Energy

mosquito lands on your arm = 1 erg

Firecracker = 5 x 10^{9} ergs

1 stick of dynamite = 2 x 10^{13} ergs

1 ton of TNT = 4 x 10^{16} ergs

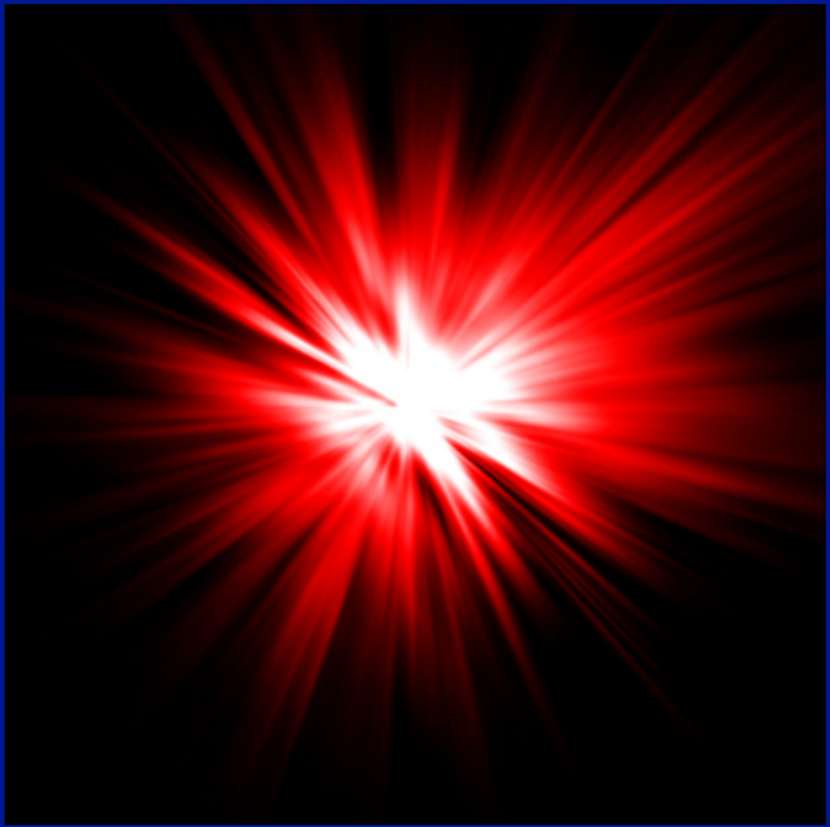
1 atomic bomb = 1 x 10^{21} ergs

Magnitude 8 earthquake = 1 x 10^{26} ergs

Earth's daily solar input = 1 x 10^{29} ergs

Planet cracker = 1 x 10^{32} ergs

Luminosity of the sun = 4 x 10^{33} ergs/sec



2) Globular Clusters

- few x 10^5 or 10^6 stars

- size about 50 pc

- very tightly packed, roughly spherical shape

- billions of years old

Clusters are crucial for stellar evolution studies because:

1) All stars in a cluster formed at about same time (so all have same age)

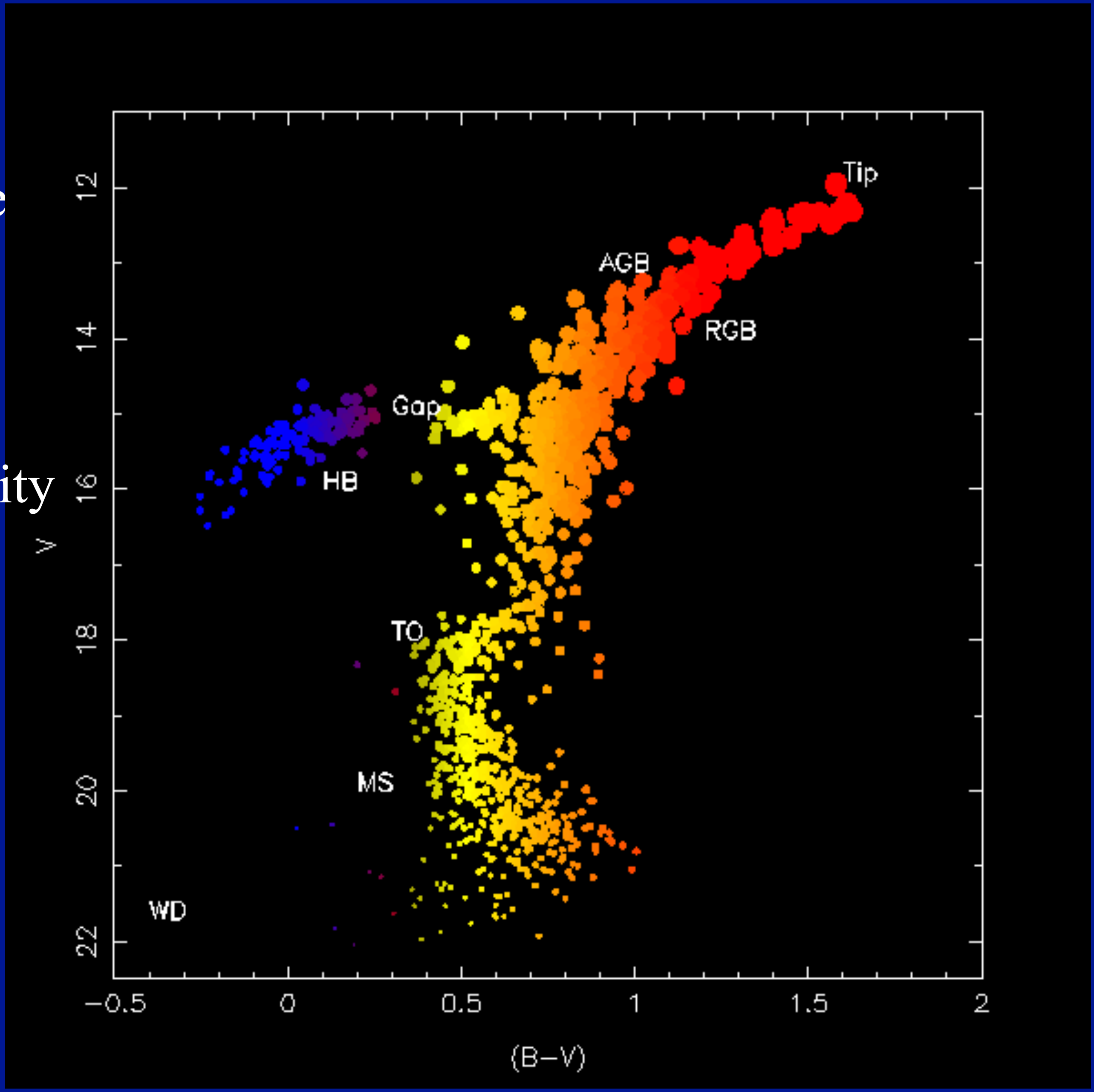
2) All stars are at about the same distance

3) All stars have same chemical composition

2) Globular Clusters

All stars about the same age
Differences all have to do with initial mass

Luminosity



Temperature

Clicker Question:

The HR diagram is a plot of stellar

A: mass vs diameter.

B: luminosity vs temperature

C: mass vs luminosity

D: temperature vs diameter

Clicker Question:

What would be the lifetime of a star three times more massive as our sun?

