

# *The Interstellar Medium*

<http://apod.nasa.gov/apod/astropix.html>

# THE INTERSTELLAR MEDIUM (ISM)

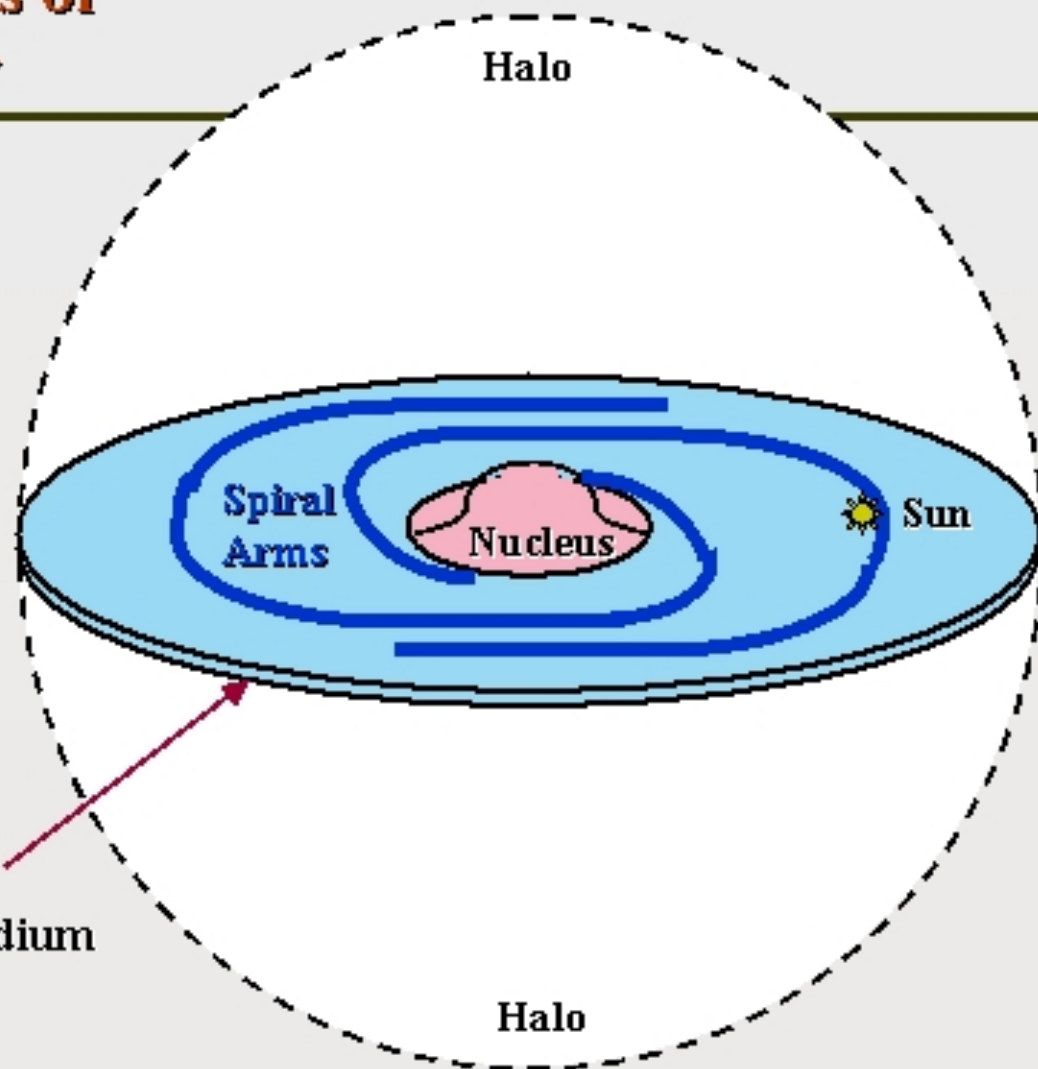
- Total mass  $\sim 5$  to  $10 \times 10^9$  solar masses of about 5 – 10% of the mass of the Milky Way Galaxy interior to the sun's orbit
- Average density overall about  $0.5 \text{ atoms/cm}^3$  or  $\sim 10^{-24} \text{ g cm}^{-3}$ , but large variations are seen
- Elemental Composition - essentially the same as the surfaces of Population I stars, but the gas may be ionized, neutral, or in molecules or dust.
  - H I – neutral atomic hydrogen
  - H<sub>2</sub> - molecular hydrogen
  - H II – ionized hydrogen
  - He I – neutral helium
  - Carbon, nitrogen, oxygen, dust, molecules, etc.

# THE INTERSTELLAR MEDIUM

- Energy input – starlight (especially O and B), supernovae, cosmic rays
- Cooling – line radiation from atoms and molecules and infrared radiation from dust
- Largely concentrated (in our Galaxy) in the disk

## Structure and Components of Our Galaxy

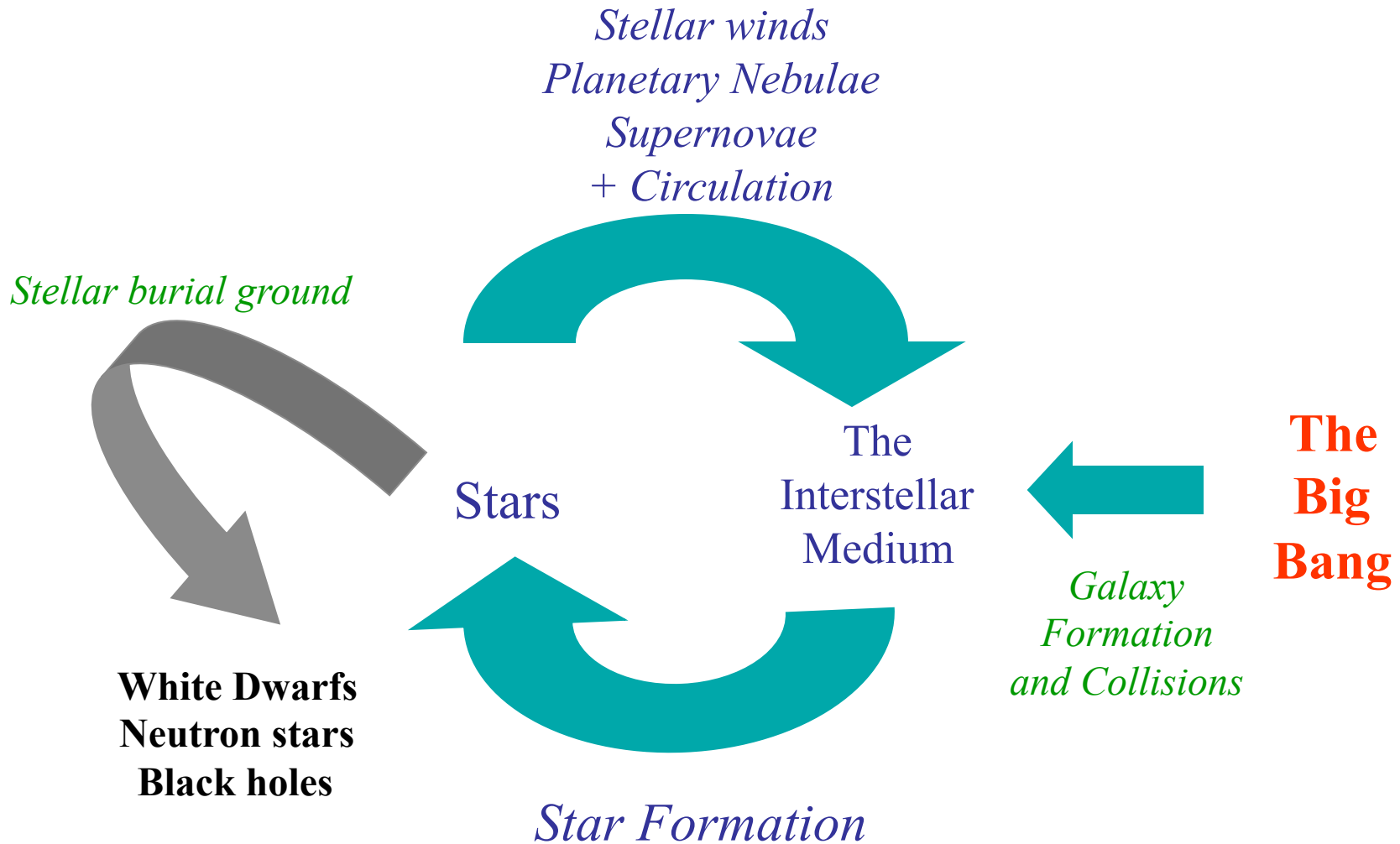
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Disk - primary location of interstellar medium

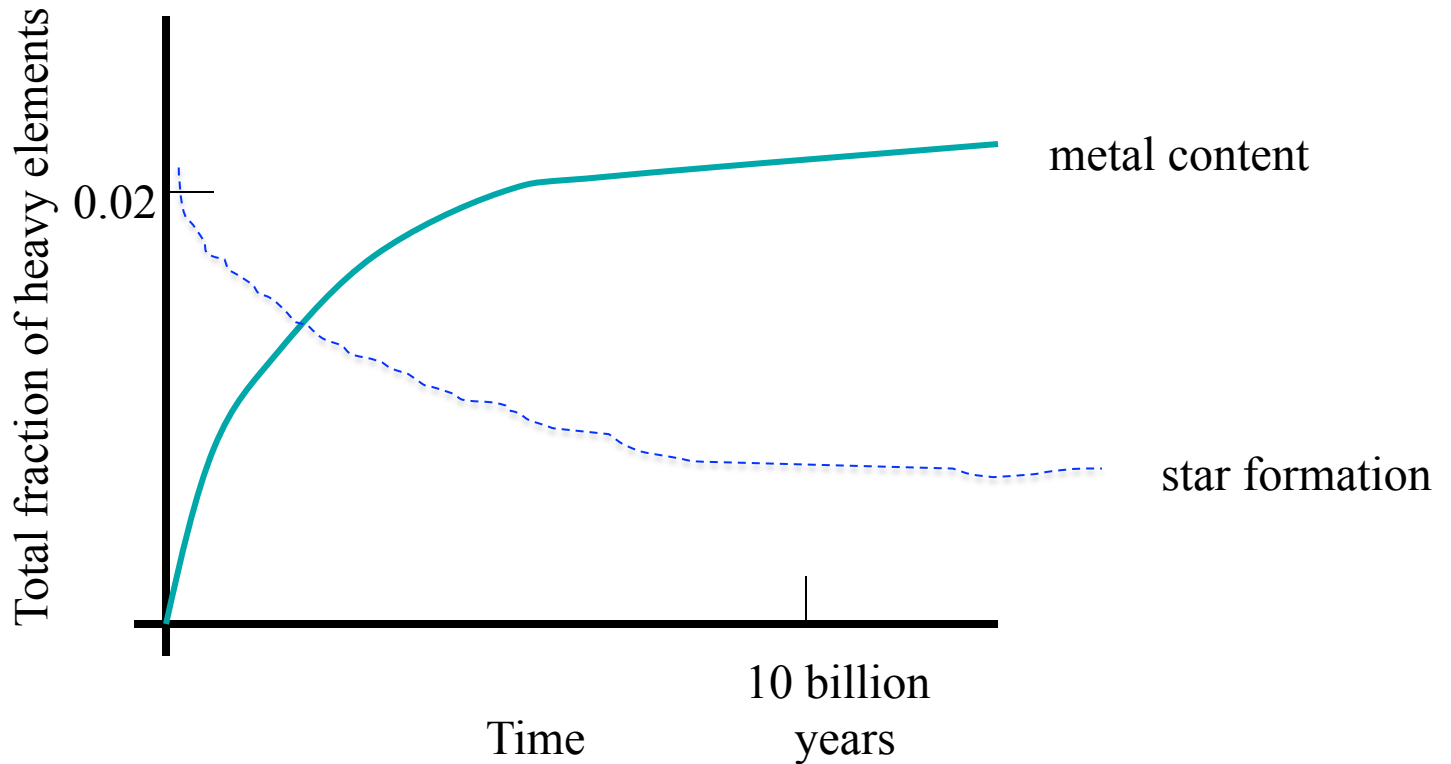


# Evolution in the ISM of the Galaxy

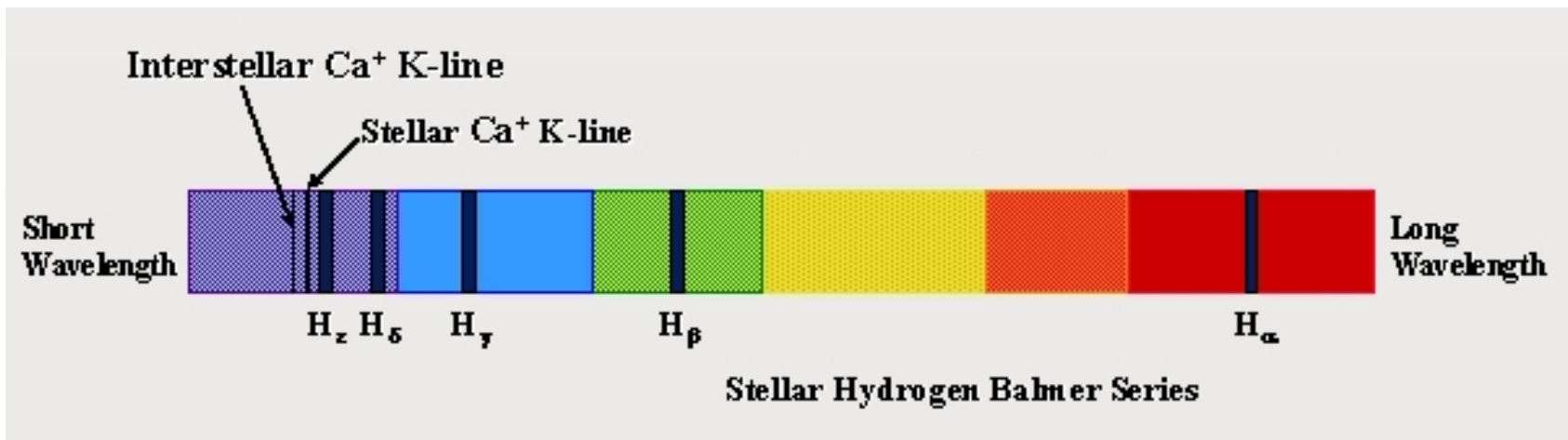


As a result the ISM is continually stirred, heated, and cooled – a dynamic environment, a bit like the earth’s atmosphere but more so because not gravitationally confined

