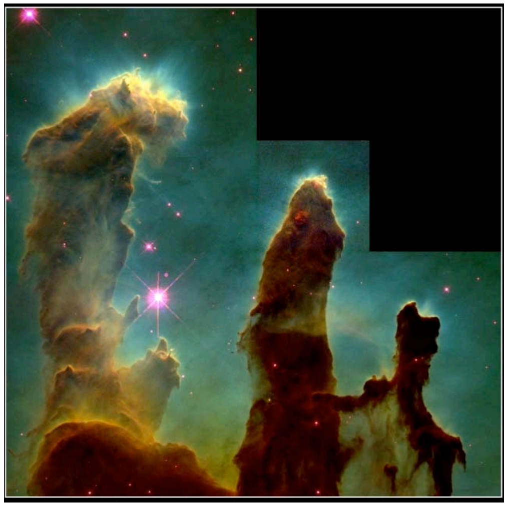
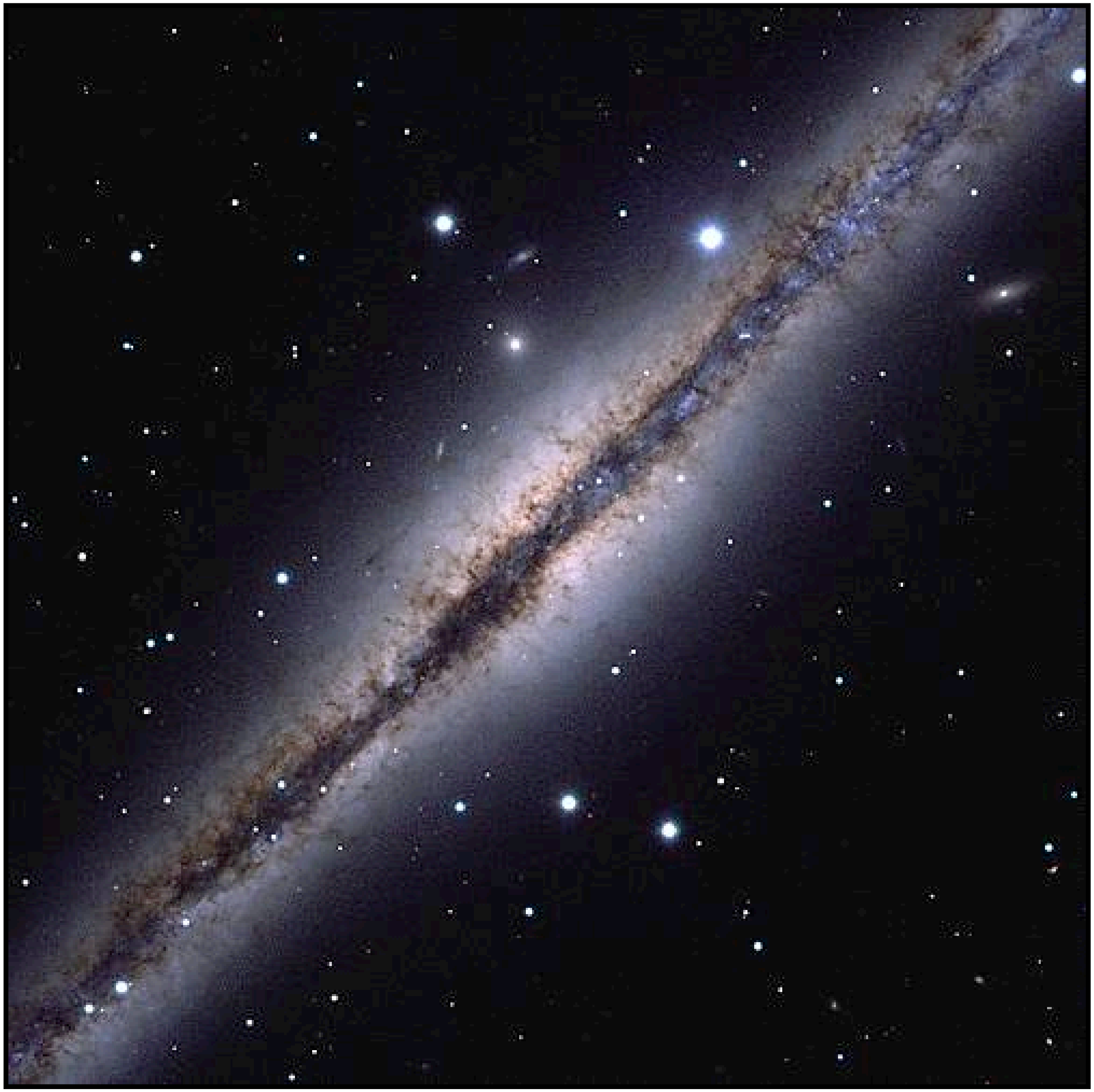


Star Formation

- 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.