A: 1 billion years = 10^9 years

B: 10 billion years = 10^{10} years

C: 100 billion years = 10^{11} years

D: 1 trillion years = 10^{12} years

Clicker Question:

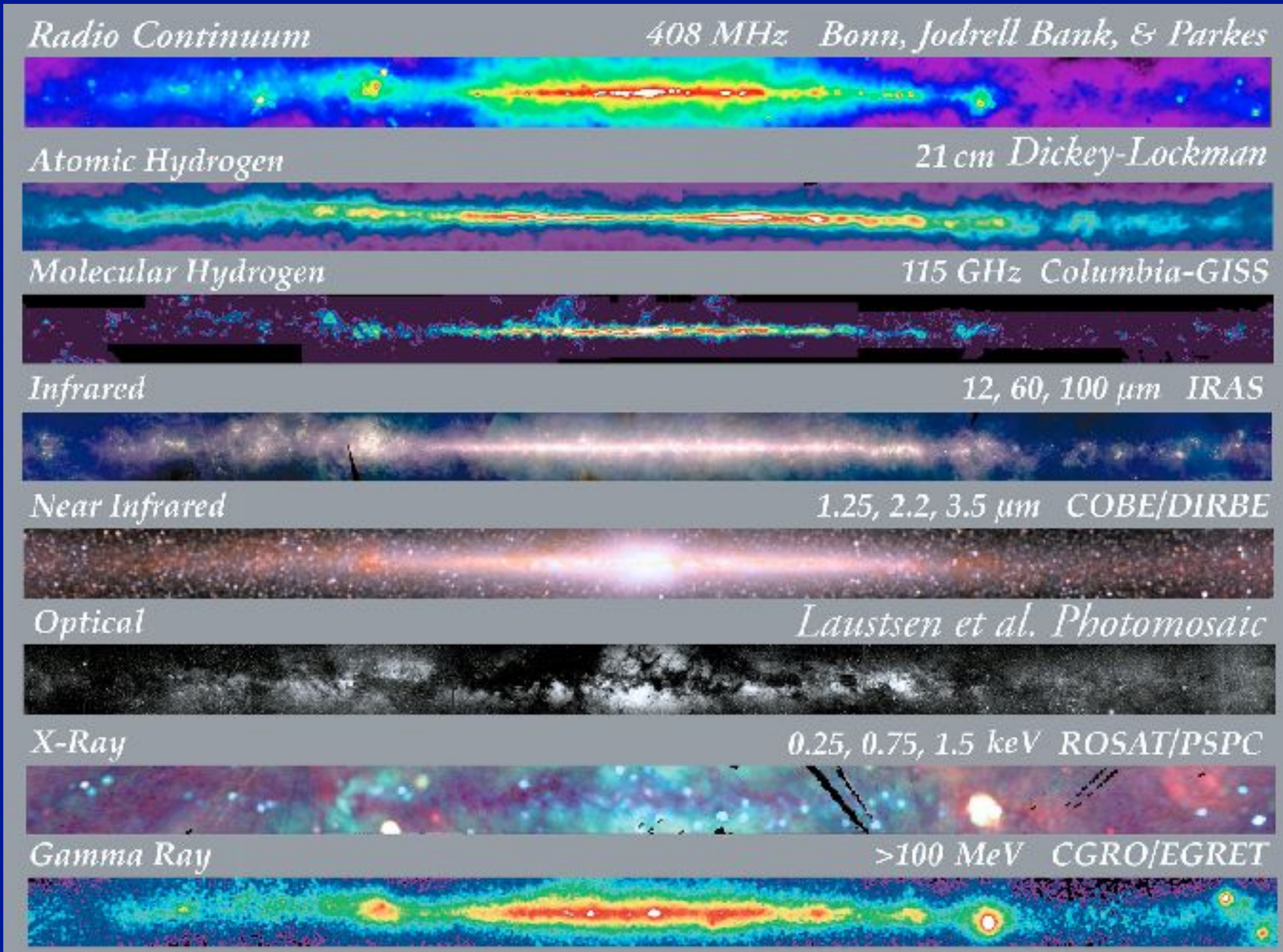
What would be the lifetime of a star one tenth as massive as our sun?

A: 1 billion years = 10^9 years

B: 10 billion years = 10^{10} years

C: 100 billion years = 10^{11} years

D: 1 trillion years = 10^{12} years


Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen
21 cm Dickey-Lockman
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET

The Interstellar Medium (ISM) of the Milky Way Galaxy

Or: The Stuff (gas and dust) Between the Stars

Why study it?

Stars form out of it.
Stars end their lives by returning gas to it.

The ISM has:

a wide range of structures
a wide range of densities (10^{-3} - 10^{7} atoms / cm^3)
a wide range of temperatures (10 K - 10^7 K)

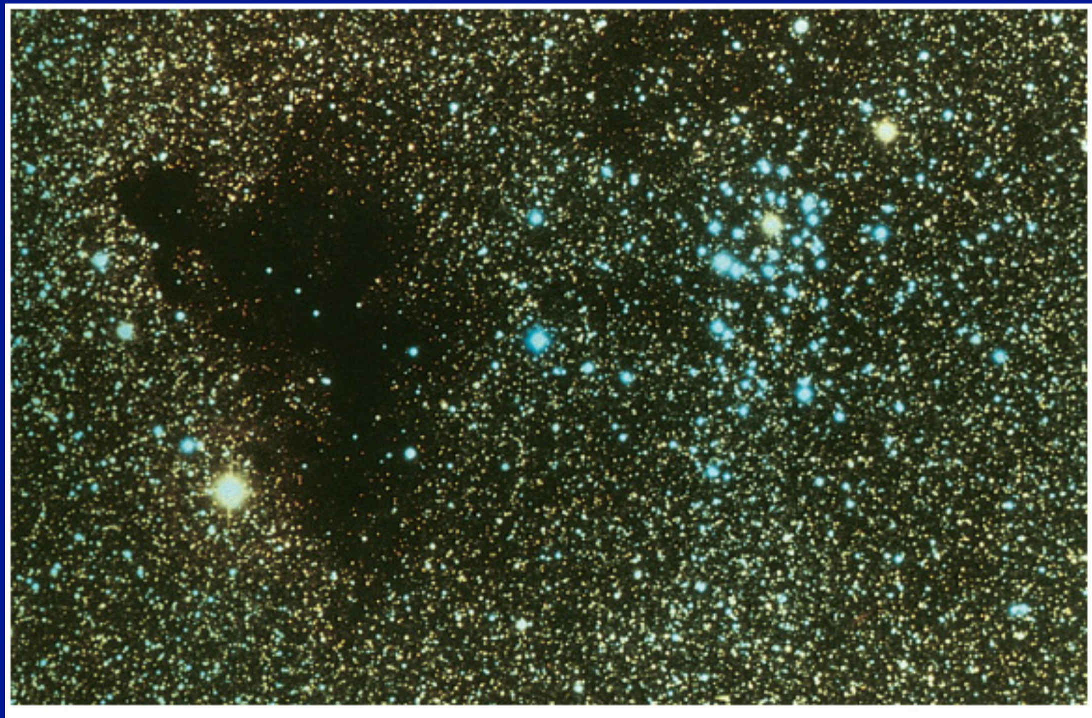
Compare density of ISM with Sun or planets:

Sun and Planets: 1-5 g / cm^3

ISM average: 1 atom / cm^3

Mass of one H atom is 10^{-24} g!
So ISM is about 10^{24} times as tenuous as a star or planet!

ISM consists of gas (mostly H, He) and dust. 98% of mass is in gas, but dust, only 2%, is also observable.

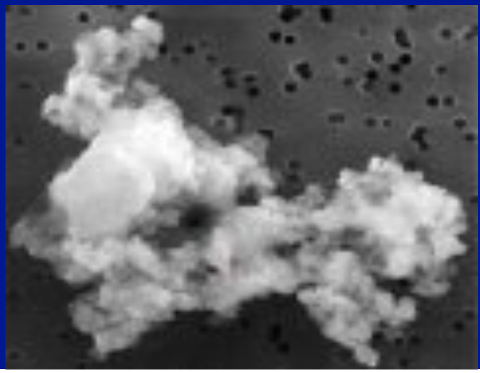


Effects of dust on light:

1) "Extinction"
   Blocks out light

2) "Reddening"
   Blocks out short wavelength light better than long wavelength light => makes objects appear redder.

Grain sizes typically 10^{-5} cm. Composition uncertain, but probably silicates, graphite and iron.



Gas Structures in the ISM

Emission Nebulae or H II Regions

Regions of gas and dust near stars just formed.

The Hydrogen is essentially fully ionized.

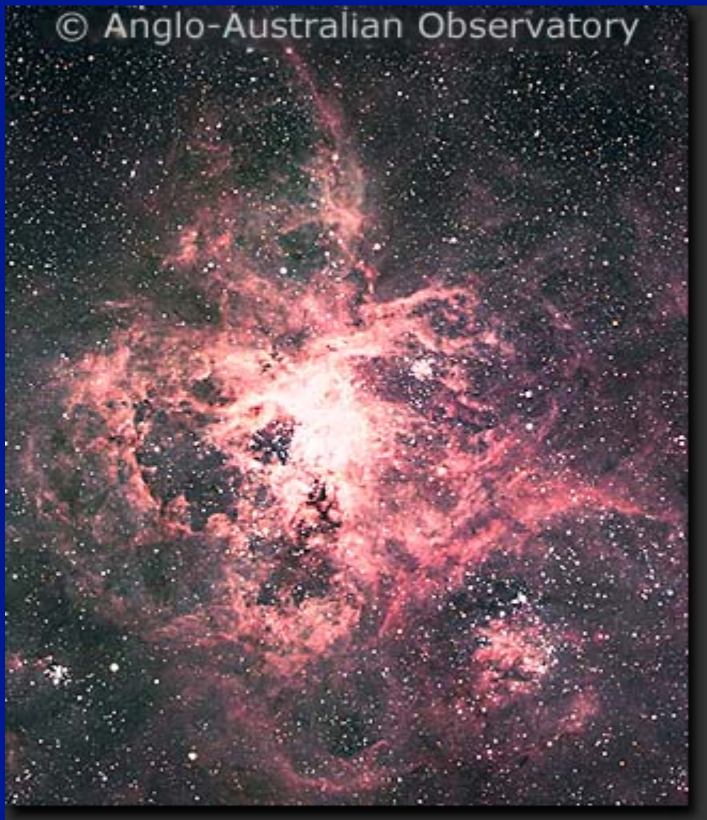
Temperatures near 10,000 K

Sizes about 1-20 pc.

