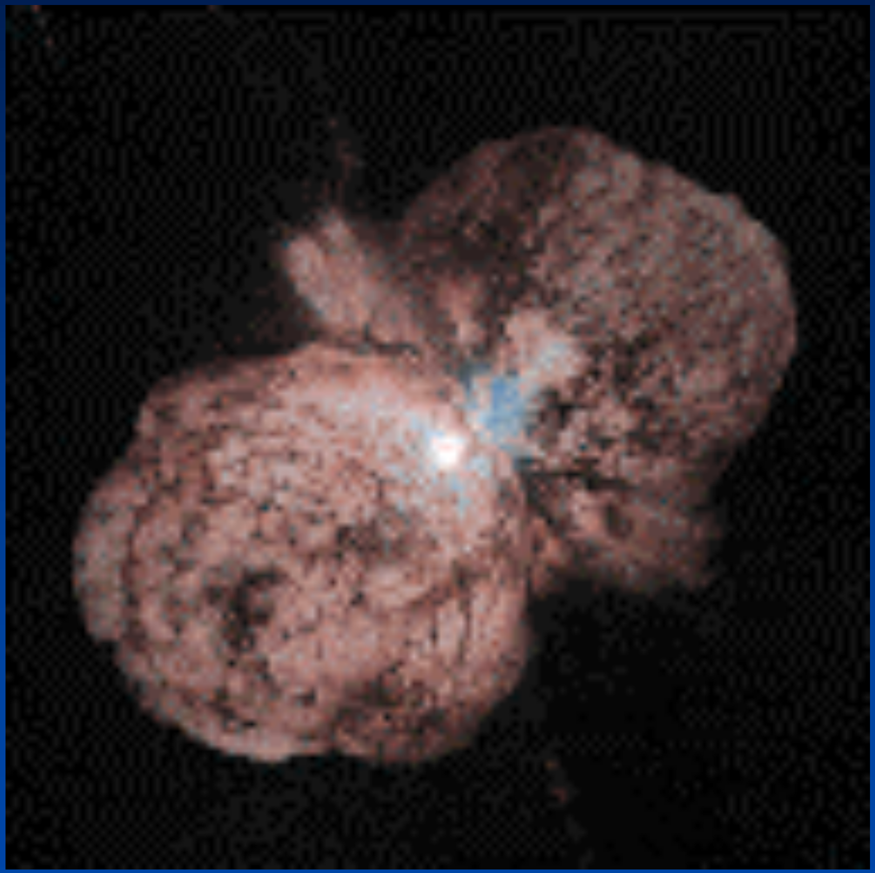
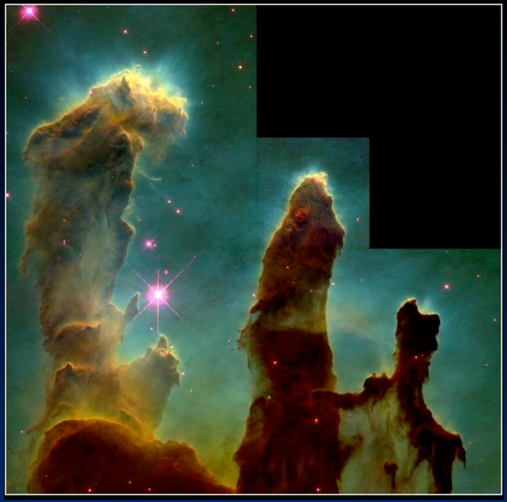
Upper Stellar Mass Limit



Eta Carina is a star of almost 100 solar masses.

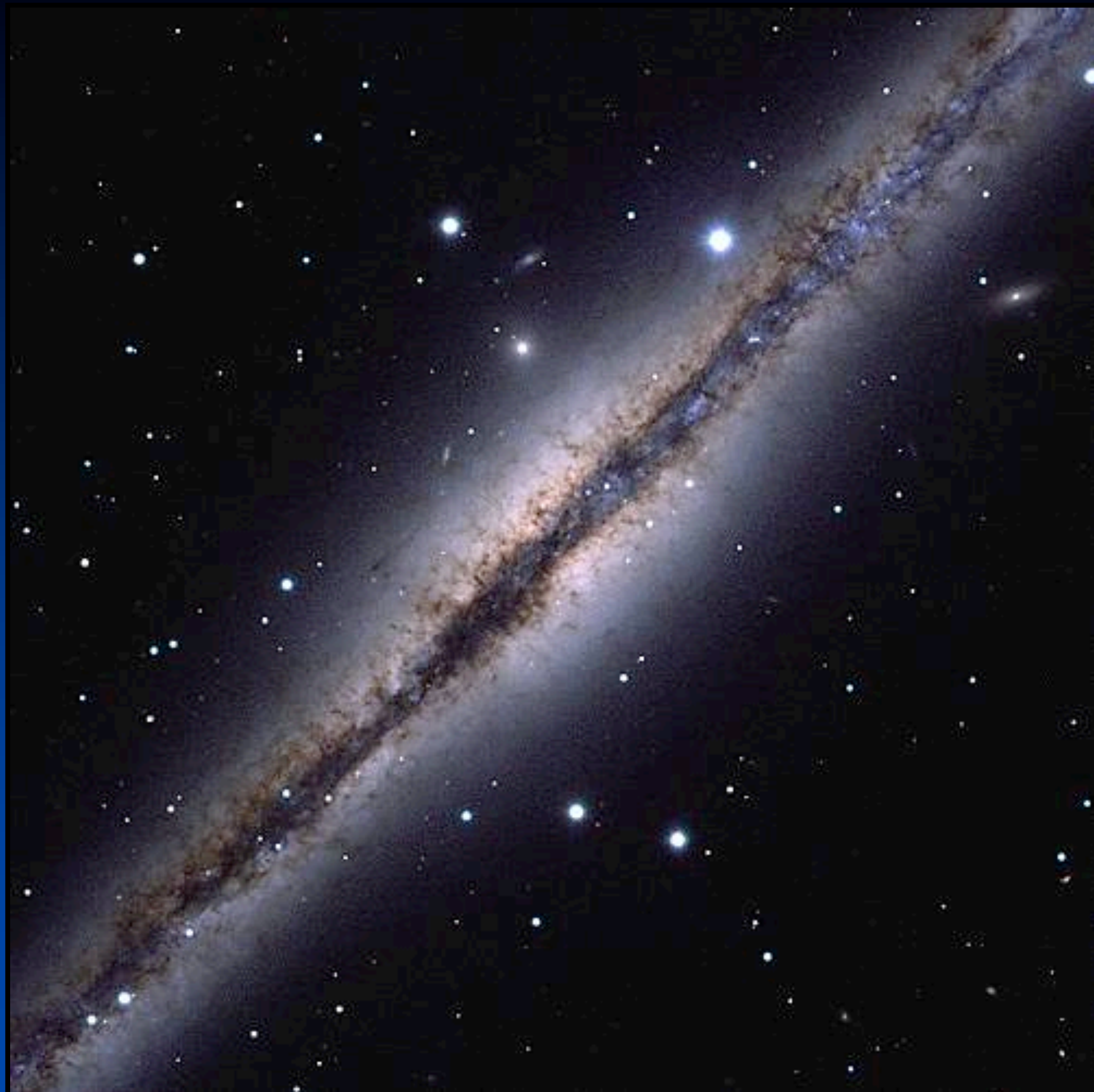
Radiation pressure is blasting off the outer parts.



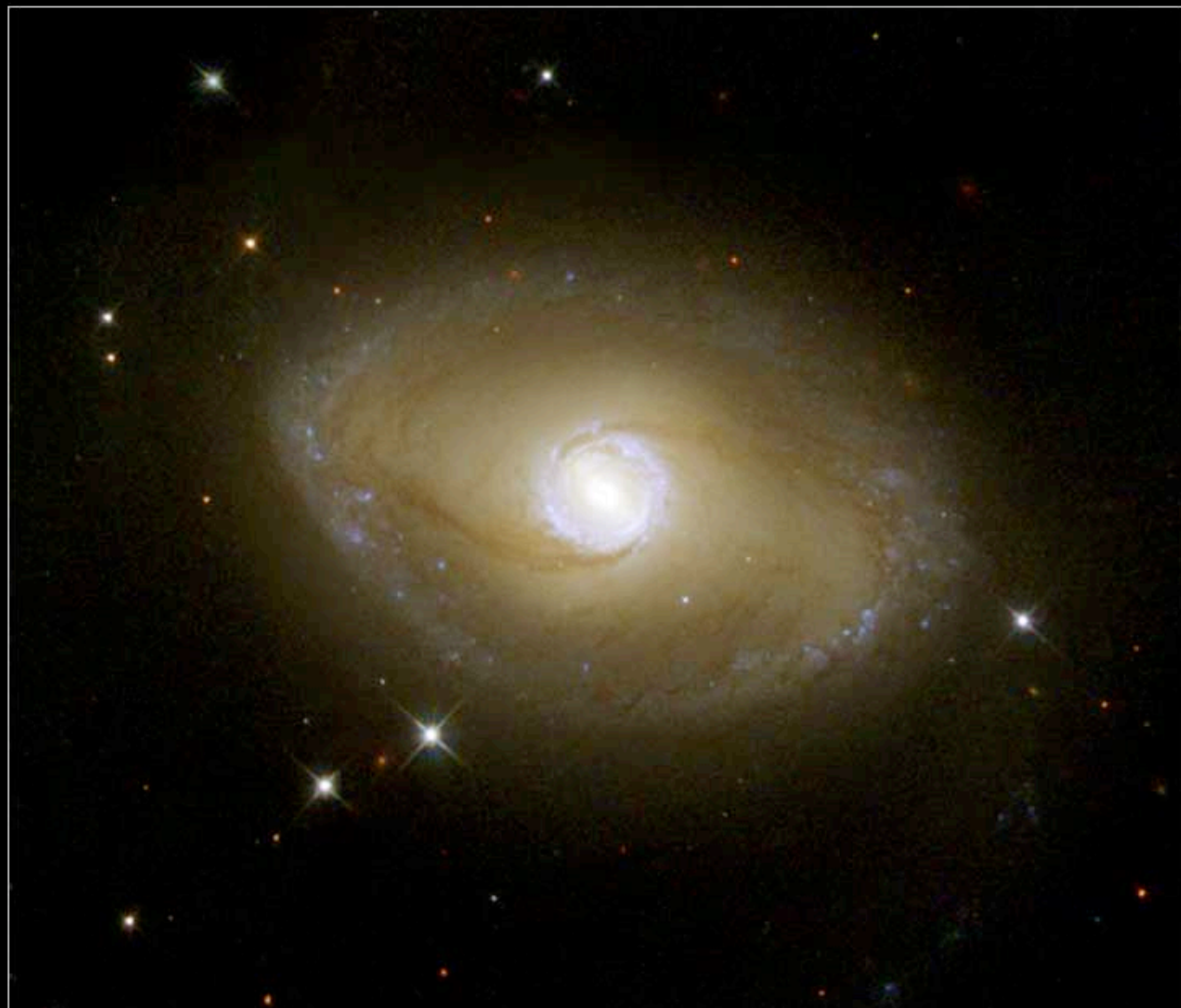
Star Formation

- Although it is one of the fundamental processes in the Universe and has been the focus of years of research, it is only in the last decade that significant progress has been made toward understanding star formation. Note that UCSC is one of the centers for the theory of star formation.

- We see young stars and star-formation regions in the disks of spiral galaxies and preferentially in spiral arms.
- Another place we see spectacular displays of star formation is in colliding galaxies.
- In both cases the star formation goes on in regions with lots of gas and dust.



Galaxy NGC 6782



Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-37

Starburst Galaxy NGC 3310

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-26

Galaxies NGC 2207 and IC 2163

Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC99-41


Polar-Ring
Galaxy
NGC 4650A
PRC99-16
Space Telescope
Science Institute
Hubble Heritage Team
(AURA/STScI/NASA)
Hubble
Heritage

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Star Formation

Red glowing gas

- Stars are made of gas and it is no surprise that wherever we see very young stars, there is gas in the vicinity.

Hot, massive, short-lived O stars.

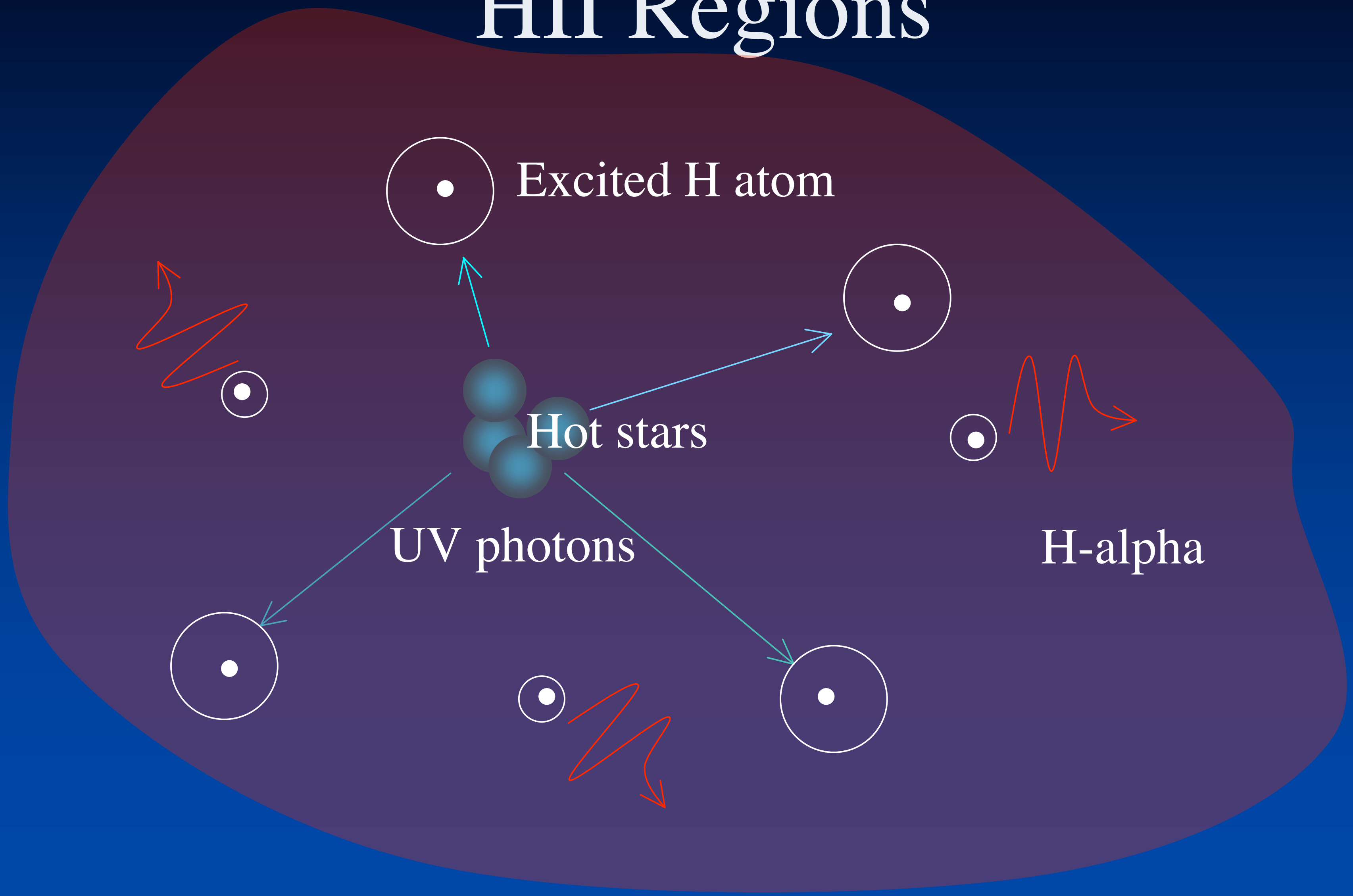
HII Region

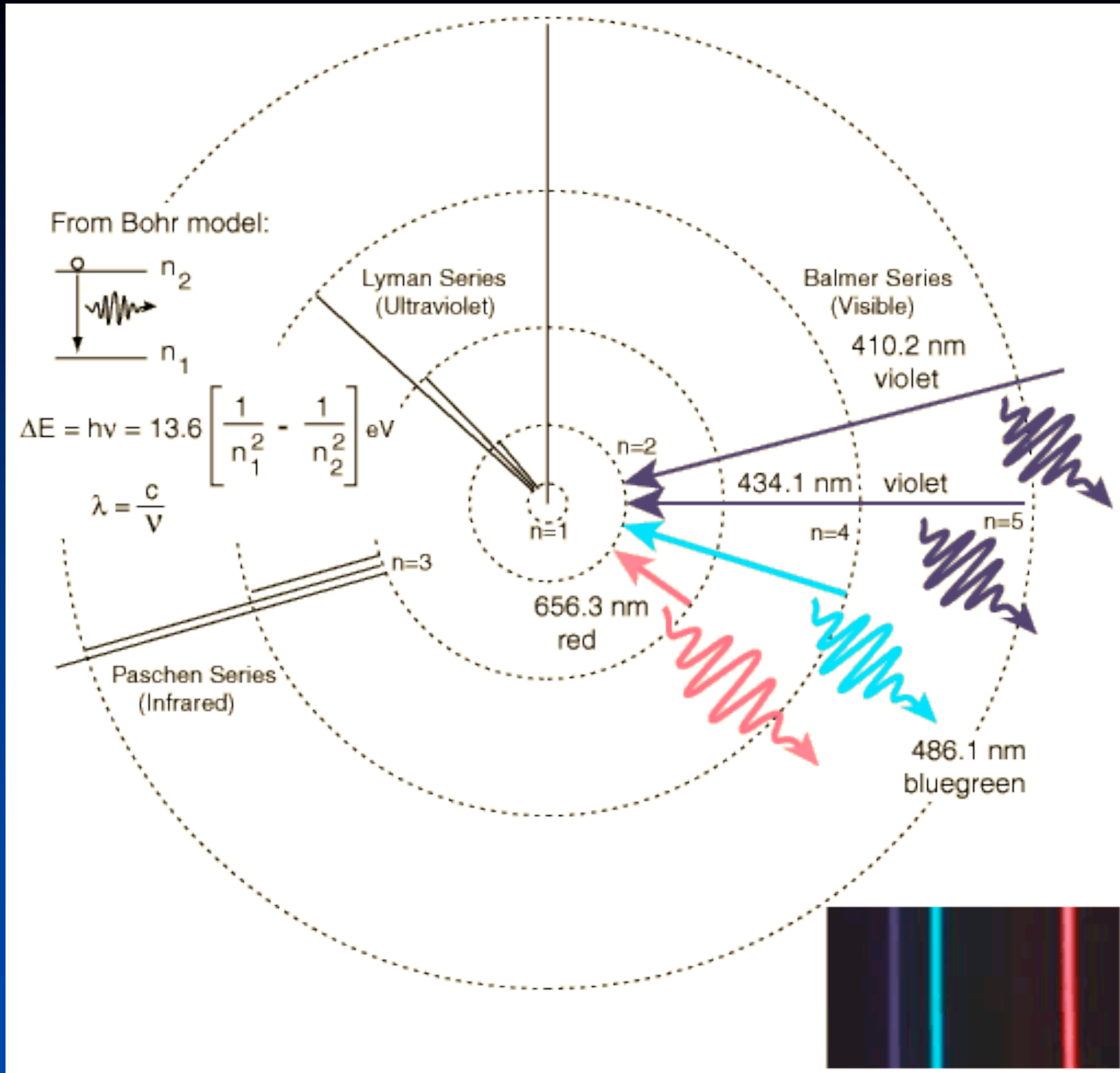
- Star formation regions are associated with beautiful nebulae called `HII' regions.

HII Regions

- HII stands for ionized hydrogen. The process is UV photons from the hot, newly formed O stars ionize hydrogen atoms in the surrounding gas.
- When electrons recombine with protons (ionized hydrogen atoms), the electrons cascade through the energy levels. A high probability step on the e- path to the ground level is to drop from the 2nd excited level to the 1st excited. This emits a red photon `H alpha'.

