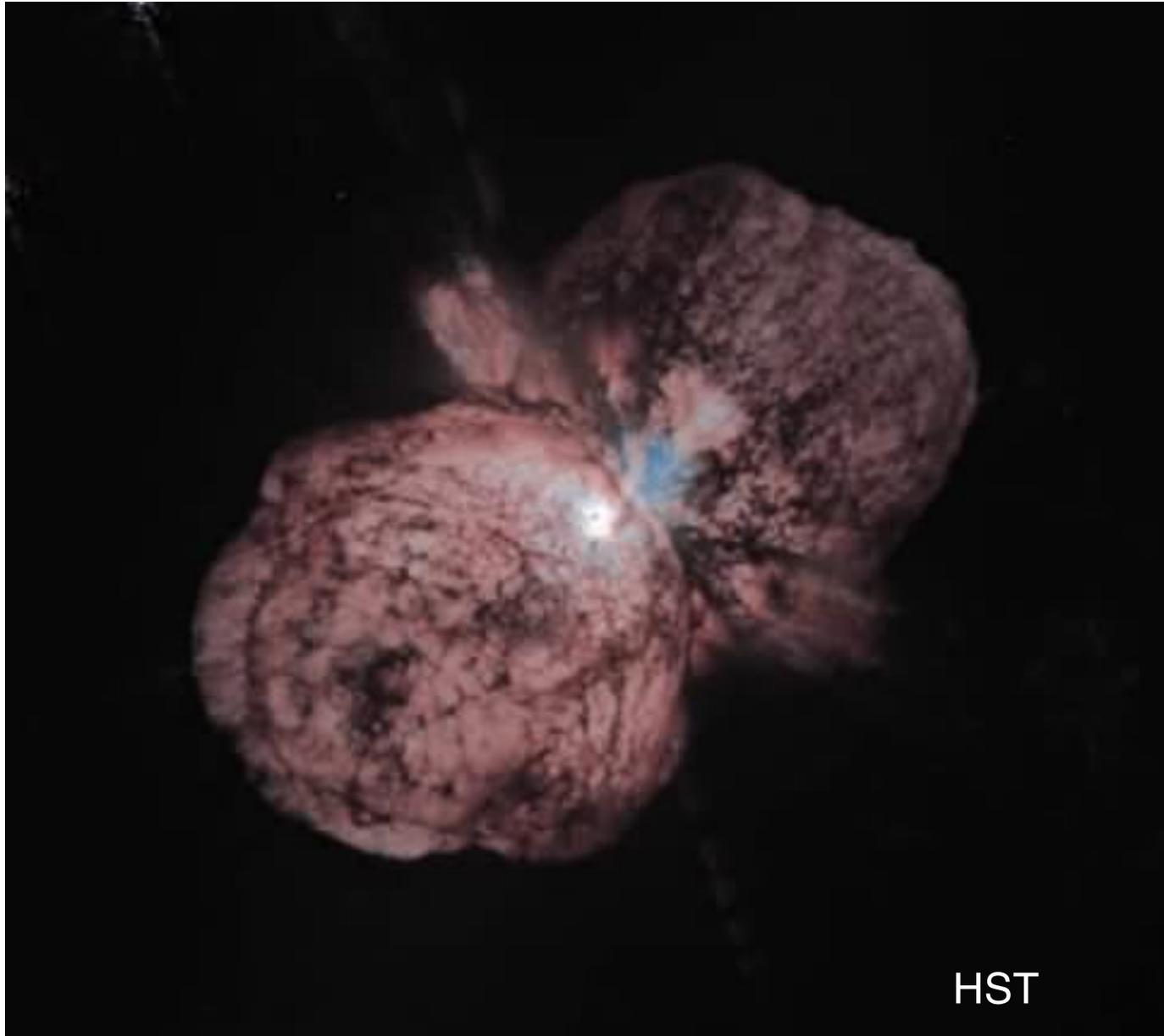
$$\frac{L_{edd}}{L_{\odot}} \simeq 38,000 \frac{M}{M_{\odot}}$$