Hot tenuous gas => emission lines
(Kirchhoff's Laws)

Rosette Nebula

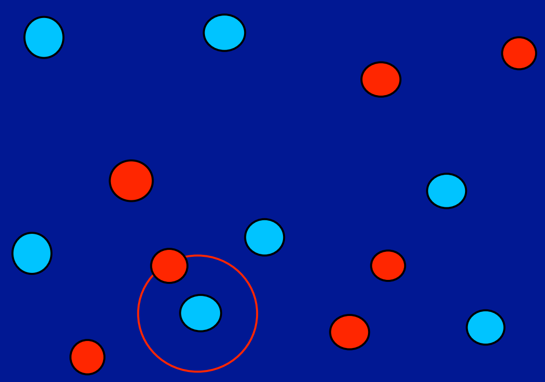
Lagoon Nebula



Tarantula Nebula

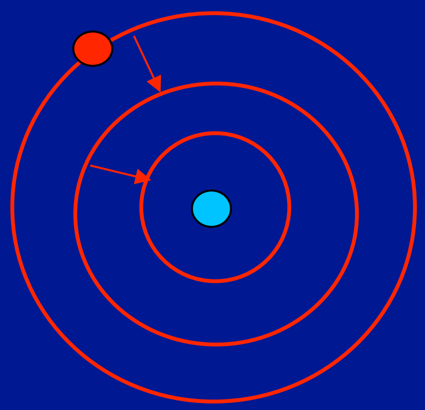
Red color comes from one emission line of H (tiny fraction of H is atoms, not ionized).

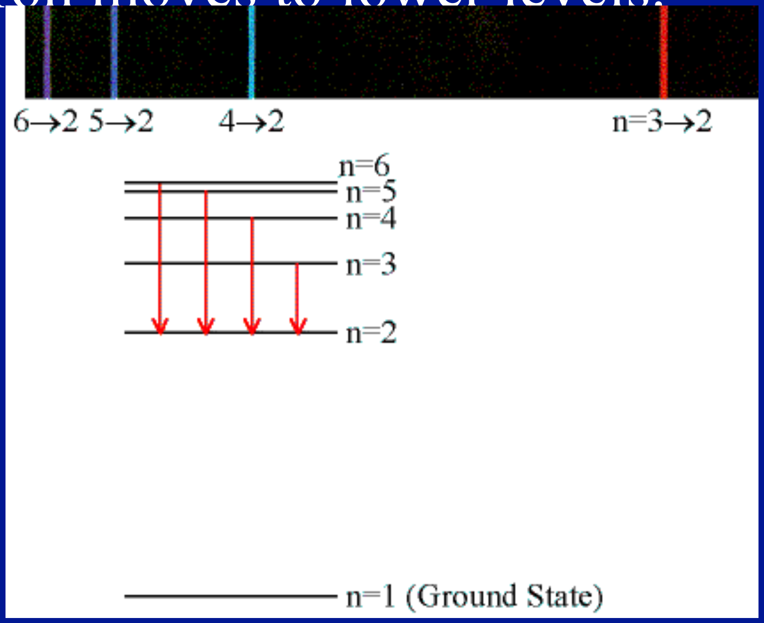
Why red? From one bright emission line of H. But that requires H atoms, and isn't all the H ionized? Not quite.



Sea of protons and electrons

Once in a while, a proton and electron will rejoin to form H atom. Can rejoin to any energy level. Then electron moves to lower levels.





Emits photon when it moves downwards. One transition produces red photon. This dominates emission from nebula.

Why is the gas ionized?

Remember, takes energetic UV photons to ionize H. Hot, massive stars produce huge amounts of these.

Such short-lived stars spend all their lives in the stellar nursery of their birth, so emission nebulae mark sites of ongoing star formation.

Many stars of lower mass are forming too, but make few UV photons.

Why "H II Region?

H I: Hydrogen atom
H II: Ionized Hydrogen
. . .
O III: Oxygen missing two electrons
etc.

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

H I Gas and 21-cm radiation

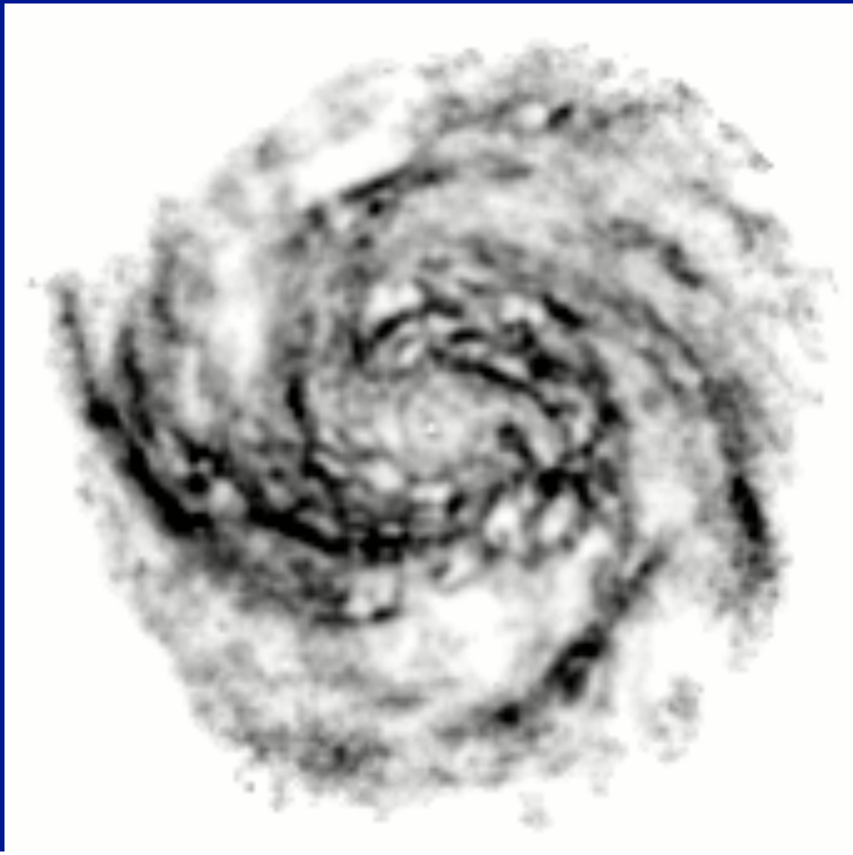
Gas in which H is atomic.

Fills much (most?) of interstellar space. Density ~1 atom / cm^3.

Too cold (~100 K) to give optical emission lines.
Primarily observed through radiation of H at wavelength of 21 cm.

H I accounts for almost half the mass in the ISM: ~2 x 10^9 M_{Sun} !