HII Regions




From Bohr model:
n2
n1
ΔE = hν = 13.6 [1/n1^2 - 1/n2^2] eV
λ = c/ν
Lyman Series
(Ultraviolet)
Balmer Series
(Visible)
410.2 nm
violet
434.1 nm
violet
n=2
n=1
n=3
n=4
n=5
656.3 nm
red
486.1 nm
bluegreen
Paschen Series
(Infrared)

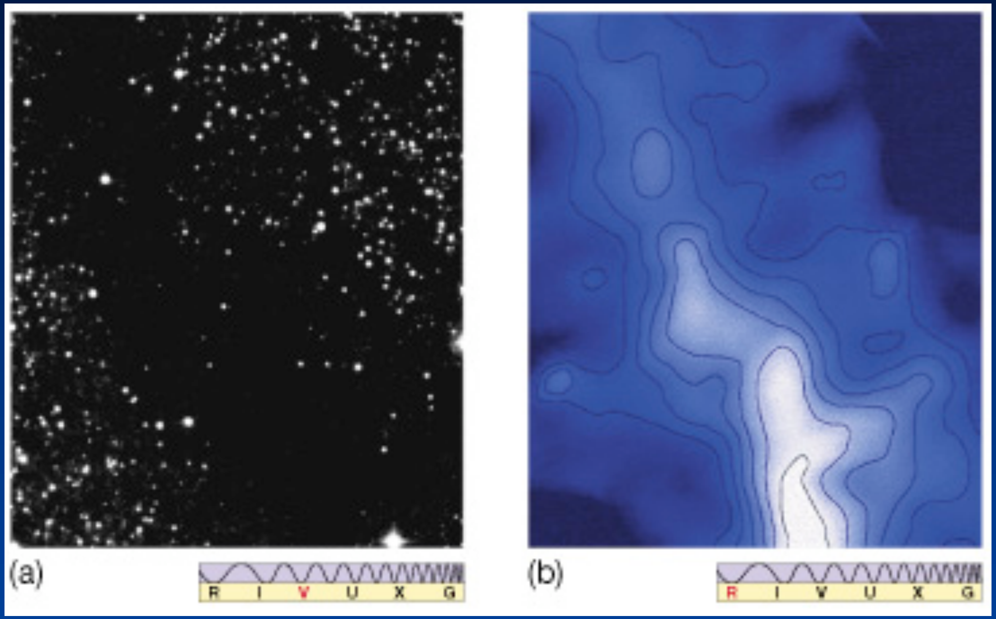
Forbidden Emission Lines

- The green color seen in many nebulae is due to an emission line that originally could not be identified with any known atoms. It was proposed that a new element, `nebulium' was the source.
- It was subsequently realized to come from a so-called `forbidden' transition in oxygen atoms. The energy states are not truly forbidden, but only long-lived (hours). Even in the best laboratory vacuums on Earth, atoms in these states are de-excited via collisions before a photon can be emitted.

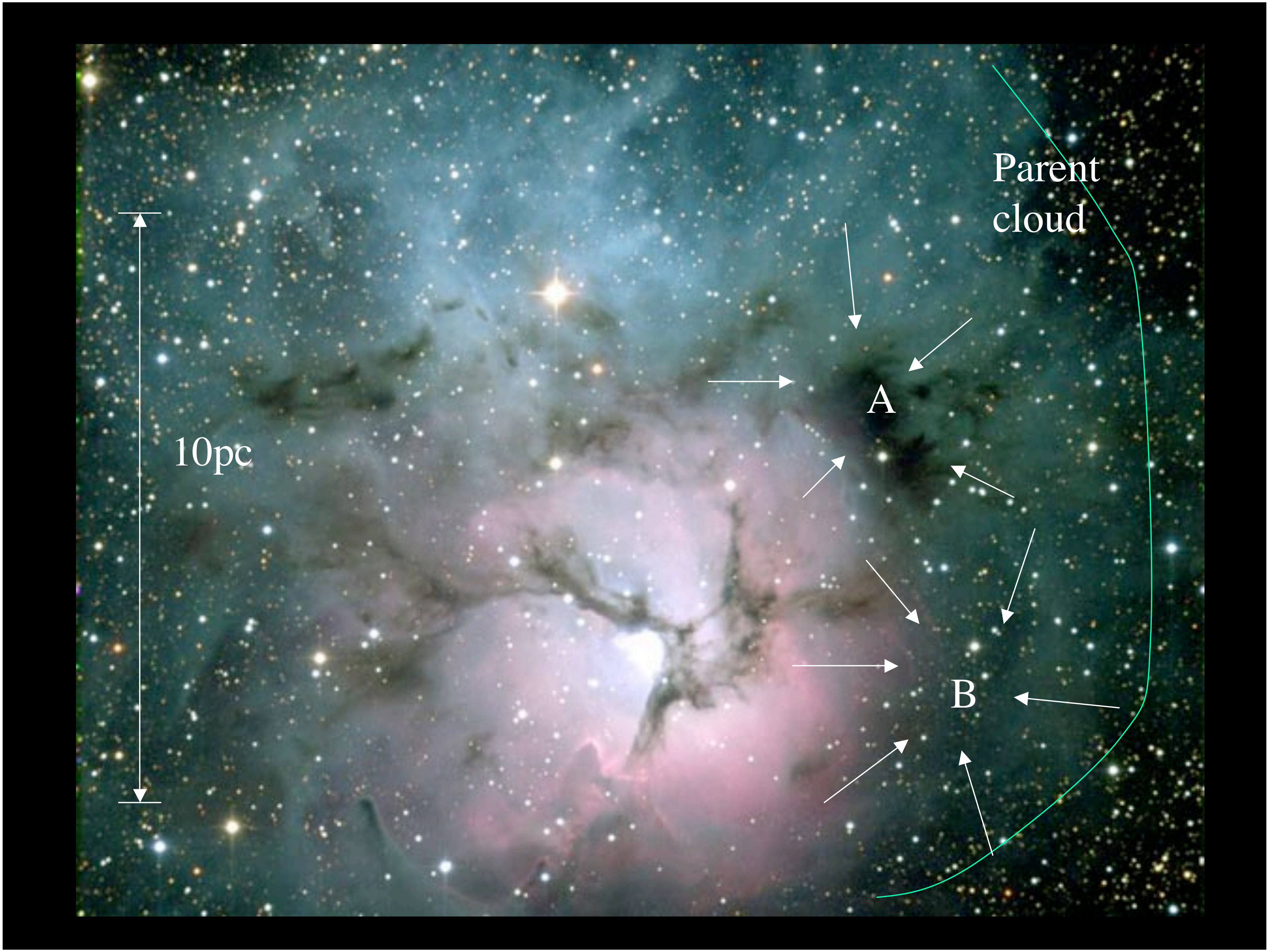
Star Formation Gas

- Warm gas is identified by the light of optical emission lights.
- Cold gas is seen via emission in the radio.
- HI (neutral hydrogen) emits strongly at 21cm
- Many molecules emit radio emission lines.
- Gas motions can be derived (Doppler).

Star Formation Gas



Gas is spatially very well correlated with dust


Parent
cloud
10pc
A
B

Star Formation

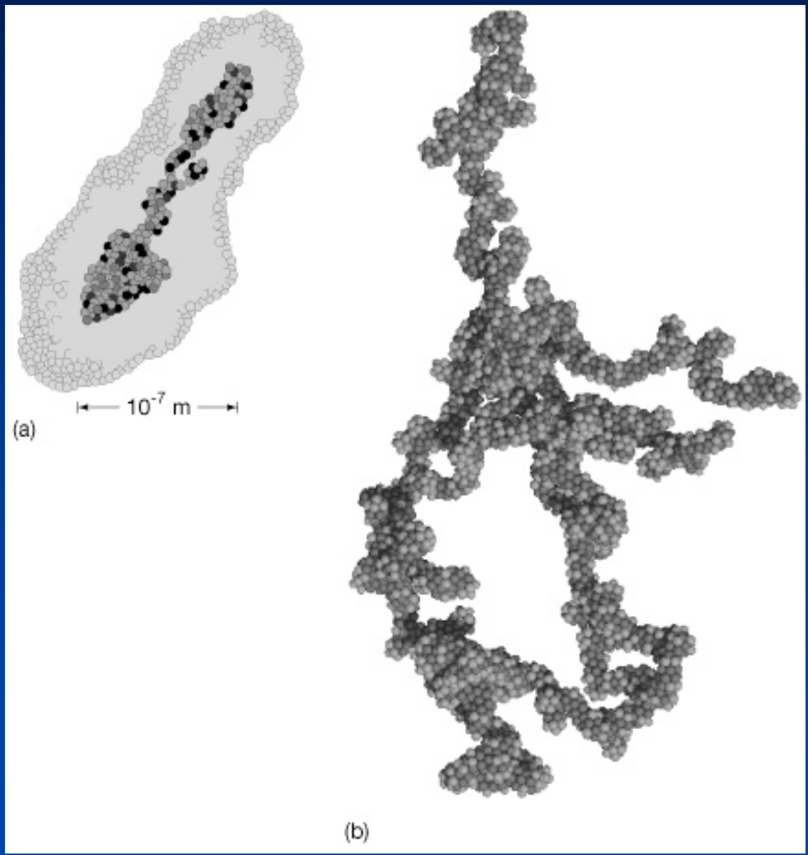
Dust is one of the main reasons it has been difficult to unravel the mysteries of star formation.


AAT 77

Thackeray's Globules in IC 2944

Hubble Heritage

Dust



- The dust particle are very small. Smoke particles are about this same size.

Star Formation Theory

- Long ago the basic idea was understood.
- Think about a cloud of gas in the interstellar medium. It has a temperature that supports it against gravitational collapse. If a gas cloud of a given mass cools off, eventually it starts to collapse under its own gravity.

  The critical temperature is 10k.

Dust and Star Formation

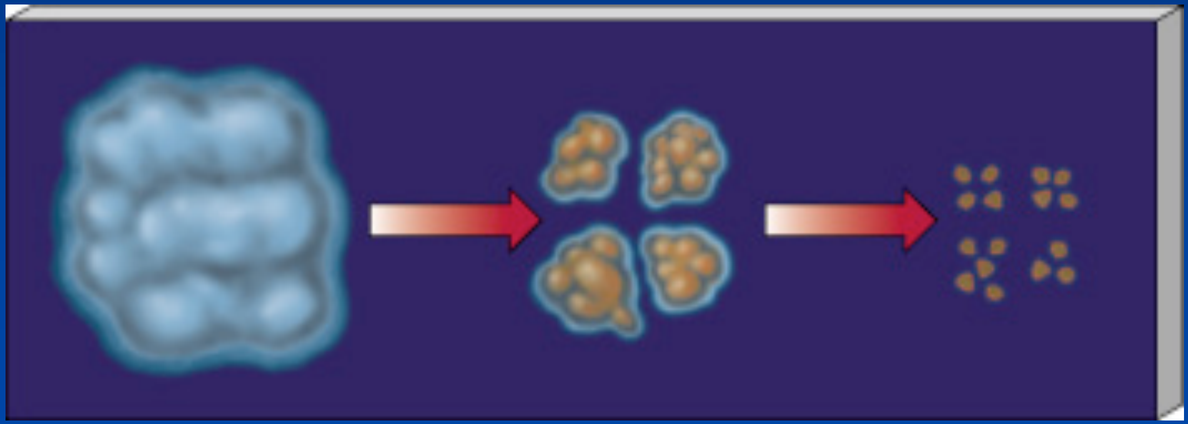
- This is where dust (smoke would be a better term) comes in.
- 10k is VERY cold, the ambient starlight in the Galaxy is enough to keep gas warmer than this unless there is shielding from dust.
- The downside of star formation taking place deep in the heart of dusty regions is the difficulty of observing what is going on with visible light.

Protostars

- Start with a gas cloud of $\underline{\sim 2000 M_o}$ and a radius of $\underline{\sim 5pc.}$
- Mix in enough dust to shield the region and it will cool to 10k and begin to contract.
- Usually, this is a cloud embedded in a larger, warmer cloud.

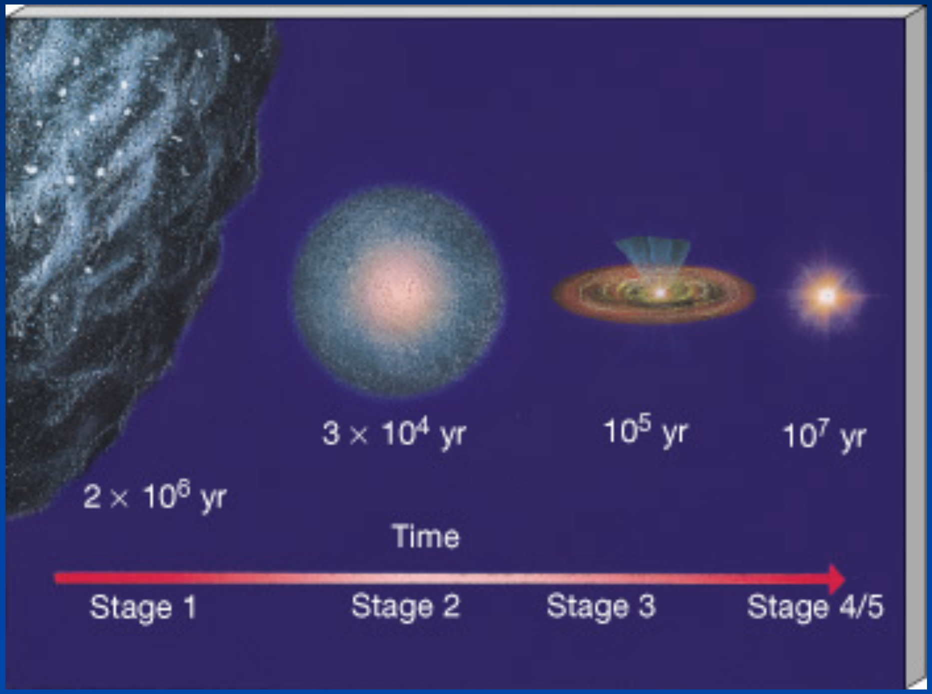
Protostar Collapse

- It is clear that larger dense molecular clouds fragment as they collapse. Exactly how this occurs is not well understood.
- Stars form in clusters

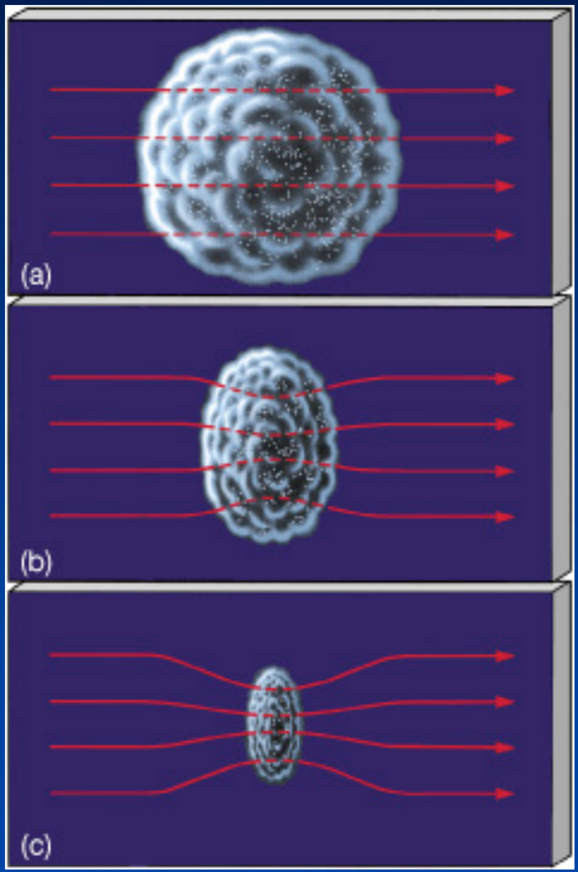


Protostar Collapse

- Conservation of angular momentum forces individual collapsing clouds into disks through which material flows down to the central object.

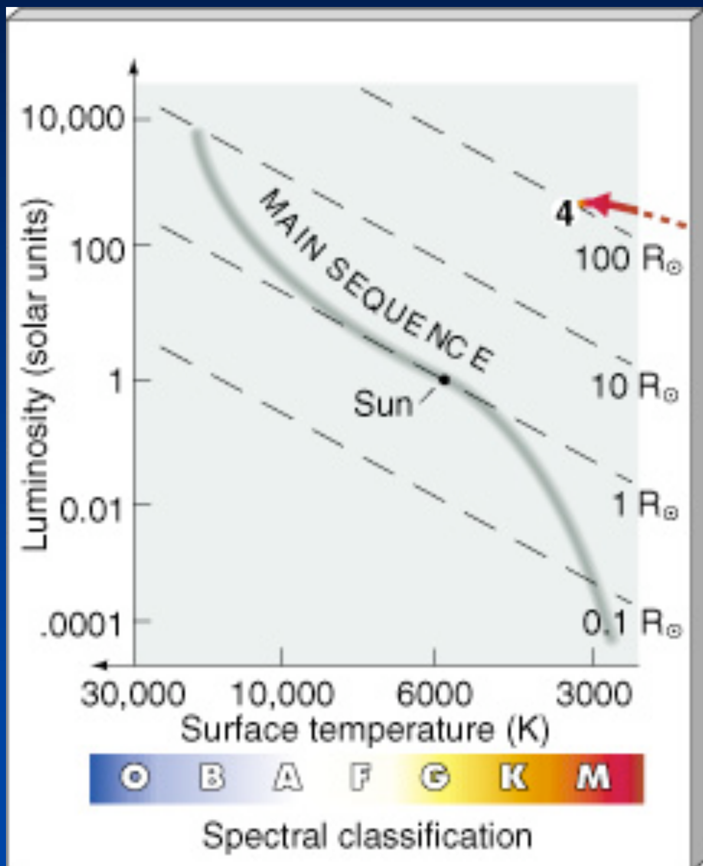


Protostar Collapse



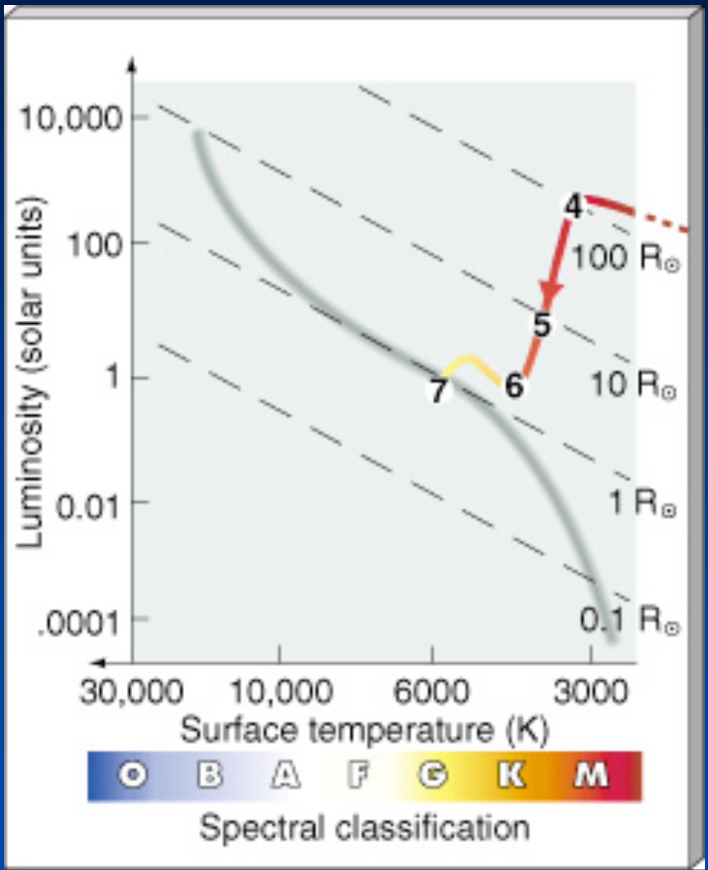
- Magnetic fields are present in the interstellar medium and suppress star formation.
- Somehow nature manages to overcome this difficulty.

Protostars



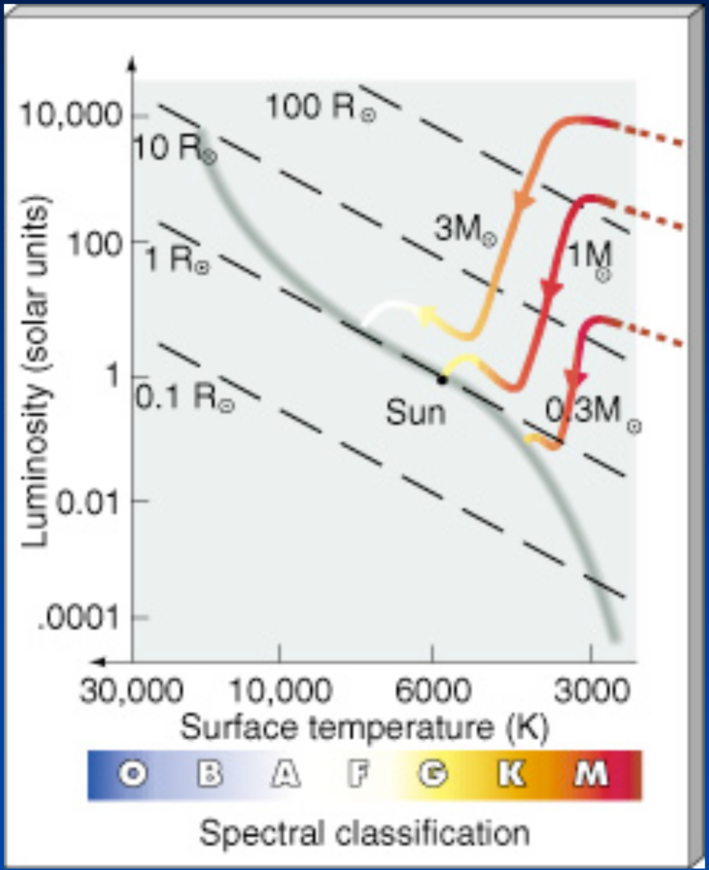
- At first the collapsing cloud is very cold. As it collapses it converts gravitational potential energy into radiation and internal heating.
- While the protostar is cooler than ~2000K it doesn't appear on the H-R Diagram.