Galaxies NGC 2207 and IC 2163

Hubble Heritage

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

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

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

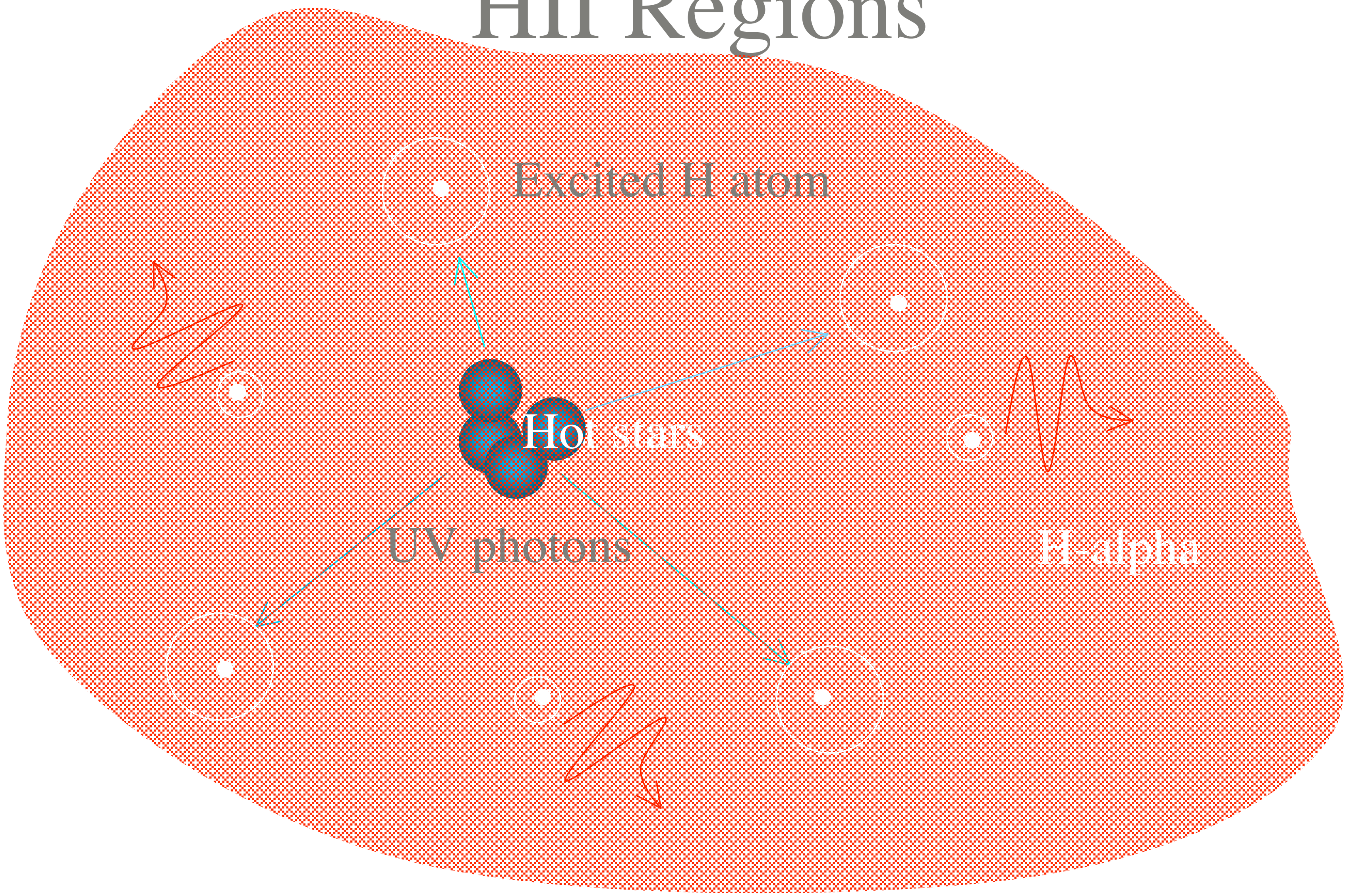
HII Region

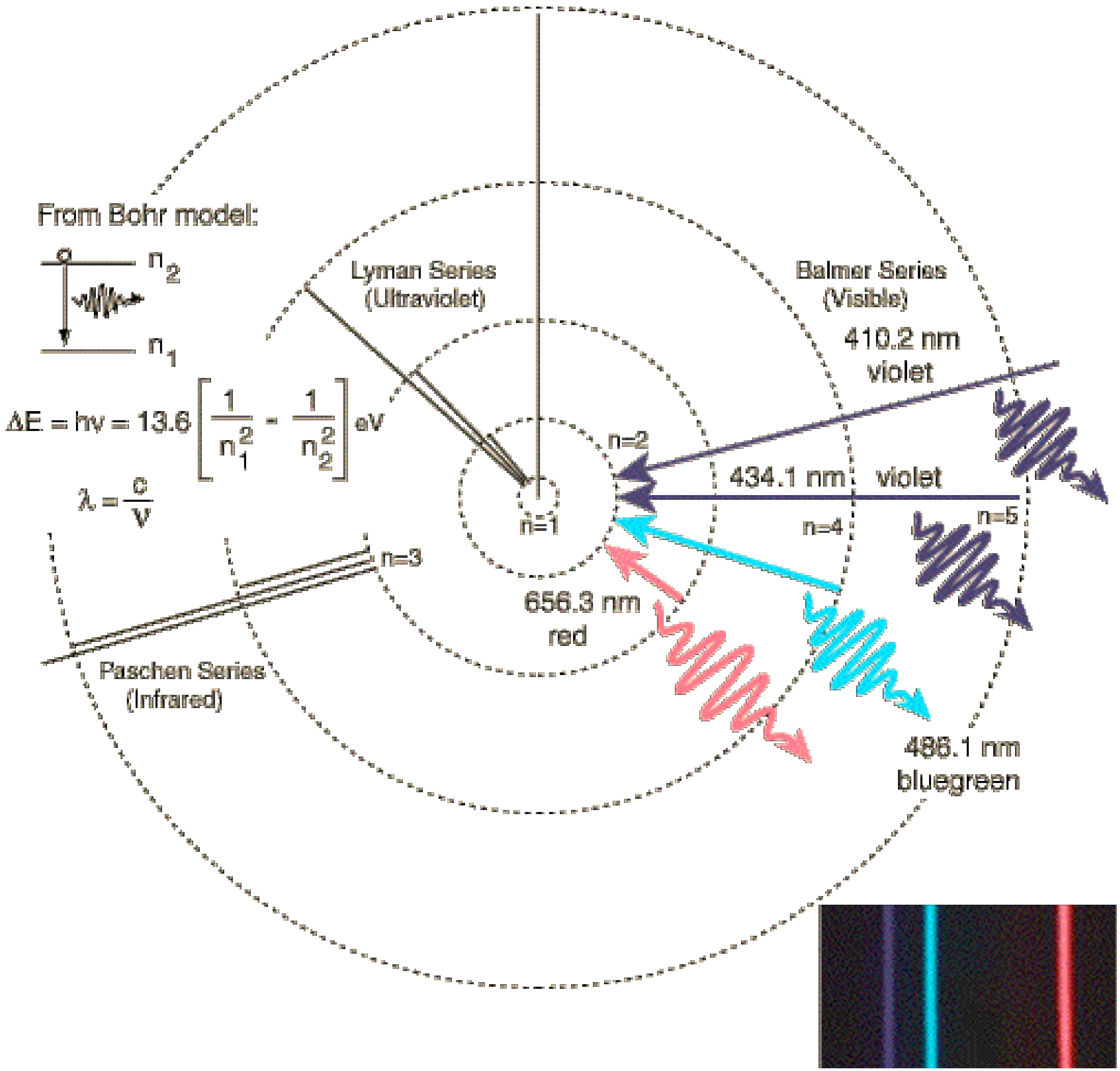
- Star formation regions are associated with beautiful nebulae called `HII’ regions.

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:
n_2
n_1
$\Delta E = h\nu = 13.6\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] eV$
$\lambda = \frac{c}{\nu}$
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)

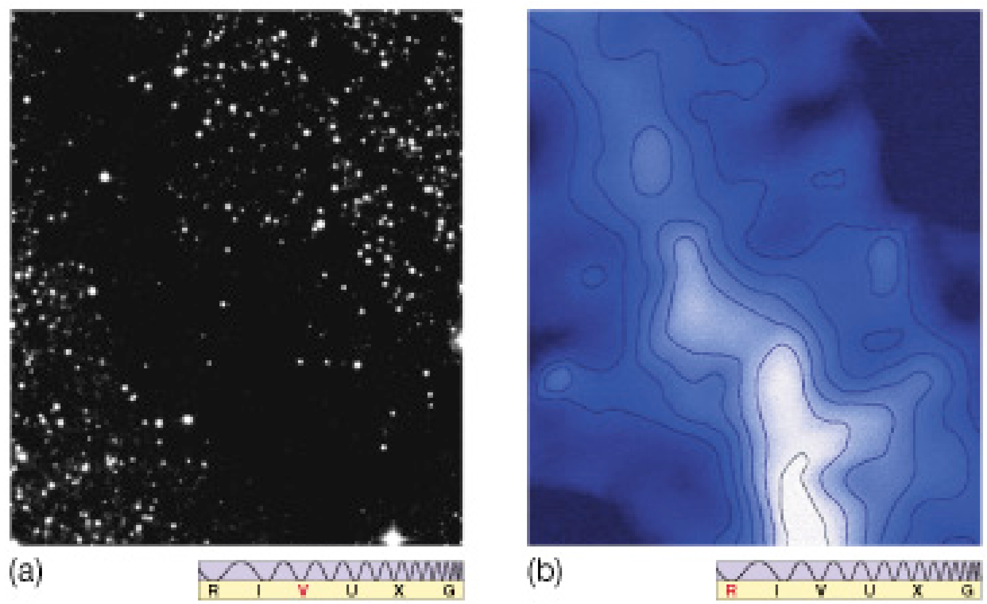
Forbidden Emission Lines

- 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.

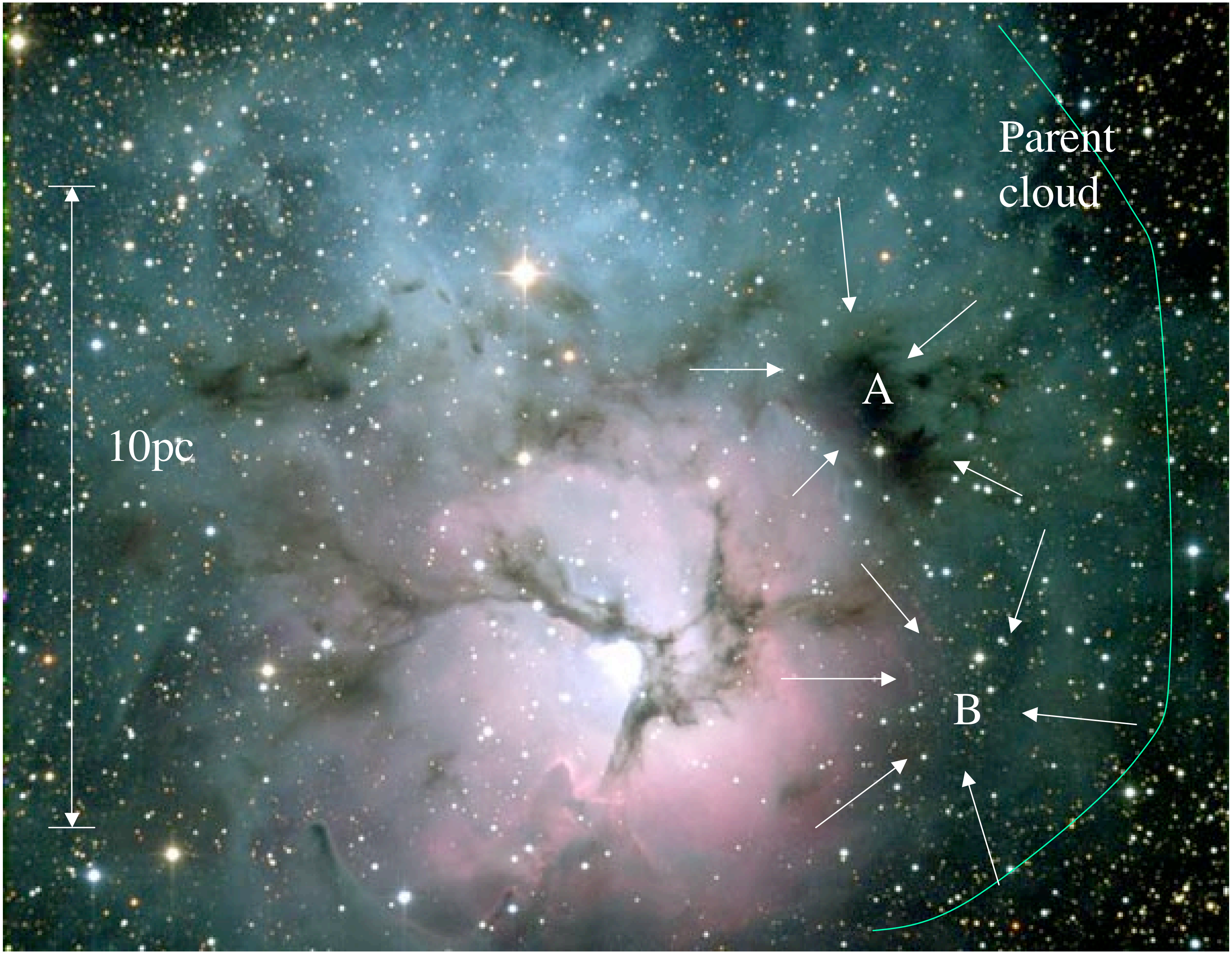
Star Formation Gas

- 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).