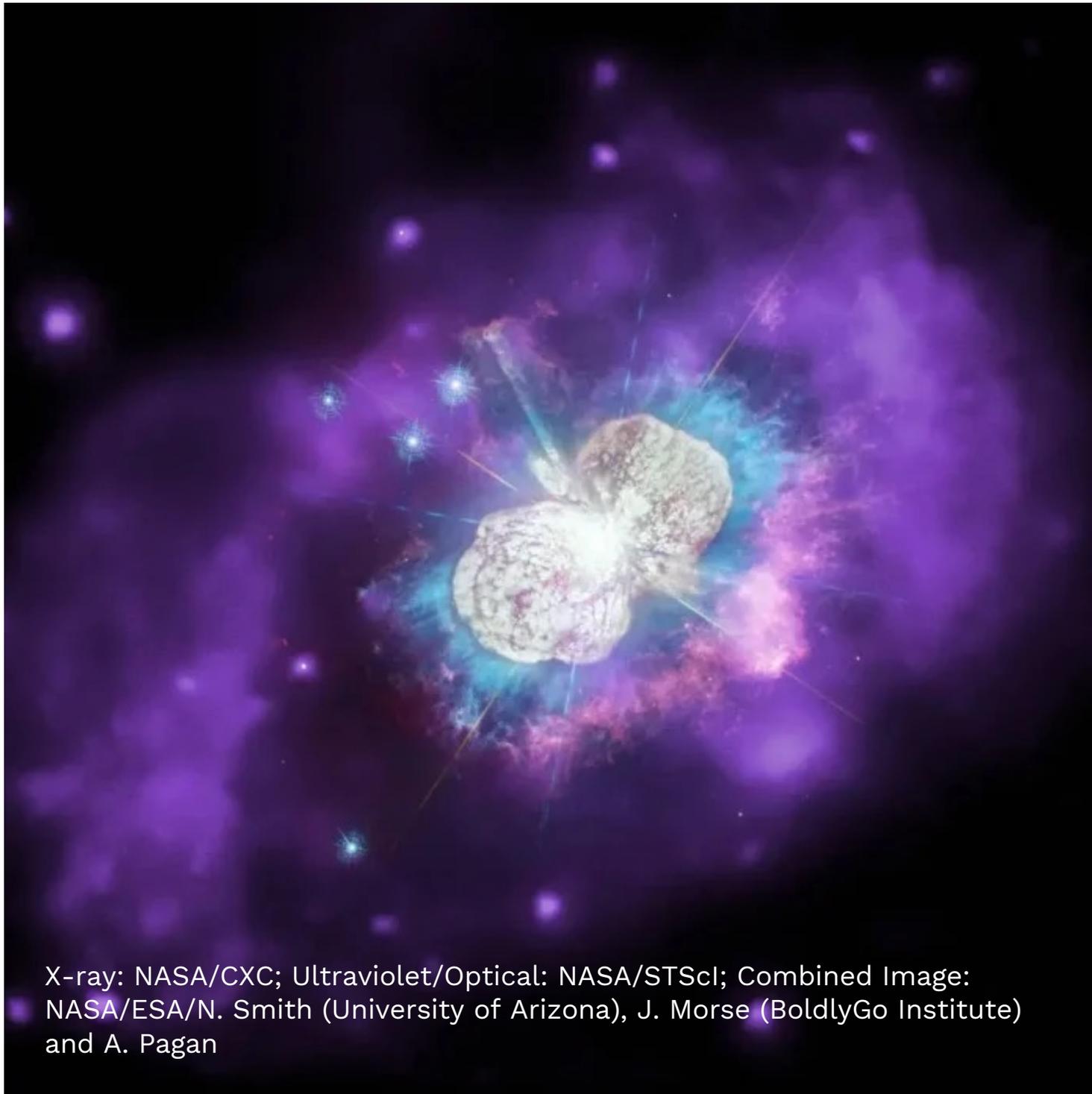
From massive star models + observations, we know $L \propto M^3$

$$L \sim 0.002 L_{edd} \text{ for } M \sim 10 M_{\odot}$$

$$L \sim L_{edd} \text{ for } M \sim 100 M_{\odot}$$

Thus, for $M > 100 M_{\odot}$, there is huge mass loss, unstable.
Example is Eta Carina, $M \sim 120 M_{\odot}$.