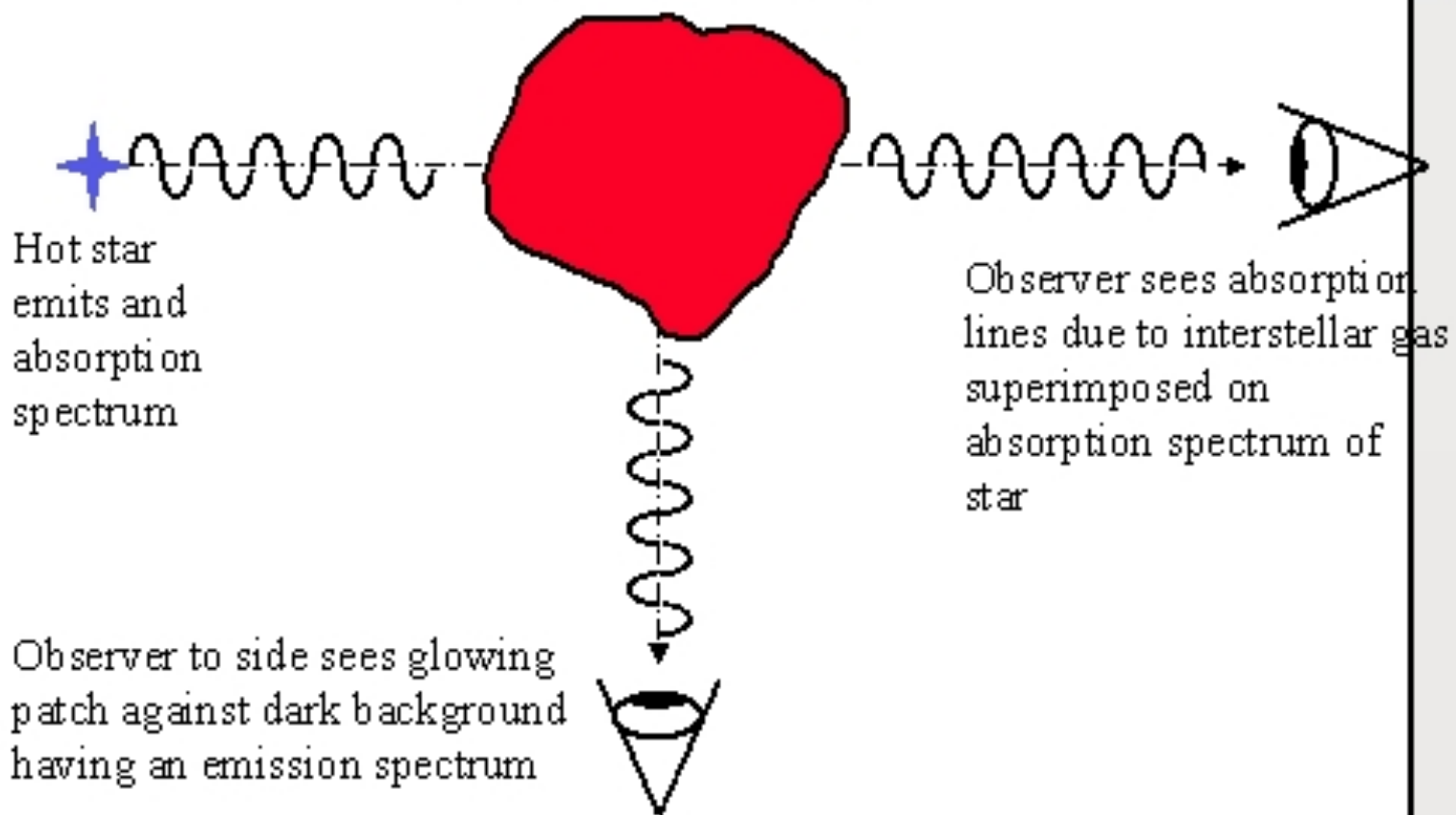
And its composition evolves as the products of stellar evolution are mixed back in by stellar winds, supernovae, etc.:



The interstellar medium (hereafter ISM) was first discovered in 1904, with the observation of stationary calcium absorption lines superimposed on the Doppler shifting spectrum of a spectroscopic binary. Since the calcium lines were not changing in wavelength, they could not originate in the stellar atmospheres of the binary star, and so had to be between the telescope and the star. Since no terrestrial source was identified, the calcium had to be *interstellar*.



Interstellar gas absorbs and re-emits  
or scatters certain wavelengths



Hot star  
emits and  
absorption  
spectrum

Observer sees absorption  
lines due to interstellar gas  
superimposed on  
absorption spectrum of  
star

Observer to side sees glowing  
patch against dark background  
having an emission spectrum

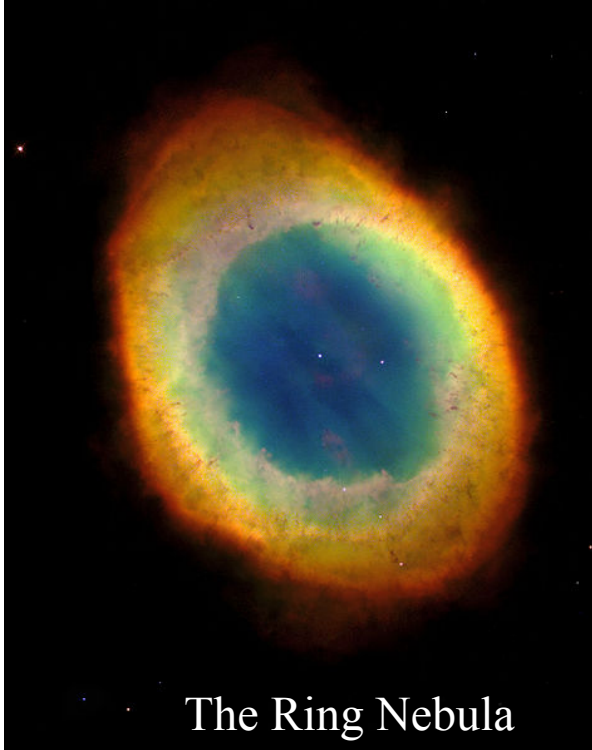
## REFLECTION NEBULAE

Reflection nebulae are clouds of dust which are simply reflecting the light of a nearby star or stars. The energy from the nearby star, or stars, is insufficient to ionize the gas of the nebula to create an emission nebula, but is enough to give sufficient scattering to make the dust visible. Thus, the spectrum shown by reflection nebulae is similar to that of the illuminating stars, but bluer due to the efficiency with which blue light is scattered.

*The “Witchhead Nebula” - about 1000 ly away. situated at Orion’s feet, glows primarily by light reflected from Rigel, just out this field.*

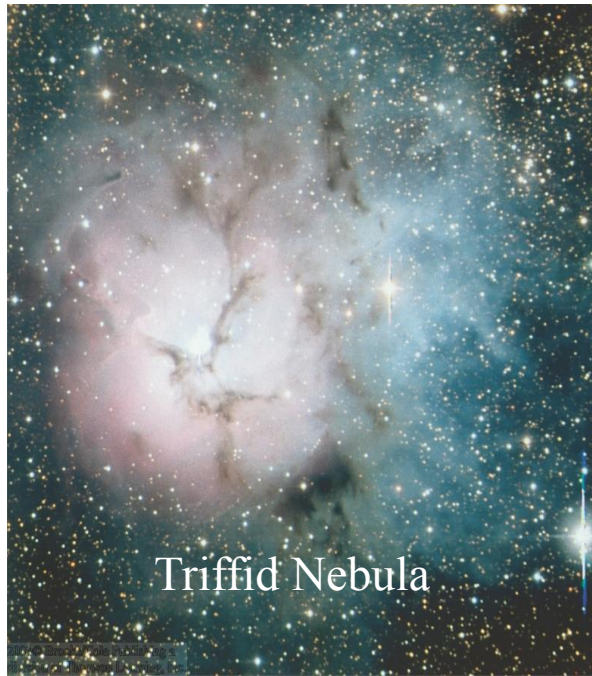


## EMISSION NEBULAE



The Ring Nebula

Emission nebulae are clouds of ionized gas emitting light of various colors. The most common source for ionization are high-energy photons emitted from an embedded hot star.



Triffid Nebula

Examples are planetary nebulae (left – top) and emission nebulae (left – bottom).



<http://oldweb.aao.gov.au/images/captions/uks004.html>

Rho Ophiuchi  
360 ly  
(B-star, binary)

Sigma  
Scorpi  
735 ly  
Spectroscopic binary  
B1 – III and B1-V

distant  
globular

Antares  
(~600 ly)

Distant globular cluster  
4500 ly

© Australian Astronomical Observatory

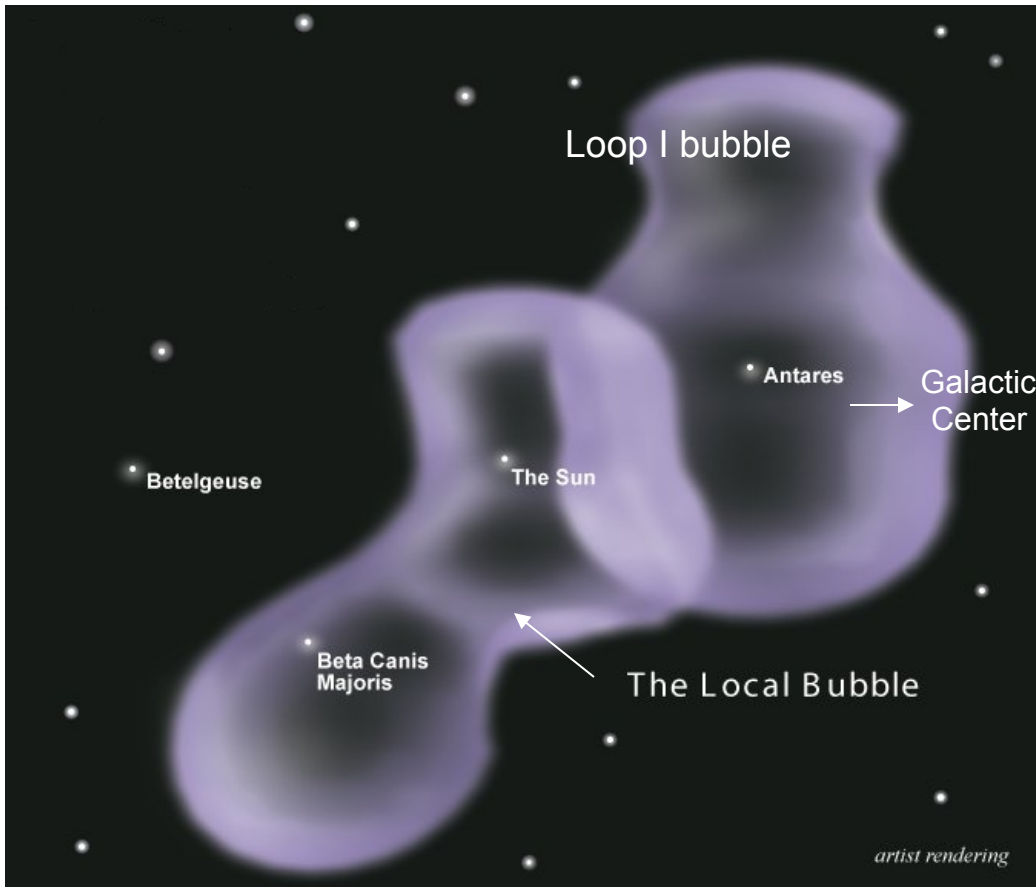
# ANTARES

- Aka Alpha-Scorpius, a magnitude 1.06 star, about 15 times the mass of the sun
- Luminosity 10,000 times that of the sun; Spectral Class M I,  $T = 3100$  K, not a main sequence star  $(B-V) = 1.83$ . Much like Betelgeuse.
- 
- Radius about 4 AU
- In a binary with a 7 solar mass main sequence star (Type B4) with a period of 878 years. Separation 4 arc sec
- Name means “Rival to Mars”, sometimes called the “Heart of the Serpent”.