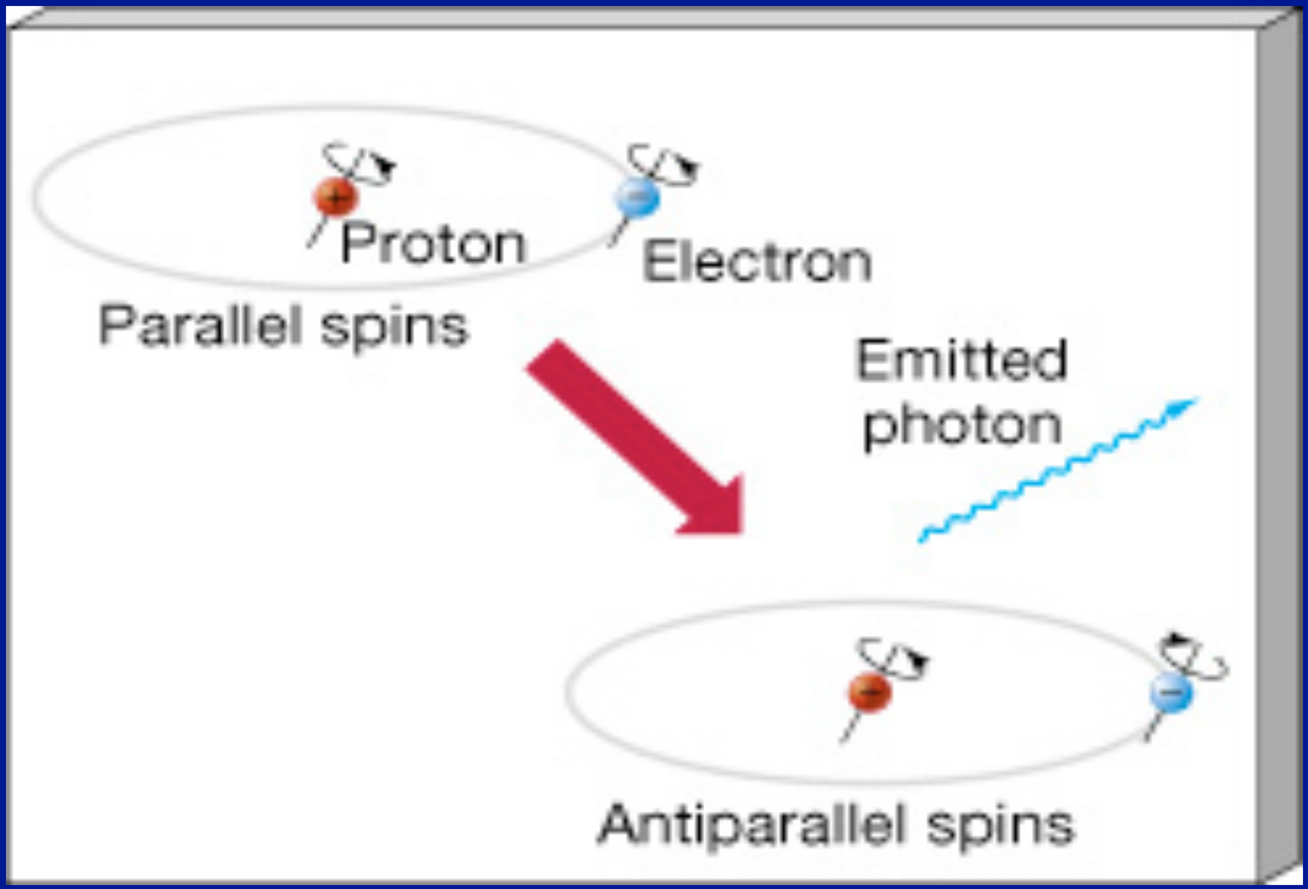
Galaxy IC 342 in visible light



HI in IC 342 from VLA

Origin of 21-cm photon:

The proton and electron each have “spin”.   A result from quantum mechanics: if both spinning the same way, atom's energy is slightly higher. Eventually will make transition to state of opposite spins. Energy difference is small -> radio photon emitted, wavelength 21-cm.



Molecular Gas

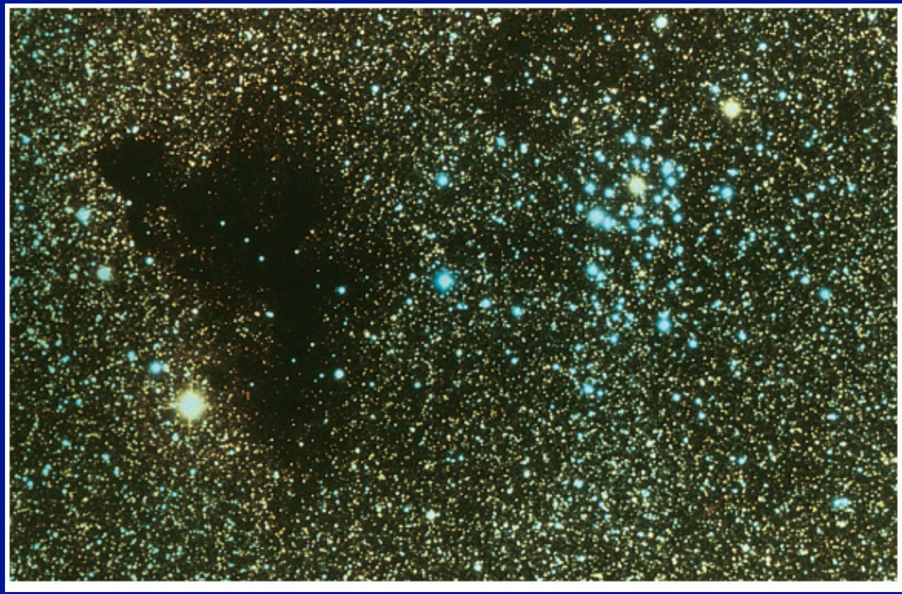
It's in the form of cold (~10 K) dense (~10^3 - 10^7 molecules / cm^3) clouds.

Molecular cloud masses: 10^3 - 10^6 M_{Sun} !

Sizes: a few to 100 pc.

1000 or so molecular clouds in ISM. Total mass about equal to H I mass.

Optically, seen as dark dust clouds.



Clicker Question:

What does does ionized Helium, He II, contain?

A: He nucleus only

B: He nucleus and one electron

C: He nucleus and two electrons

D: He nucleus and three electrons

Clicker Question:

What is an H II region?

A: A cold region where the hydrogen gas is mostly molecular

B: A region filled with neutral hydrogen gas

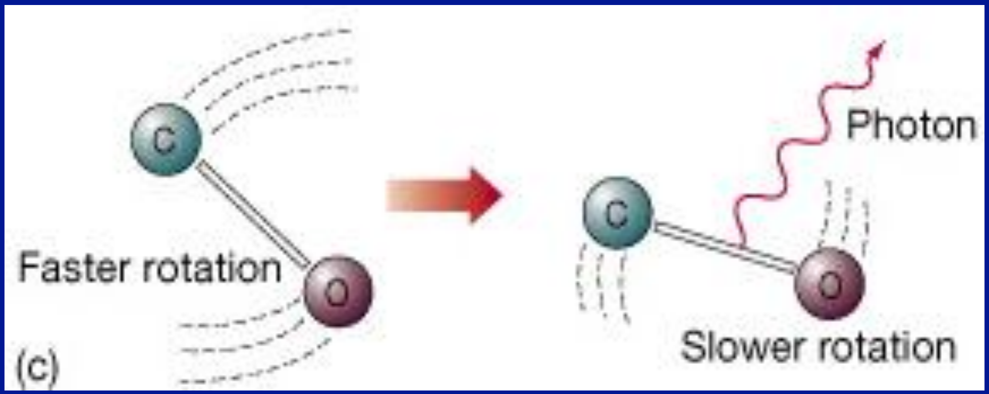
C: A region where there is hydrogen gas is mostly ionized.