Protostars

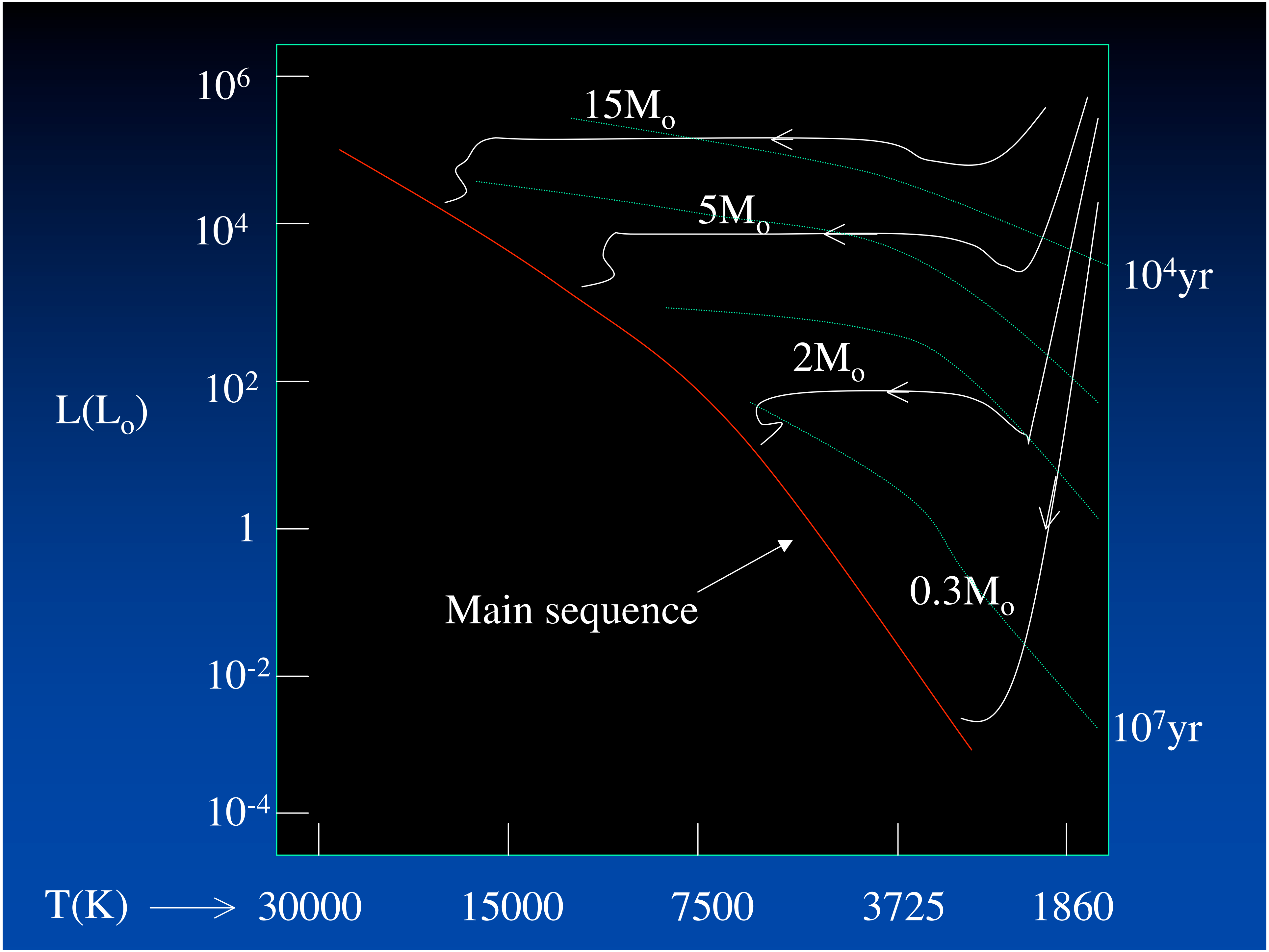


- For 1 solar mass protostars, their first appearance in the H-R diagram as large (surface area), cool objects -- the upper right of the diagram.
- When the central temperature reaches 10 million K, a star is born and the main-sequence life begins.

Protostars



- Low-mass stars follow parallel tracks from the right (cool) side of the H-R Diagram to their spot on the main sequence.



10^6
10^4
10^2
1
10^{-2}
10^{-4}
$L(L_o)$
$15M_o$
$5M_o$
$2M_o$
$0.3M_o$
Main sequence
10^4yr
10^7yr
T(K) ⟶
30000
15000
7500
3725
1860

Star Formation Theory

- Massive stars evolve to the main sequence very quickly (10,000 years), less massive stars evolve more slowly -- up to 10 million years.
- The long `flat' sections imply contraction. Increasing T_{eff} at constant L means the surface area is decreasing.

Star Formation Observations

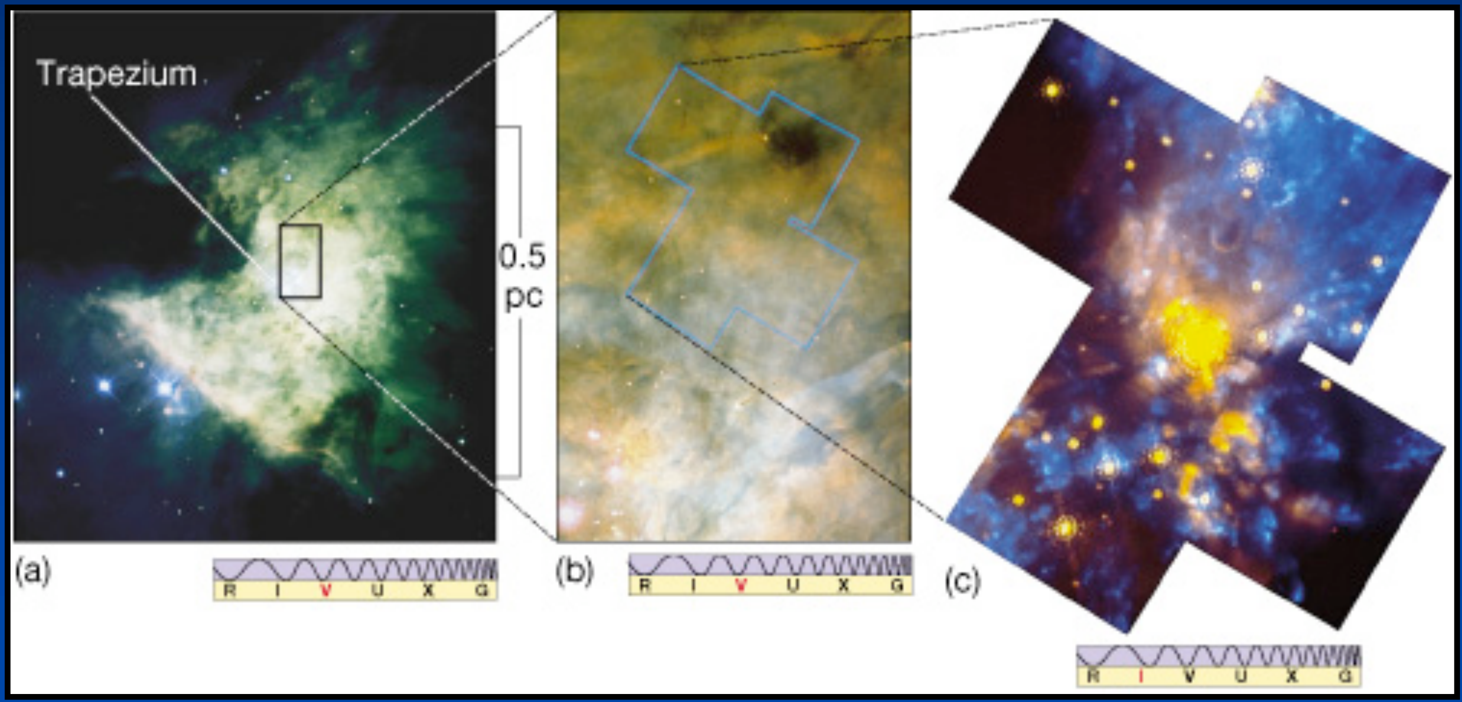
- Two observational advances have led to breakthroughs in understanding and observing this first stage of star formation.

(1) Infrared Detectors

(2) Hubble Space Telescope

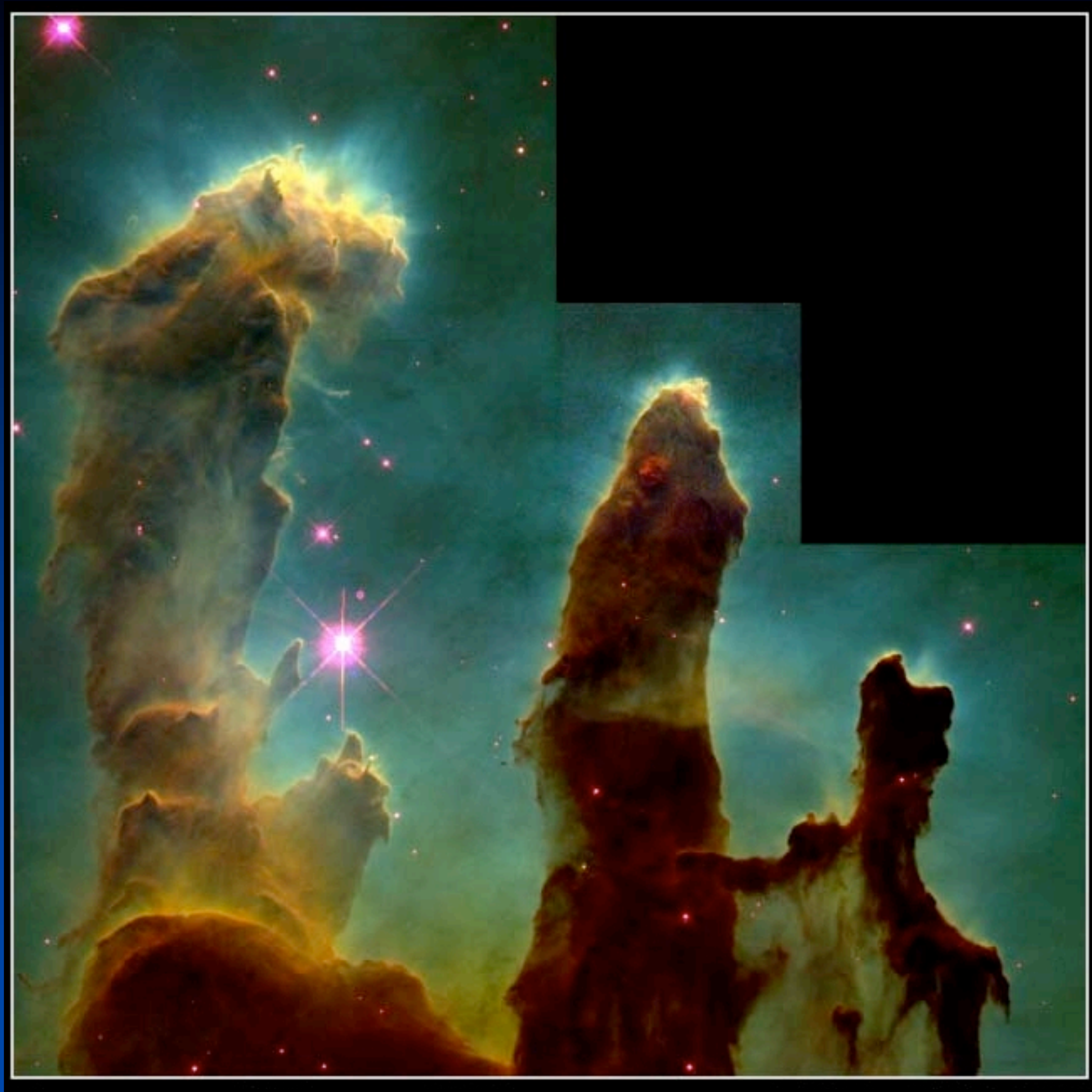
Infrared Observations

- Just as interstellar dust affects blue light more than red, it affects IR radiation less than it does red light. With IR detectors on telescopes, we can peer through the dust into the centers of dark clouds.



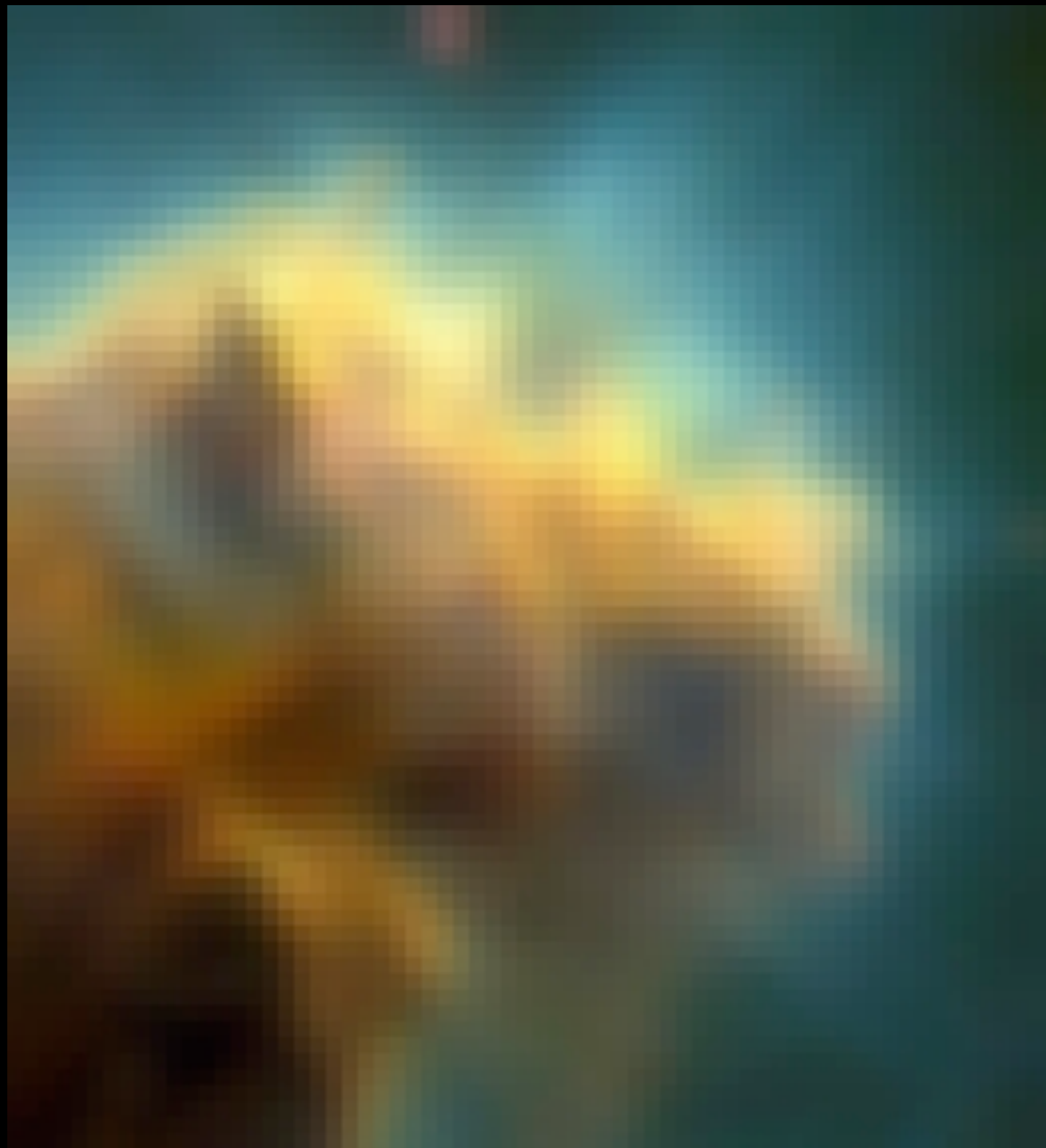
HST Spatial Resolution

- By coincidence, the size and distance of the nearest star formation regions are such that the high spatial resolution (0.1 arcsec) of HST just resolves individual stars in the process of forming.