# THE LOCAL BUBBLE

[http://www.daviddarling.info/encyclopedia/L/Local\\_Bubble.html](http://www.daviddarling.info/encyclopedia/L/Local_Bubble.html)



*The “Local Bubble” is a region of low density ( $\sim 0.05 \text{ cm}^{-3}$  and high temperature ( $\sim 10^6 \text{ K}$ ) has been inflated by numerous supernova explosions. It is about 300 light years long and peanut-shaped. Its smallest dimension is in the plane of the Milky Way Galaxy. It is actually open ended, so more like a tube through the galaxy than a bubble. The hydrogen is ionized.*

Our local bubble abuts another bubble - **the Loop I bubble - also known as the Scorpius-Centaurus Association.**

Simulations suggest 14 - 19 supernovae in Sco-Cen during the last 15 My. Such bubbles are common throughout the Galaxy.

## Scorpius-Centaurus Association (the Loop 1 Bubble)

- Nearest *OB association* to sun. Distance 400 to 500 ly  
Contains many of the bright blue stars in the constellations Scorpius, Centaurus, and Lupus, including as its brightest member, Antares - a 15 solar mass red supergiant. Sometime in the next  $\sim 100,000$  years Antares will be a supernova.
- Total  $\sim 1000 - 2000$  stars, including most of the brightest stars in the Southern Cross.
- Many supernovae have happened here in the last 15 My. Their remnants are found
- These explosions have blown an evacuated cavity - the “Loop I bubble” in the ISM next to the Local Bubble.

(INSIDE THE LOCAL BUBBLE IS)

## **THE LOCAL CLOUD**

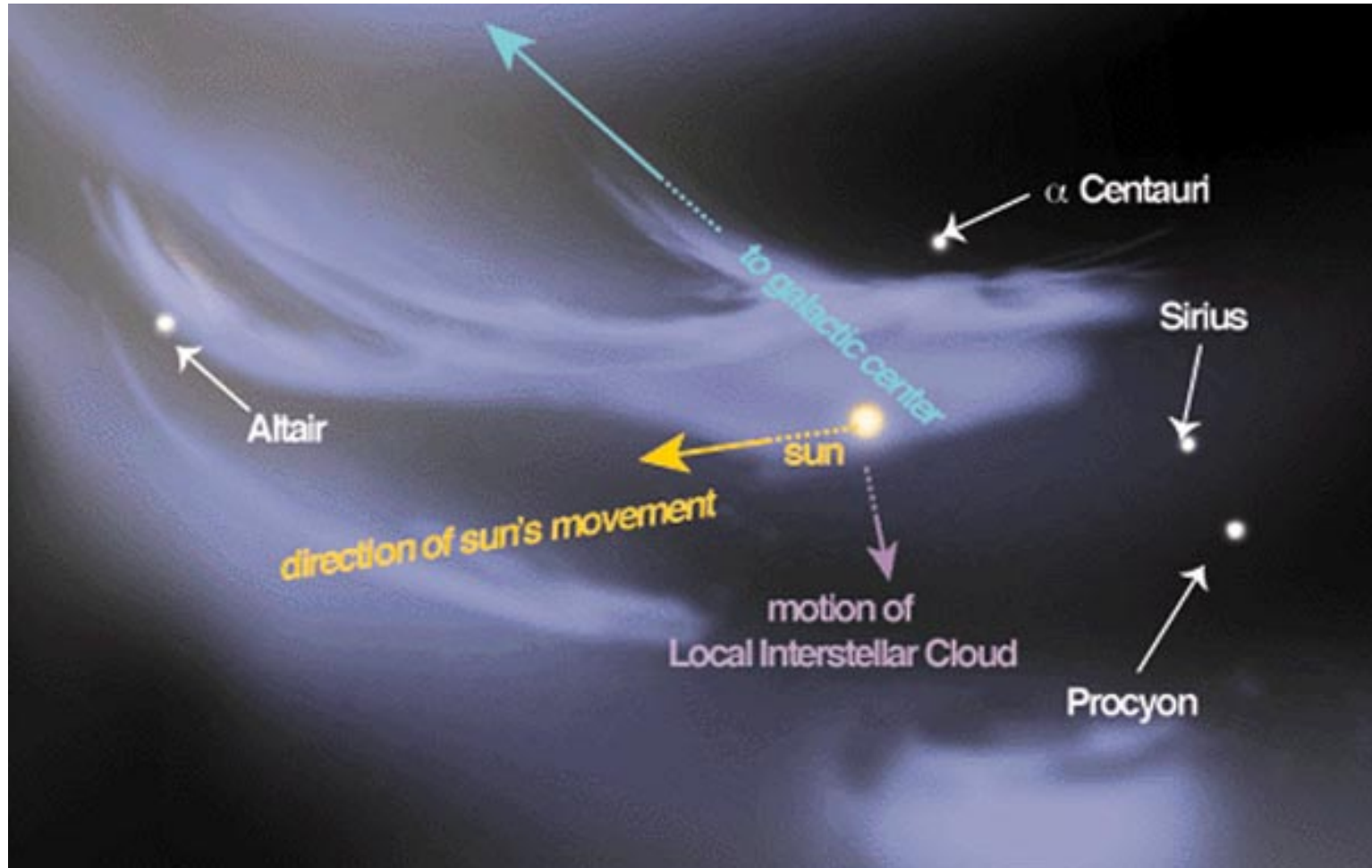
The Local Cloud, sometimes called the Local Fluff, is an interstellar cloud (roughly 30 light years across) through which our solar system is currently moving. The sun entered the Local Cloud between 45,000 and 150,000 years ago and is expected to remain within it for another 10,000 to 20,000 years. The cloud, which is inside the Local Bubble, has a temperature of  $7000^{\circ}$  K. Its density is about 0.25 atoms per cubic centimeter, is greater than the Local Bubble, and it is much cooler.

The cloud is flowing outwards from the Scorpius-Centaurus Association. This cloud and many others may have been formed where the Local Bubble and the Loop I Bubble collided.

# Sun and the local cloud

(few tenths solar mass)

←————— about 10 pc —————→



distance to Sirius is 2.7 pc

Local Cloud -  $\sim 10$  pc

$\sim 0.25/\text{cm}^3$  7000 K

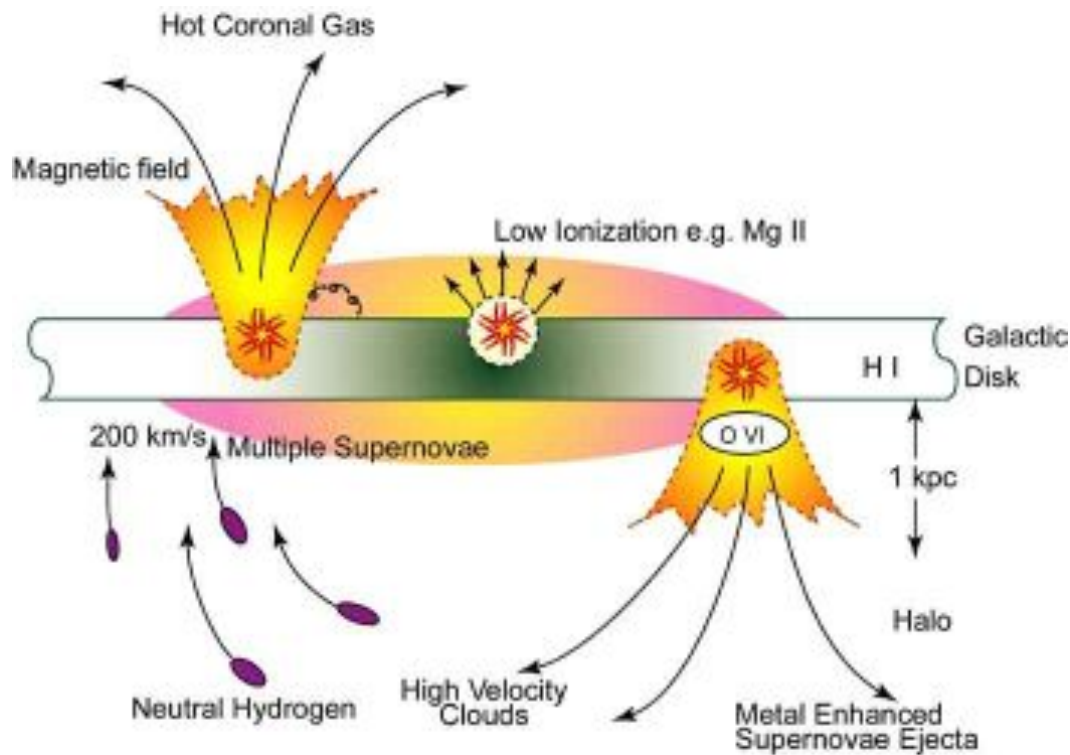
Local Bubble -  $\sim 100$  pc

$\sim 0.01 - 0.05/\text{cm}^3$   $\sim 10^6$  K

Very heterogeneous, the boundaries are not sharp  
and neither is a sphere

*From all this we may correctly infer that the interstellar medium is a clumpy, heterogeneous place with wide variations in temperature and density.*

*The galaxy also has inflows and outflows.*



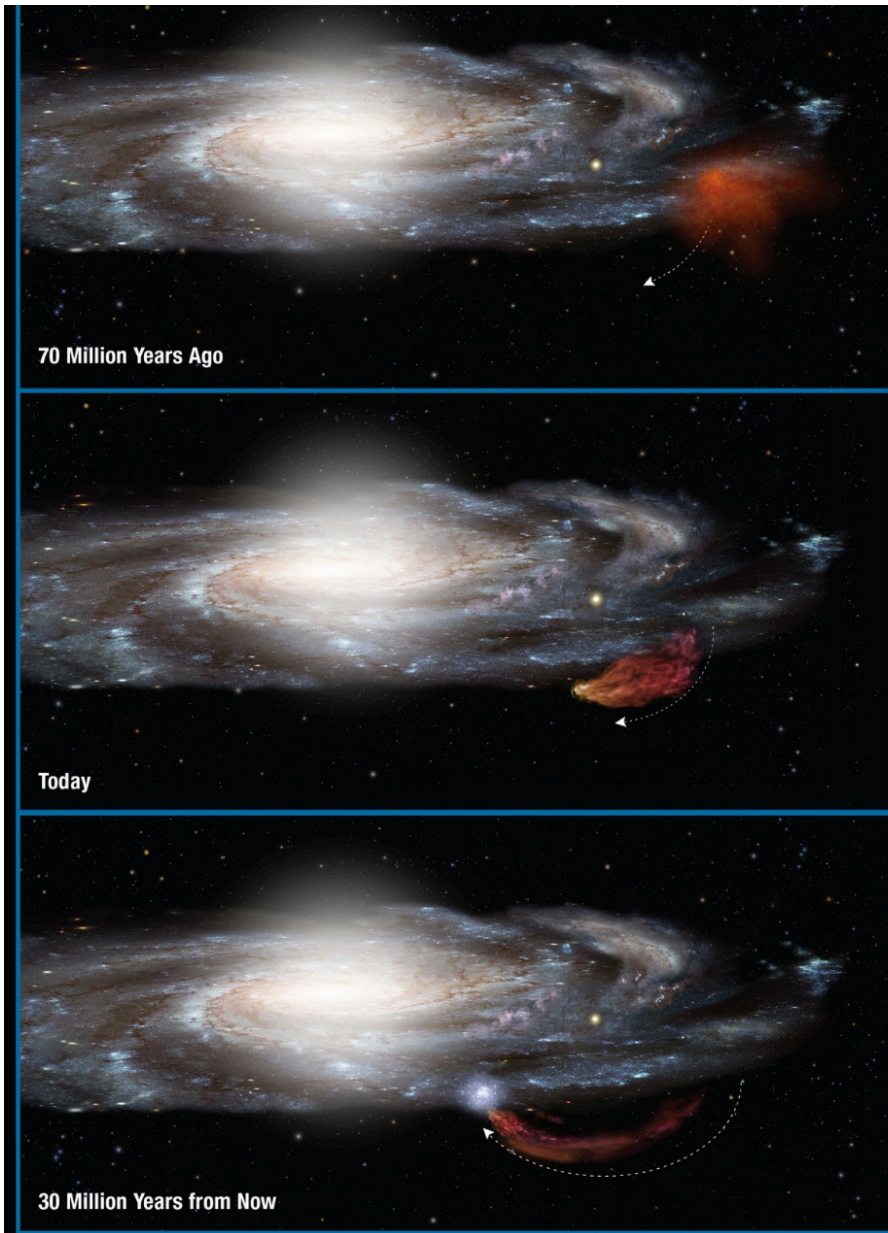
*January, 2016, Reuters*

## Monstrous Cosmic Gas Cloud Set To Ignite The Milky Way!

“Smith Cloud” moving towards us at 310 km/s. Composition of the cloud looks like it may have come from the Milky Way to start with. Maybe a lump of dark matter accreted some baryons on a previous pass.