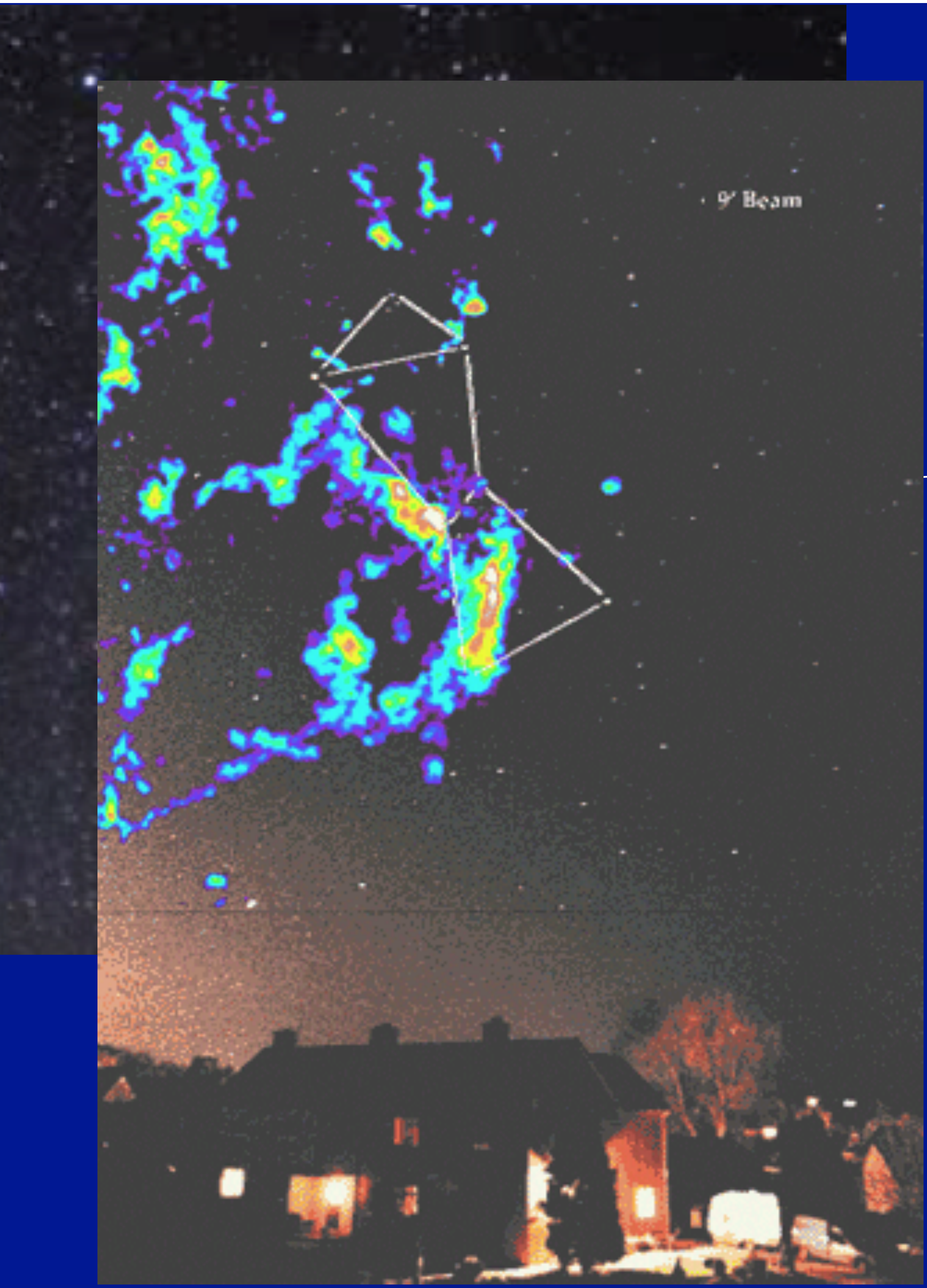
D: A region where the hydrogen gas is mostly atomic.

We can observe emission from molecules. Most abundant is H_2 (don't confuse with H II), but its emission is extremely weak, so other "trace" molecules observed:

CO	(carbon monoxide)
H_2O	(water vapor)
HCN	(hydrogen cyanide)
NH_3	(ammonia)
etc. . .	

These emit photons with wavelengths near 1 mm when they make a rotational energy level transition. Observed with radio telescopes.





False-color of CO emission from Orion molecular cloud complex.
Best studied case. 500 pc away.
400,000 M_{Sun} of gas.
Note complicated structure!

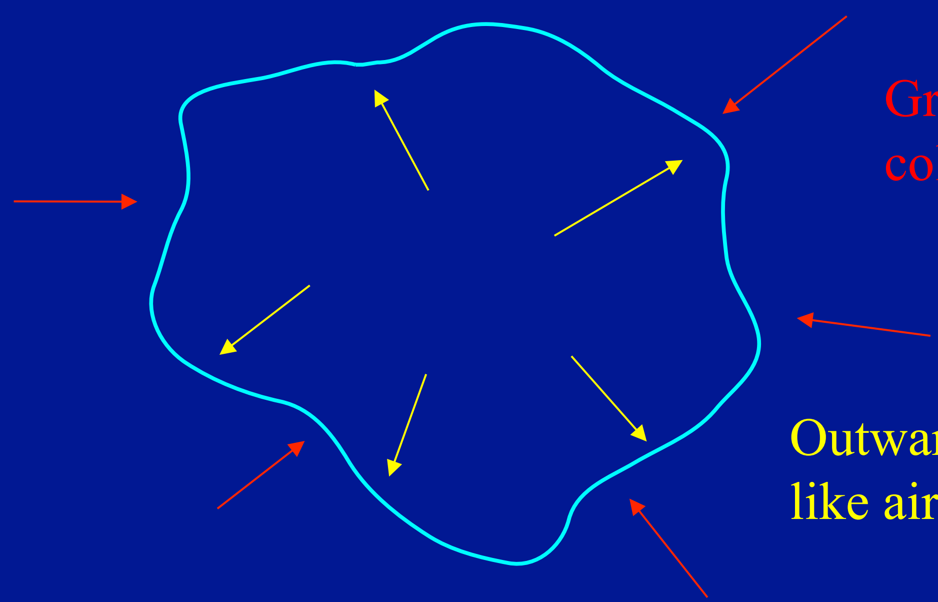
approximate position of Orion nebula

Molecular Clouds important because stars form out of them!
They tend to be associated with Emission Nebulae.

Star Formation

Stars form out of molecular gas clouds. Clouds must collapse to form stars (remember, stars are ~10^{20} x denser than a molecular cloud).

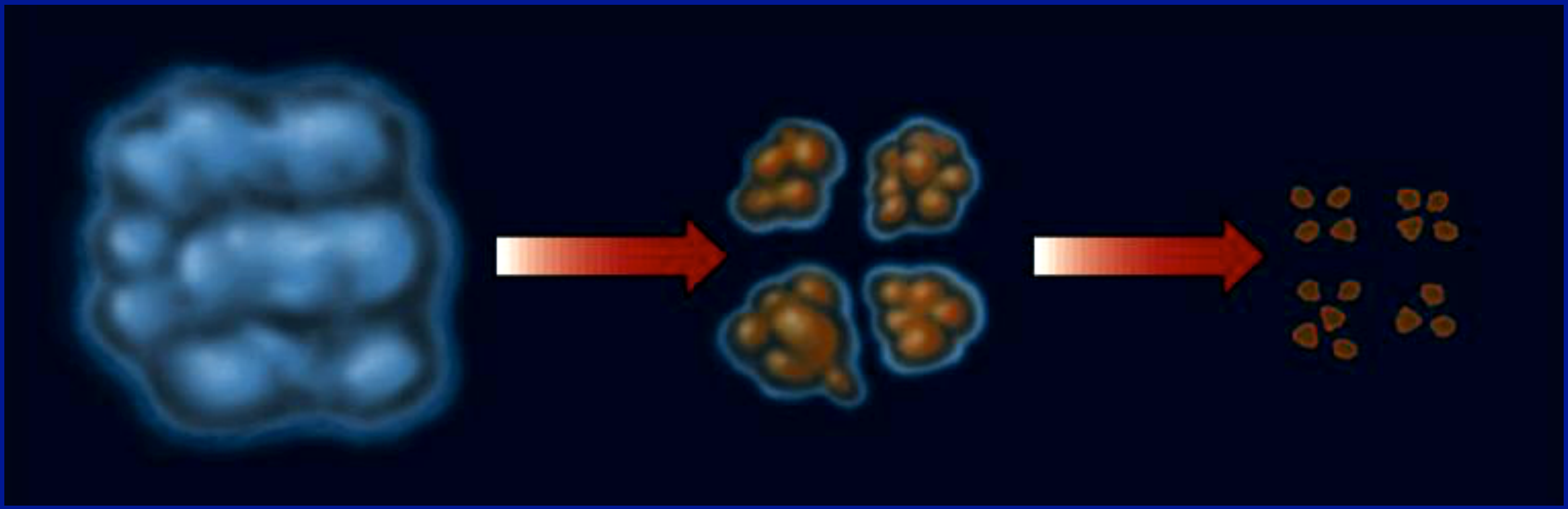
Probably new molecular clouds form continually out of less dense gas. Some collapse under their own gravity. Others may be more stable. Magnetic fields and rotation also have some influence.