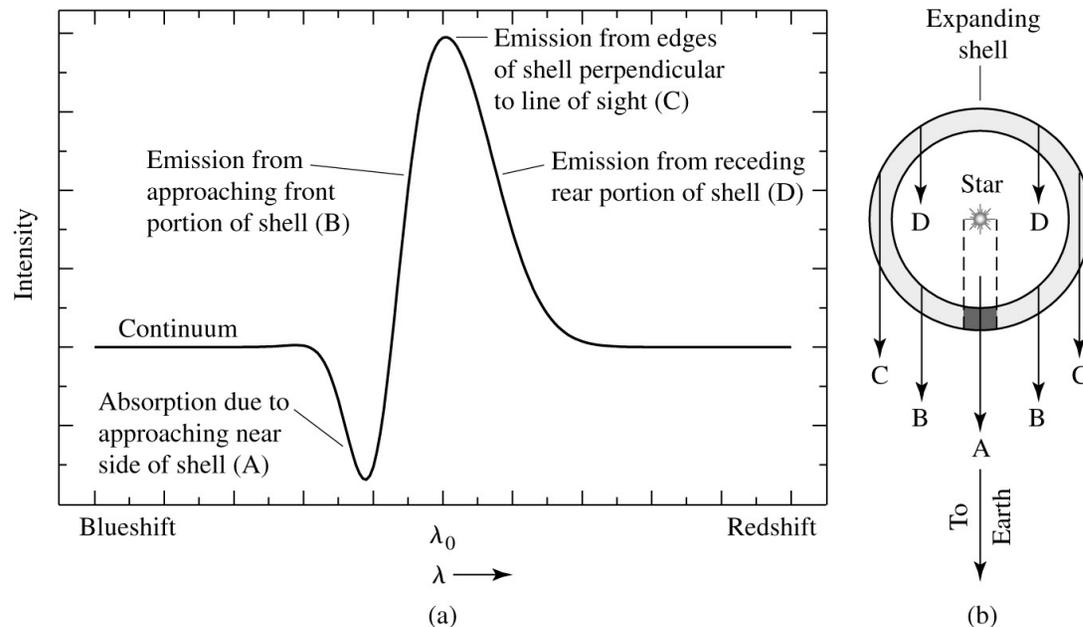




X-ray: NASA/CXC; Ultraviolet/Optical: NASA/STScI; Combined Image:
NASA/ESA/N. Smith (University of Arizona), J. Morse (BoldlyGo Institute)
and A. Pagan

So are there observational evidence of this theory of star formation?
 How do we know this is happening when it is deep inside dark, opaque clouds?

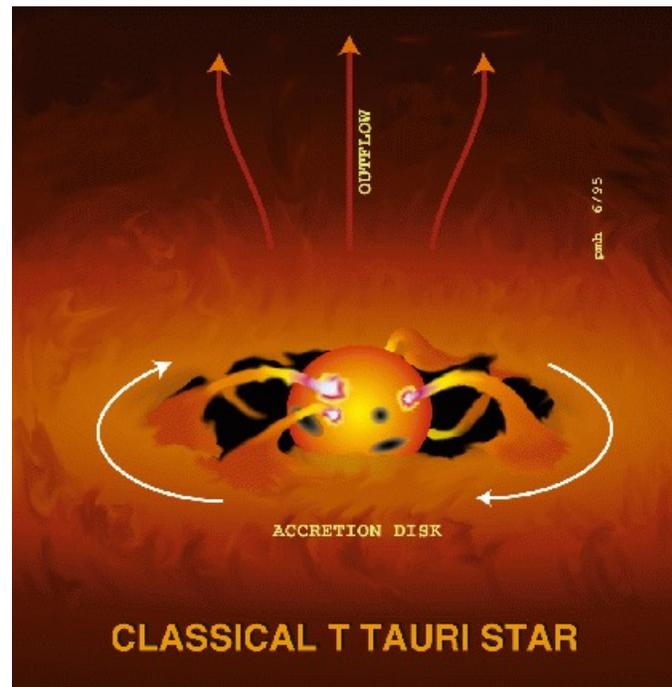
- 1) IR sources embedded in molecular clouds (evidence of energy from collapsing clouds)
- 2) T Tauri stars - low mass pre-MS stars often highly variable with strong emission lines. Exhibits *P Cygni* line profiles, interpreted as mass loss.

