The Interstellar Medium

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

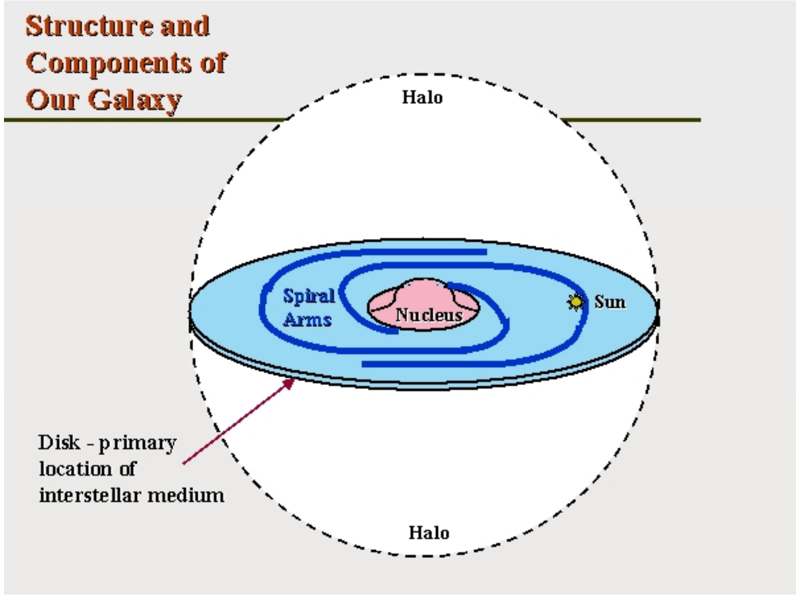
THE INTERSTELLAR MEDIUM (ISM)

- Total mass ~ 5 to 10 x 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 atoms/cm^3 or ~10^{-24} 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.

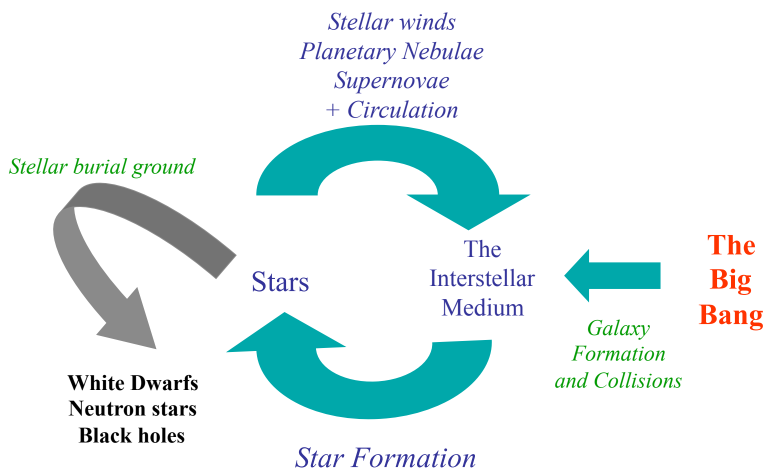
  H I – neutral atomic hydrogen
  H_2 - molecular hydrogen
  H II – ionized hydrogen
  He I – neutral helium
  Carbon, nitrogen, oxygen, dust, molecules, etc.