11,000 ly across - over two million solar masses

Hundreds of high velocity clouds are known This one is just far away





# THE (TOO) MANY PHASES OF THE INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
<b>Molecular Clouds</b>	< 1% but ~40% of mass	70	10 - 20	$10^2 - 10^6$	H <sub>2</sub>	Radio and infrared (molecules)
<b>Cold Neutral Medium (CNM)</b>	1 - 5%	100 - 300	50 - 100	20 - 50	H I	21 cm
<b>Warm Neutral Medium (WNM)</b>	10 - 20%	300 - 400 (Local cloud)	5000- 8000	0.2 - 0.5	H I	21 cm
<b>Warm partly Ionized Medium (WIM)</b>	20 - 50%	1000	6000 - 12000	0.2 - 0.5	H I, H II	H <sub>α</sub>
<b>H II Regions</b>	<1%	70	8000	$10^2 - 10^4$	H II	H <sub>α</sub>
<b>Coronal Gas (Hot Ionized Medium (HIM))</b>	30 - 70% but <5% of mass	1000 - 3000 (Local Bubble)	$10^6 - 10^7$	$10^{-4} - 10^{-2}$	H II metals also ionized	x-ray ultraviolet ionized metals recombination



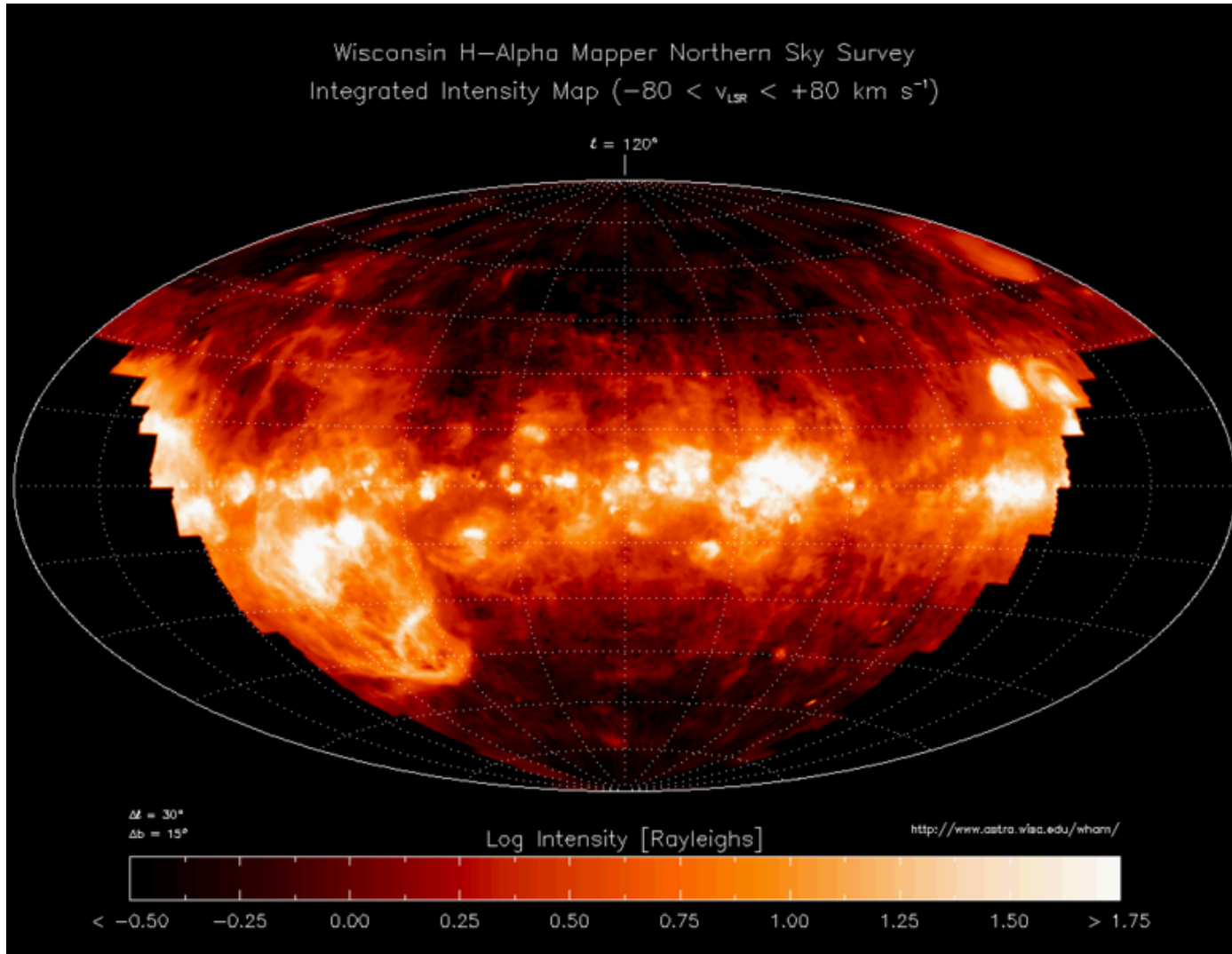
# THE THREE COMPONENT INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
<b>Cold dense Molecular Clouds</b>	<b>&lt; 1% but ~40% of mass</b>	<b>70 - 300</b>	<b>10 - 100</b>	<b><math>10^2 - 10^6</math></b>	<b>H<sub>2</sub></b>	<b>Radio and infrared (molecules)</b>
<b>Warm Neutral Medium (WNM)</b>	<b>30-70% volume about 50% of mass</b>	<b>300 - 1000</b>	<b>100- 10000</b>	<b>0.2 – 50</b>	<b>H I</b>	<b>21 cm</b>
<b>Coronal Gas (Hot Ionized Medium)</b>	<b>30 – 70% but &lt;5% of mass</b>	<b>1000 - 3000</b>	<b><math>10^6 - 10^7</math></b>	<b><math>10^{-4} - 10^{-2}</math></b>	<b>H II metals also ionized</b>	<b>x-ray ultraviolet ionized metals recombination</b>

## **THE NEUTRAL AND WEAKLY IONIZED MEDIA (about one-half the mass and volume of the ISM)**

- Neutral (H I) and partially ionized hydrogen
- Study with 21 cm (H I) and emission lines (H I + H II)
- Scale height greater for hotter gas – 100 – 1000 pc
- Cooler gas often found in clouds. Not actively forming stars. Rough pressure equilibrium.
- Peaks 8 – 13 kpc from galactic center, i.e. outside the sun's orbit

# WARM IONIZED MEDIUM



Distribution of ionized hydrogen (H II) in the local vicinity as viewed in Balmer alpha. Warm partly ionized medium.

# WHAM H $\alpha$ Map

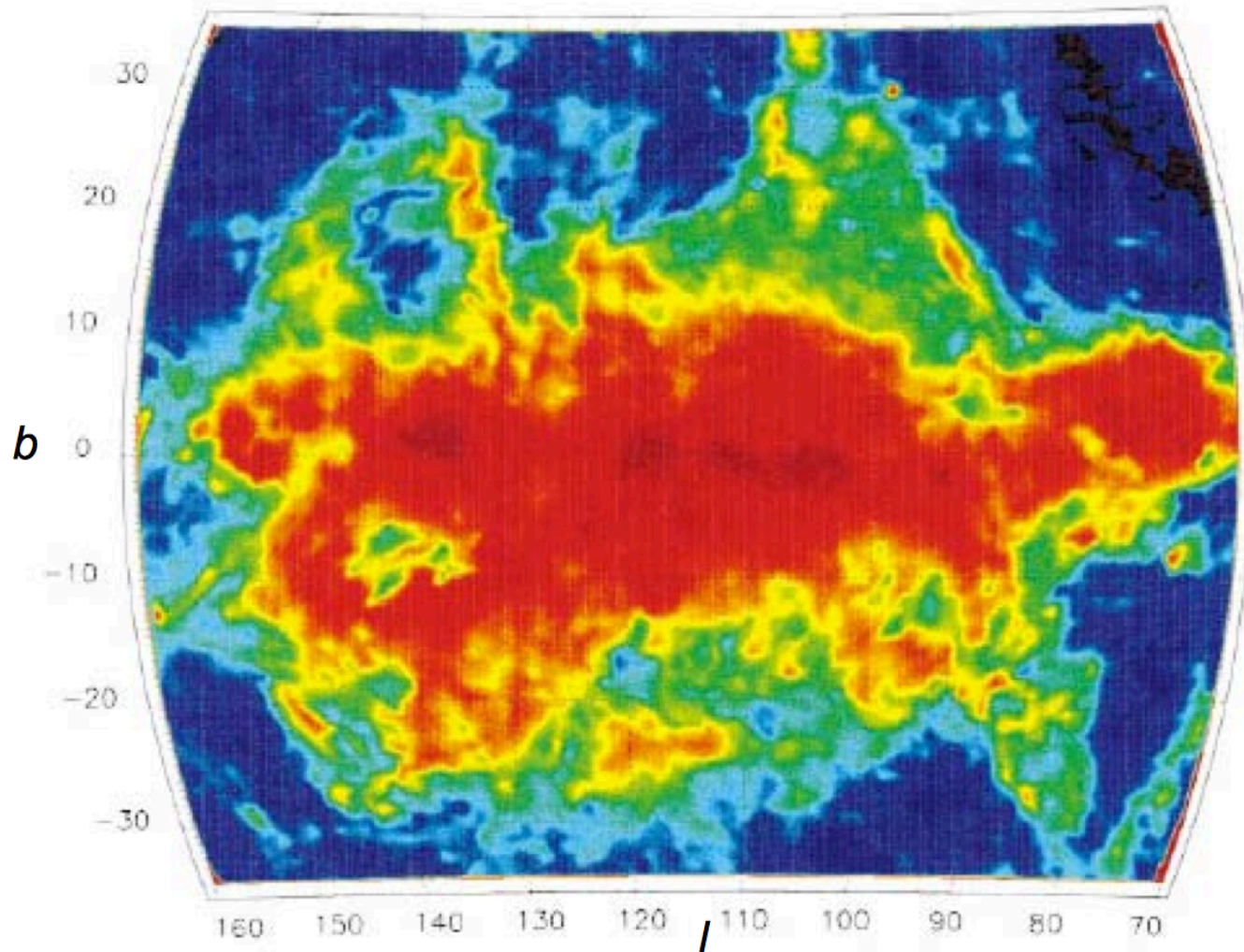


FIG. 6. High-resolution H $\alpha$  map of a 90°x70° portion of the sky centered on ( $l=115^\circ, b=0^\circ$ ) at velocities between -60 and 40 km s $^{-1}$ , from the WHAM survey. Figure courtesy of L. M. Haffner. [Color]

90°x70° map centered at ( $l = 115^\circ, b = 0^\circ$ )

# THE THREE COMPONENT INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
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<b>Warm Neutral Medium (WNM)</b>	<b>30-70%</b>	<b>300 - 1000</b>	<b>100- 10000</b>	<b>0.2 – 50</b>	<b>H I</b>	<b>21 cm</b>
<b>Coronal Gas (Hot Ionized Medium)</b>	<b>30 – 70% but &lt;5% of mass</b>	<b>1000 - 3000</b>	<b><math>10^6 - 10^7</math></b>	<b><math>10^{-4} - 10^{-2}</math></b>	<b>H II metals also ionized</b>	<b>x-ray ultraviolet ionized metals recombination</b>