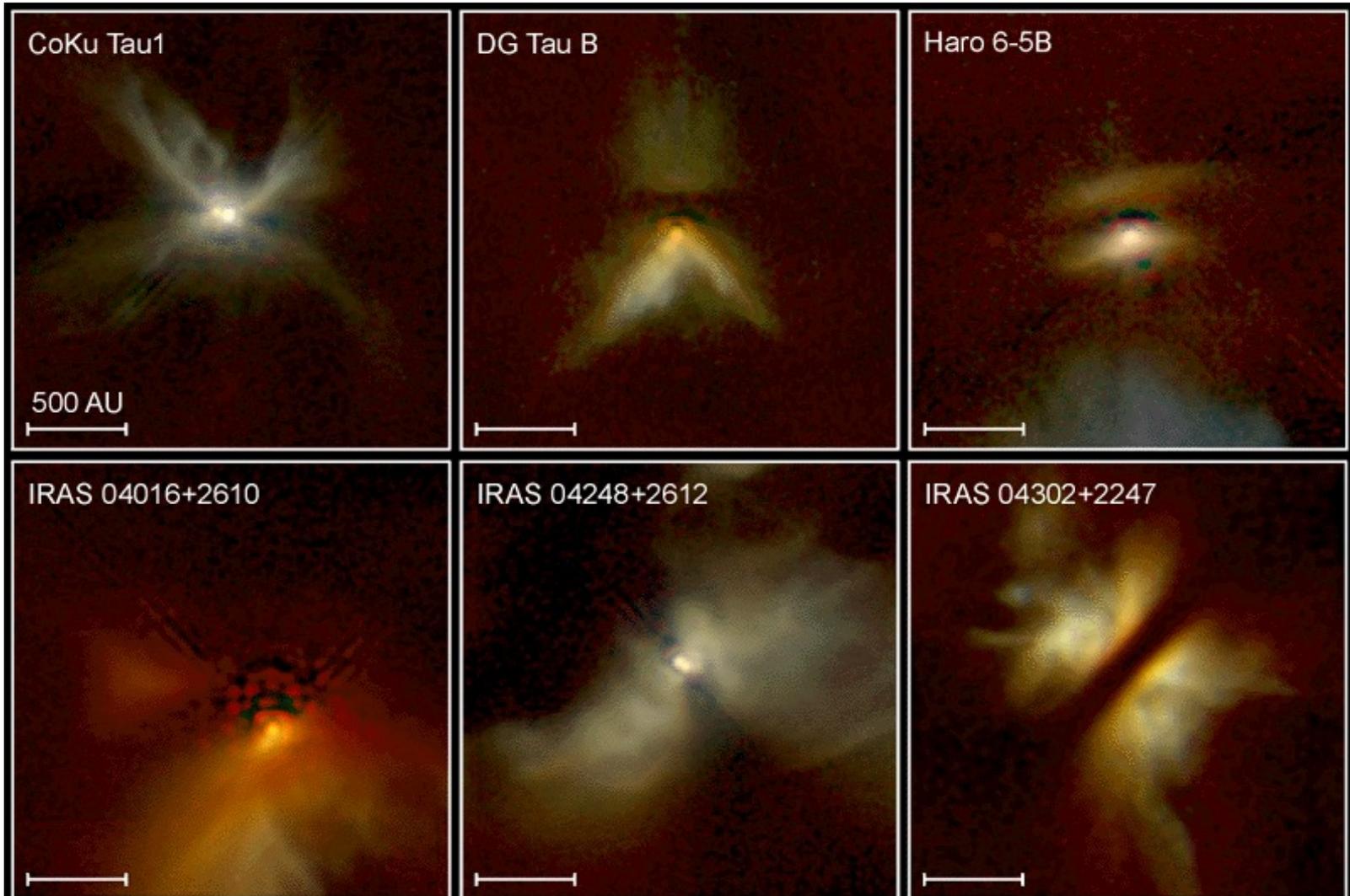


Classical T Tauri stars surrounded by discs of gas and dust, due to initial rotation of cloud.

Weak-lined T Tauri stars have lost their disks and are more evolved.

Found embedded in cloud of gas in which they were born (Trapezium Cluster in Orion Nebula is an example).