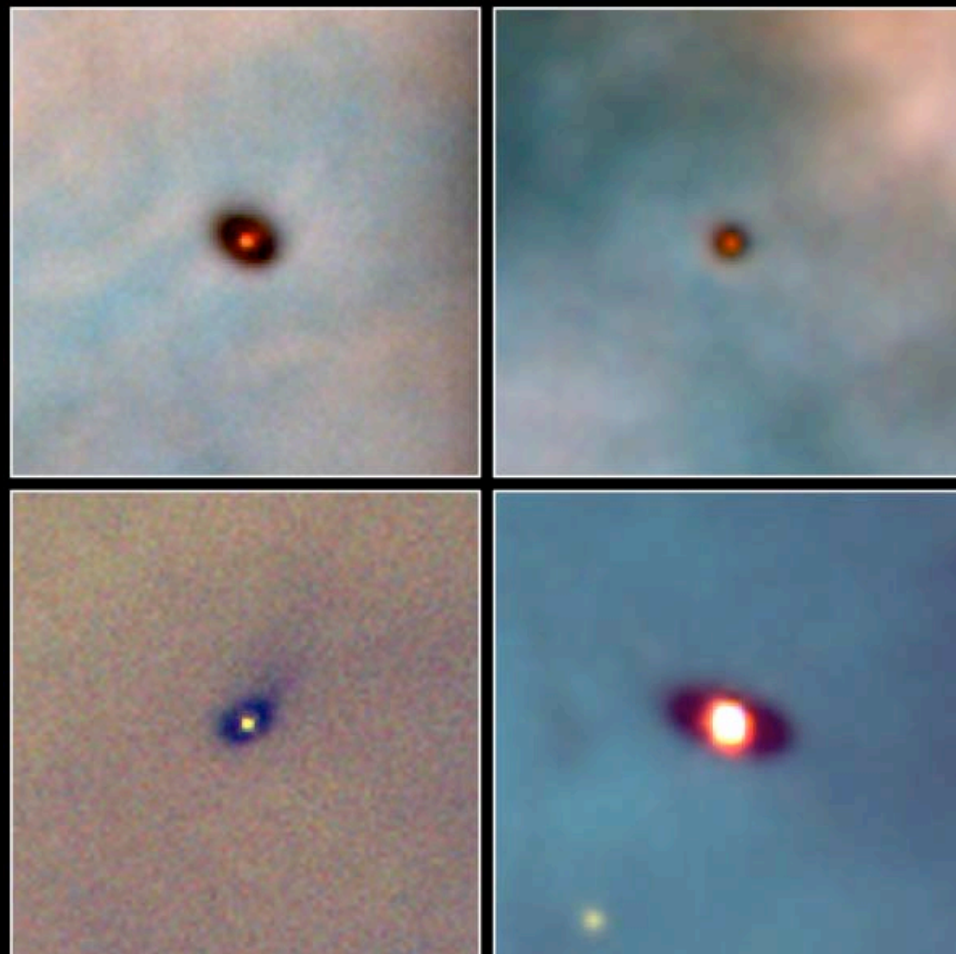
Star-Birth Clouds · M16 HST · WFPC2

PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA



Star Formation

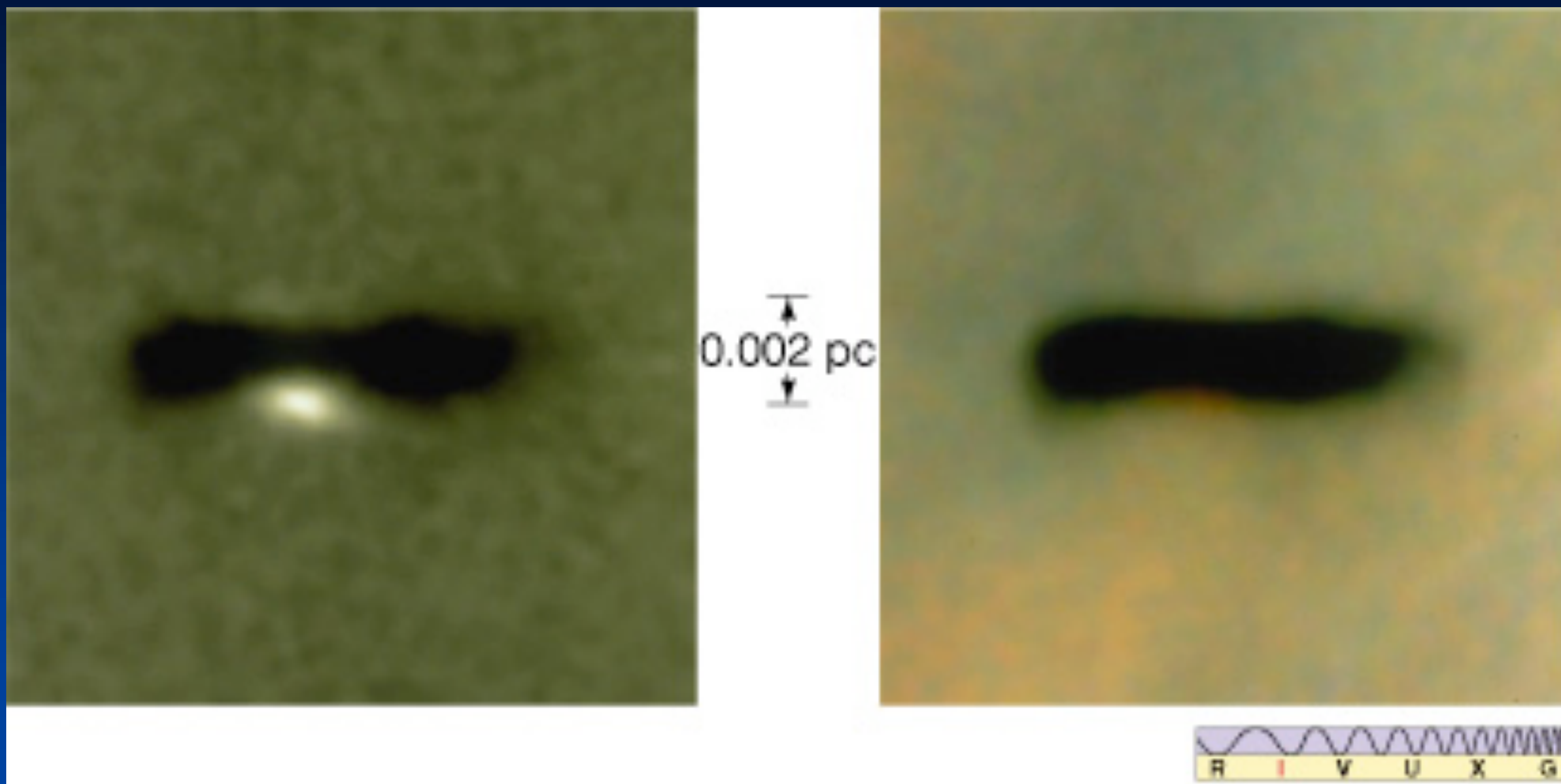
- With HST in particular and now with AO and IR detectors on large ground-based telescopes we are observing the various stages of protostar contraction.
- The presence of disks was predicted long ago and verified for the first time about ten years ago. We got lucky in that the disks were a little larger than expected.



Protoplanetary Disks
Orion Nebula

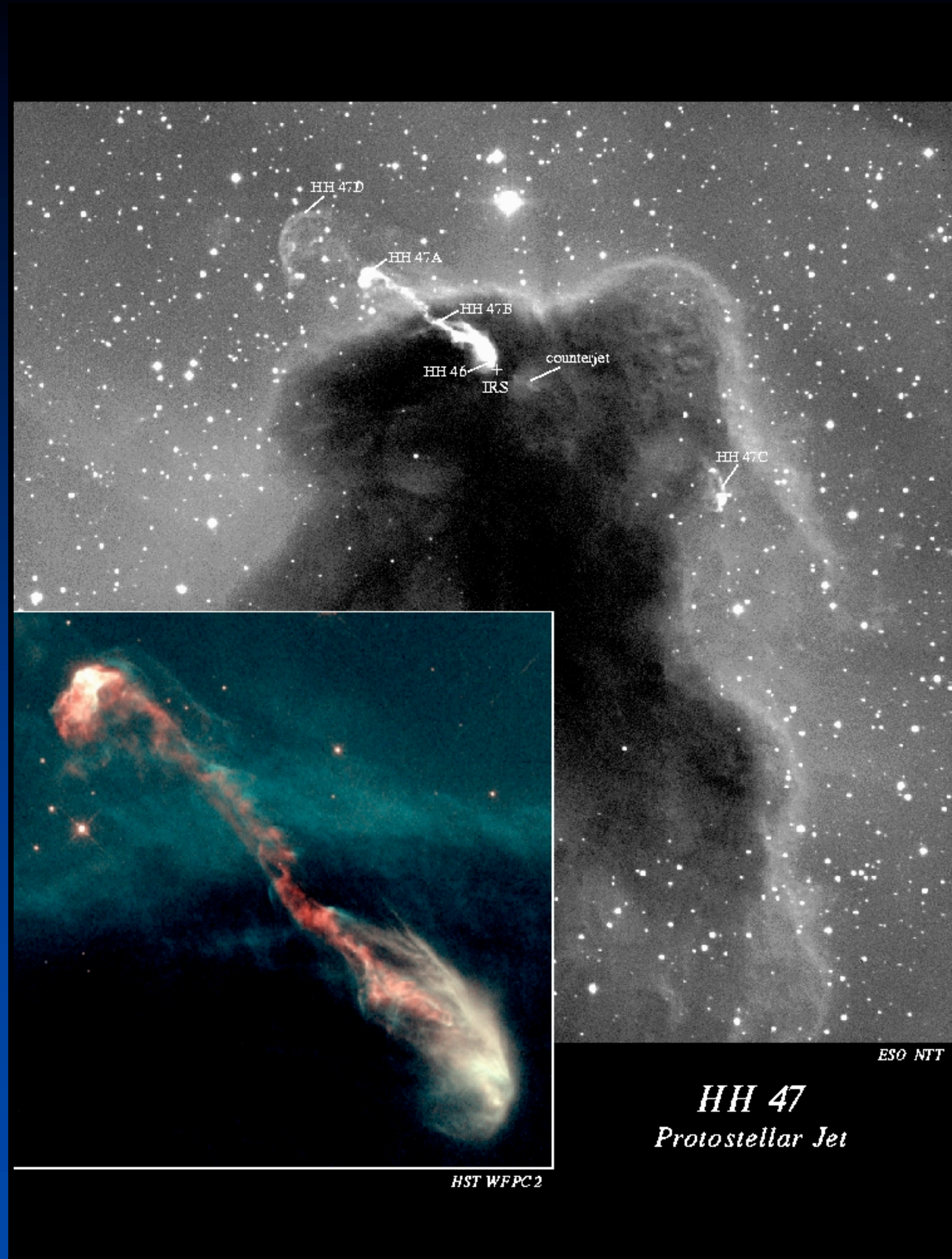
HST • WFPC2

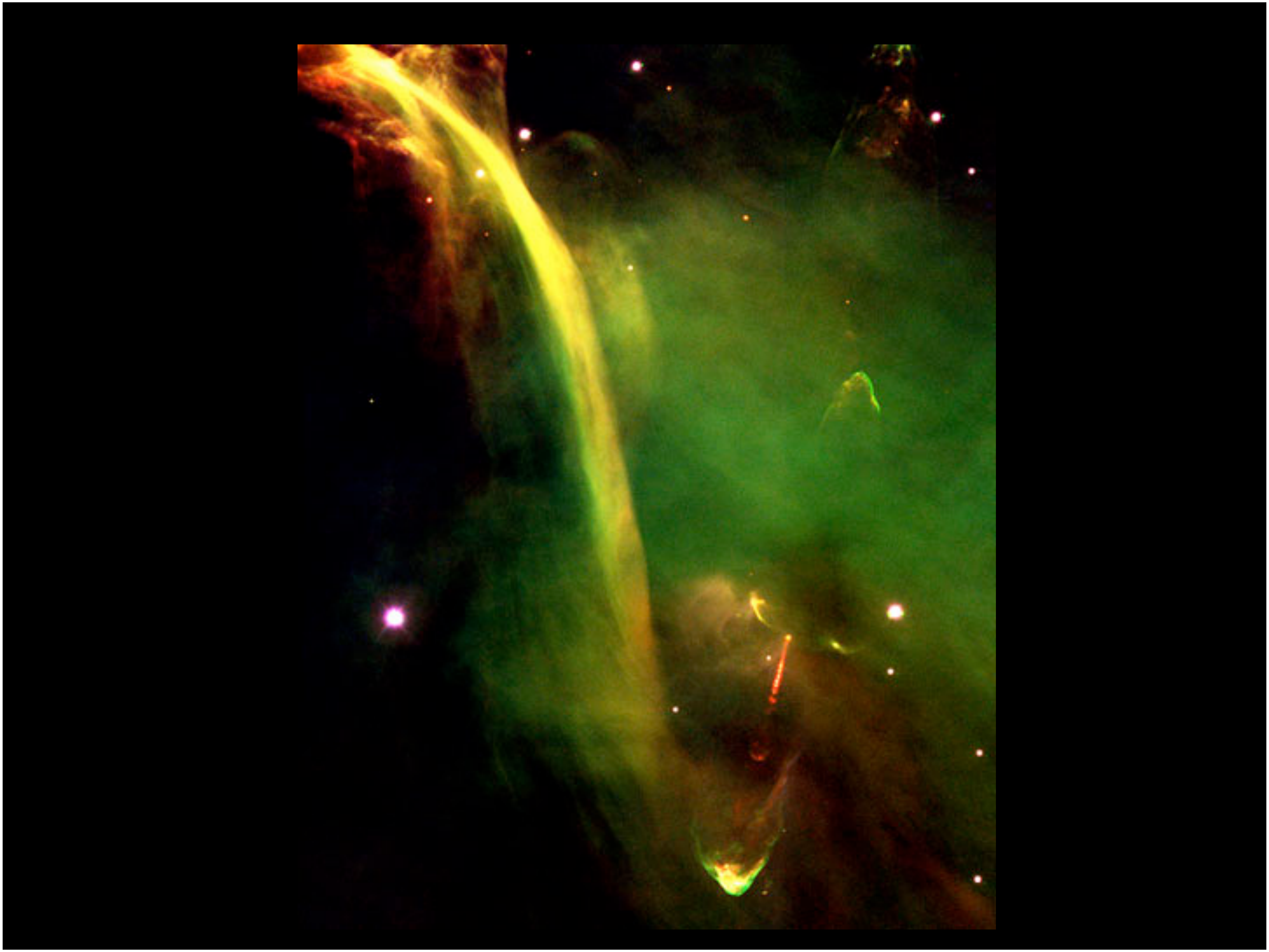
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

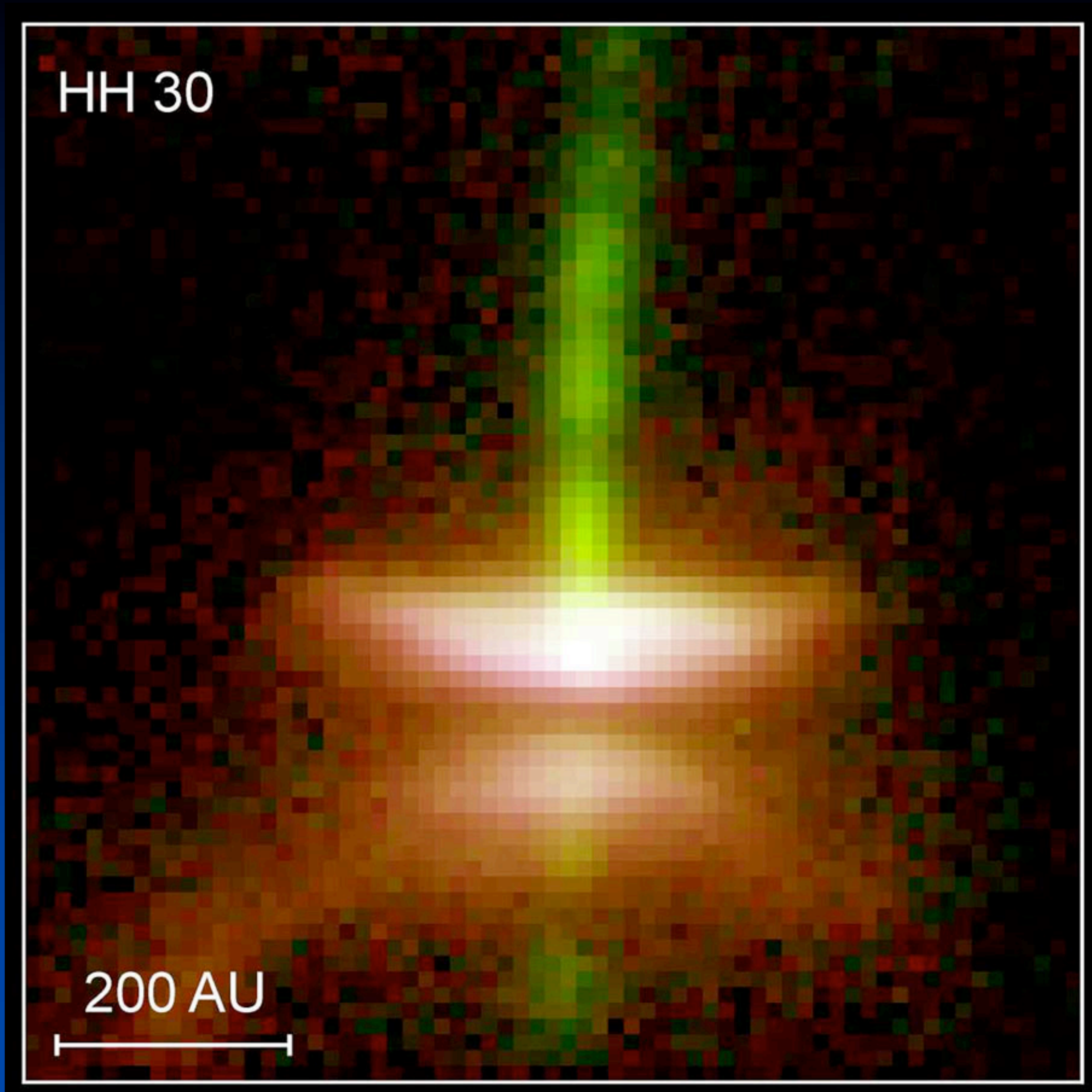

0.002 pc
R I V U X G

Star Formation: Outflows

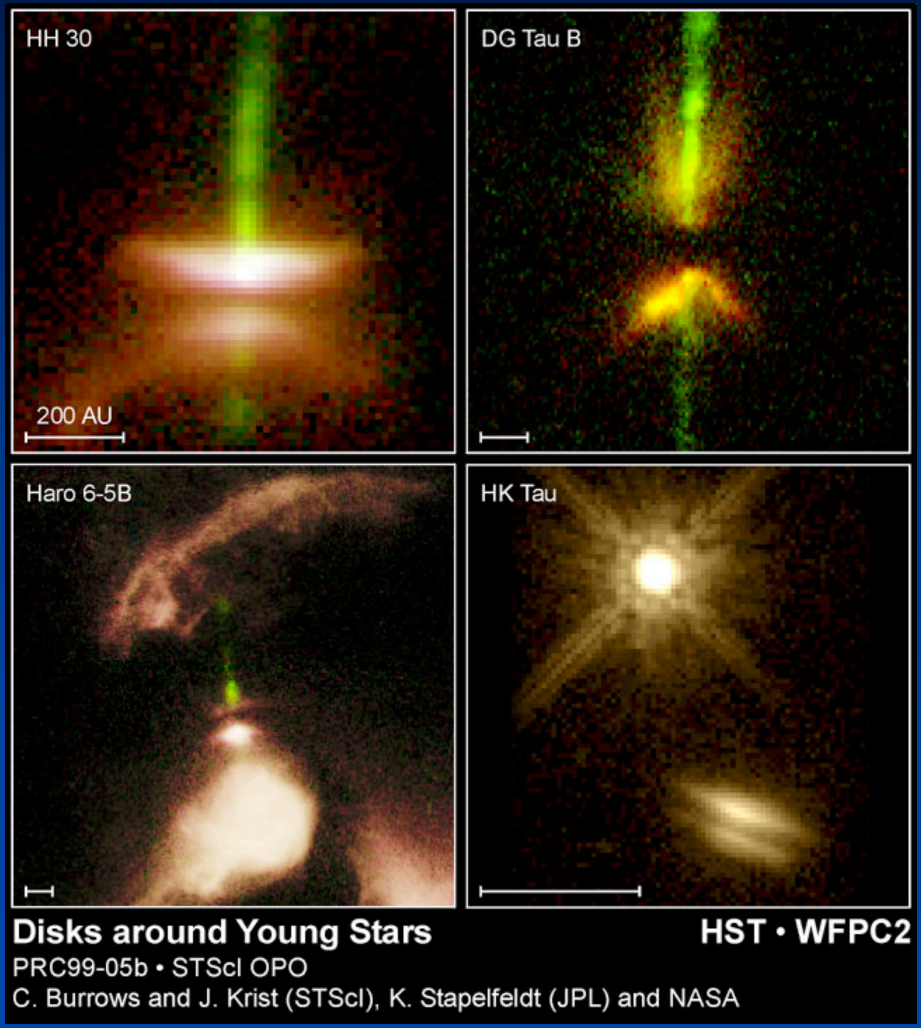
- One surprise in star formation is the presence of energetic bipolar outflows.
- These have been known for some years as `Herbig-Haro' objects that showed large proper motions.