## *Coronal Gas Regions*

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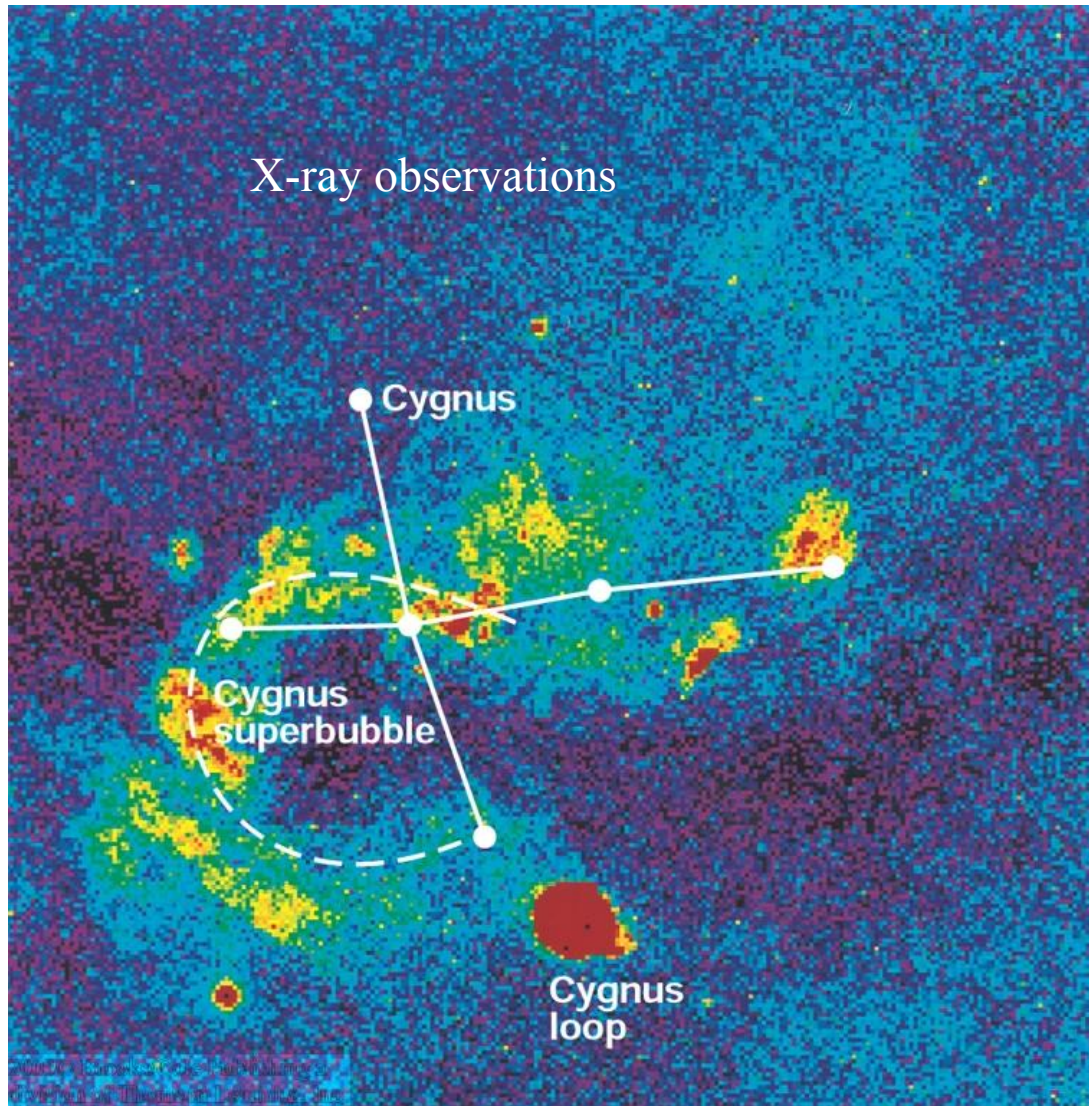
- ◆ **Coronal gas regions** - pockets of very hot, very low density, gas that were probably produced in supernova explosions
  - Temperatures up to one million degrees Kelvin
  - Densities as low as  $10^{-4}$  particles/cm<sup>3</sup>
  - Sizes of hundreds of light years
- ◆ Coronal gas regions extend out of disk and into corona, somewhat like a fountain, with gas falling back into disk
- ◆ Coronal gas regions constitute about 5% of mass of interstellar medium

## ***Coronal Gas - continued***

- Large fraction of the volume (~50%).
- Emission lines in the ultraviolet, e.g., O VI  
X-rays
- Found in vicinity of supernova remnants and above and below disk. Heated by supernova shocks? *uv* light of O stars?



# CORONAL GAS



Called “coronal gas” because of its similarity to solar coronal gas, but very different origin.

Probably originates from supernova explosions and winds from very hot stars

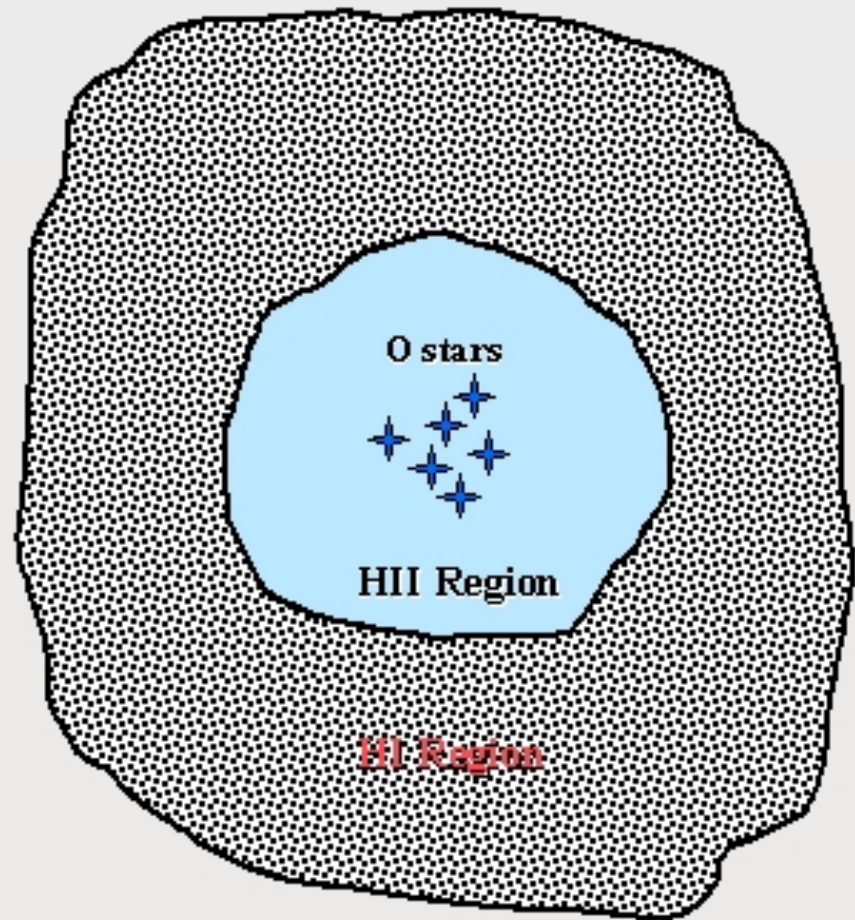
Also recall the “Local Bubble”



# *HII Regions*

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- ◆ Interstellar matter excited and ionized by ultraviolet photons from hot O and B (earlier than B3) stars
- ◆ Spectrum is emission
- ◆ HII region surrounded by cooler, denser, HI region



# *H II Regions*

- About 700 in our Galaxy
- Ionized by intense uv-flux from stars within, especially O stars
- Detected in radio from high n transitions in hydrogen. Also optical emission in Balmer and Lyman series.
- Appear reddish, sometime with a greenish tinge from oxygen emission lines.  $T \sim 10^4$  K. Highly variable density from a few atoms per cc to a million. May contain many stars.
- Most abundant between 4 to 8 kpc and in spiral arms of the Milky Way. **Trace regions of recent star formation.**

## ***H II Regions - continued***

- Brightest is less than a million years old.
- Often have molecular clouds at their boundaries
- Colorful, but not a major part of the Galaxy's mass or volume



Messier 51



The Great Nebula in Orion. An illuminated portion of a nearby (1300 ly) giant molecular cloud. The field of view here is 32 arc min. Each arc min at this distance is about 0.4 ly.

A better resolved image of the Trapezium from the Hubble Space Telescope.

John Balley et al (1997)







Lagoon Nebula – in Sagittarius – 5000 ly away – spans 90 x 40 arc min and 130 by 60 light years. Another H II region on the boundary of a molecular cloud (like Orion)

# THE THREE COMPONENT INTERSTELLAR MEDIUM

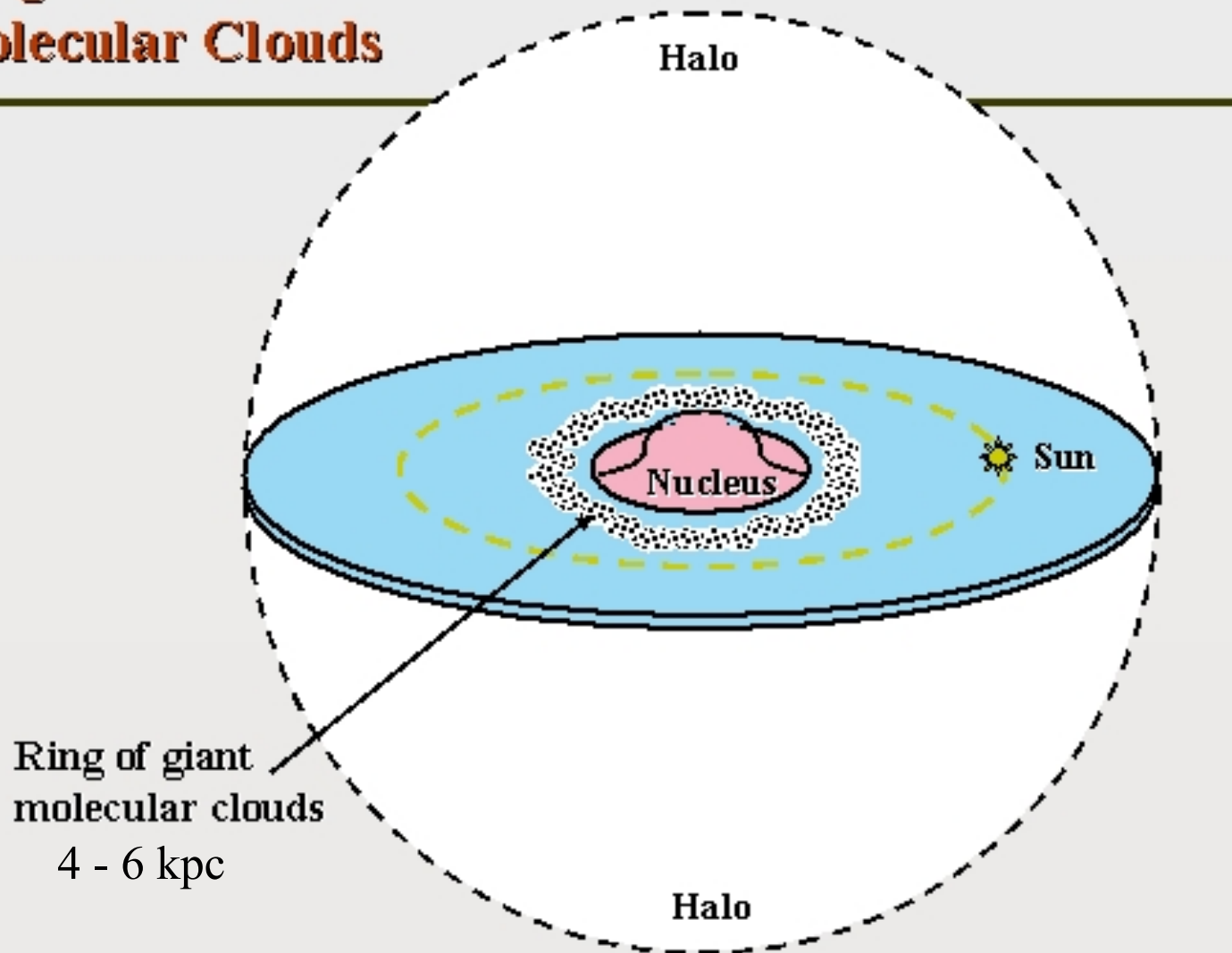
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## ***Molecular Hydrogen ( $H_2$ )***

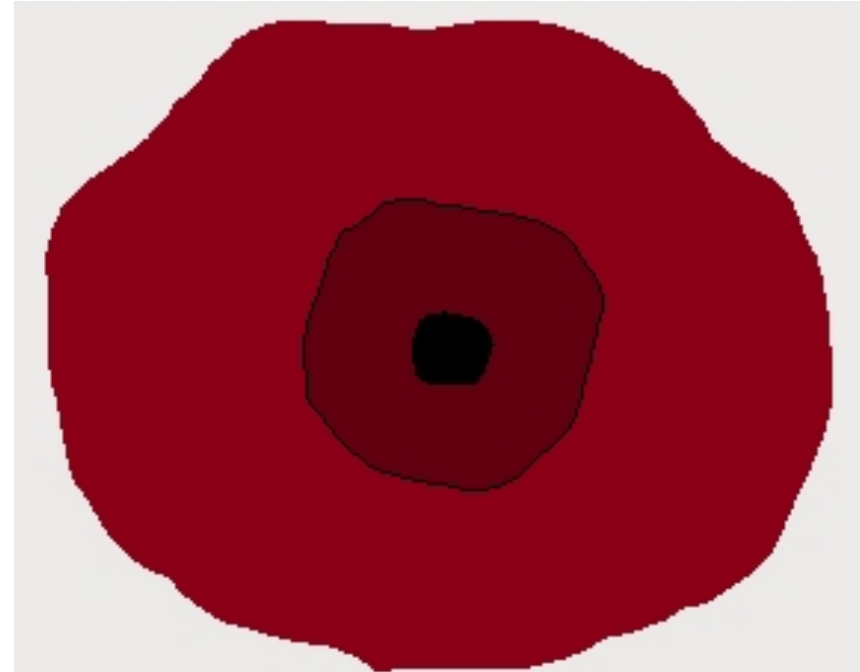
- Traced by the radio emission of CO which is found in the same (cold, dense) conditions with a near constant proportionality to molecular hydrogen.  $H_2$  itself is not observable in the radio.
- Mostly concentrated in a ring around the center of the Galaxy interior to the sun's orbit at 4 to 6 kpc
- Mostly clumped into clouds ranging in mass from several solar masses to  $10^6$  solar masses and sizes from less than a ly to 600 ly