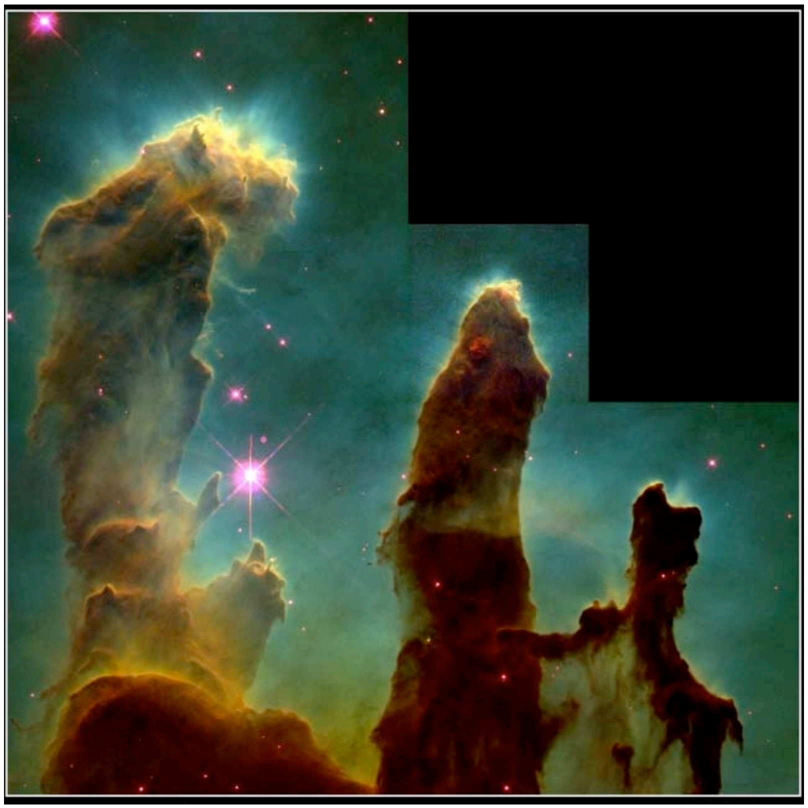
Star Formation Gas



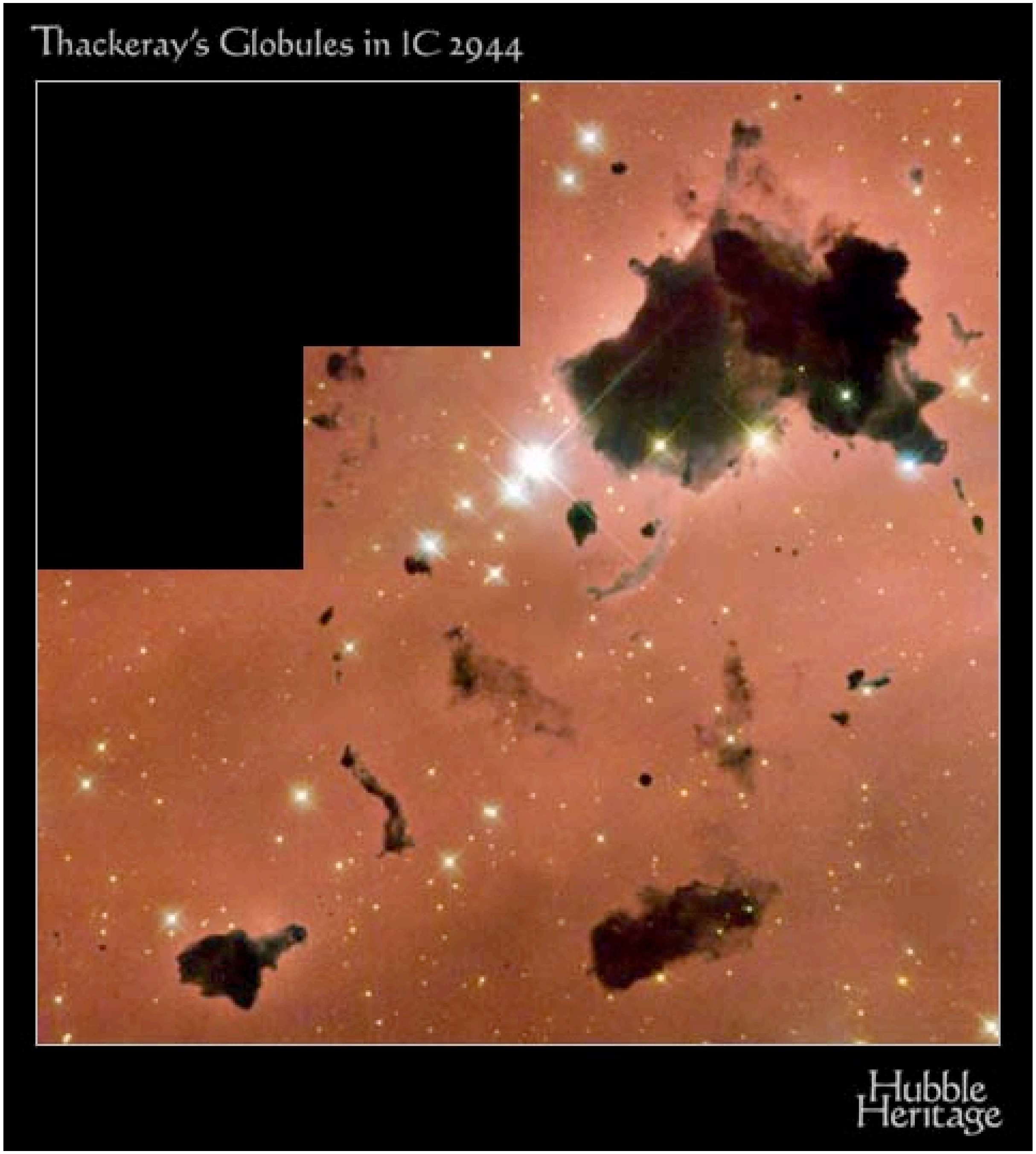
- Gas is spatially very well correlated with dust. Gas molecules may be the site where dust has a change to form.


Parent
cloud
10pc
A
B

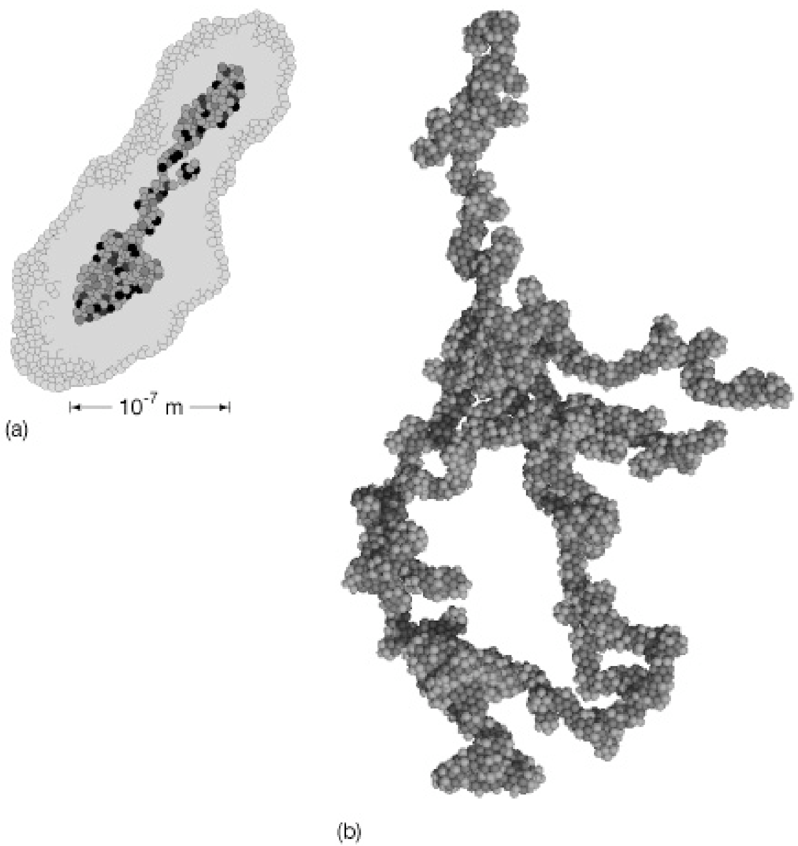
Star Formation



- The other, less obvious, ingredient in star formation regions is dust. This turns out to be one of the main reasons it has been hard to unravel the mysteries of star formation.


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

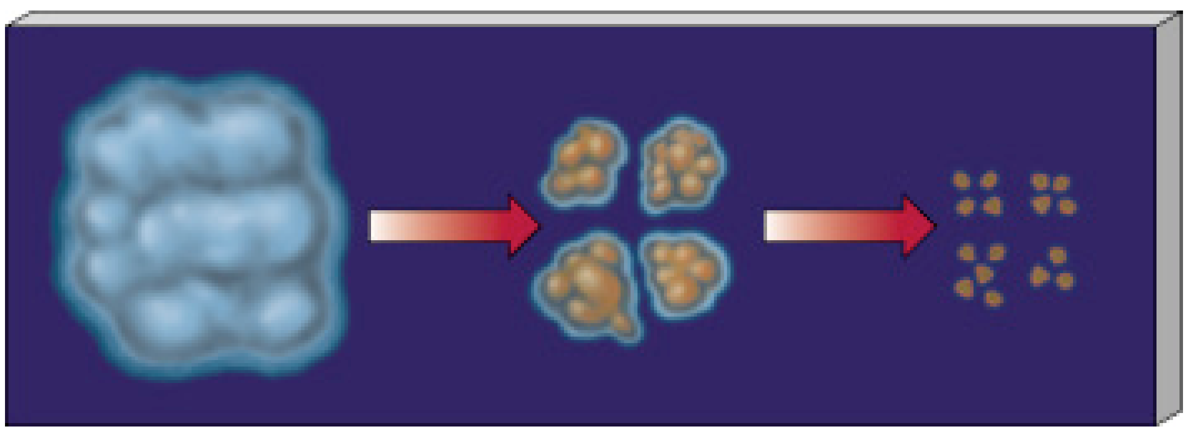
- This is where dust (smoke would be a better term) comes in.
- 10k is VERY cold, the ambient starlight in the Galaxy is enough to keep gas warmer than this unless there is shielding from dust.
- The downside of star formation taking place deep in the heart of dusty regions is the difficulty of observing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

Protostars

- Start with a gas cloud of ~2000M_o and a radius of ~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.