HH 47D
HH 47A
HH 47B
counterjet
HH 46
IRS
HH 47C
ESO NTT
HH 47
Protostellar Jet
HST WFPC2




HH 30
200 AU

Star Formation: Outflows

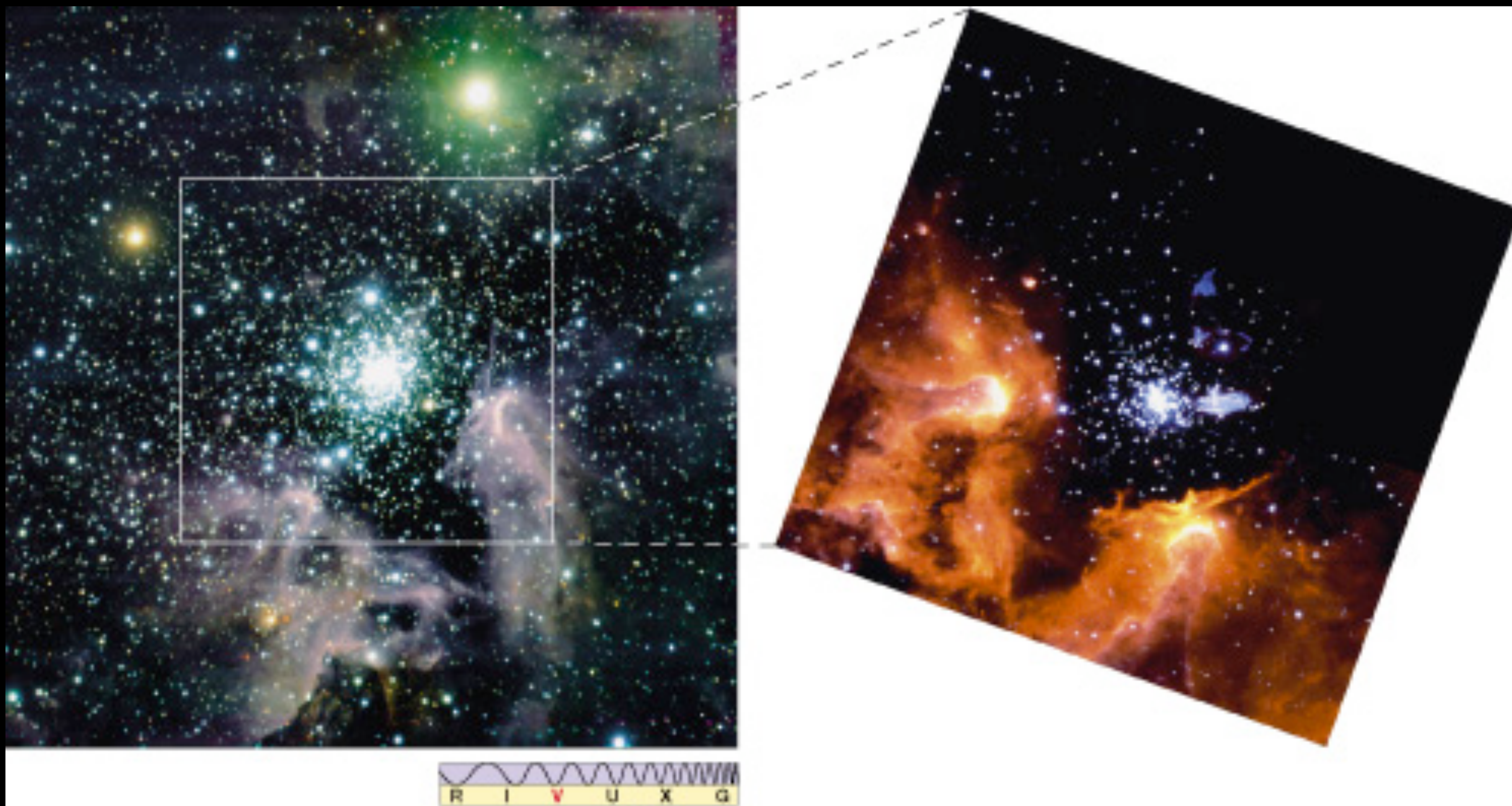


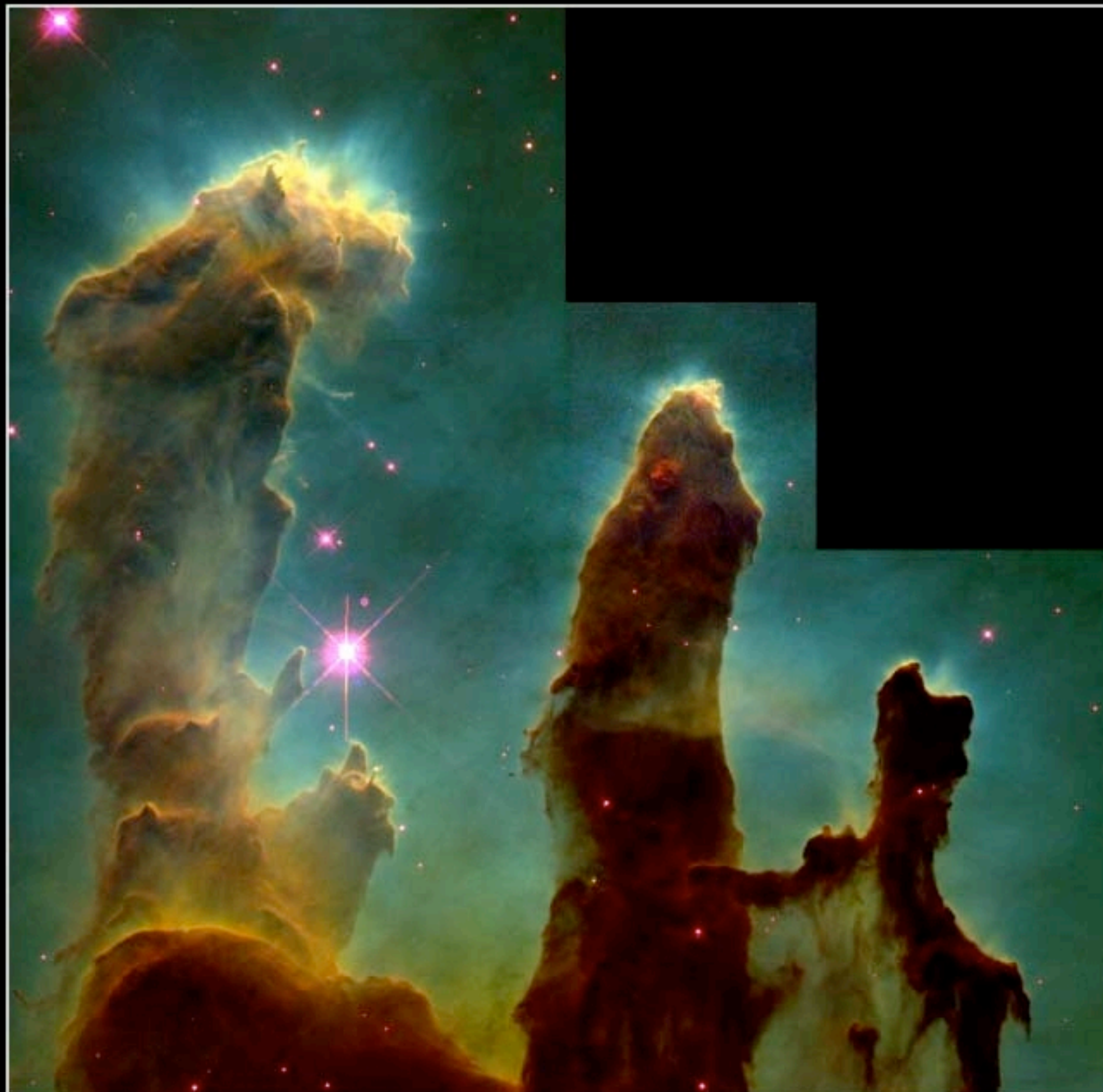
Star Formation Outflows

- Some of the outflows are now observed to be more than a kiloparsec in length. These outflows help to set the mass of stars and contribute significant energy toward stirring up the interstellar medium.

Star Formation: Step 2

- Stars generally (maybe always) form in clusters. Within a large molecular cloud, many condensations collapse out and form stars.
- When the first O stars begin to shine, the UV photons light up an HII region and begin to evaporate a cavity in the original cloud.


R I V U X G



Star Clusters

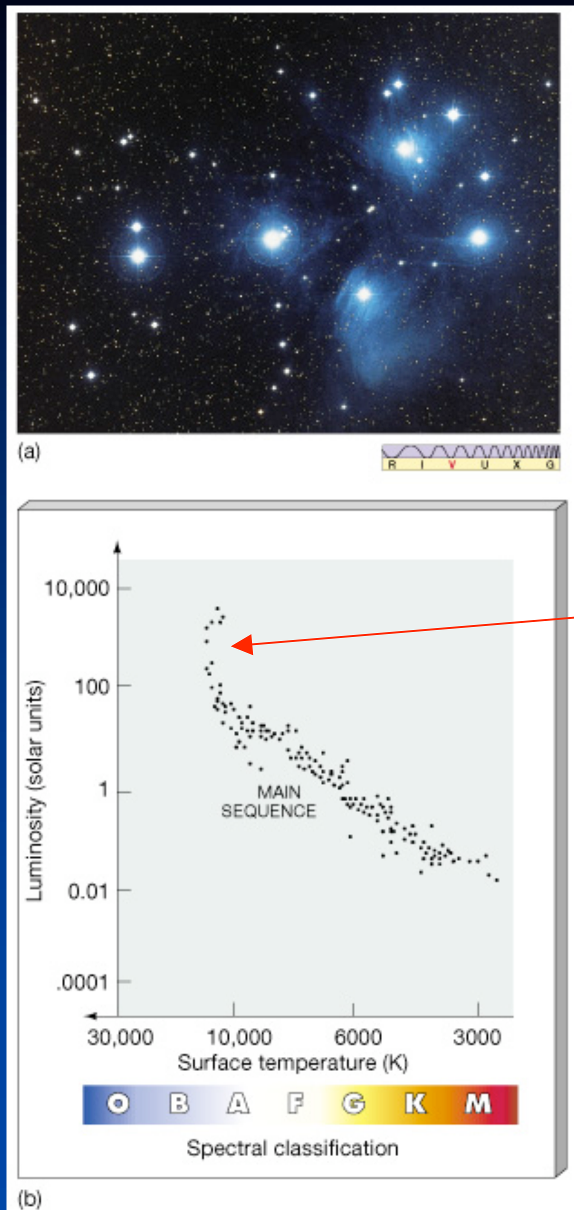
- Eventually, photons and stellar winds clear out the remaining gas and dust and leave behind the stars.
- Reflection nebulae provide evidence for remaining dust on the far side of the Pleiades

Star Clusters

- It may be that all stars are born in clusters.
- A good question is therefore why are most stars we see in the Galaxy not members of obvious clusters?
- The answer is that the majority of newly-formed clusters are very weakly gravitationally bound. Perturbations from passing molecular clouds, spiral arms or mass loss from the cluster stars `unbind’ most clusters.

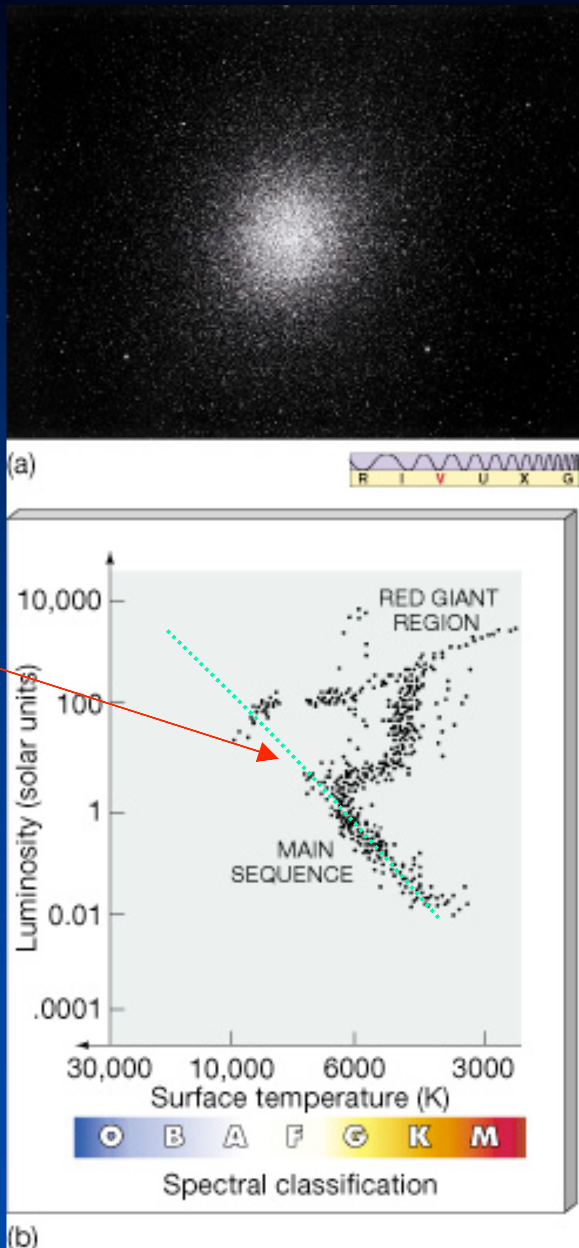
Star Cluster Ages

- We can use the H-R Diagram of the stars in a cluster to determine the age of the cluster.
- A cluster starts off with stars along the full main sequence.
- Because stars with larger mass evolve more quickly, the hot, luminous end of the main sequence becomes depleted with time.
- The `main-sequence turnoff' moves to progressively lower mass, L and T with time.

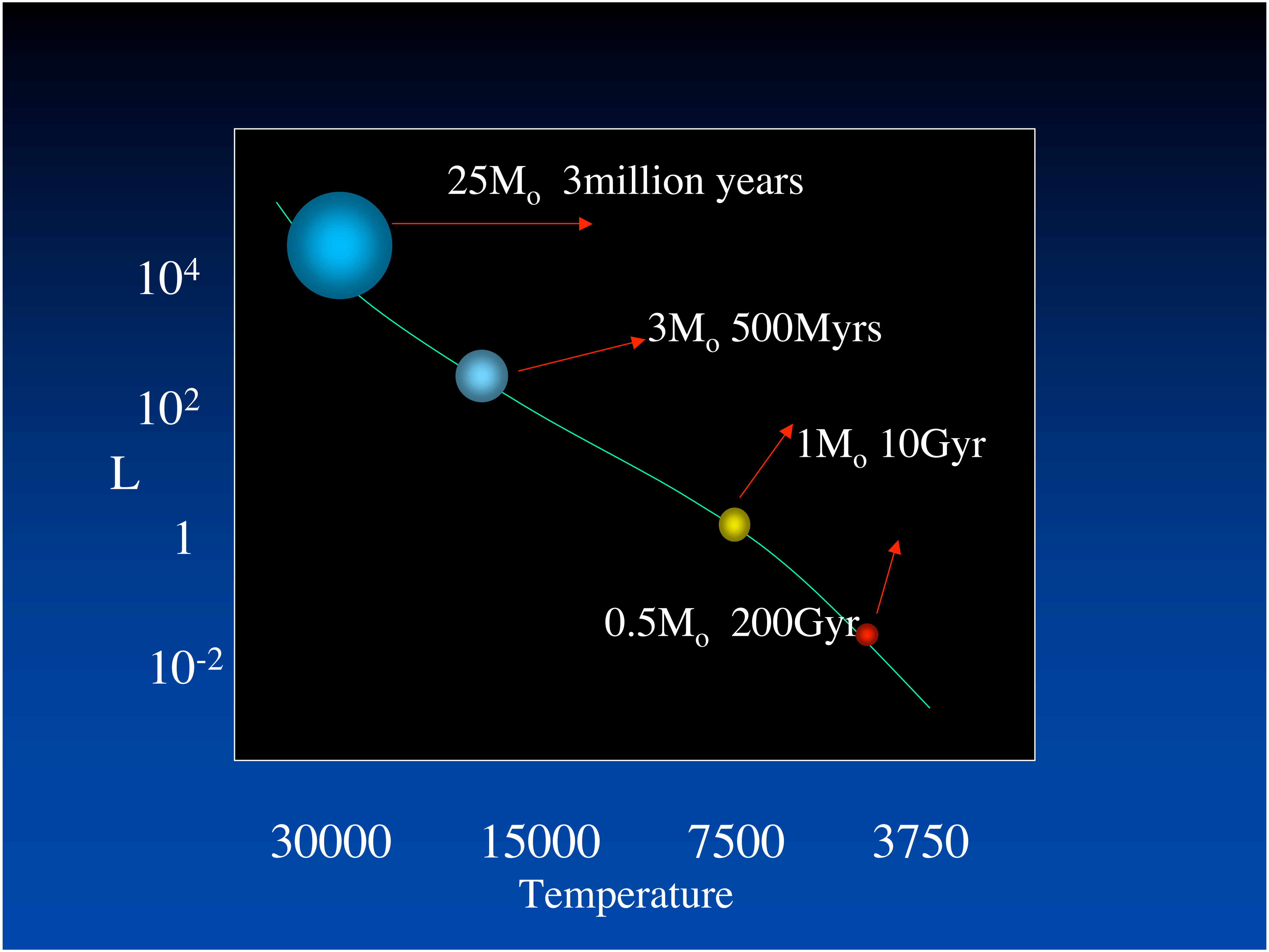


- Young clusters contain short-lived, massive stars in their main sequence

MSTO



- Other clusters are missing the high-mass stars and we can infer the cluster age is the main-sequence lifetime of the highest mass star still on the main-sequence.

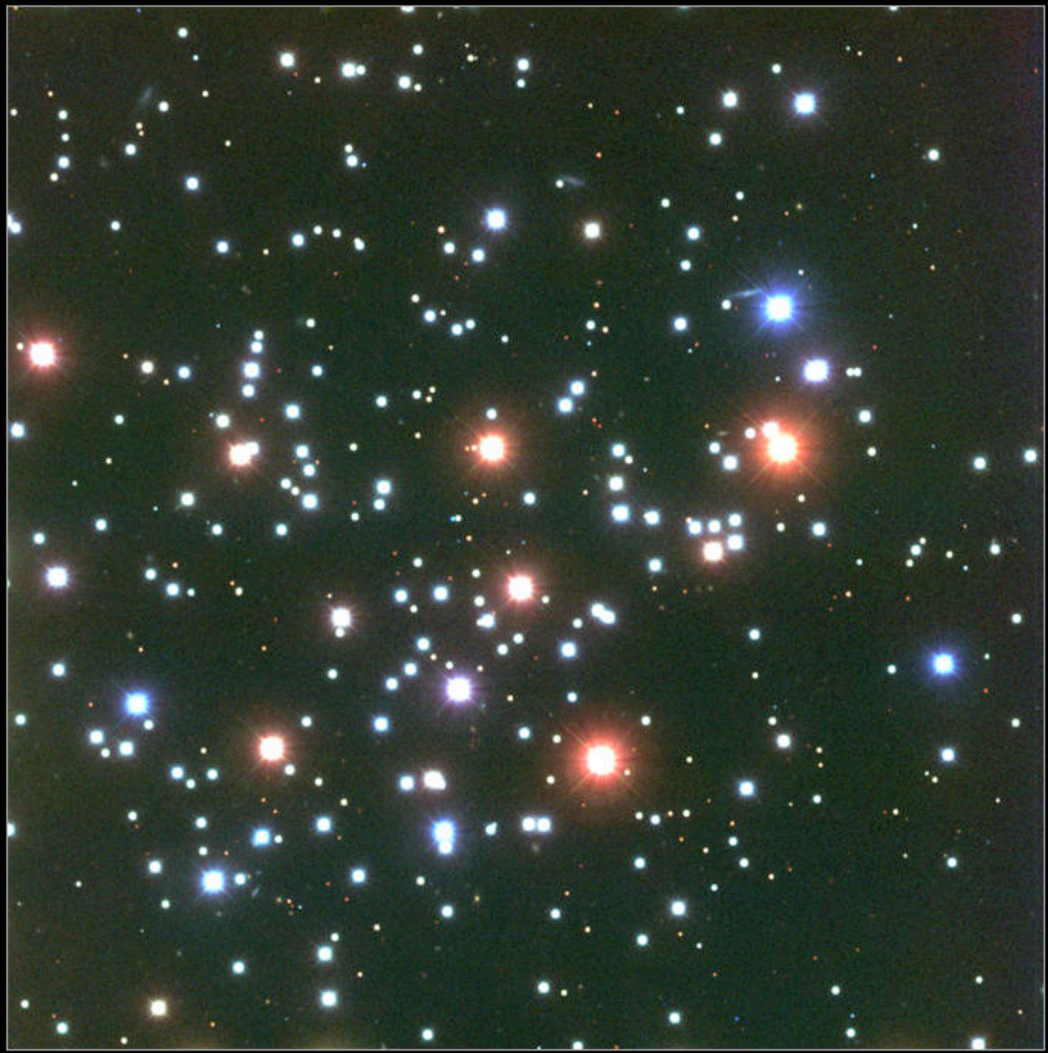


$25M_o$ 3million years
$3M_o$ 500Myrs
$1M_o$ 10Gyr
$0.5M_o$ 200Gyr
10^4
10^2
L
1
10^{-2}
30000
15000
7500
3750
Temperature

Star Clusters

- There are two basic types of clusters in the Galaxy.
- Globular Clusters are mostly in the halo of the Galaxy, contain >100,000 stars and are very ancient.
- Open clusters are in the disk, contain between several and a few thousand stars and range in age from 0 to 10Gyr

M67



Galaxy Ages

- Deriving galaxy ages is much harder because most galaxies have a star formation history rather than a single-age population of stars.
- Still, simply by looking at color pictures it is possible to infer that there are many young stars in some galaxies, and none in others.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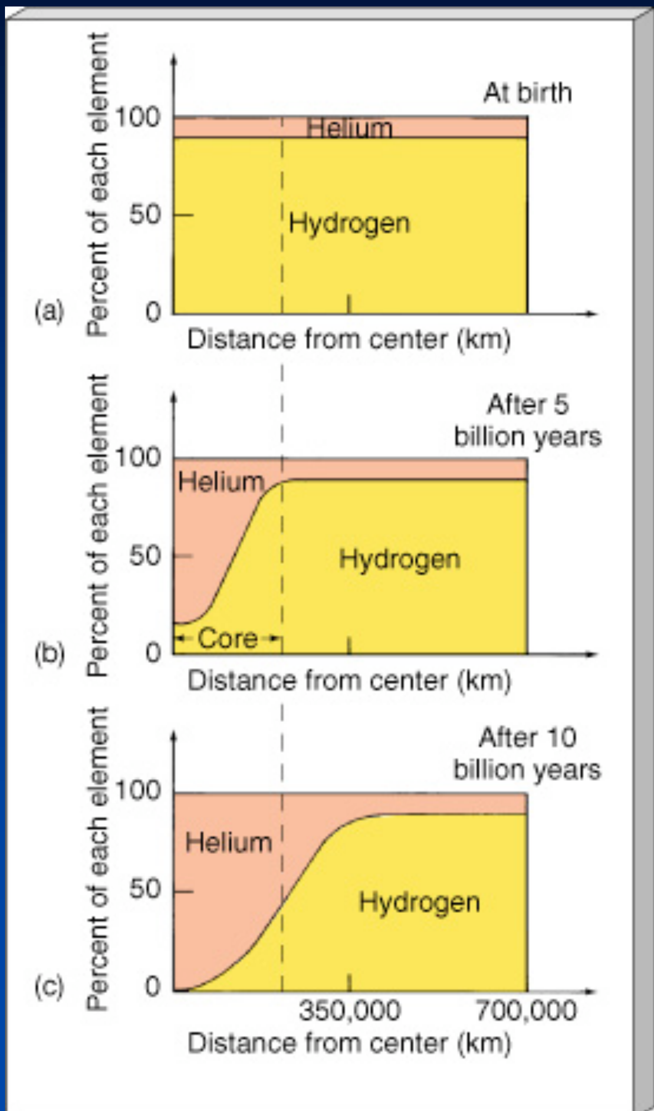
AAT 60

Stellar Evolution

- When hydrogen fusion starts at the end of the protostar stage, a star is born on the `zero-age main sequence’.
- As hydrogen is being converted into helium in the core of a star, its structure changes slowly and stellar evolution begins.