# Ring of Giant Molecular Clouds



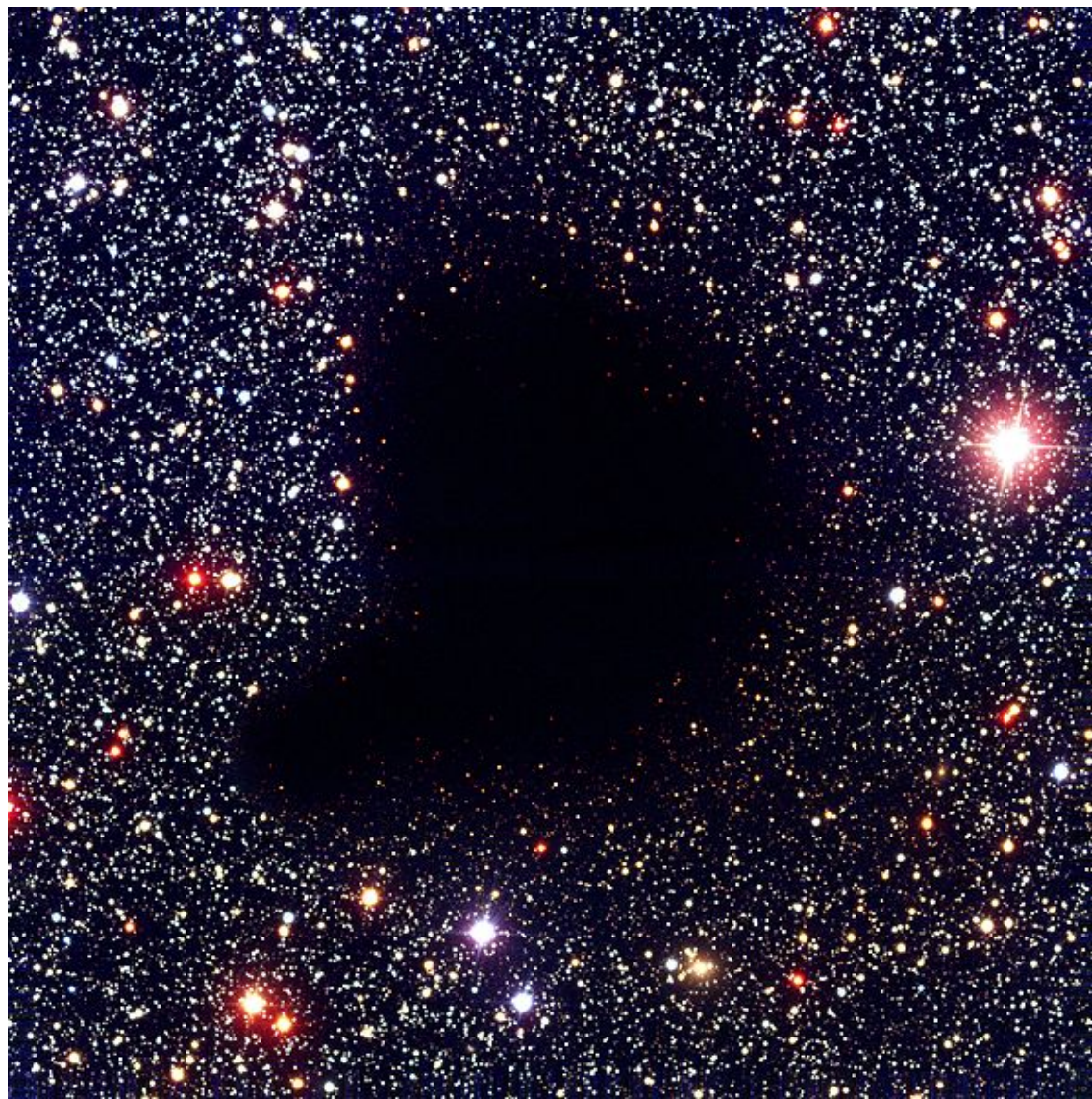
# MOLECULAR CLOUDS

- In the cool dense gas, dust forms and accumulates icy mantles
- This dust shields molecules from destruction by uv light
- Molecules emit radio and the dust emits IR, keeping the cloud cool.
- About 40% of the mass of the ISM is molecular clouds (but a small fraction of the volume)



## Molecular Clouds (continued)

- Live  $\sim$  few  $\times 10^6$  [http://en.wikipedia.org/wiki/Molecular\\_cloud](http://en.wikipedia.org/wiki/Molecular_cloud)
- Cold, dense, definitely regions of active star formation, but only about 2% of the cloud mass ends up as stars
- *Giant* molecular clouds may have masses  $M \sim 10^3 - 10^6$  solar masses. [Taurus a few thousand solar masses; Orion 200,000] and sizes of 10' s of parsecs (Orion  $\sim 70$  pc - stretching several degrees from Belt to sword)
- Small molecular clouds are sometimes called “Bok globules”, with highly variable masses  $\sim 1 - 100$  solar masses. Found near H II regions.  $\sim$  light years in size.
- 
- Dust 0.1% to 1% of the mass.
- Origin uncertain. May be formed by compression of ISM around a large OB association. They are transient structures, not supported by pressure against gravity

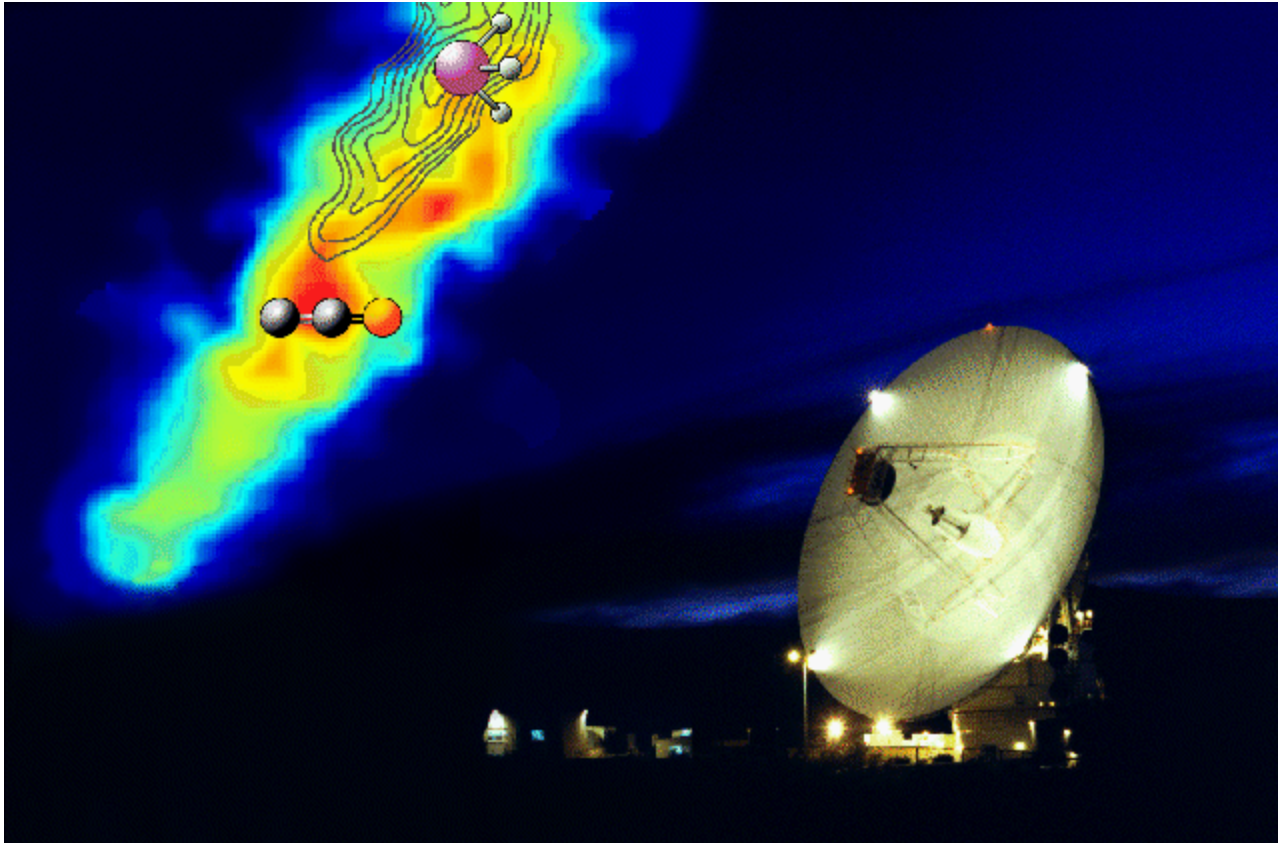


Barnard 68 is a Bok globule 410 ly away (one of the closest) size about 12,000 AU (similar to Oort cloud in our solar system)  $T = 16$  K, about two solar masses. Coldest matter in universe. Definitely forming stars.



129 different molecules had been detected in space by 2006.  
Most are “organic”.  $\text{HC}_{11}\text{N}$  is the heaviest.

<http://www.cv.nrao.edu/~awootten/allmols.html>



<http://dsnra.jpl.nasa.gov/IMS/>



Molecules with Nine Atoms		
(CH <sub>3</sub> ) <sub>2</sub> O dimethyl ether	CH <sub>3</sub> CH <sub>2</sub> CN ethylcyanide	CH <sub>3</sub> CH <sub>2</sub> OH ethanol
CH <sub>3</sub> C <sub>4</sub> H methylbutadiyne	HCC-CC-CC-CN cyanoheptatriyne	C <sub>8</sub> H
CH <sub>3</sub> C(O)NH <sub>2</sub> acetamide	C <sub>8</sub> H <sup>-</sup>	CH <sub>3</sub> CHCH <sub>2</sub> propylene

Molecules with Ten Atoms	
(CH <sub>3</sub> ) <sub>2</sub> CO acetone	HOCH <sub>2</sub> CH <sub>2</sub> OH ethylene glycol
H <sub>3</sub> C-CH <sub>2</sub> -C(O)H propanal	CH <sub>3</sub> (CC) <sub>2</sub> CN methylcyanodiacetylene

Molecules with Eleven Atoms		
HCC-CC-CC-CC-CN cyanooctatetrayne	CH <sub>3</sub> C <sub>6</sub> H methyltriacetylene	HC(O)OCH <sub>2</sub> CH <sub>3</sub> ethyl formate

Molecules with Twelve Atoms	
C <sub>6</sub> H <sub>6</sub> benzene	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> CN <i>n</i> -propyl cyanide

Molecules with Thirteen Atoms
HCC-CC-CC-CC-CC-CN cyanodecapentayne

# *Selected Interstellar Molecules*

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<b>Symbol</b>	<b>Molecule</b>	<b>Symbol</b>	<b>Molecule</b>
<b>H<sub>2</sub></b>	<b>molecular hydrogen</b>	<b>H<sub>2</sub>S</b>	<b>hydrogen sulfide</b>
<b>C<sub>2</sub></b>	<b>diatomic carbon</b>	<b>N<sub>2</sub>O</b>	<b>nitrous oxide</b>
<b>CN</b>	<b>cyanogen</b>	<b>H<sub>2</sub>CO</b>	<b>formaldehyde</b>
<b>CO</b>	<b>carbon monoxide</b>	<b>C<sub>2</sub>H<sub>2</sub></b>	<b>acetylene</b>
<b>NO</b>	<b>nitric oxide</b>	<b>NH<sub>3</sub></b>	<b>ammonia</b>
<b>OH</b>	<b>hydroxyl</b>	<b>HCO<sub>2</sub>H</b>	<b>formic acid</b>
<b>NaCl</b>	<b>sodium chloride</b>	<b>CH<sub>4</sub></b>	<b>methane</b>
<b>HCN</b>	<b>hydrogen cyanide</b>	<b>CH<sub>3</sub>OH</b>	<b>methyl alcohol</b>
<b>H<sub>2</sub>O</b>	<b>water</b>	<b>CH<sub>3</sub>CH<sub>2</sub>OH</b>	<b>ethyl alcohol</b>

In 2003 an amino acid, glycine, was detected in a molecular cloud

## Nearest Example of a Giant Molecular Cloud: Orion

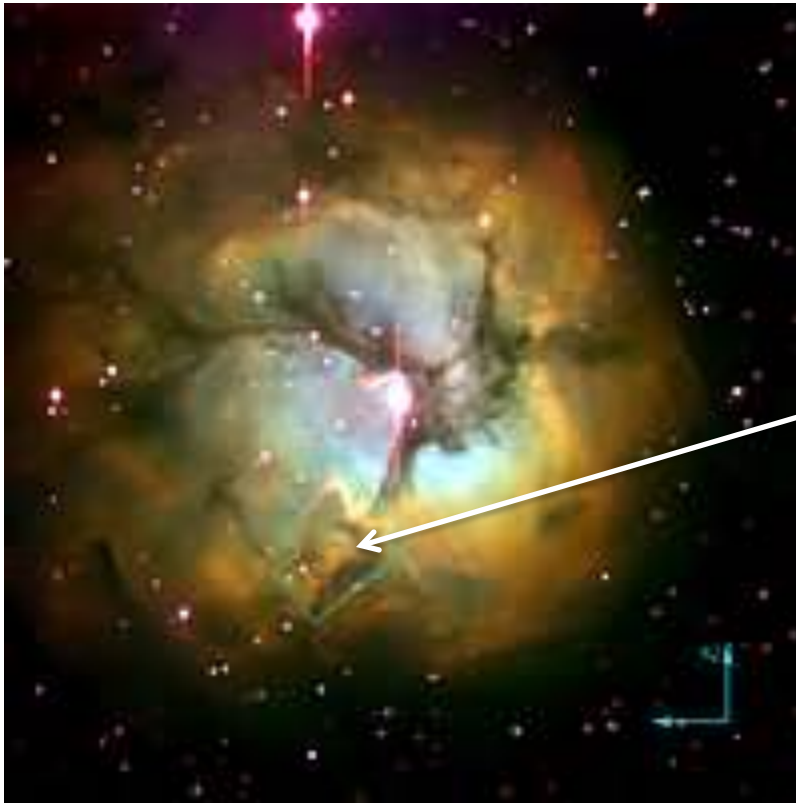
[http://www.daviddarling.info/encyclopedia/O/Orion\\_Complex.html](http://www.daviddarling.info/encyclopedia/O/Orion_Complex.html)

- Size 70 pc (diameter)
- distance  $\sim$  450 pc
- $M \sim$  200,000 solar masses
- Age  $\sim$  12 My
- Evidence for thousands of embedded young stars. Best seen in infrared.
- Spitzer IR telescope in 2006 found evidence for 2300 “dusty disks” around young stars in the Orion complex - planetary systems in the making.