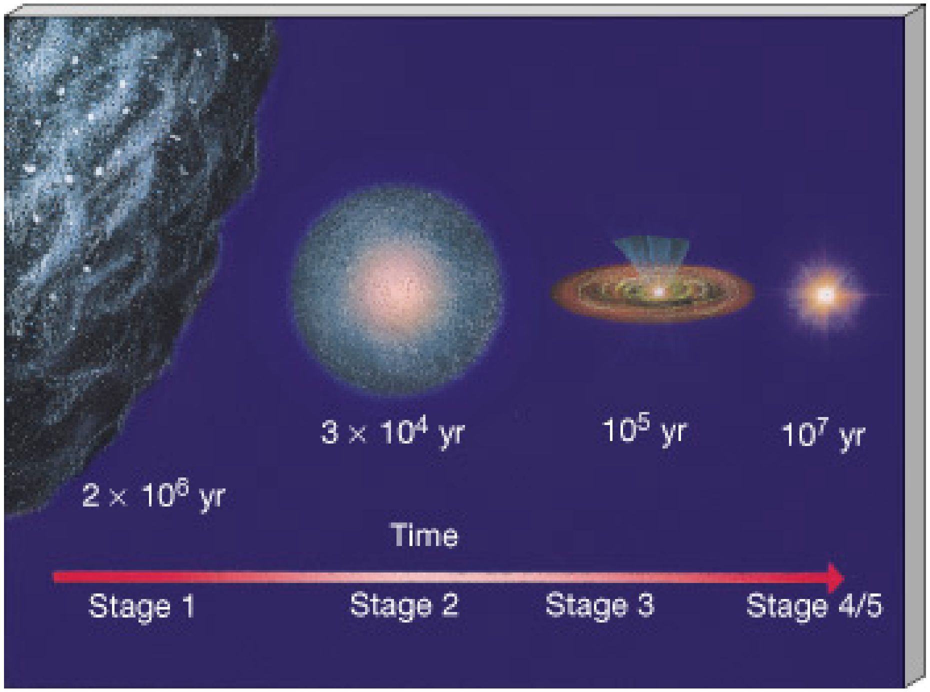
Protostar Collapse

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

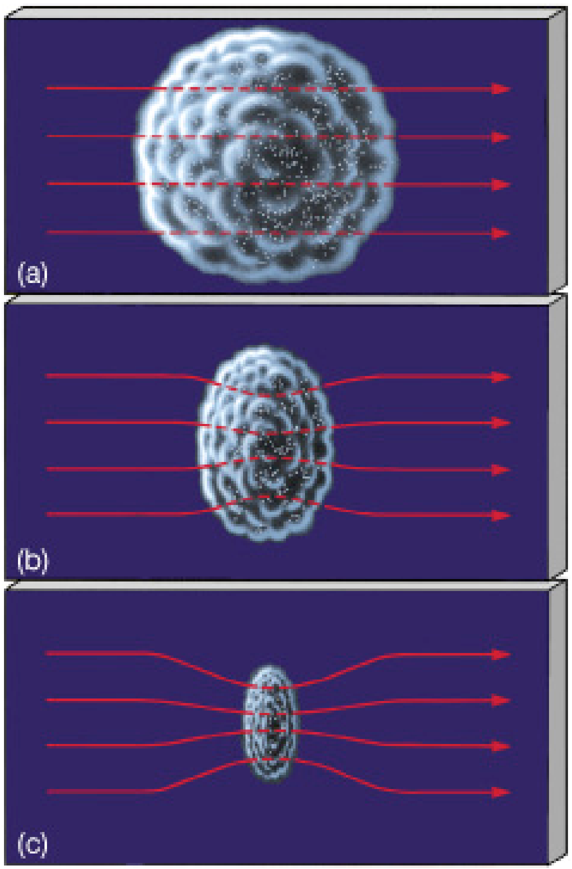


Protostar Collapse

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

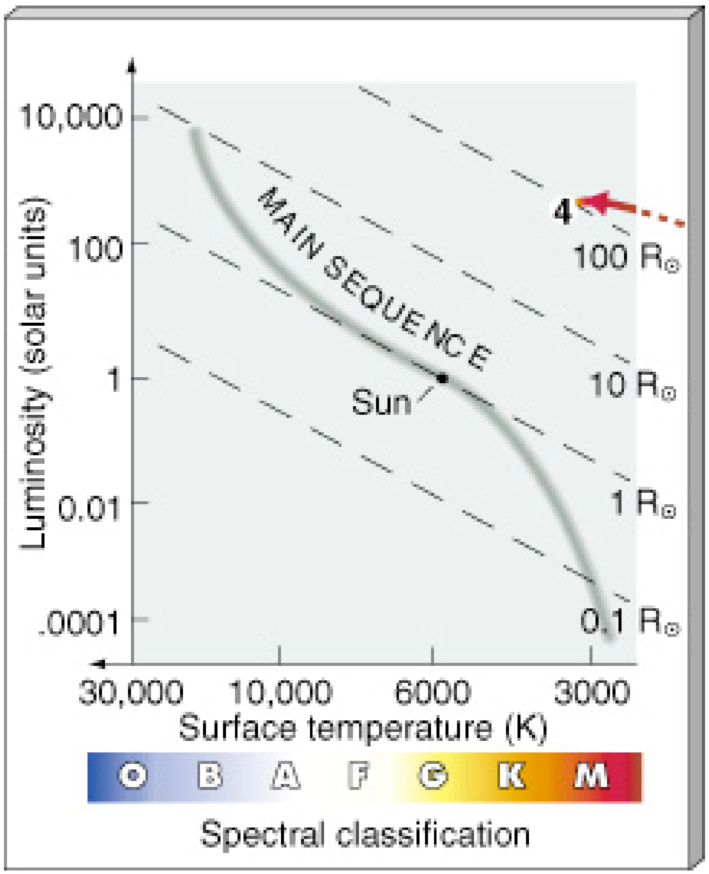


Protostar Collapse



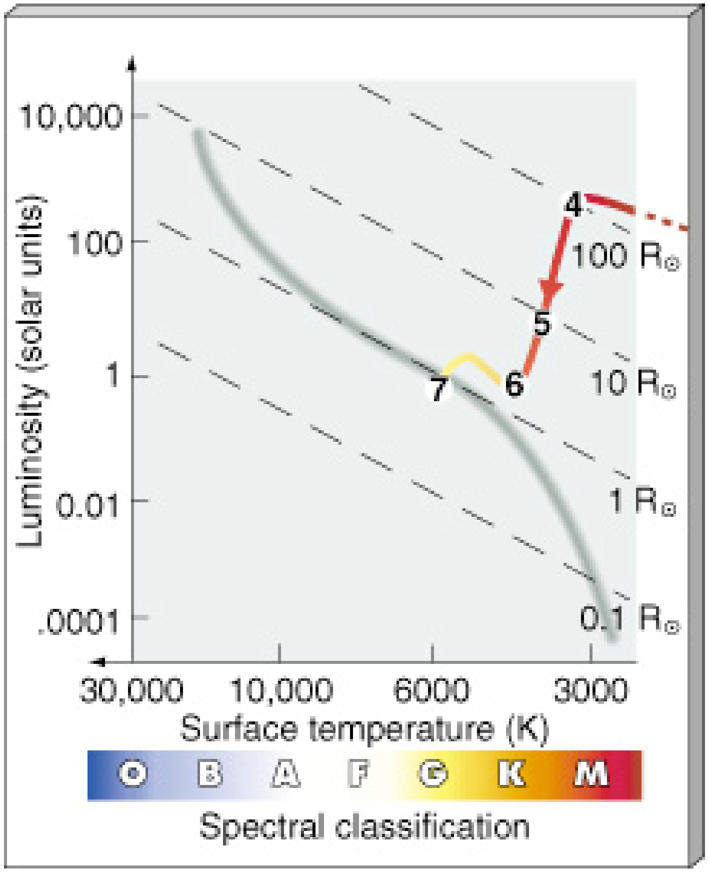
- Magnetic fields are present in the interstellar medium and suppress star formation.
- Somehow nature manages to overcome this difficulty.

Protostars



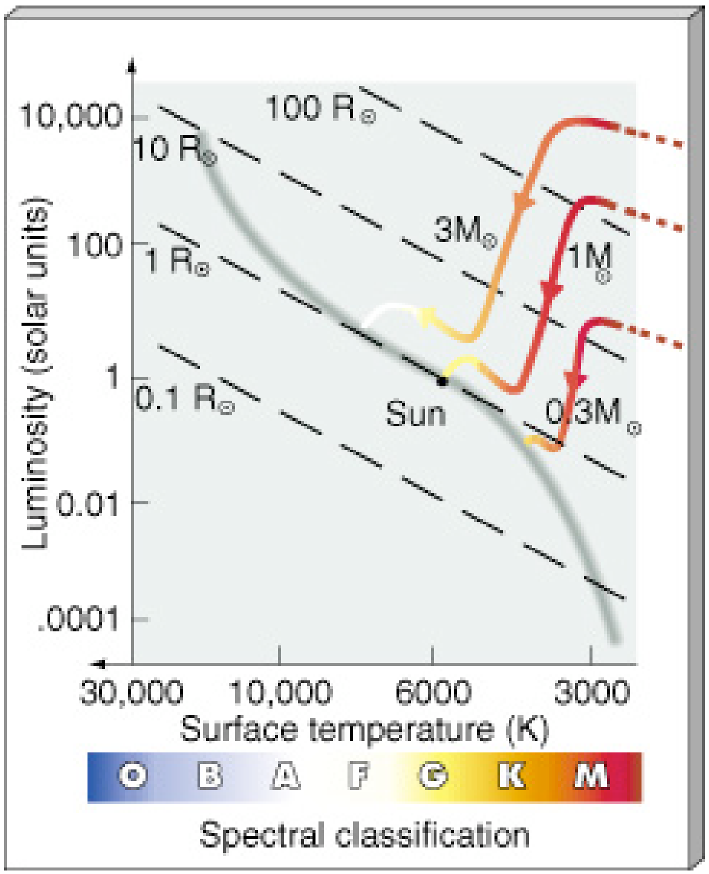
- At first the collapsing cloud is very cold. As it collapses it converts gravitational potential energy into radiation and internal heating.
- While the protostar is cooler than ~2000K it doesn't appear on the H-R Diagram.

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.