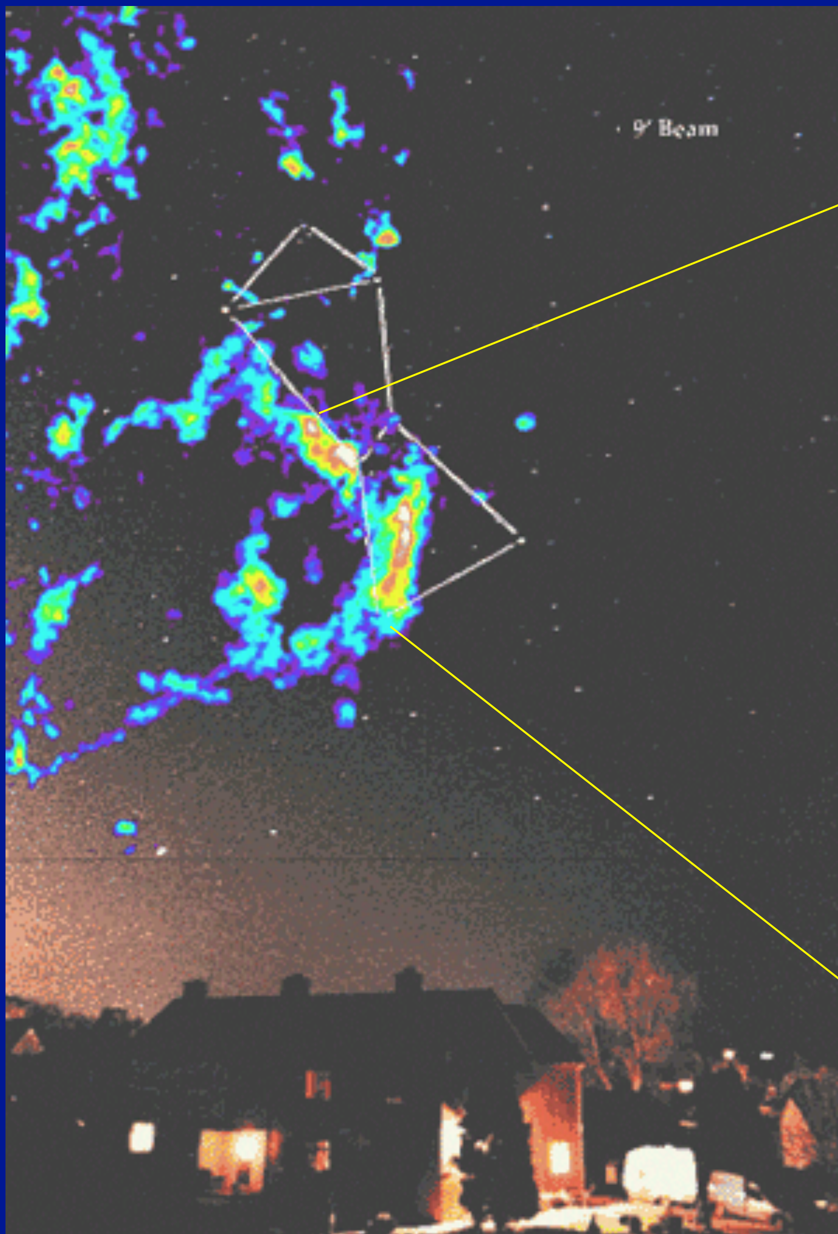


Gravity makes cloud want to collapse.

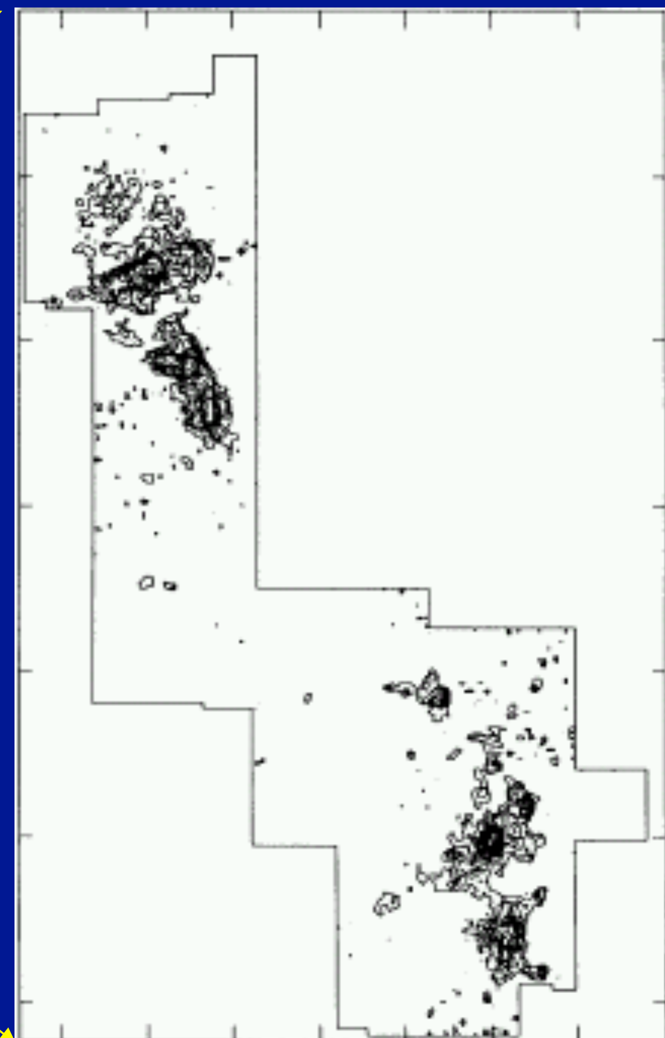
Outward gas pressure resists collapse, like air in a bike pump.

When a cloud starts to collapse, it should fragment. Fragments then collapse on their own, fragmenting further. End product is 100's or 1000's of dense clumps each destined to form star, binary star, etc. Hence a cloud gives birth to a cluster of stars.

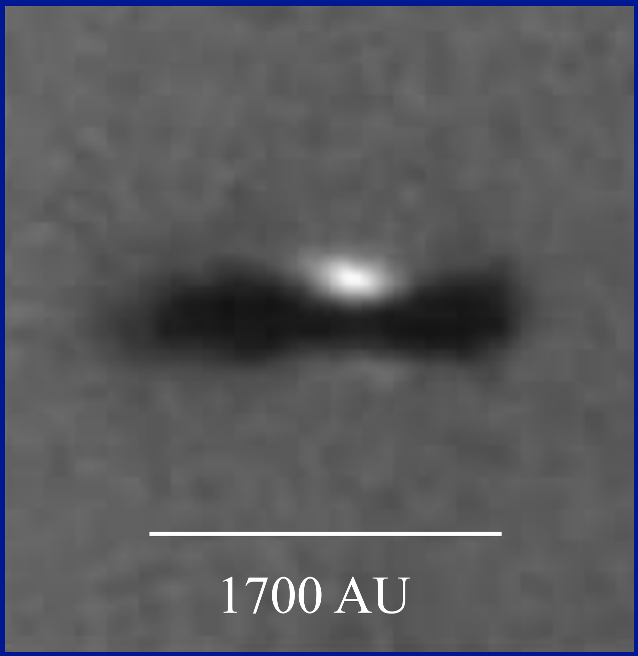




Fragments in Orion molecular cloud, about 1000 x denser than average gas in cloud.



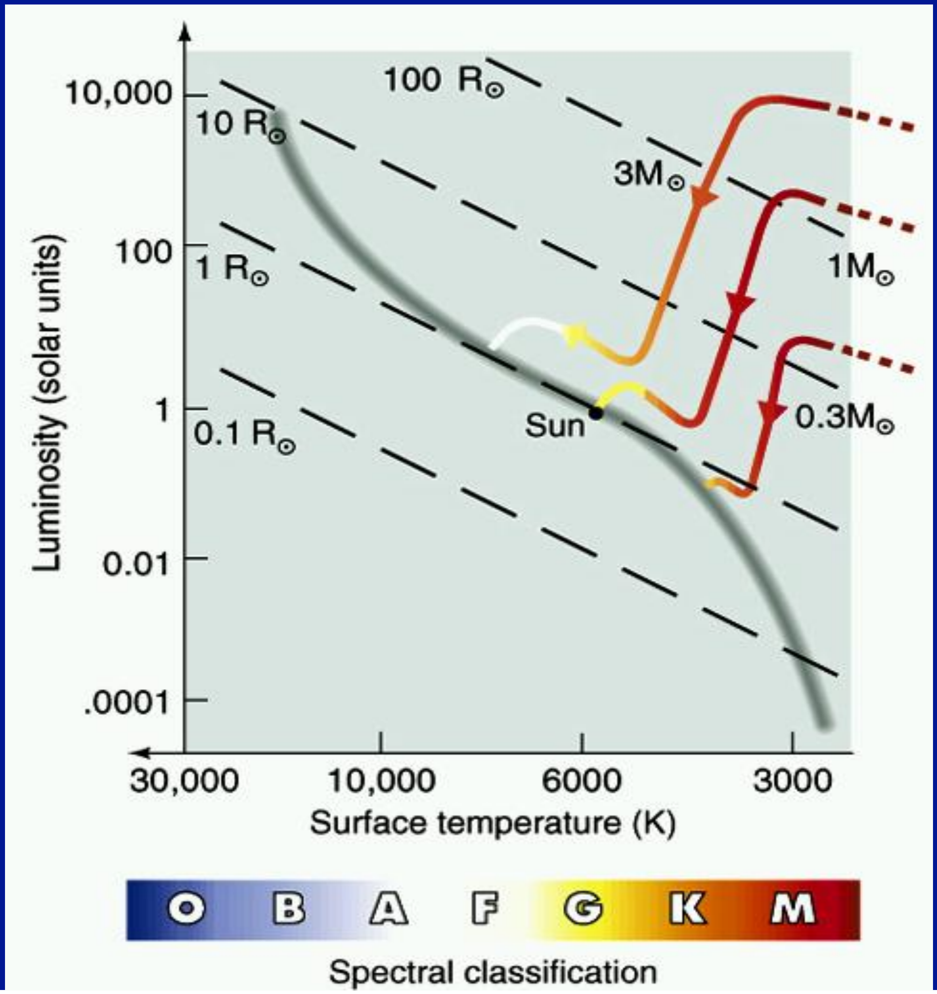
As a clump collapses, it heats up. Becomes very luminous.
Now a protostar. May form proto-planetary disk.