Spitzer Infrared Observatory (in space) view of Orion  
40 light years across  
Many young embedded stars visible in infrared



(HST 1997)



about the  
angular size of  
the moon.  
roughly 40 ly  
across

The *Trifid Nebula*, 1600 parsecs away in the constellation Sagittarius, is also a molecular cloud where new stars are being born. Here the bright emission of the central stars is eroding the surroundings of several nearby stars about 8 light years away. Note the nebula is quite dusty. The stalk has survived because at its tip there is still gas that is dense enough to resist being boiled away by the nearby bright stars.





Star birth in the Eagle Nebula, 7000 light years away in the constellation Serpens.

This is a column of cool molecular hydrogen and dust that is an incubator for new stars. Each finger-like protrusion is larger than our solar system.

This “pillar of creation” is being slowly eroded away by the ultraviolet light of nearby young stars.

**Star-Birth Clouds • M16**

**HST • WFPC2**

PRC95-44b • ST ScI OPO • November 2, 1995

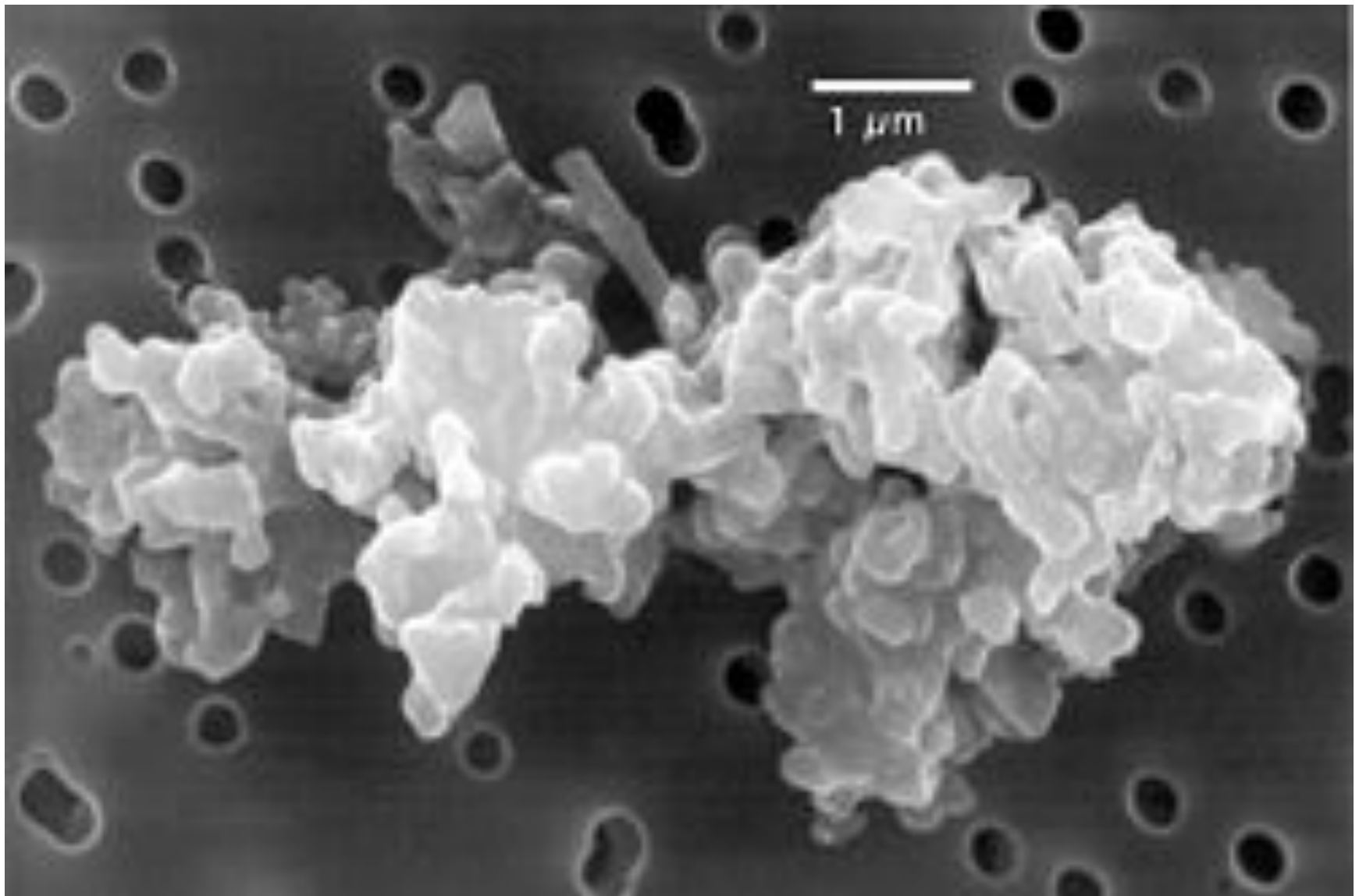
J. Hester and P. Scowen (AZ State Univ.), NASA



# *Interstellar Dust*

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- ◆ **Interstellar dust** - microscopic solid grains containing large numbers of atoms that are concentrated in large dark interstellar clouds along plane of Galaxy
  - About 1% of mass of interstellar medium
  - Source of strong extinction of radiation along plane of Galaxy
  - Grain size is about  $5 \times 10^{-5}$  cm or about wavelength of visible light
  - Composition, about  $100 \times 10^6$  atoms/grain, graphite, iron particles, silicon carbide, silicates, frozen gases (ices)



Interplanetary dust in our solar system

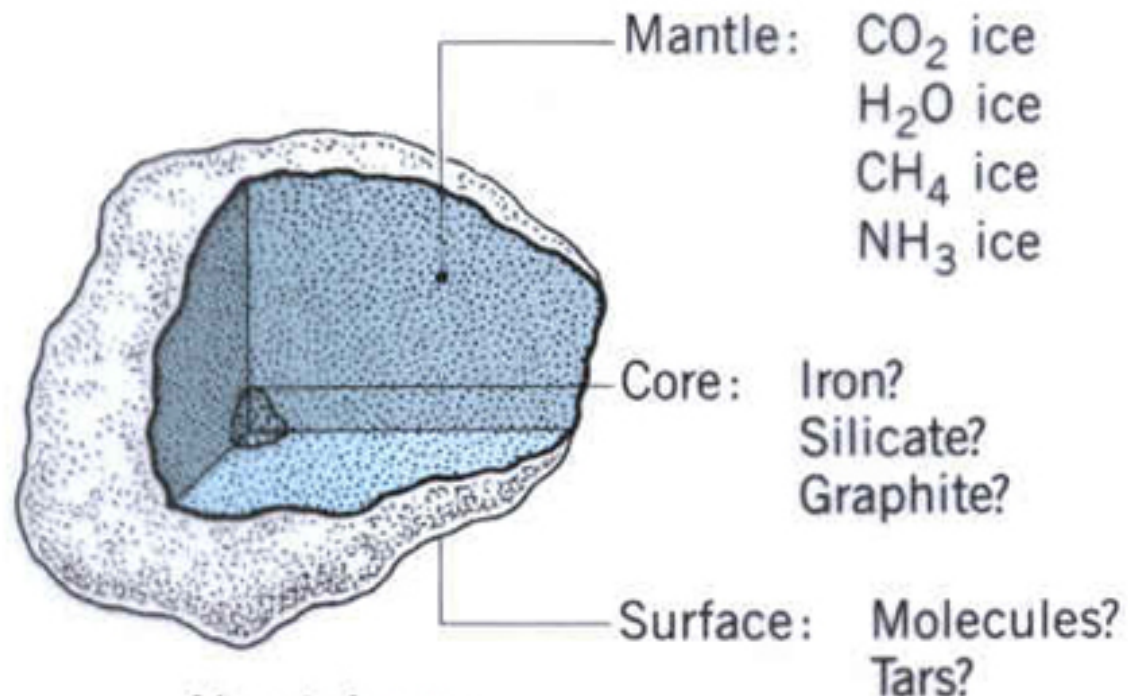
Interstellar dust is much smaller ( $\sim 0.1 - 1$  micron =  $1000 - 10000\text{\AA}$ )

[http://en.wikipedia.org/wiki/Cosmic\\_dust](http://en.wikipedia.org/wiki/Cosmic_dust)

Andromeda galaxy in an infrared  
image taken by the Spitzer Space Telescope



# In a molecular cloud dust grains accrete icy mantles



← ~0.5 μ →

1 μ = 10<sup>-6</sup> m = 10<sup>-4</sup> cm

Dust comes in a broad range of sizes but typically 0.1 to 1 microns  
Therefore very effective in scattering light

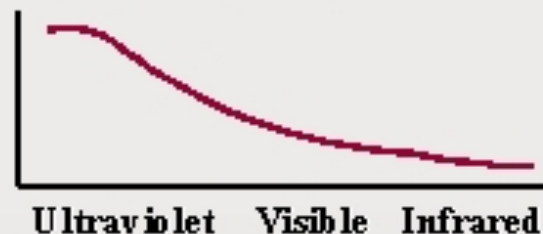
# *Extinction By Interstellar Dust*

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- ◆ **Interstellar extinction** - distant stars appear fainter and reddened due to absorption of photons by interstellar dust grains

- Grains better absorbers of short wavelength photons than long wavelength photons

Absorption



- Loss of light is about 2 magnitudes for every 1000 parsecs radiation traverses interstellar dust
- $10^{11}$  photons from center of our Galaxy, traverse about 30,000 ly of interstellar dust, 1 photon reaches Sun



## STAR FORMATION

*In which component(s) of the ISM can star formation take place?*

*A necessary condition is a region of gas that has greater gravitational binding energy than internal energy. (The force pulling the region together must be greater than the pressure pushing it apart.)*

*Since internal energy increases with the amount of mass that is present while binding energy increases as  $M^2$ , there is a critical mass that is bound.*



# STAR FORMATION IN THE THREE COMPONENT INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
<b>Cold dense Molecular Clouds</b>	<b>&lt; 1% but ~40% of mass</b>	<b>70 - 300</b>	<b>10 - 100</b>	<b><math>10^2 - 10^6</math></b>	<b>H<sub>2</sub></b>	<b>Radio and infrared (molecules)</b>
<b>Warm Neutral Medium (WNM)</b>	<b>30-70%</b>	<b>300 - 1000</b>	<b>100- 10000</b>	<b>0.2 – 50</b>	<b>H I</b>	<b>21 cm</b>
<b>Coronal Gas (Hot Ionized Medium)</b>	<b>30 – 70% but &lt;5% of mass</b>	<b>1000 - 3000</b>	<b><math>10^6 - 10^7</math></b>	<b><math>10^{-4} - 10^{-2}</math></b>	<b>H II metals also ionized</b>	<b>x-ray ultraviolet ionized metals recombination</b>

# The Jean's Mass

$$\Omega \approx \text{KE}$$

*Ignore factor of 2 in the Virial Theorem. The clouds we are envisioning have not reached equilibrium.*

$$\begin{aligned}\Omega &\approx \frac{3}{5} \frac{GM^2}{R} \approx (\text{Number of particles}) \left( \frac{3}{2} kT \right) \\ &\approx \frac{M}{m_H} \frac{3}{2} kT \quad (\text{if made of pure hydrogen}) \\ &= N_A M \frac{3}{2} kT \quad (N_A \text{ is Avogadro's Number, } 6.02 \times 10^{23})\end{aligned}$$