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

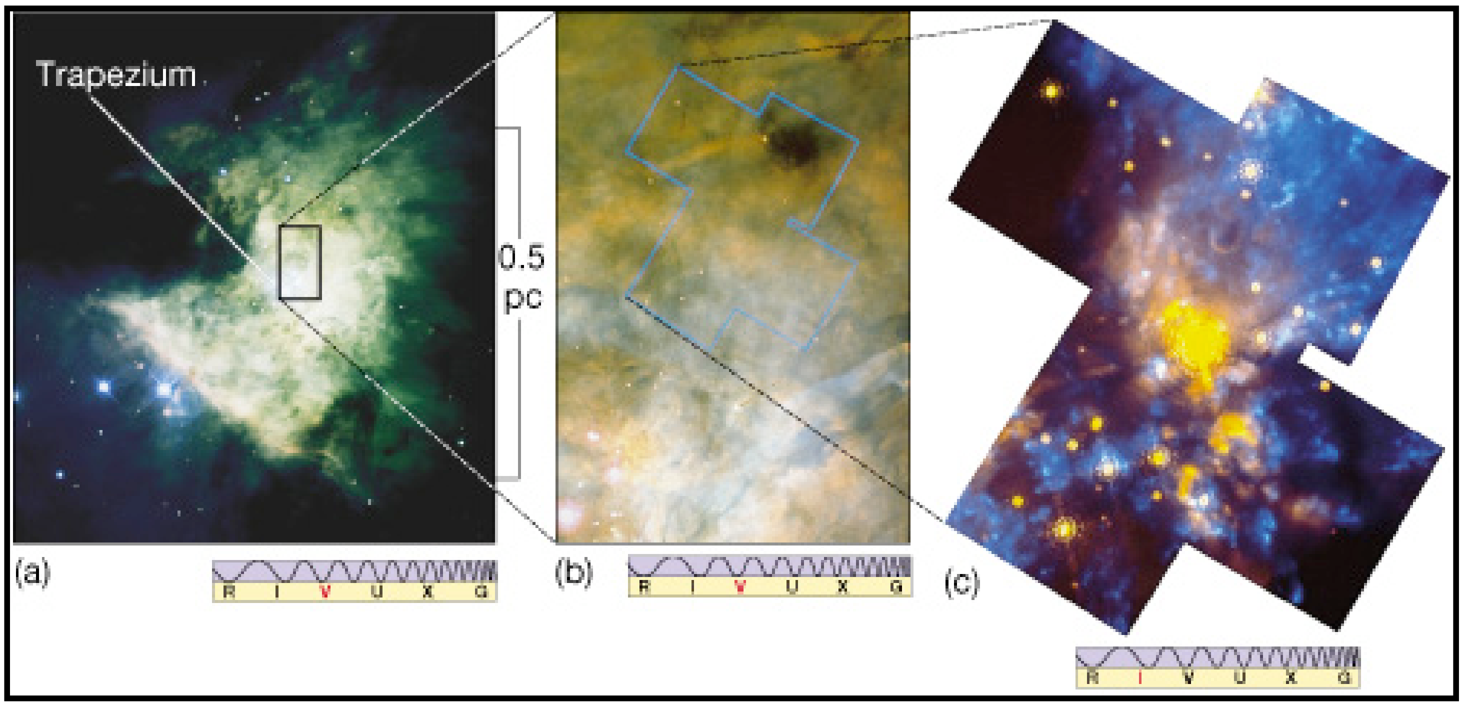
- Two observational advances have led to breakthroughs in understanding and observing this first stage of star formation.

  (1) Infrared Detectors

  (2) Hubble Space Telescope

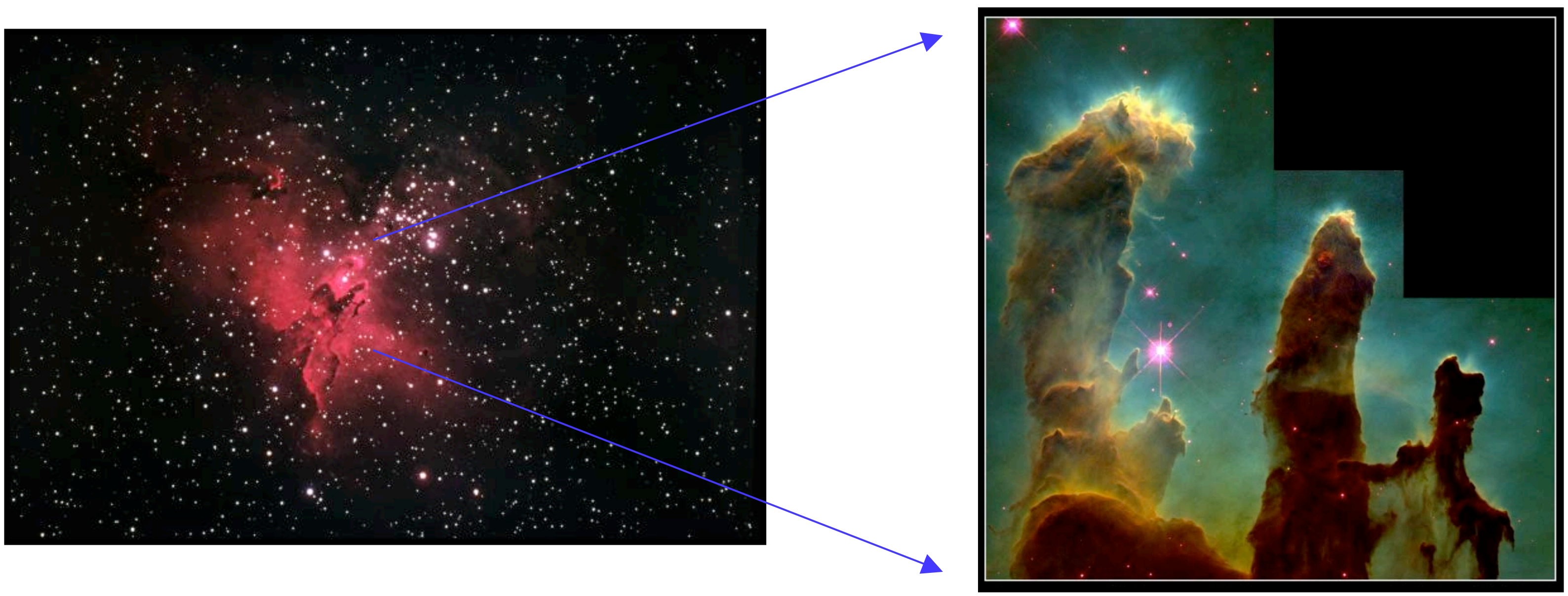
Infrared Observations

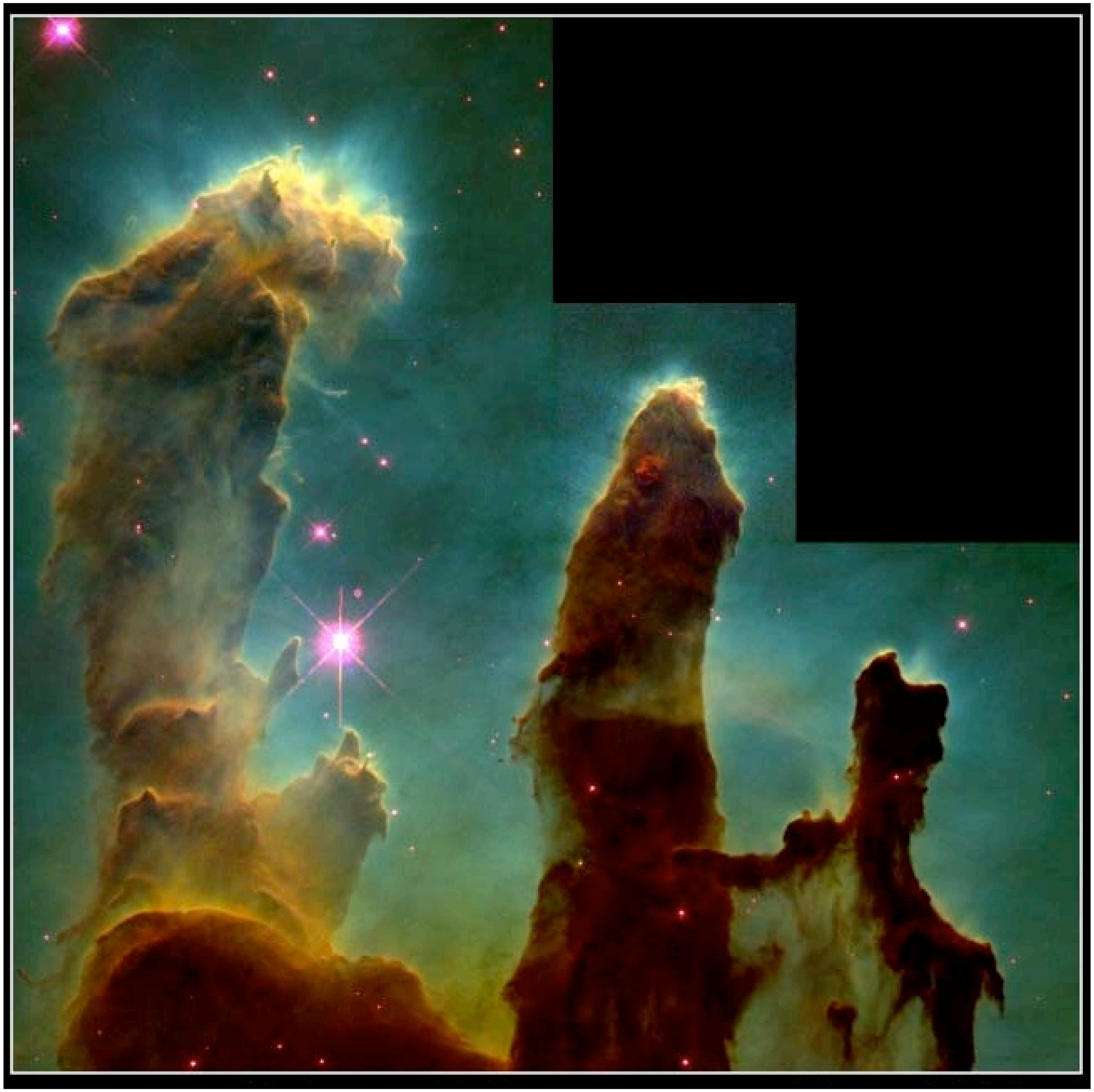
- Just as interstellar dust affects blue light more than red, it affects IR radiation less than it does red light. With IR detectors on telescopes, we can peer through the dust into the centers of dark clouds.