Stellar Evolution



- The structure of the Sun has been changing continuously since it settled in on the main sequence.
- The Hydrogen in the core is being converted into Helium.

Stellar Evolution

- As the helium core grows, it compresses. Helium doesn't fuse to heavier elements for two reasons.

(1) with 2 p+ per nucleus, the electric repulsion force is higher than was the case for H-fusion. This means that helium fusion requires a higher temperature than hydrogen fusion -- 100 million K

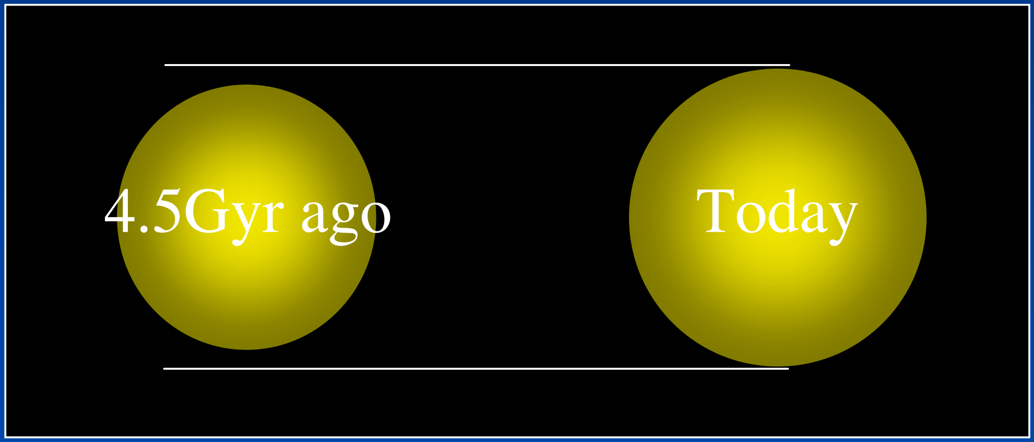
(2) $He^4 + He^4 = Be^8$. This reaction doesn't release energy, it requires input energy. This particular Be isotope is very unstable.

Stellar Evolution

- As the Helium core contracts, it releases gravitational potential energy and heats up.
- Hydrogen fusion continues in a shell around the helium core.
- *Once a significant helium core is built, the star has two energy sources*.
- Curiously, as the fuel is being used up in the core of a star, its luminosity is increasing

Stellar Evolution

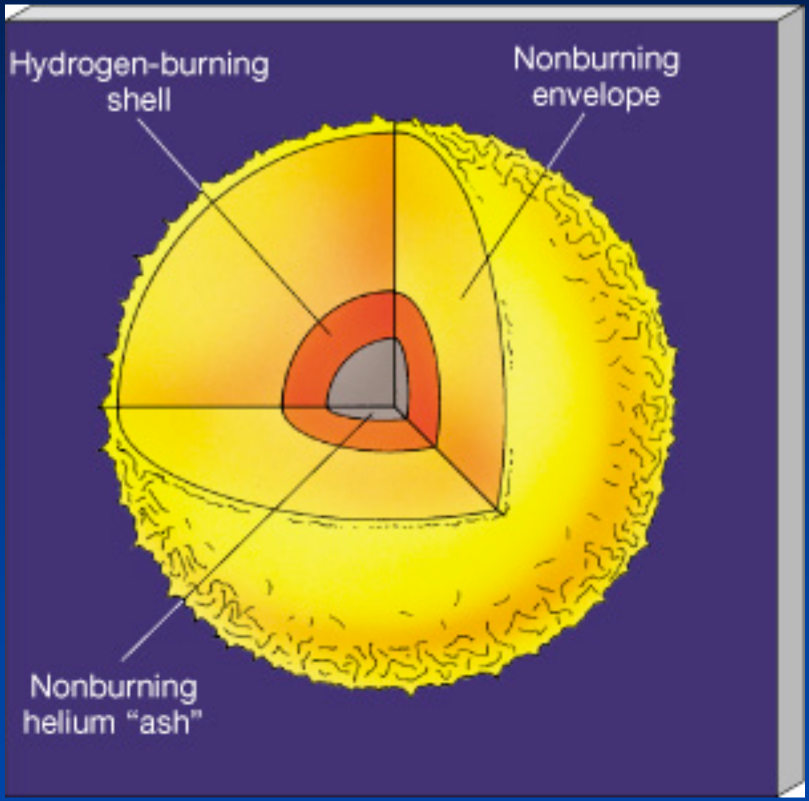
- Stars begin to evolve off the zero-age main sequence from day 1.
- Compared to 4.5 Gyr ago, the radius of the Sun has increased by 6% and the luminosity by 40%.



Stellar Evolution

- In the case of the Sun (or any $1M_o$ star) the gradual increase in radius and luminosity will continue for another 5 billion years.
- While hydrogen fusion is the dominant energy source, there is a useful thermostat operating. If the Sun contracted and heated up, the fusion rates would increase and cause the Sun to re-expand.

Evolution to Red Giant

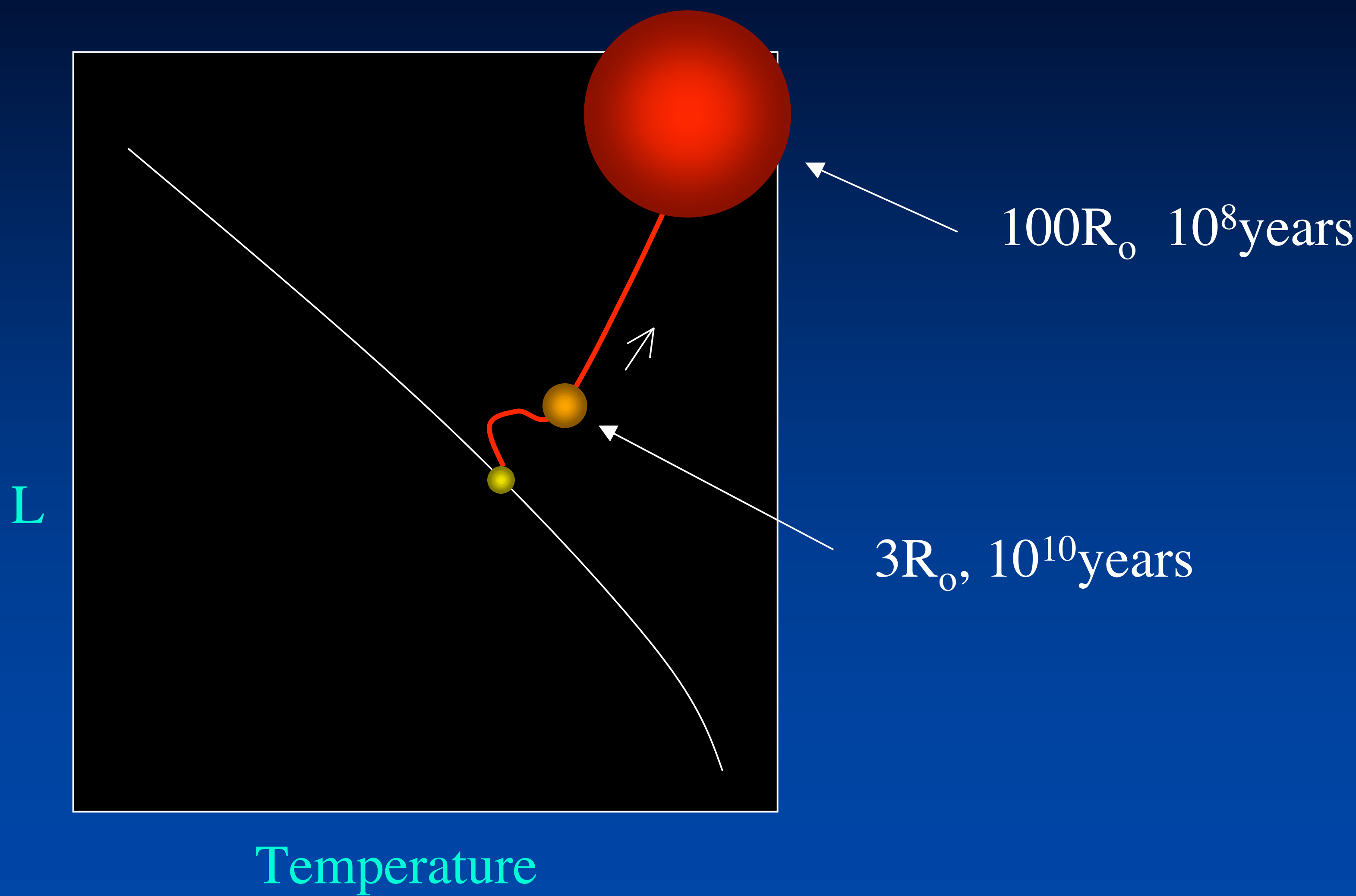


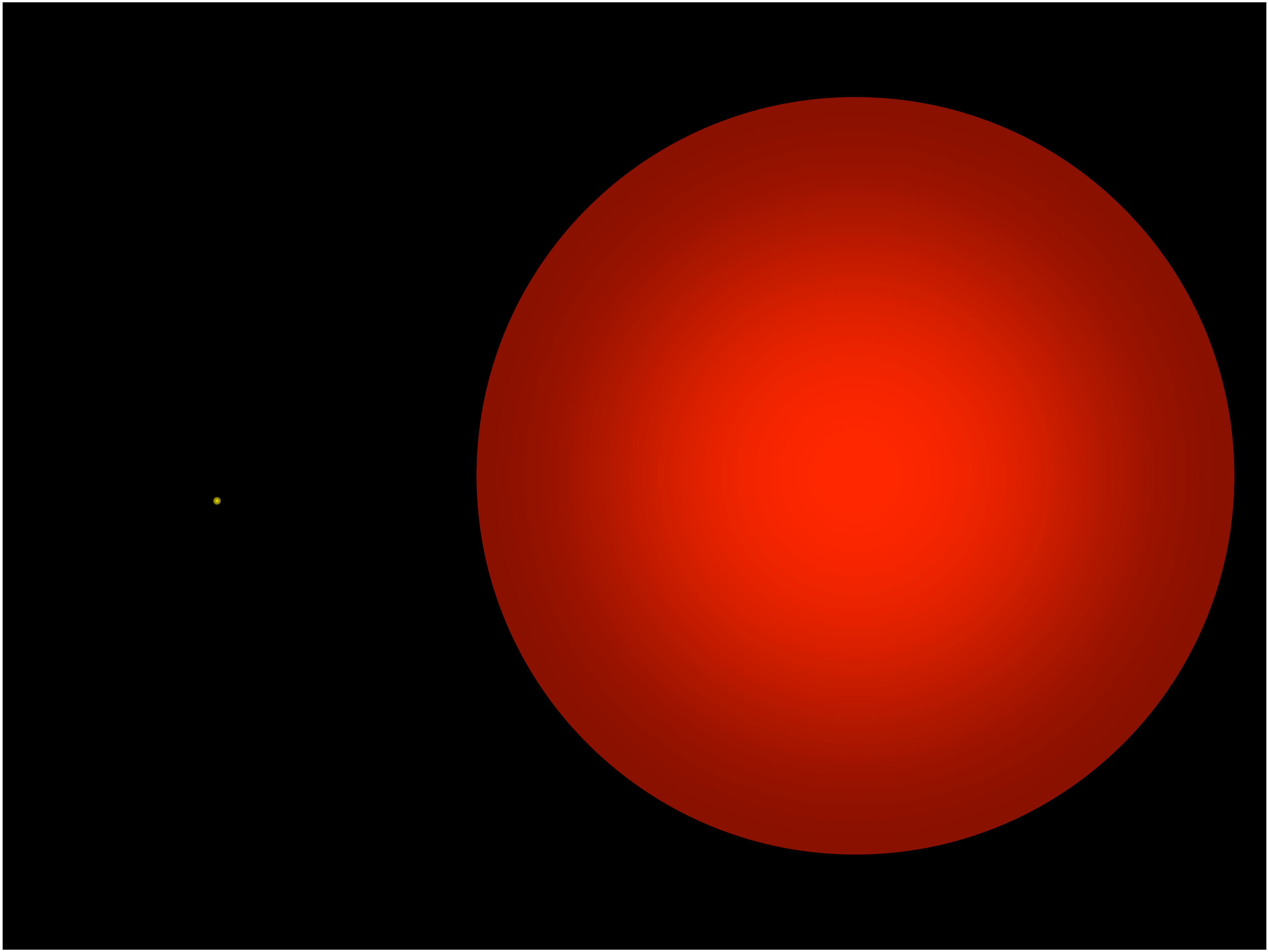
- As the contracting helium core grows and the total energy generated by GPE and the hydrogen fusion shell increases.
- L goes up!
- As L goes up the star also expands.

Red Giants

- Hydrostatic equilibrium is lost and the tendency of the Sun to expand wins a little bit at a time. The Sun is becoming a Red Giant. Will eventually reach:
- $L \rightarrow 2000L_o$
- $R \rightarrow 0.5AU$
- $T_{surface} \rightarrow 3500k$

Red Giant





Sun as a Red Giant

- When the Sun becomes a Red Giant Mercury and Venus will be vaporized, the Earth burned to a crisp. Long before the Sun reaches the tip of the RGB (red giant branch) the oceans will be boiled away and most life will be gone.
- The most `Earthlike' environment at this point will be Titan, a moon of Saturn.

RGB Evolution

As the Sun approaches the tip of the RGB

	Central T	Central Density
Sun	$15x10^6$ k	10^2 grams/cm^2
Red Giant	$100x10^6$k	10^5 grams/cm^2

For stars around $1M_o$, with these conditions in the core a strange quantum mechanical property of e- dominates the pressure.

Electron Degeneracy

- Electrons are particles called `fermions' (rather than `bosons') that obey a law of nature called the Pauli Exclusion Principle.
- This law says that you can only have two electrons per unit 6-D phase-space volume in a gas.

$$\boxed{\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z}$$

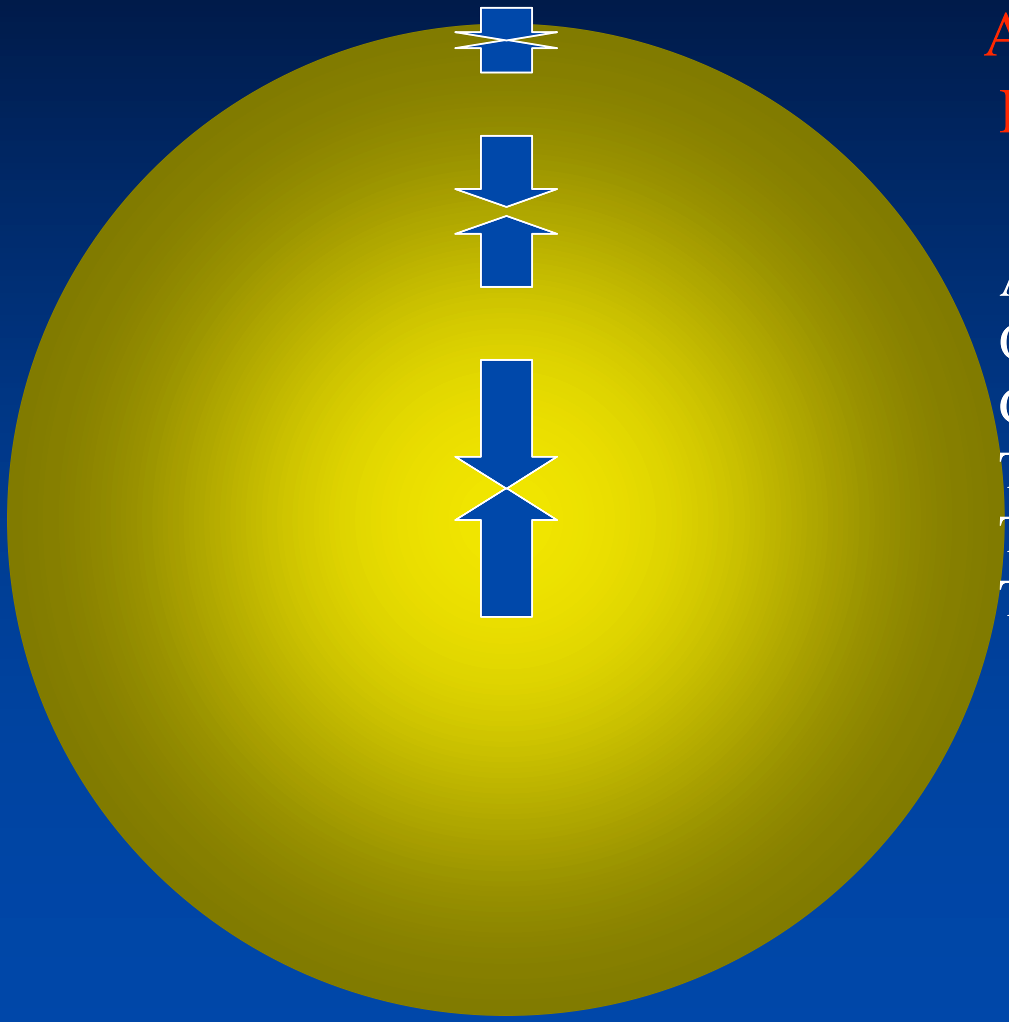
Electron Degeneracy

- When you have two e- per phase-space cell in a gas the gas is said to be degenerate and it has reached a density maximum -- you can't pack it any tighter.
- Such a gas is supported against gravitational collapse by electron degeneracy pressure.
- This is what supports the helium core of a red giant star as it approaches the tip of the RGB.

Review Q3 material

- Stellar Structure
- Stellar energy production
  - Calculation of requirements
  - Forces of nature
  - Nuclear energy
- Sun
  - Stellar wind
  - Neutrinos
- Stellar ages
- Star formation
- Evolution off the main sequence

Hydrostatic Equilibrium



At each radius

$P_{grav}=P_{thermal}$

As the weight of
Overlying material
Goes up, the
Temperature needs
To go up to keep
To pressure balance

Coal Burning

- Suppose all 2 x 10^{33}grams of the Sun are coal. The total energy you could generate would be:

$$E_{total} = \left(4 \times 10^{12} \frac{ergs}{gram}\right) \times \left(2 \times 10^{33}\, grams\right) = 8 \times 10^{45}\, ergs$$

Efficiency of coal burning

Total mass of the Sun

Coal Burning Lifetime

$$t = \frac{8 \times 10^{45} \cancel{ergs}}{4 \times 10^{33} \dfrac{\cancel{ergs}}{\sec}} = 2 \times 10^{12} \sec = 6300\, years$$

- If you were not sure of the right equation, remember dimensional analysis!

P-P Chain

- The net result is

$$\boxed{4H^1 \dashrightarrow He^4 + \text{energy} + 2 \text{ neutrinos}}$$

where the released energy is in the form of gamma rays.