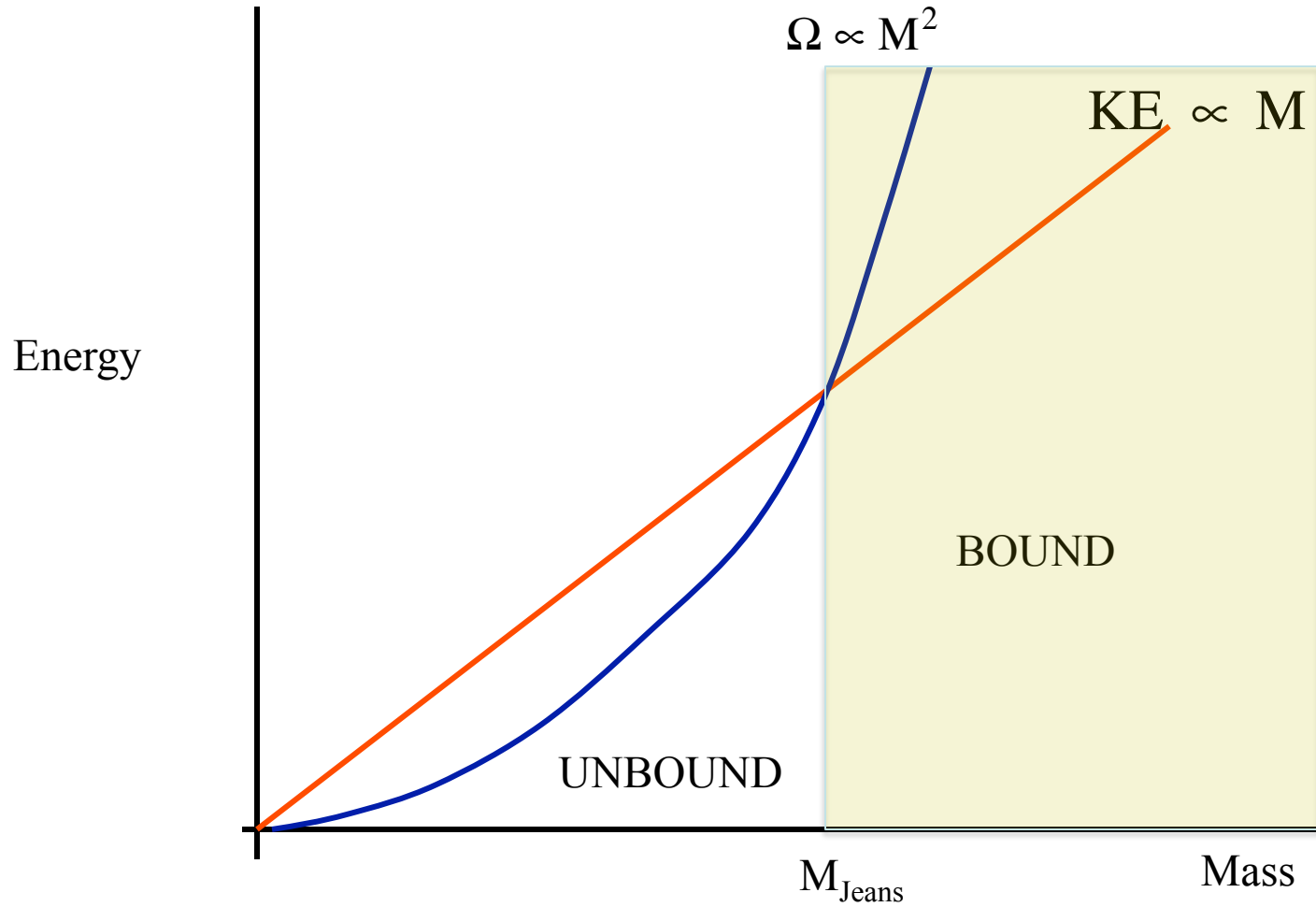
This can be solved for the "Jean's Mass",  $M_J$

$$\frac{3}{5} \frac{GM_J^2}{R} = \frac{3}{2} N_A M_J kT$$

$$M_J = \frac{5N_A kTR}{2G}$$

*Clouds of gas with radius  $R$  and temperature  $T$  that have a mass bigger than this are unstable to gravitational collapse*

For masses larger than the Jean's Mass gravitational binding energy exceeds internal energy



It is easier to measure densities and temperatures rather than radii, so the equation on the previous page can be transformed using

$$R = \left( \frac{3M}{4\pi\rho} \right)^{1/3} \quad \text{assume sphere, constant density} \quad M = \frac{4}{3}\pi R^3 \rho$$

previous page

$$M_J = \frac{5N_A kTR}{2G} = \frac{5N_A kT}{2G} \left( \frac{3M_J}{4\pi\rho} \right)^{1/3}$$

$$M_J^{2/3} = \frac{5N_A k}{2G} \left( \frac{3}{4\pi} \right)^{1/3} \left( \frac{T^3}{\rho} \right)^{1/3}$$

$$M_J = \left( \frac{5N_A k}{2G} \right)^{3/2} \left( \frac{3}{4\pi} \right)^{1/2} \left( \frac{T^3}{\rho} \right)^{1/2}$$

$$= 8.5 \times 10^{22} \text{ gm} \left( \frac{T^{3/2}}{\rho^{1/2}} \right) = 4.2 \times 10^{-11} \left( \frac{T^{3/2}}{\rho^{1/2}} \right) M_\odot$$

It is more frequent that one finds the density in this context expressed as atoms/cm<sup>3</sup> rather than gm/cm<sup>3</sup>.

If  $n = \rho N_A$  (actually true only for H I), then

$$M_J = 8.5 \times 10^{22} \frac{T^{3/2} N_A^{1/2}}{n^{1/2}} \text{ gm}$$

$$M_J = 34 \frac{T^{3/2}}{n^{1/2}} M_\odot$$

where  $n$  is the density in atoms cm<sup>-3</sup>.

By this criterion, only molecular clouds and possibly portions of the coldest neutral medium (depending on mass) are unstable to collapse.

**Example:** Molecular cloud;  $T = 20 \text{ K}$ ,  $n = 10^4 \text{ atoms cm}^{-3}$

$$\begin{aligned} M_J &= 34 \frac{T^{3/2}}{n^{1/2}} \\ &= 34 \frac{(20)^{3/2}}{(10^4)^{1/2}} = 34 \frac{89.4}{100} \\ &= 30 M_\odot \end{aligned}$$

Any cloud with this temperature and density and a mass over 30 solar masses is unstable to collapse



## How long does the collapse take?

$$v_{esc} = \sqrt{\frac{2GM}{R}} \quad \tau_{ff} \approx \frac{R}{v_{esc}} = \sqrt{\frac{R^3}{2GM}}$$

but,  $\rho$ , the density, is given by

$$\rho = \frac{3M}{4\pi R^3} \Rightarrow \frac{R^3}{M} = \frac{3}{4\pi\rho}$$

so,

$$\tau_{ff} \approx \sqrt{\frac{3}{8\pi G\rho}} \approx 1000 \text{ seconds} / \sqrt{\rho}$$

*Denser regions  
collapse faster*

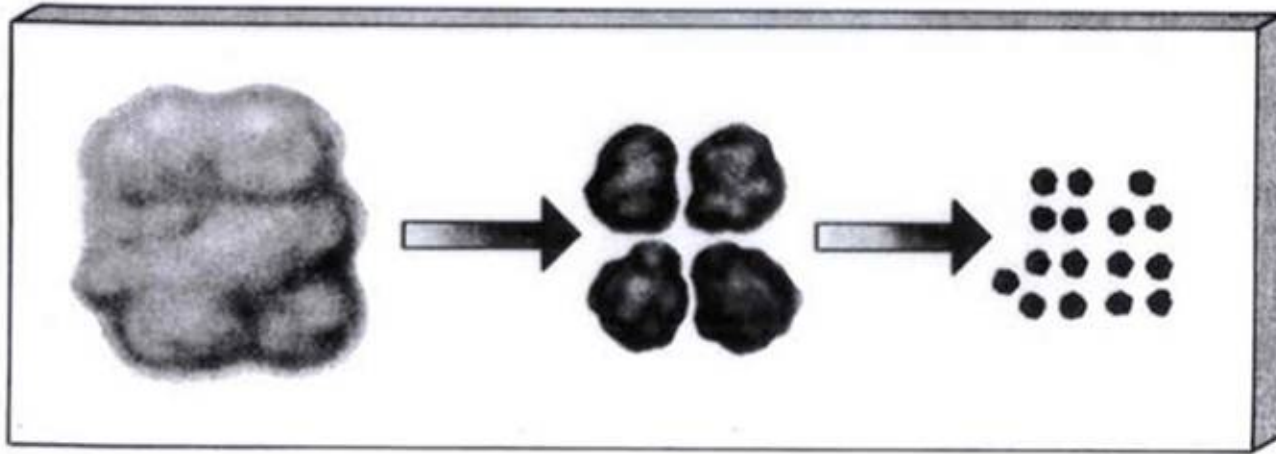
but  $\rho \approx n / N_A$ , so

$$\tau_{ff} \approx 10 \text{ million years} / \sqrt{n}$$

where  $n$  is the number of atoms per cubic cm.

1 million years if  $n = 10^4$  atoms/cm<sup>3</sup>

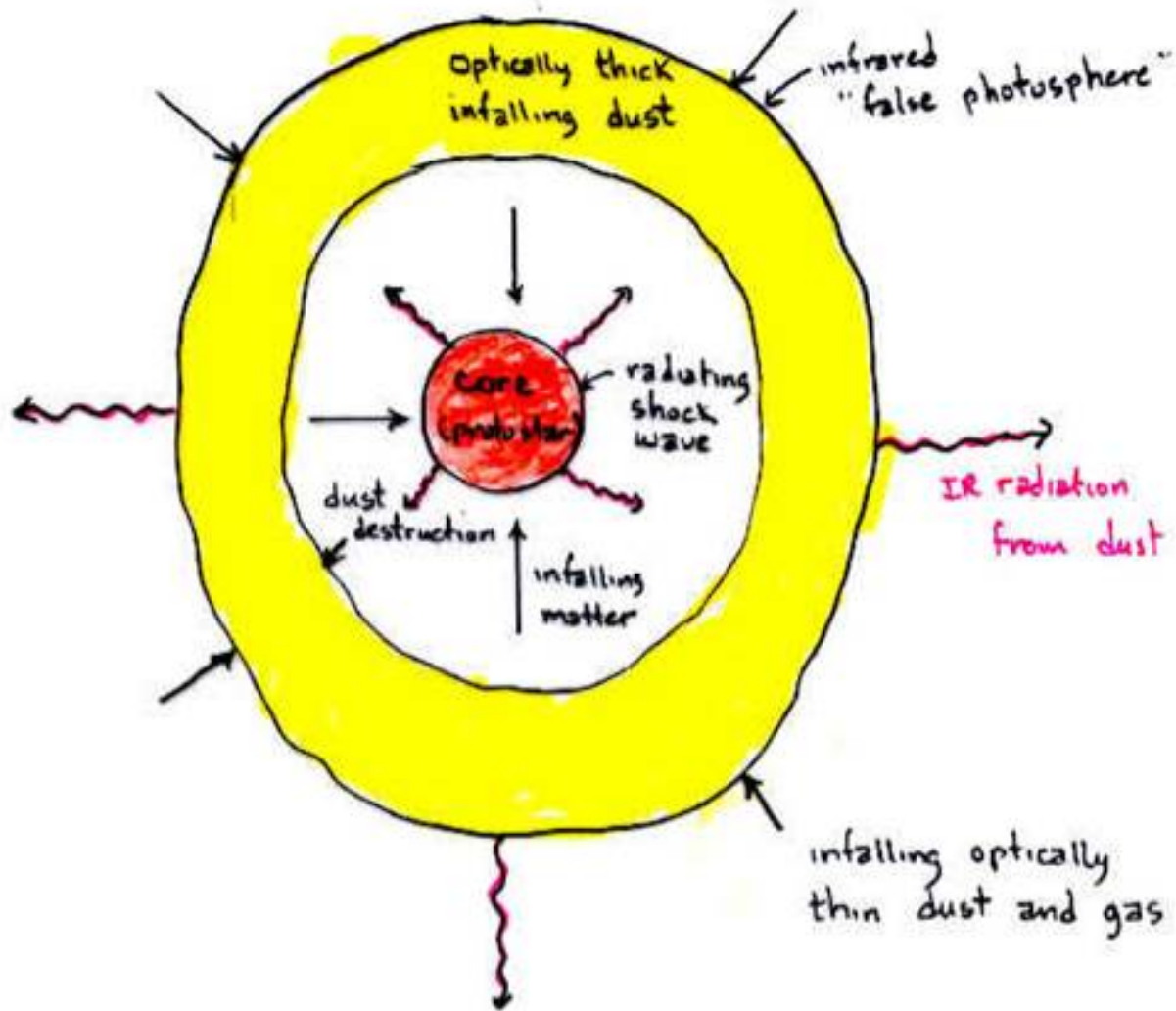
# Fragmentation



## Complications:

Rotation

Magnetic fields



Star formation is inefficient. Even of the collapsing gas only 10 – 20 % of the gas ends up in the star, and overall an even smaller fraction of the cloud collapses to protostars.