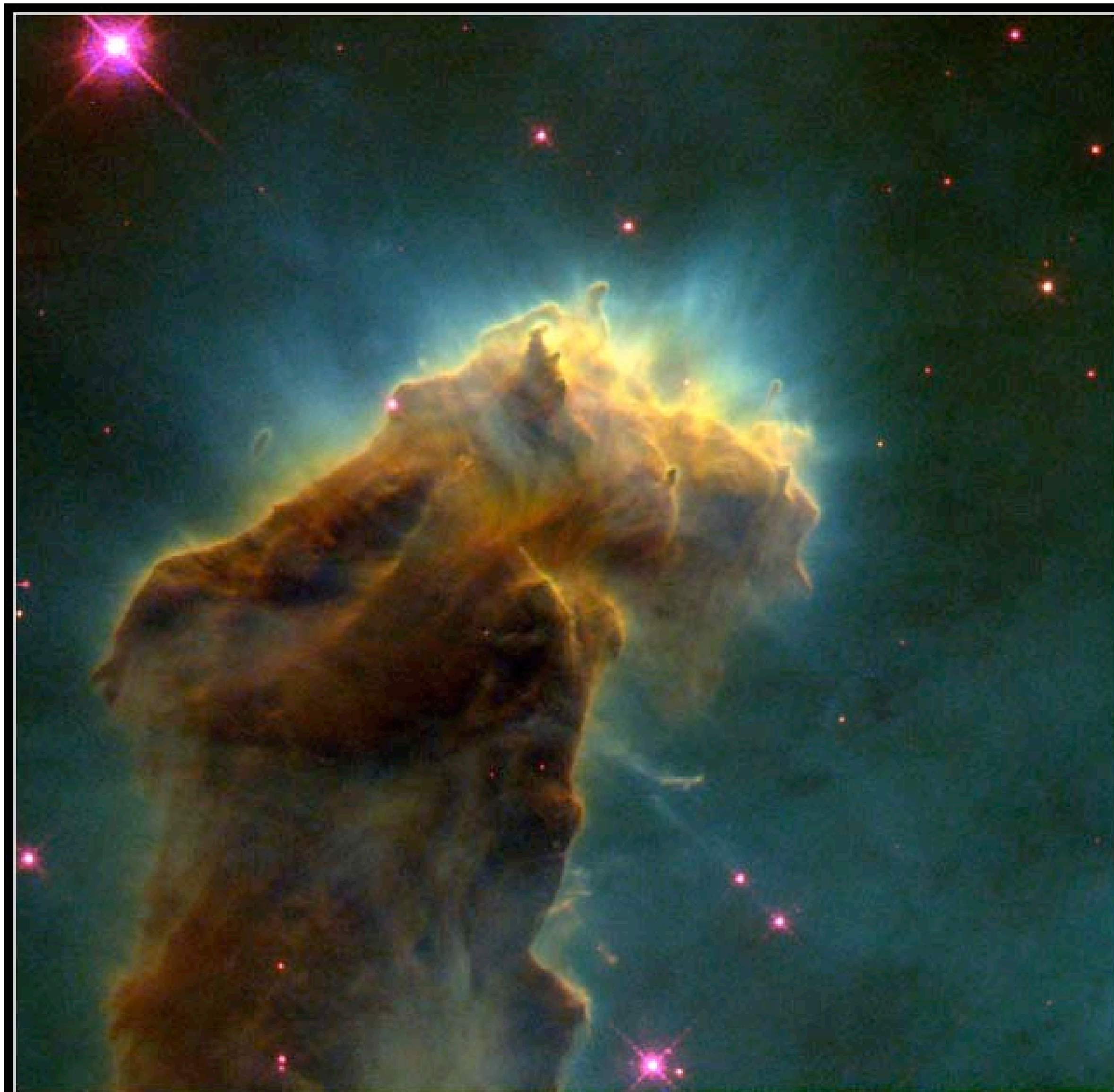


HST Spatial Resolution

- 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.