Young Stellar Disks in Infrared

HST • NICMOS

PRC99-05a • STScI OPO

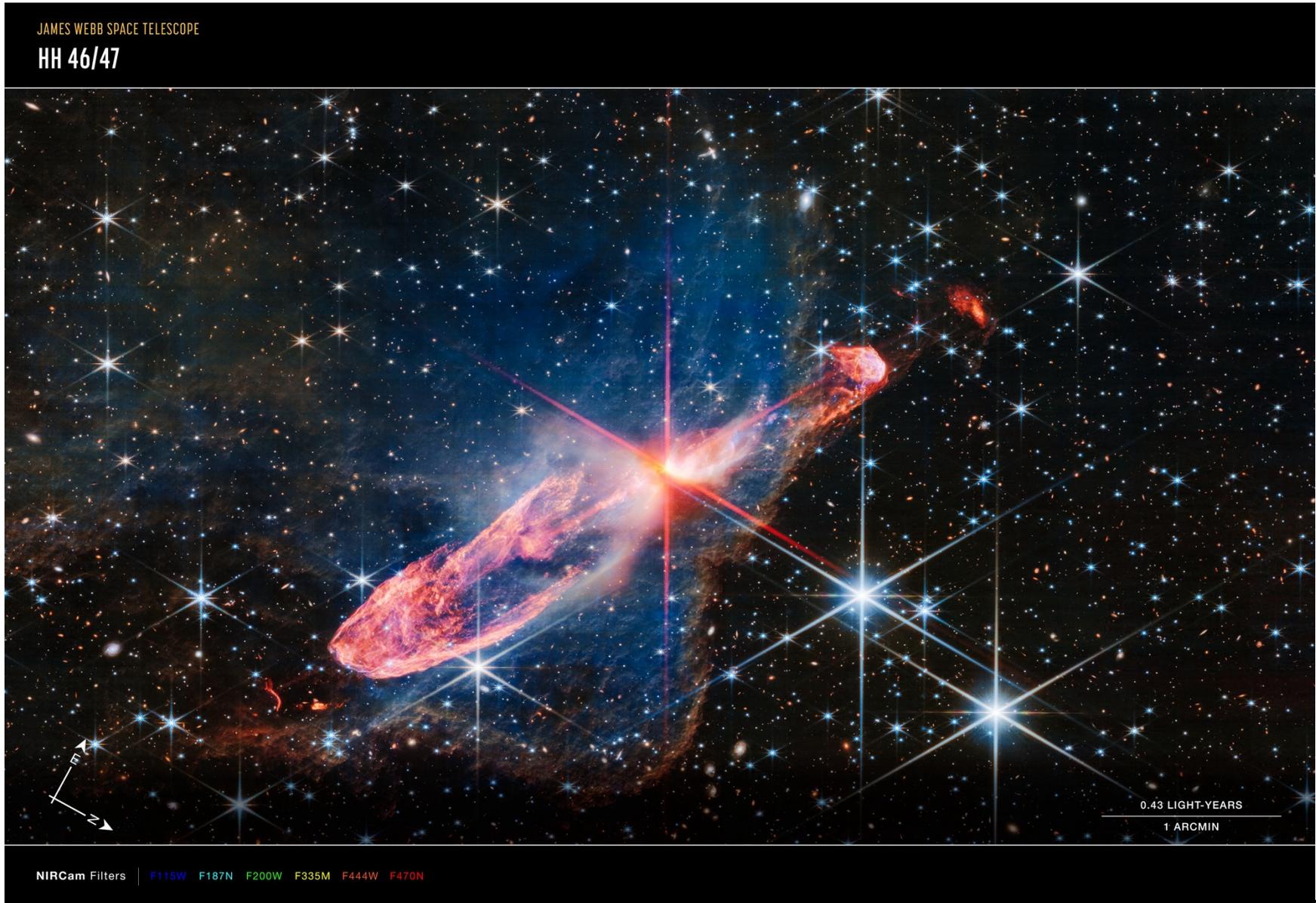
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

- 3) Herbig-Haro objects - mass loss in jets from protostellar objects. Somehow a fraction of the material accreted onto the star is ejected perpendicular to the disk plane in a highly collimated stellar jet. When jet collides with surrounding gas it forms shock waves observed as HH objects.



HH46/47

3) Herbig-Haro objects



3) Herbig-Haro objects



HH212 – ESO Where is the central star?