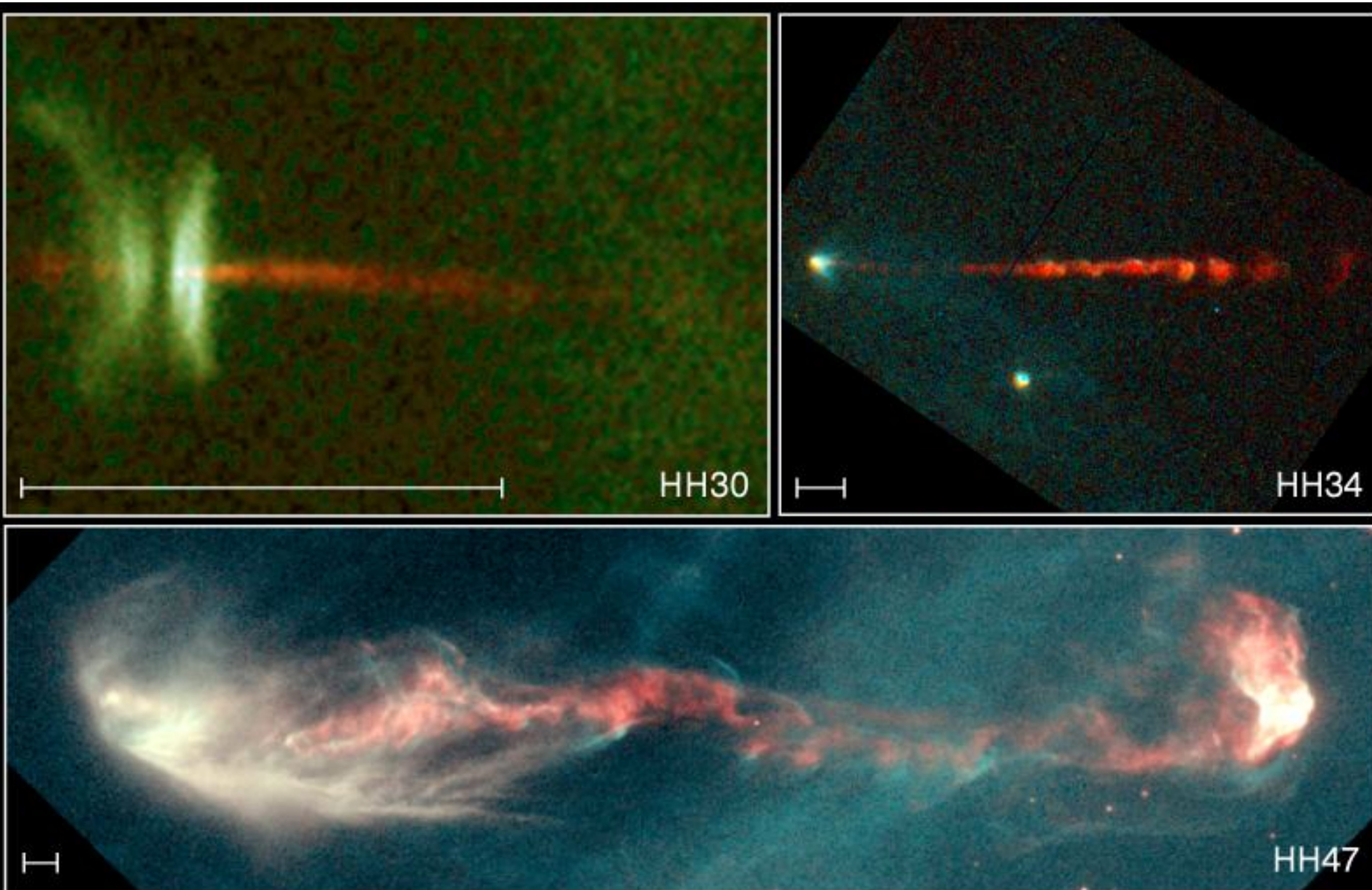


DEMO

Protostar and proto-planetary disk in Orion

Eventually hot and dense enough => spectrum approximately black-body. Can place on HR diagram.
Protostar follows "Hayashi tracks"
Dramatic mass loss





Jets from Young Stars

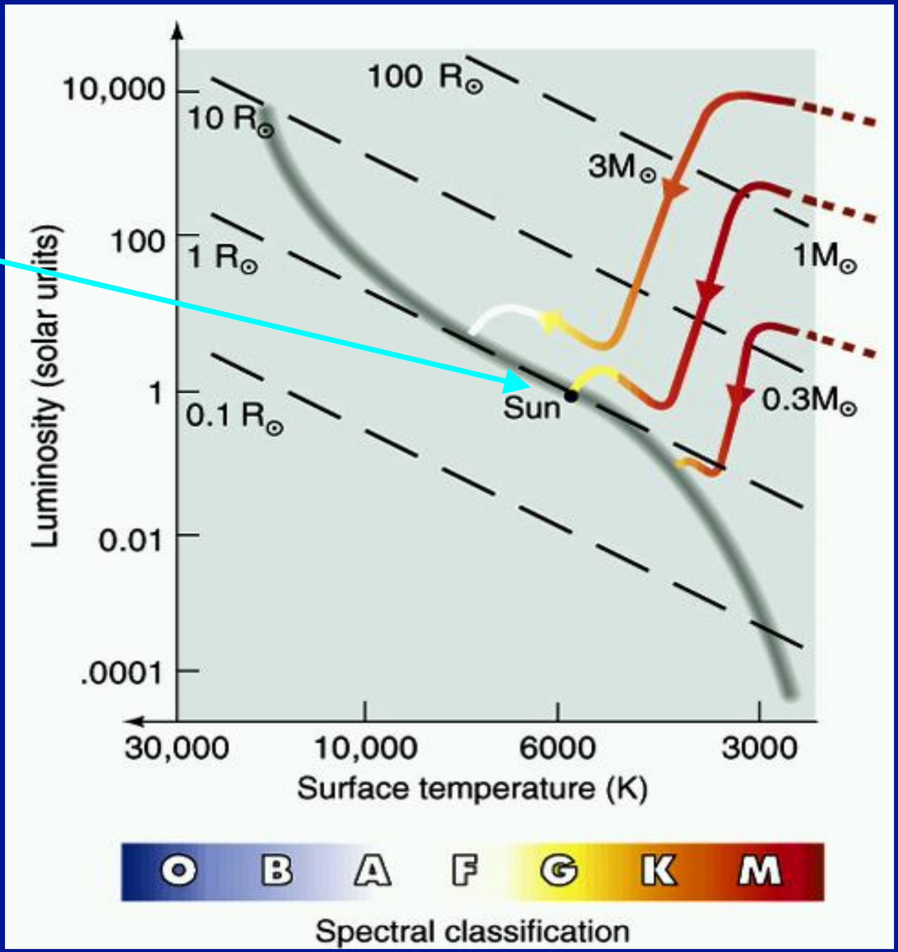
HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Finally, fusion starts, stopping collapse: a star!