The source of the energy is again a tiny bit of mass that goes missing:

Mass(4H) = 6.6943×10^{-24} grams

Mass(He^4) = 6.6466×10^{-24} grams

P-P Chain

- The amount of missing mass is:

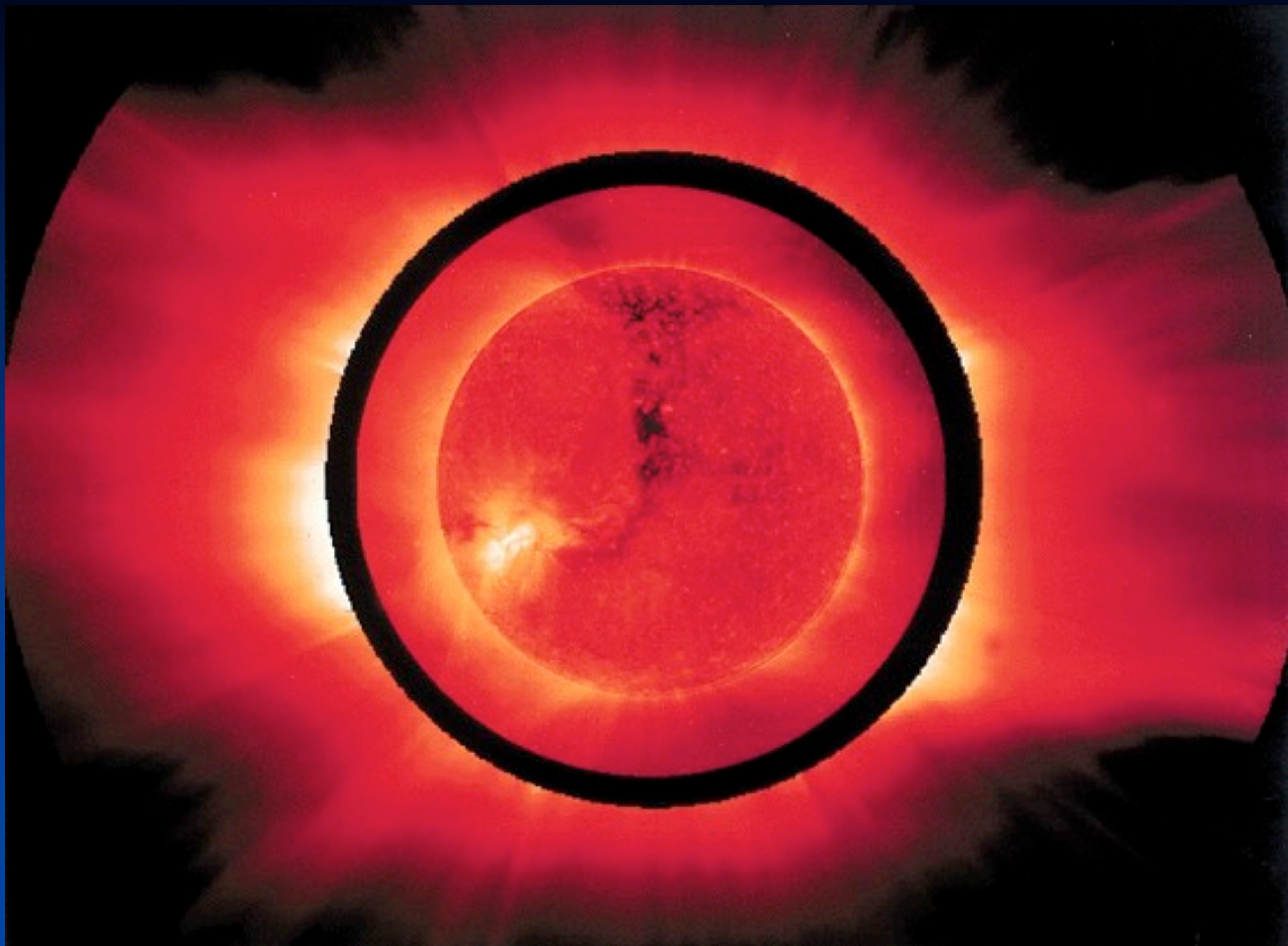
$$\boxed{\Delta mass = 0.048 \times 10^{-24}\, grams}$$

- The energy generated is:

$$\boxed{E = \Delta mc^2 = 4.3 \times 10^{-5}\, ergs}$$

- This much energy is released by $4H^1$ with a total mass of 6.6943×10^{-24}grams. The efficiency of hydrogen fusion is therefore:

$$\boxed{6.4 \times 10^{18} \text{ ergs/gram}}$$



Example Stellar Lifetime

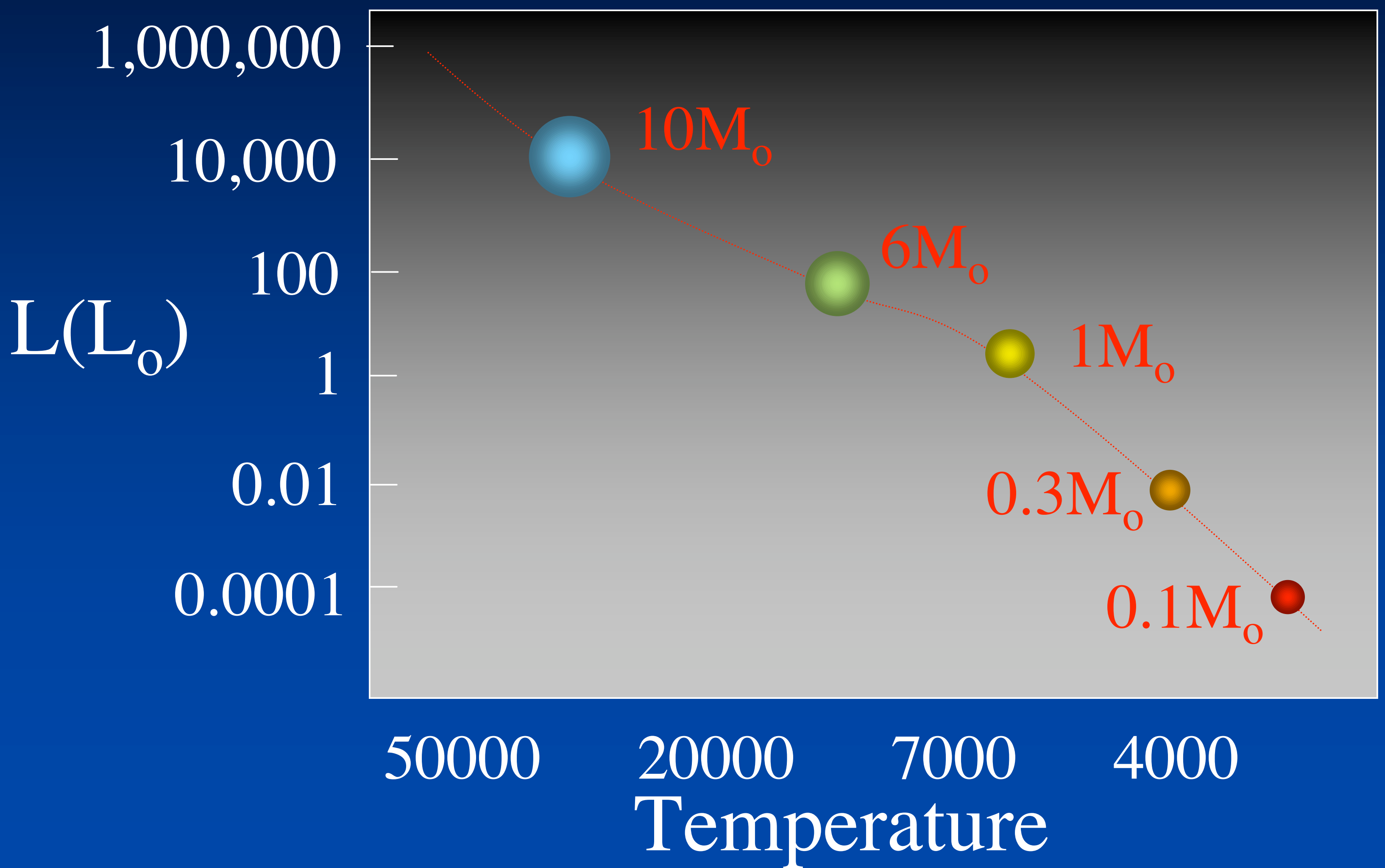
Suppose you have a $15M_o$ star with a luminosity of $L=10{,}000L_o$. How long will this star spend on the main sequence?

$$\boxed{Lifetime(15M_o) = \frac{15}{10000} \times Lifetime(1M_o)}$$

15 times as much fuel extends the life of the star

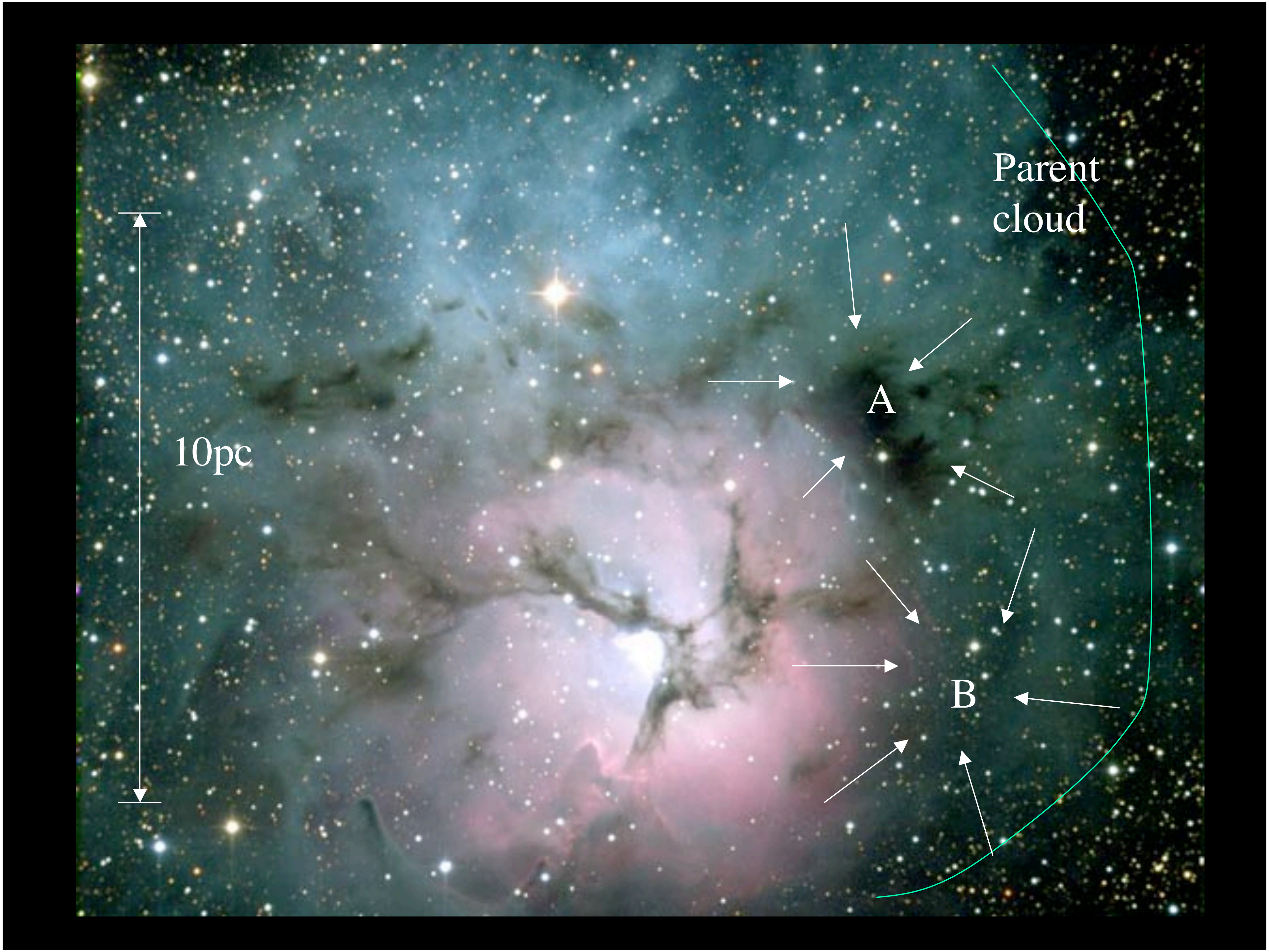
10,000 times L decreases the lifetime

Lifetimes can be read from a plot of Mass vs L



Mass Limit for Stars

- Lower mass limit for stars is 0.08 solar masses -- this is the mass below which the central temperature is <10 million K
- Upper mass limit is around 100 solar masses set by inability for a star to hang on to its outer layers because high radiation pressure (high luminosity).

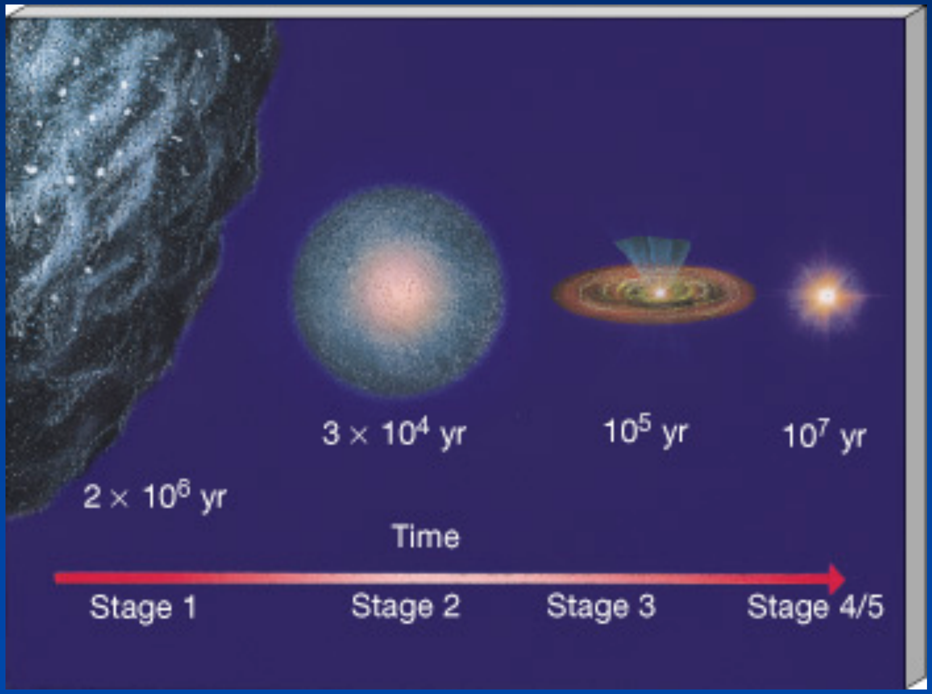

Parent
cloud
10pc
A
B

Thackeray's Globules in IC 2944

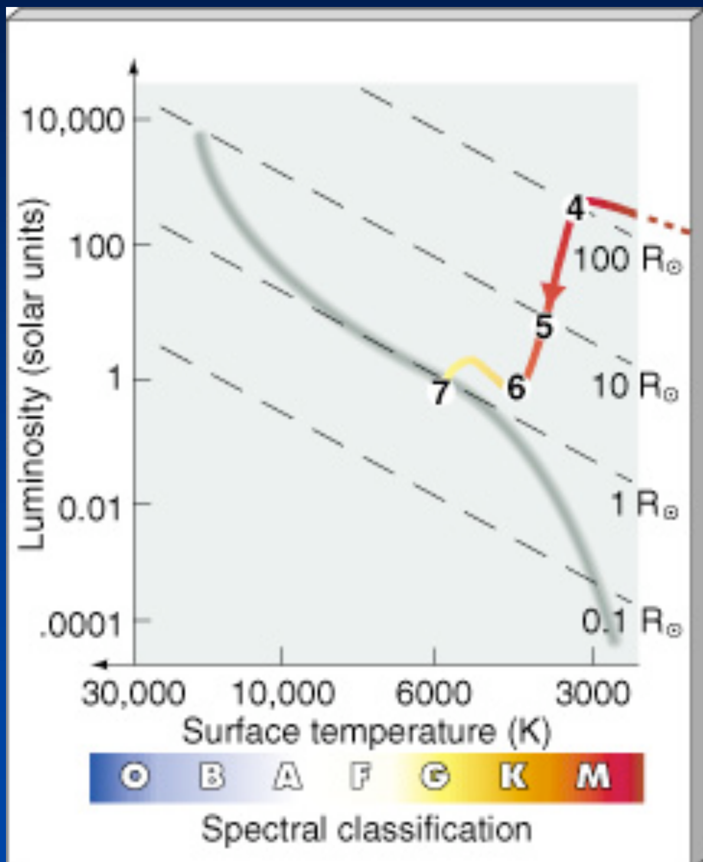
Hubble Heritage

Protostar Collapse

- Conservation of angular momentum forces individual collapsing clouds into disks through which material flows down to the central object.



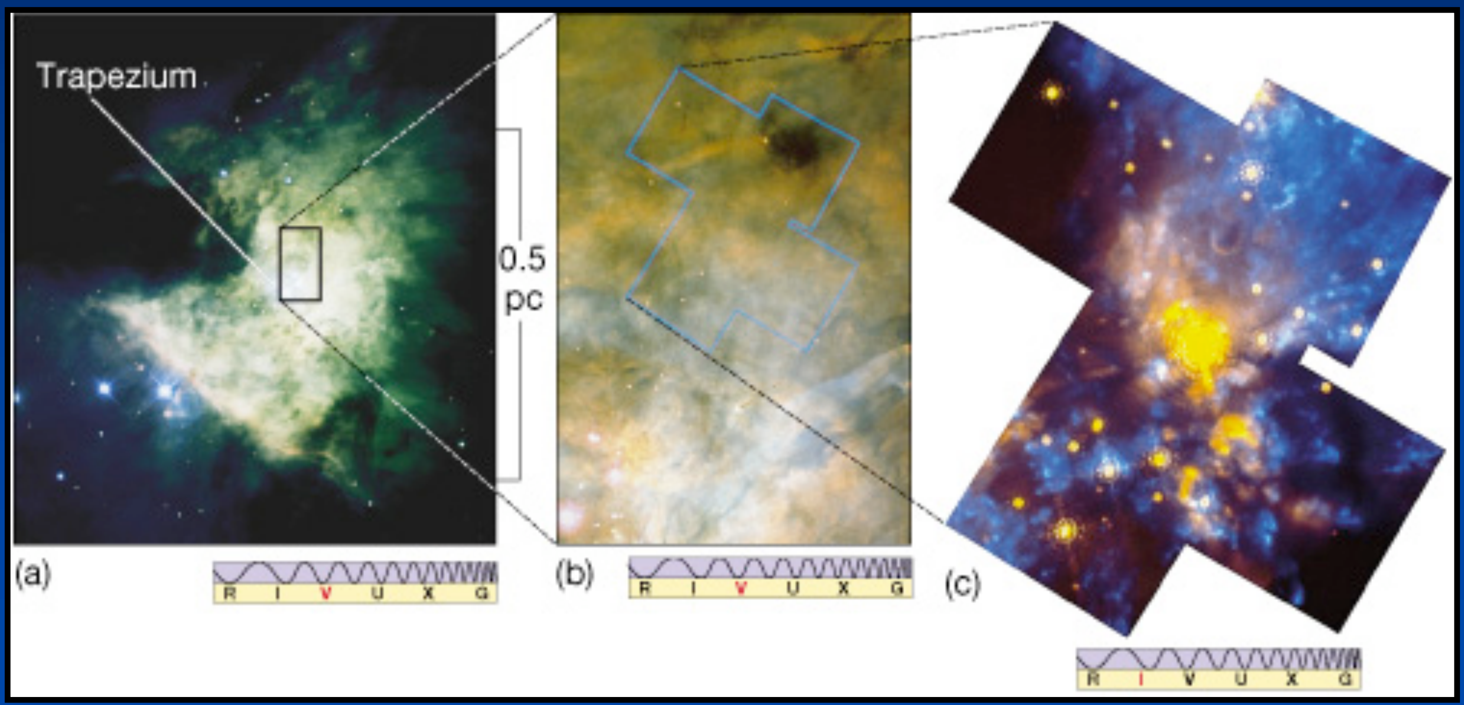
Protostars



- For 1 solar mass protostars, their first appearance in the H-R diagram as large (surface area), cool objects -- the upper right of the diagram.
- When the central temperature reaches 10 million K, a star is born and the main-sequence life begins.