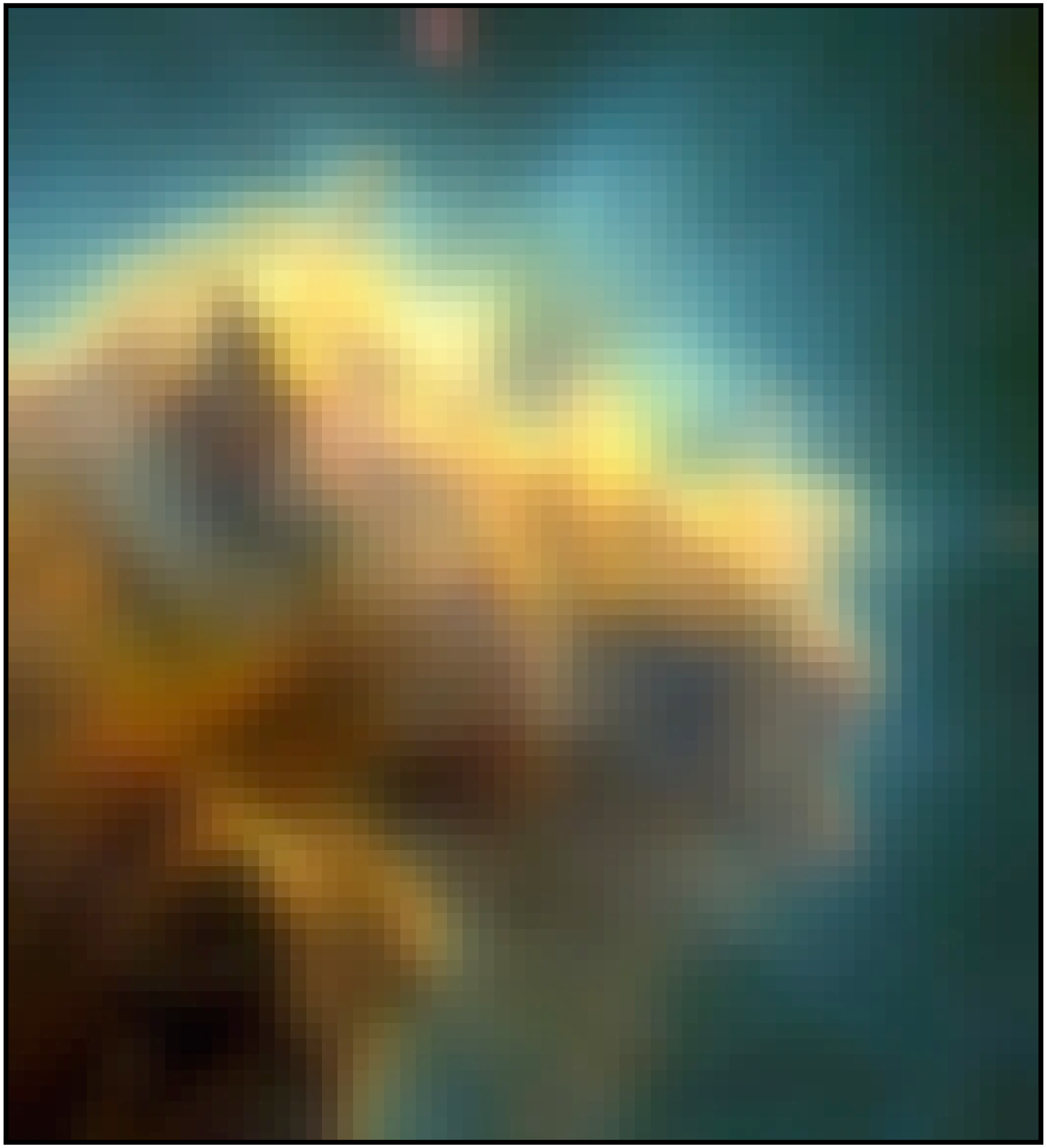






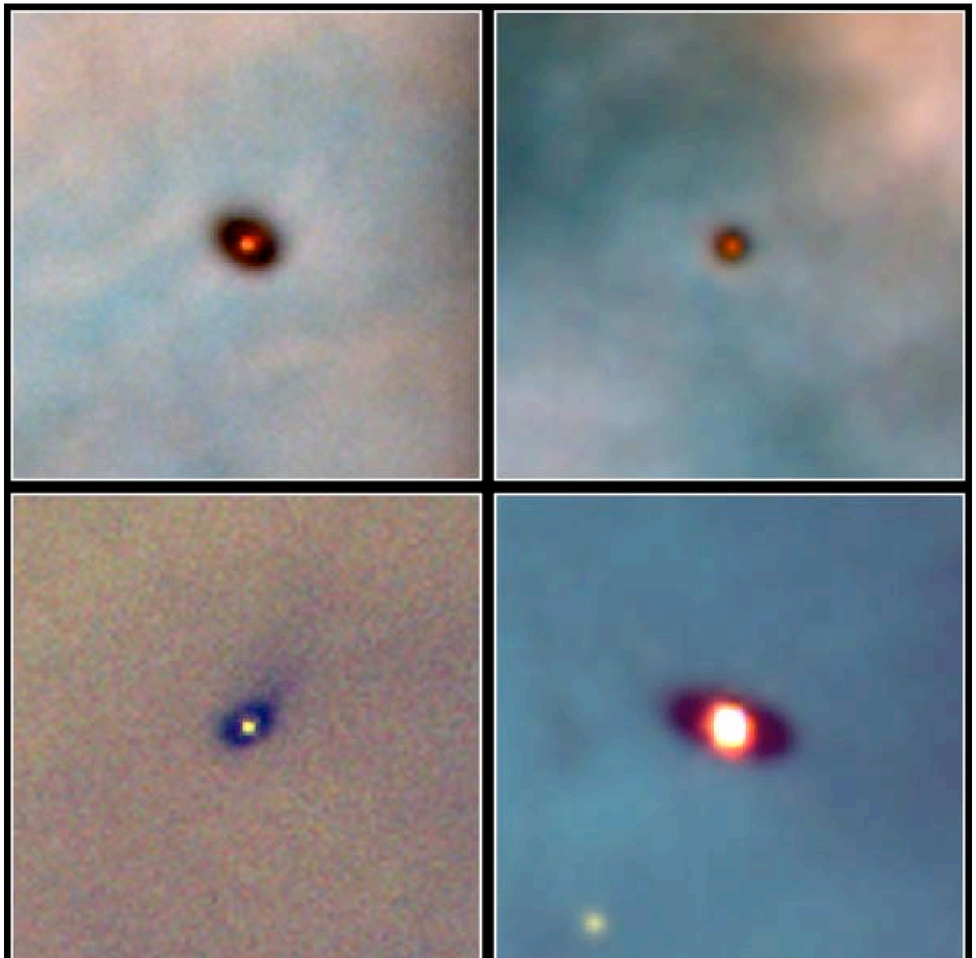
Star-Birth Clouds · M16 HST · WFPC2

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



Star Formation

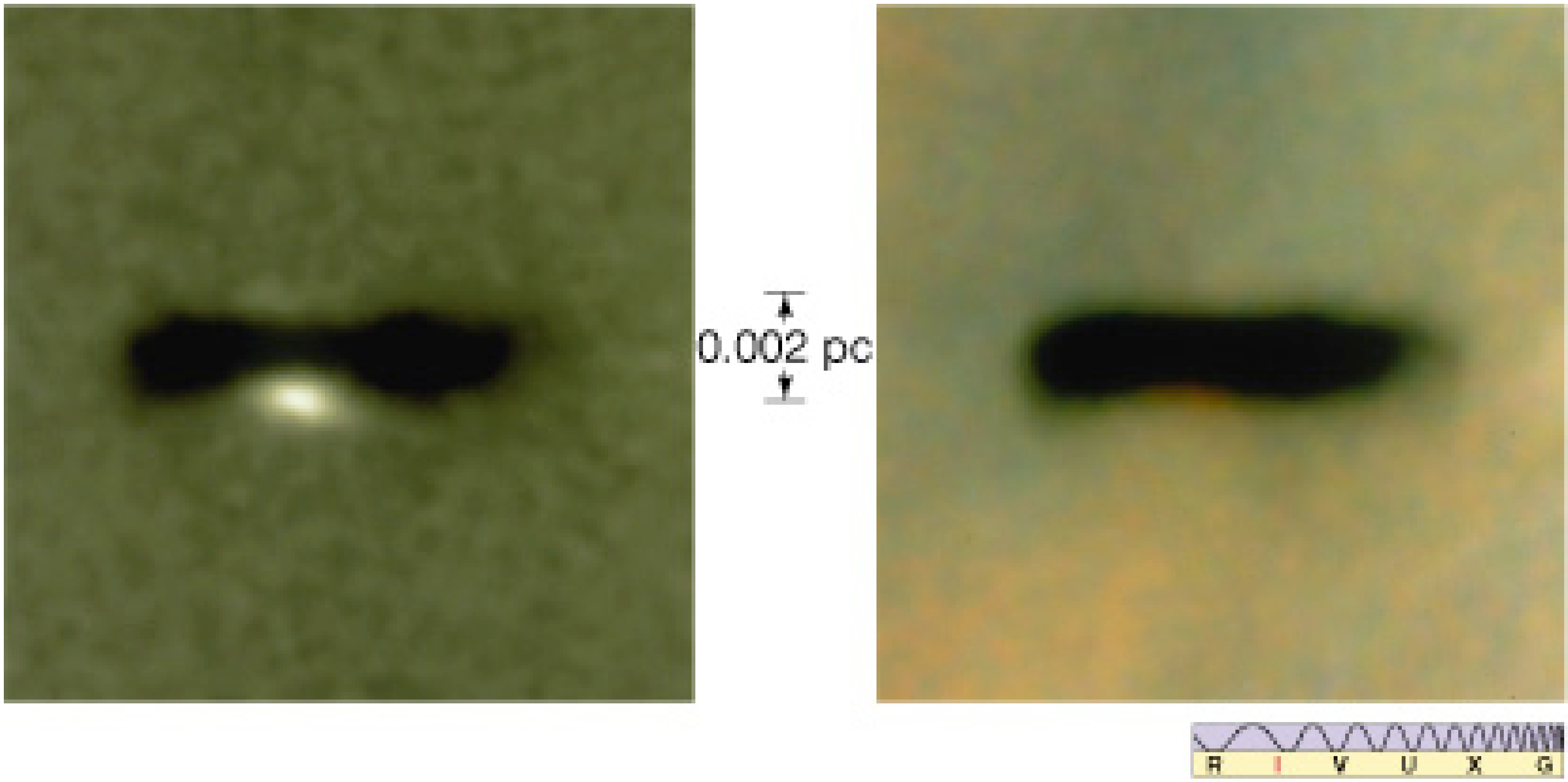
- With HST in particular and now with AO and IR detectors on large groundbased telescopes we are observing the various stages of protostar contraction.
- The presence of disks was predicted and verified for the first time about 10 years ago.