Star reaches Main Sequence at end of Hayashi Track

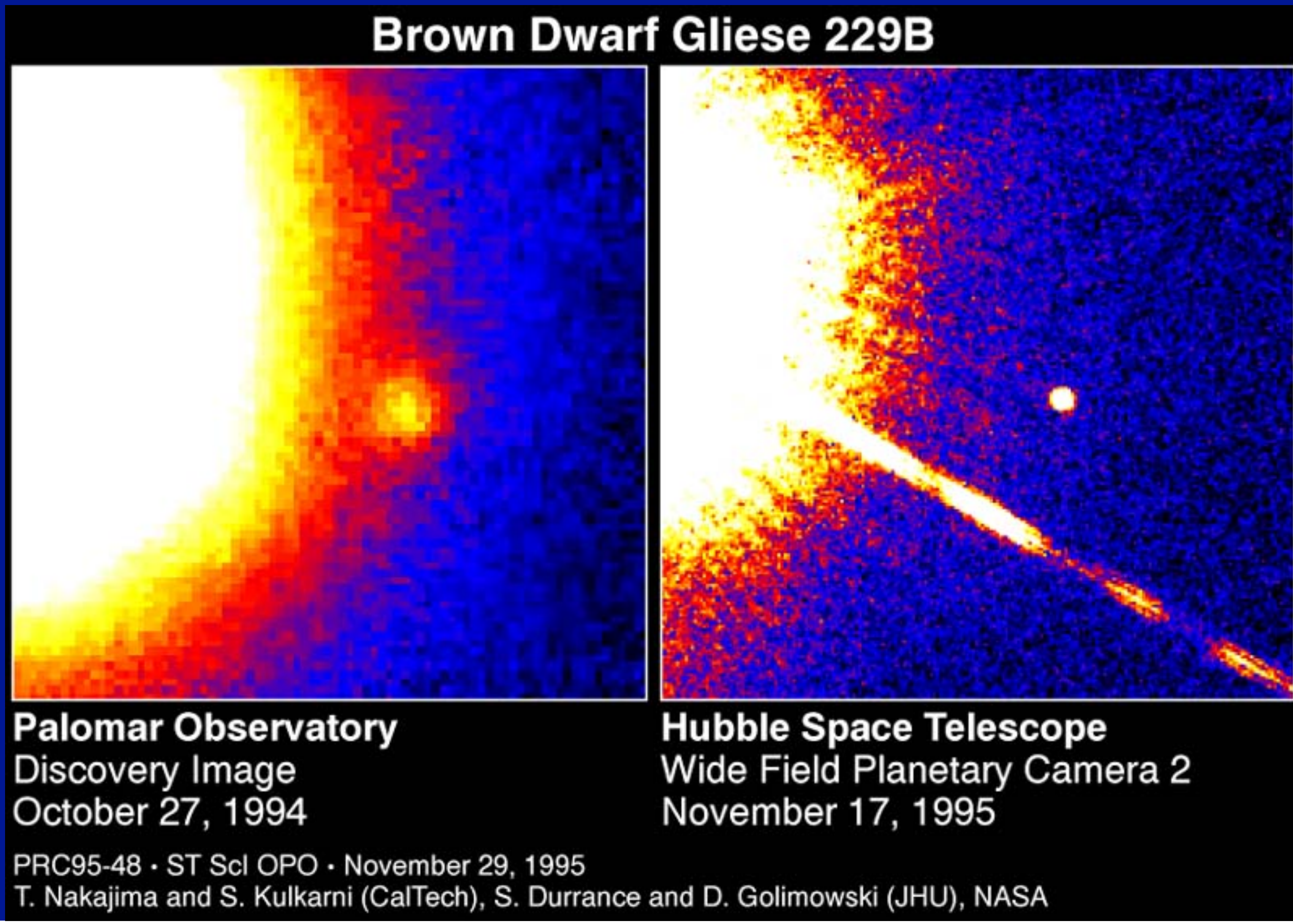


One cloud (10^3 - 10^6 M_{Sun}) forms many stars, mainly in clusters, in different parts at different times.

Massive stars (50-100 M_{Sun}) take about 10^6 years to form, least massive (0.1 M_{Sun}) about 10^9 years. Lower mass stars more likely to form.
In Milky Way, a few stars form every year.

Brown Dwarfs

Some protostars not massive (< 0.08 M_{Sun}) enough to begin fusion. These are Brown Dwarfs or failed stars. Very difficult to detect because so faint. First seen in 1994 with Palomar 200". How many are there?



Clicker Question:

A giant protostar of 100 R_{sun} is heated by what process?

A: burning of chemical elements

B: nuclear fission

C: gravitational collapse

D: nuclear fusion

Clicker Question:

Star formation in the ISM today happens most often:

A: In the Oort cloud.

B: In dense molecular clouds.

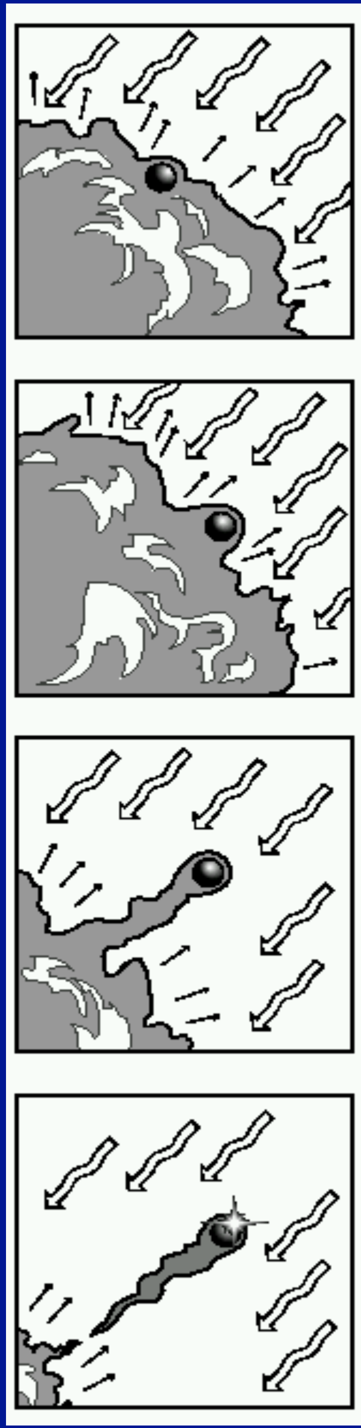
C: In the central parsecs of the Galaxy.

D: In globular clusters

The Eagle Nebula

Other hot stars illuminating these clouds

1 pc



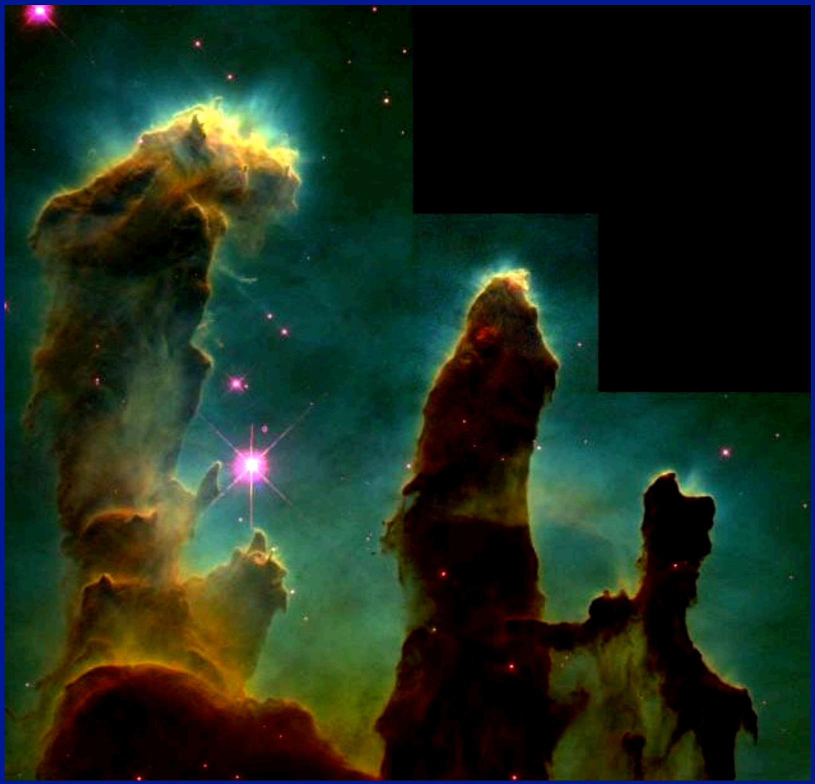
Molecular cloud surface illuminated by nearby hot stars.

Radiation evaporates the surface, revealing a dense globule - a protostar.

Shadow of the protostar protects a column of gas behind it.

Eventually structure separates from the cloud, and the protostar will be uncovered.

visible light



infrared

Remember: longer wavelength radiation is not so easily absorbed by dust!

Horsehead Nebula in Orion

Newly formed stars in Orion with Protoplanetary Disks (Hubble)