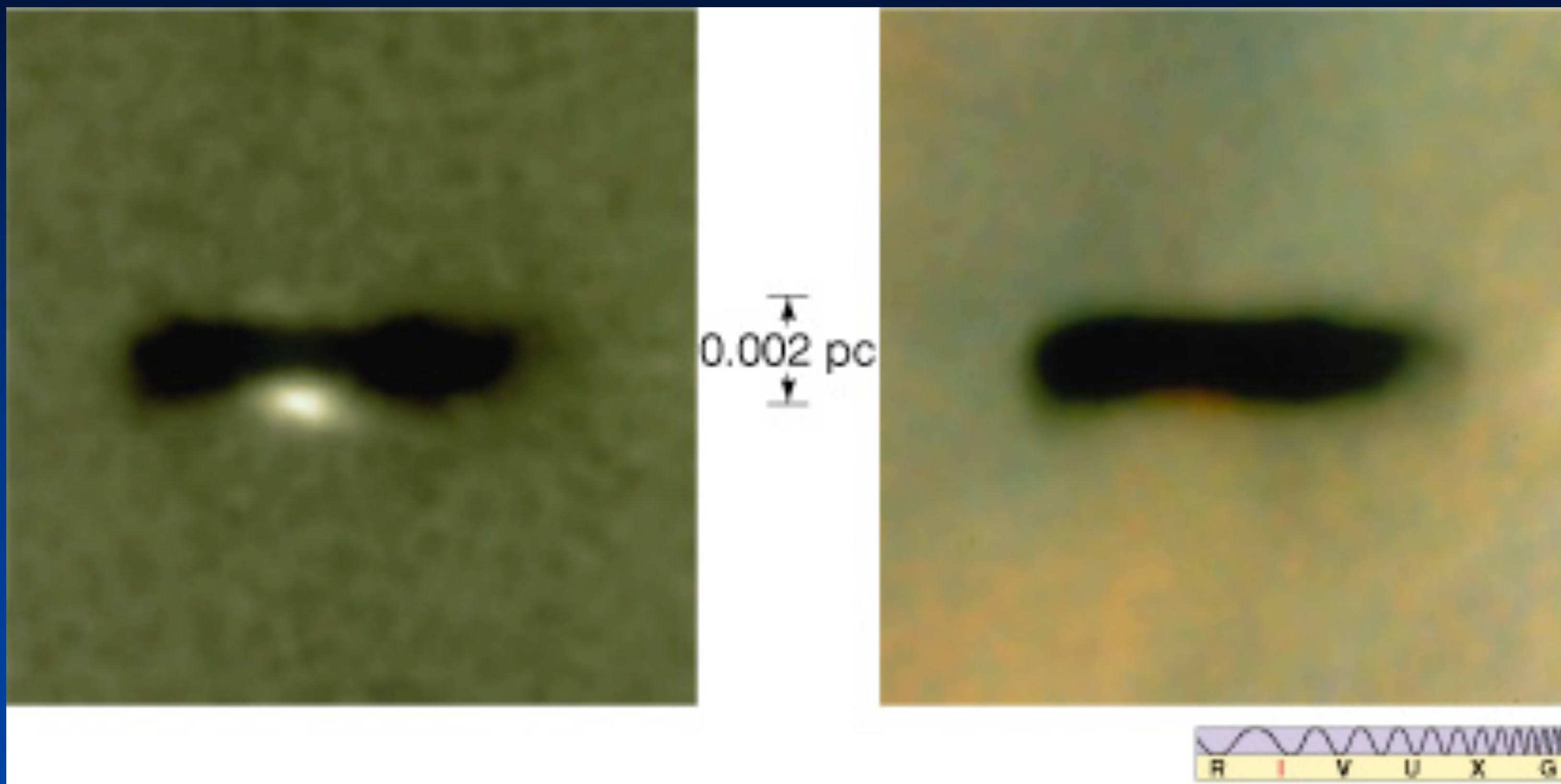
Infrared Observations

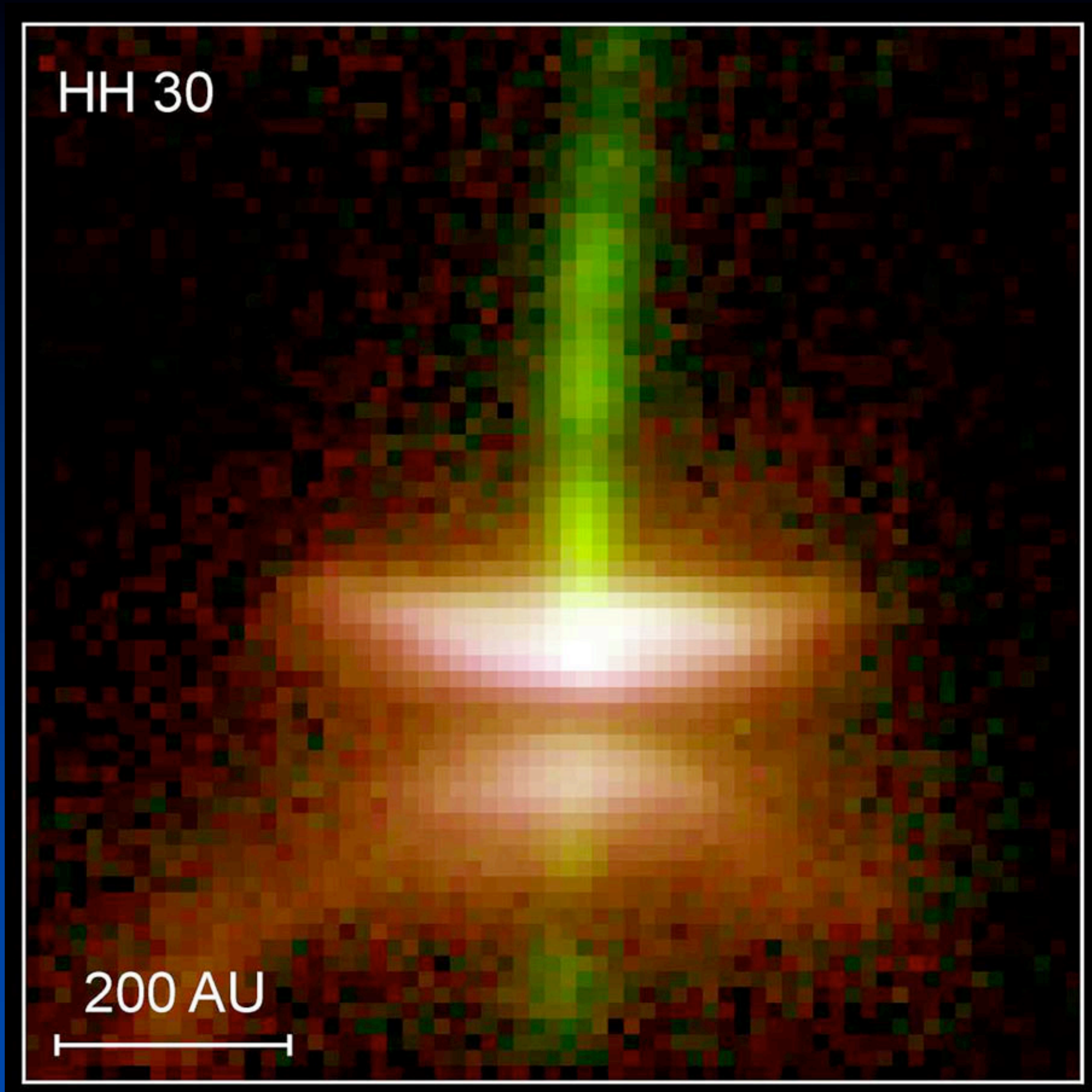
- Just as interstellar dust affects blue light more than red, it affects IR radiation less than it does red light. With IR detectors on telescopes, we can peer through the dust into the centers of dark clouds.

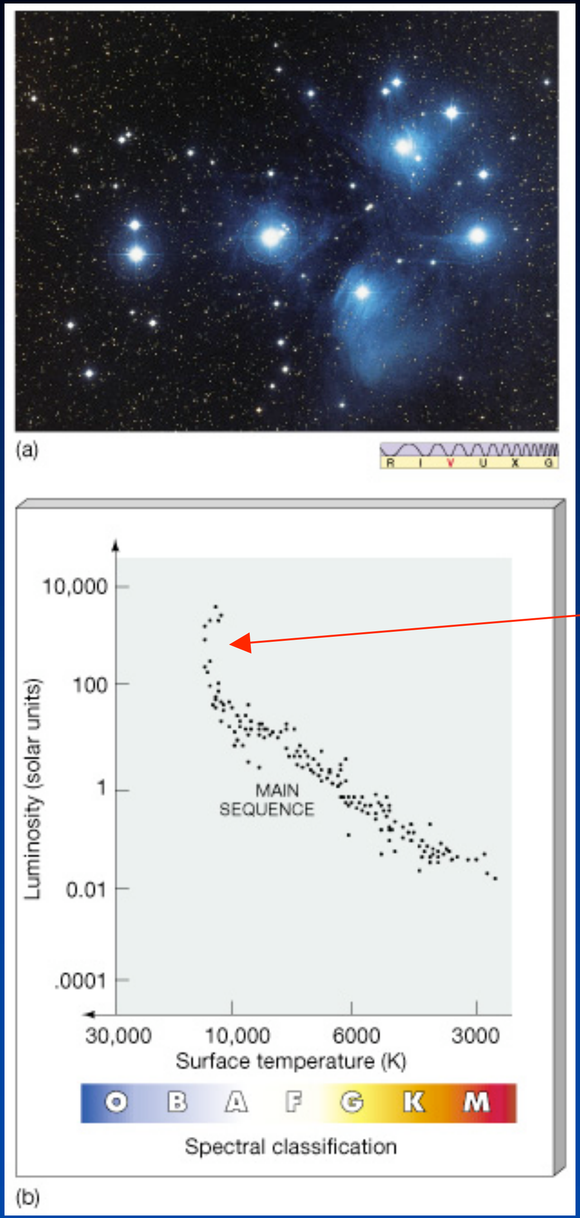


Star-Birth Clouds · M16 HST · WFPC2

PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

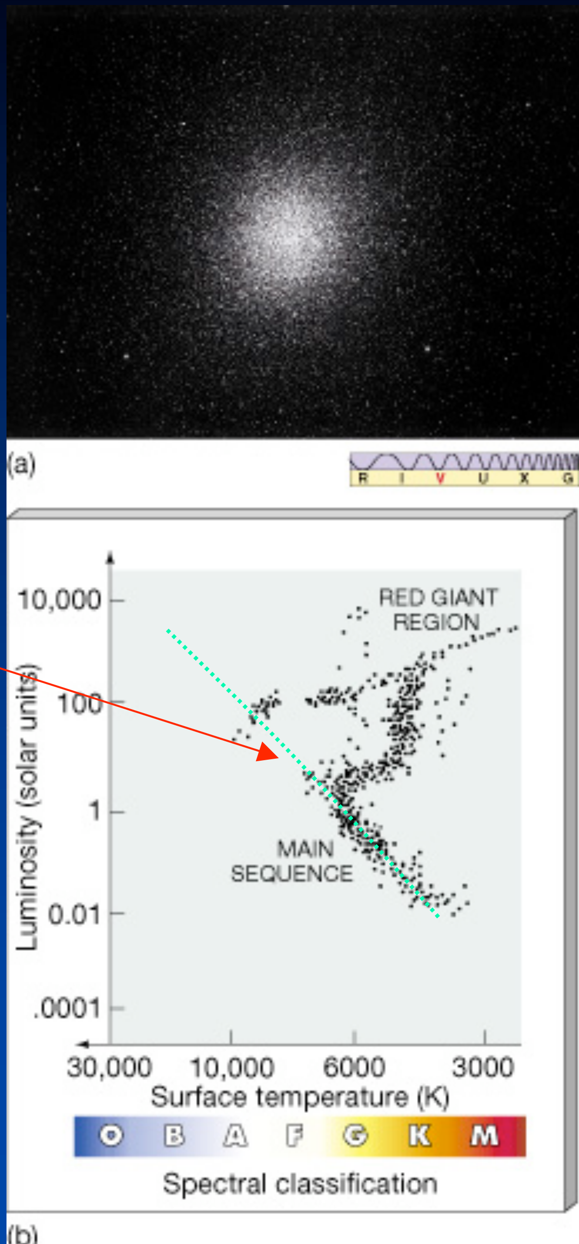

0.002 pc
R
I
V
U
X
G


HH 30
200 AU



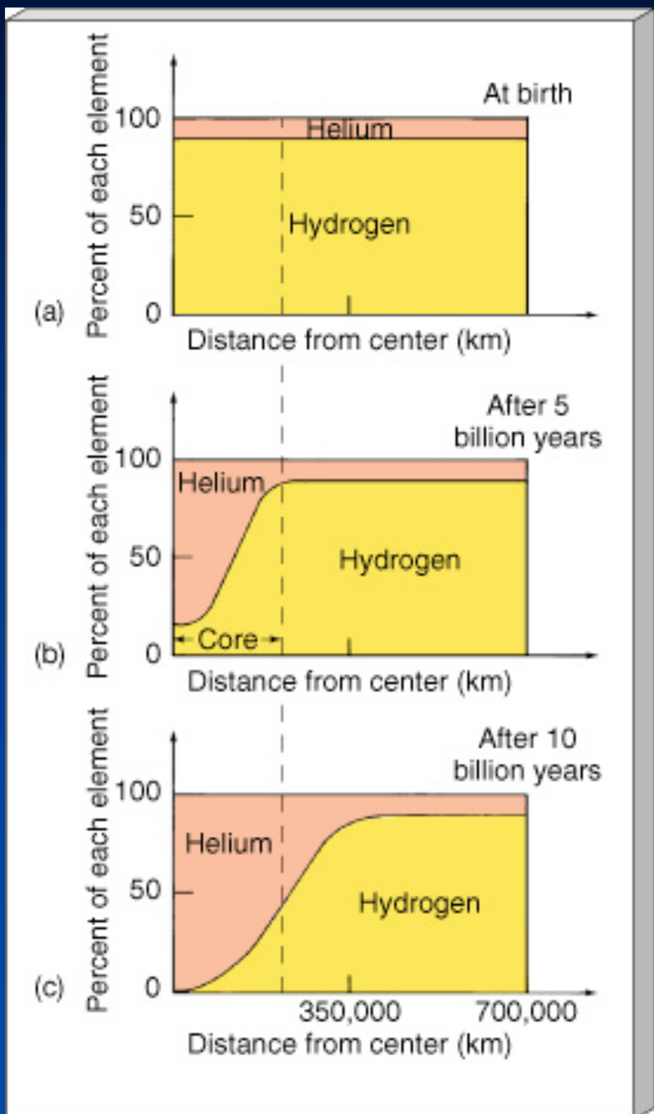
- Young clusters contain short-lived, massive stars in their main sequence

MSTO



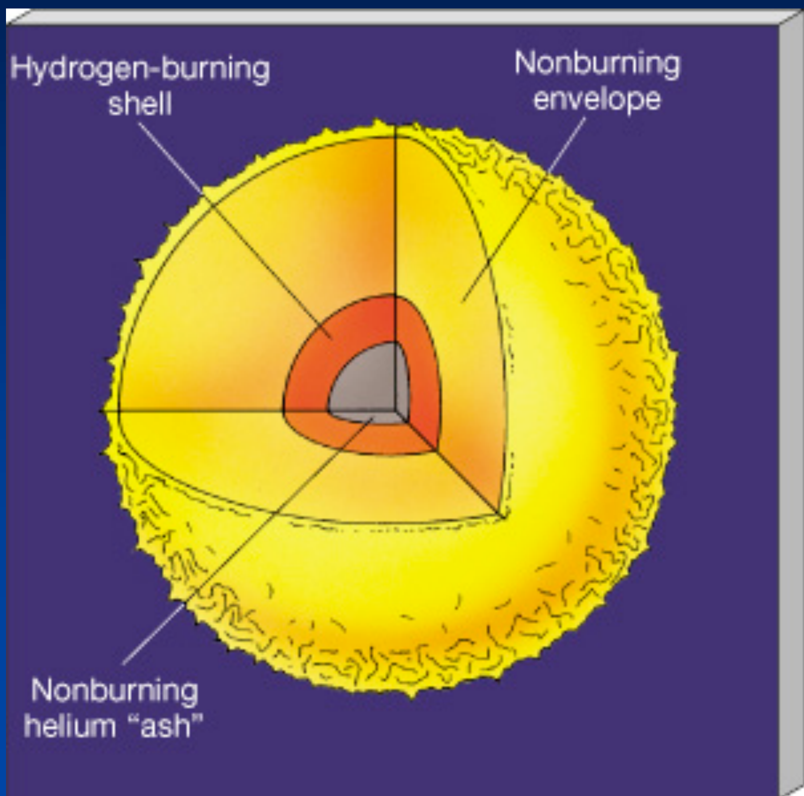
- Other clusters are missing the high-mass stars and we can infer the cluster age is the main-sequence lifetime of the highest mass star still on the main-sequence.

Stellar Evolution



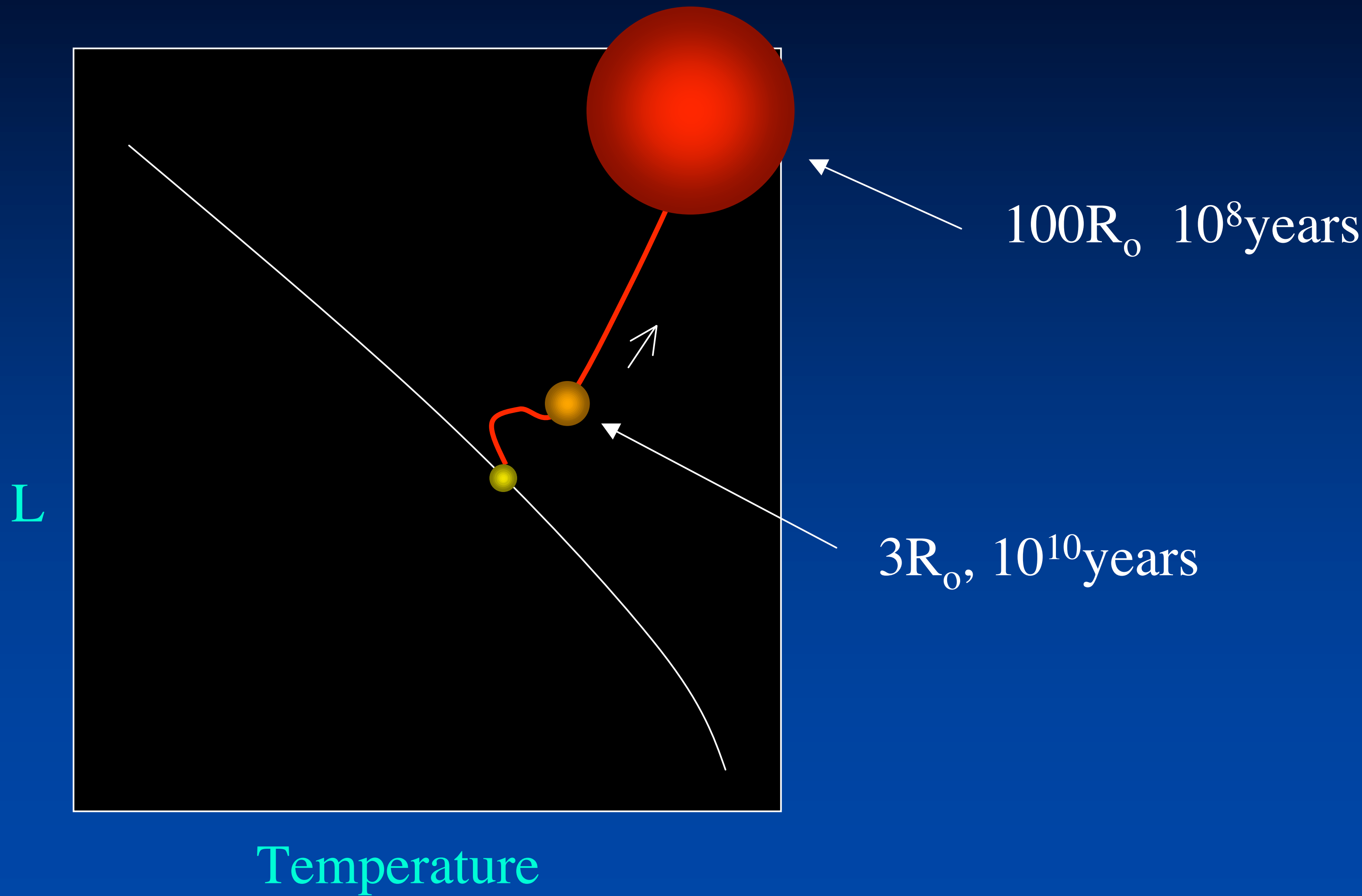
- The structure of the Sun has been changing continuously since it settled in on the main sequence.
- The Hydrogen in the core is being converted into Helium.

Evolution to Red Giant



- As the contracting helium core grows and the total energy generated by GPE and the hydrogen fusion shell increases.
- L goes up!
- As L goes up the star also expands.

Red Giant



- Why do thermonuclear reactions only occur in the Sun's core?

That is the only place in the Sun it is hot enough

- If the thermonuclear fusion in the Sun were suddenly to stop, what would eventually happen to the radius of the Sun?

The temperature would go down, the radius would shrink as gravity temporarily one the war

- Why are low temperatures necessary for protostars to form?

  Hydrostatic equilibrium: need to reduce the thermal pressure

- What is the energy source for a protostar

  Gravitational potential energy