Protoplanetary Disks
Orion Nebula

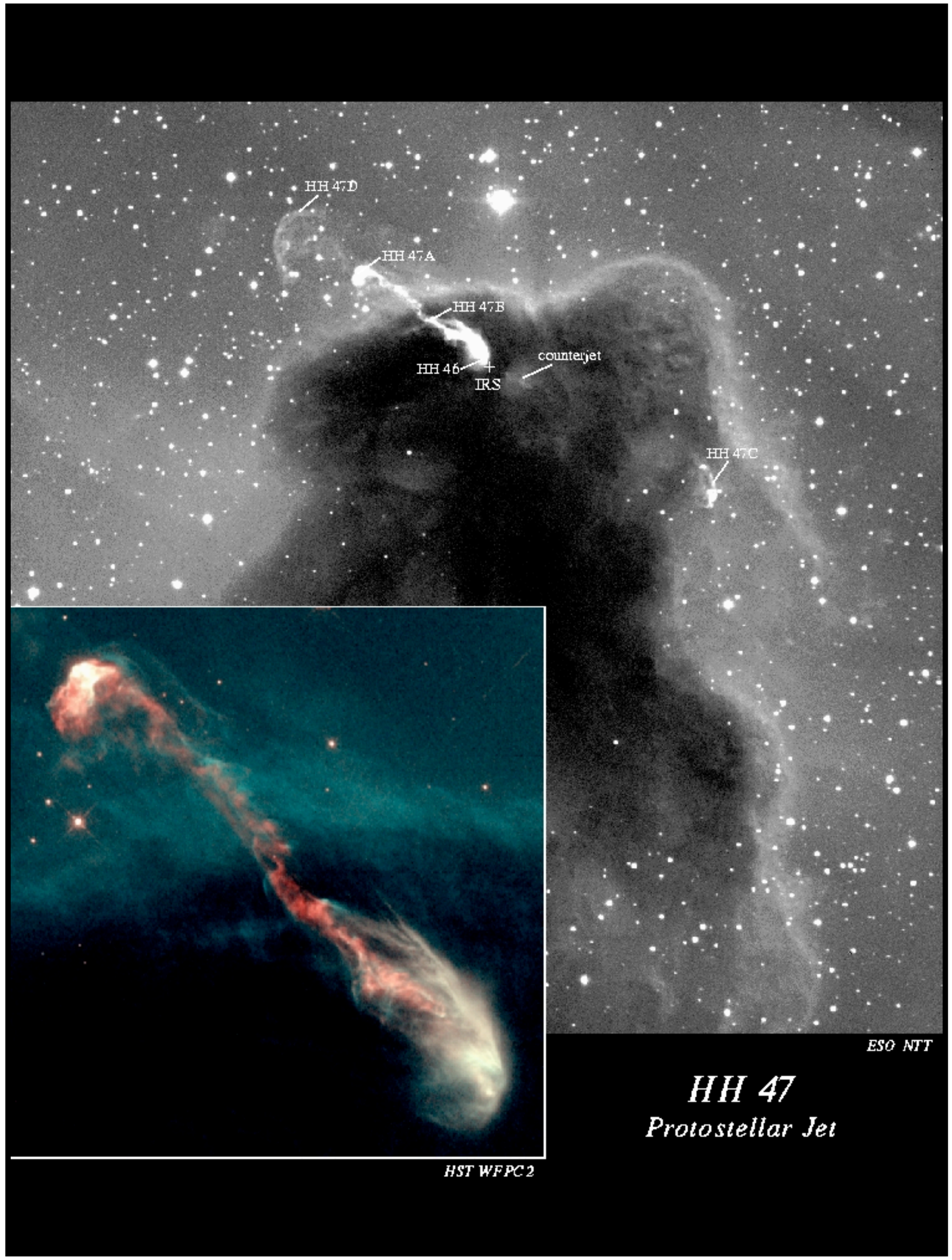
HST • WFPC2

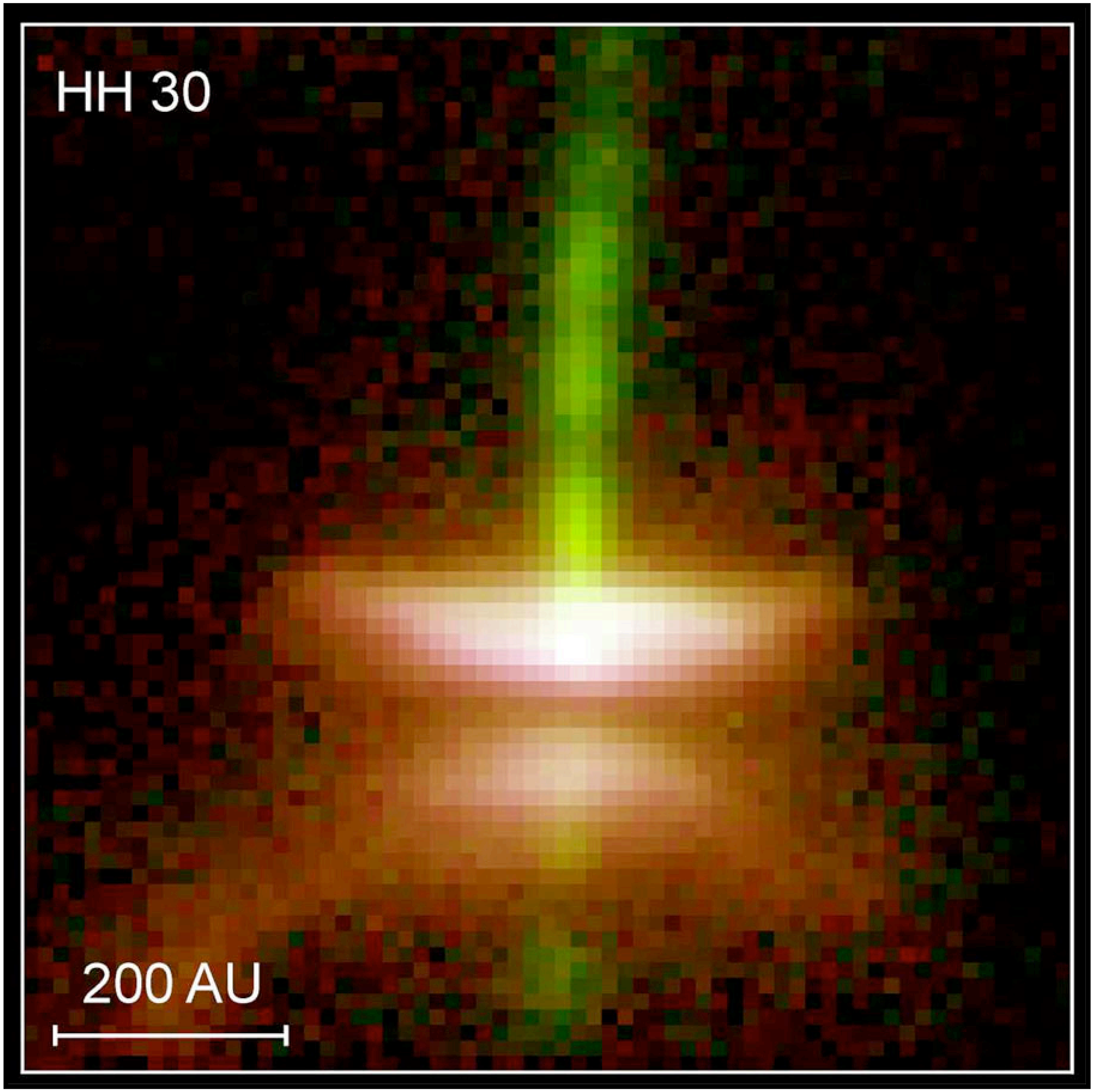
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA


0.002 pc
R
I
V
U
X
G

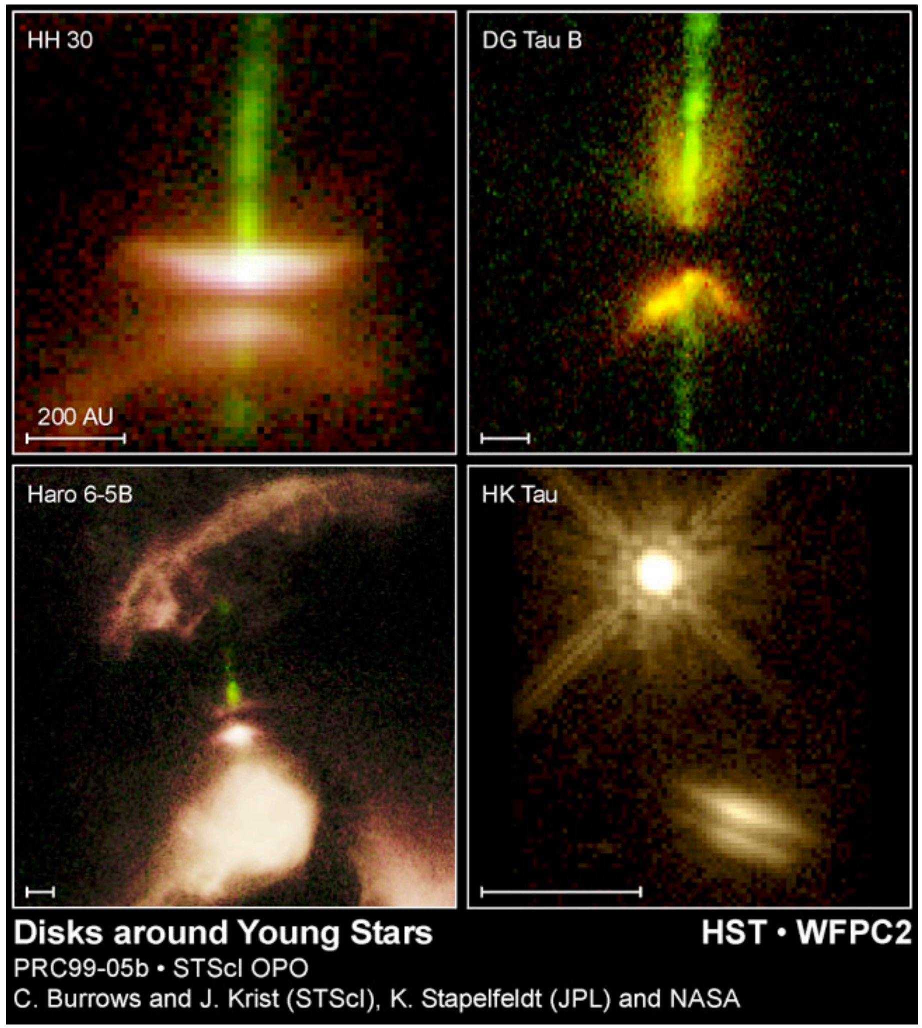
Star Formation: Outflows

- 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

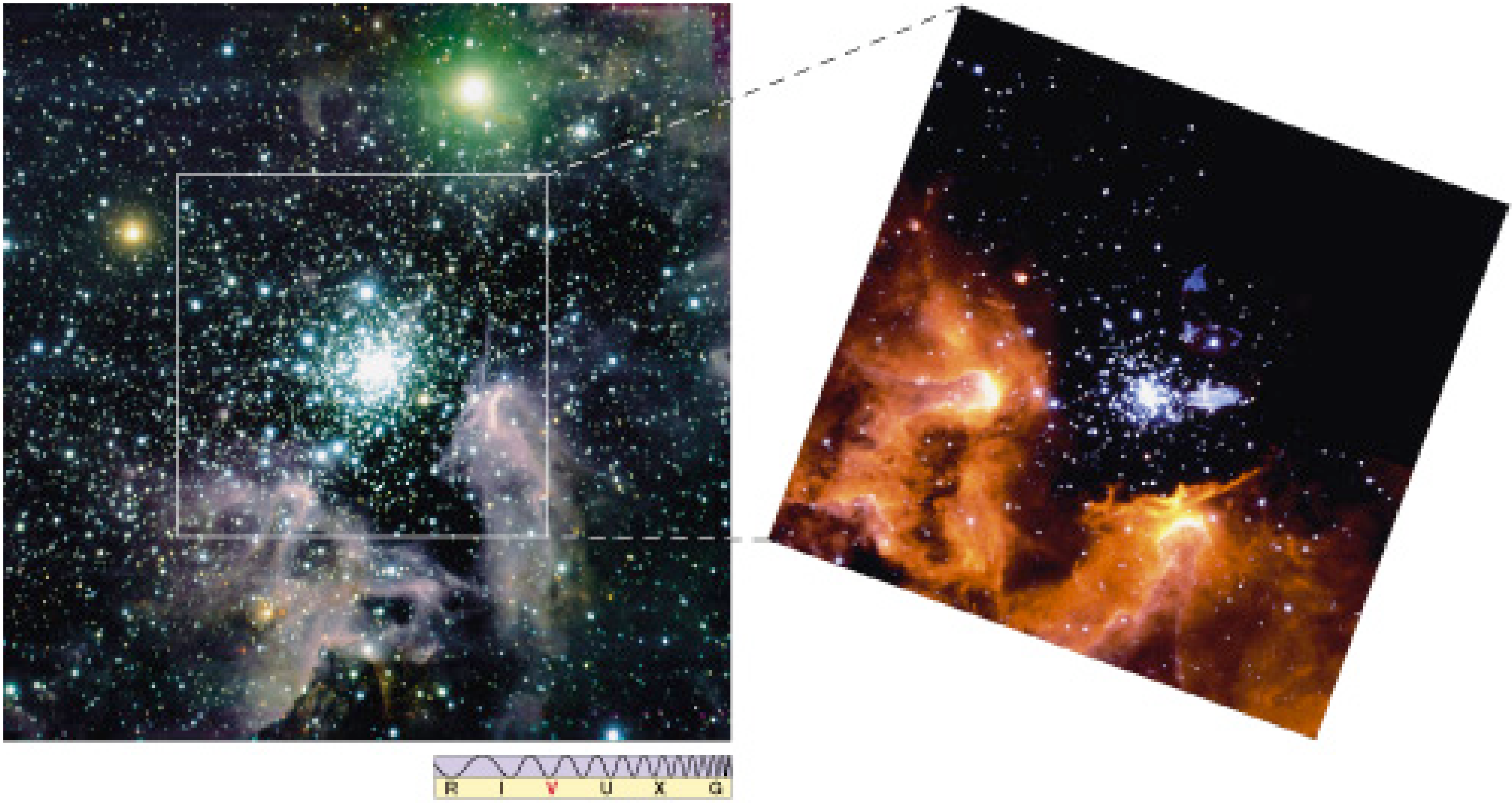


Star Formation Outflows

- 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