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

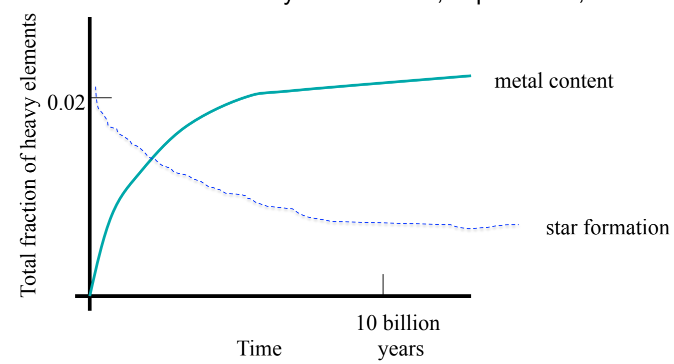


Evolution in the ISM of the Galaxy

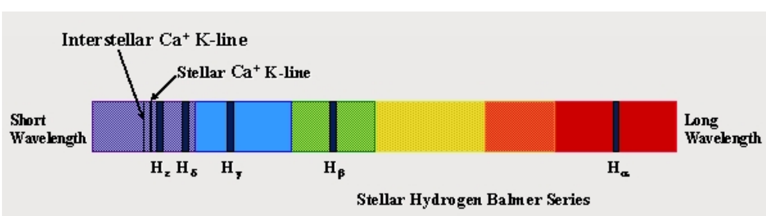


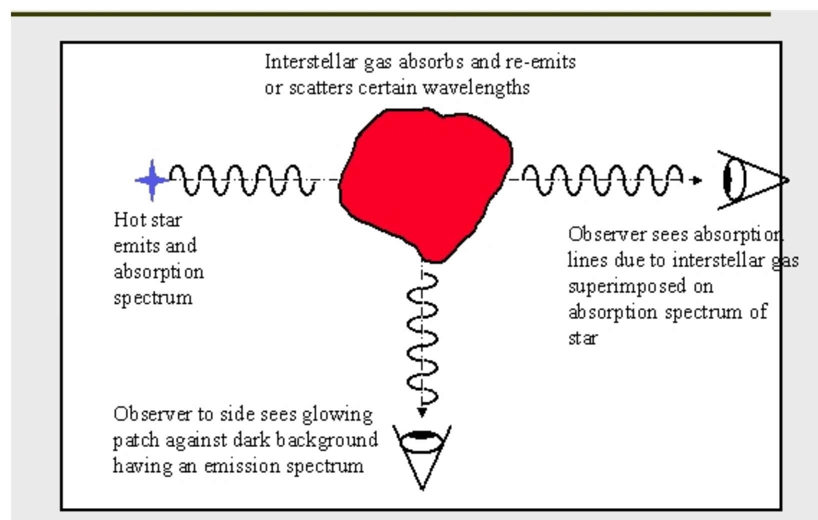
As a result the ISM is continually stirred, heated, and cooled – a dynamic environment, a bit like the earth's atmosphere but more so because not gravitationally confined

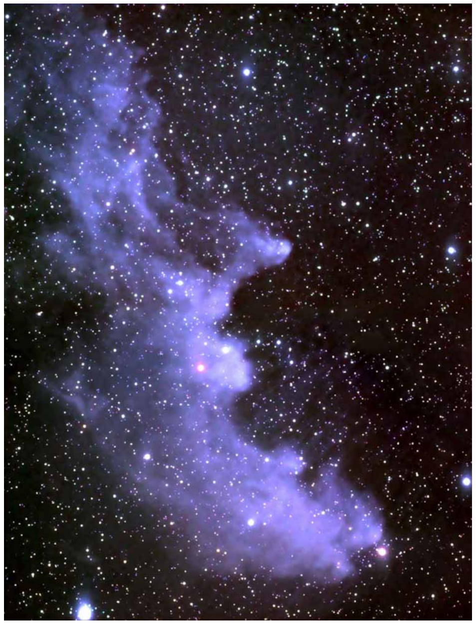
And its composition evolves as the products of stellar evolution are mixed back in by stellar winds, supernovae, etc.:



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*.



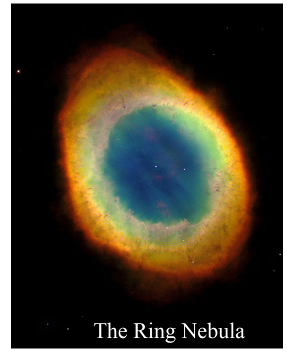


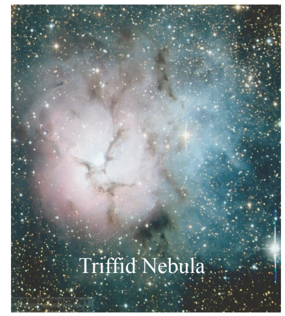


REFLECTION NEBULAE

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 "Witchead Nebula" - about 1000 ly away. situated at Orion's feet, glows primarily by light reflected from Rigel, just out this field.

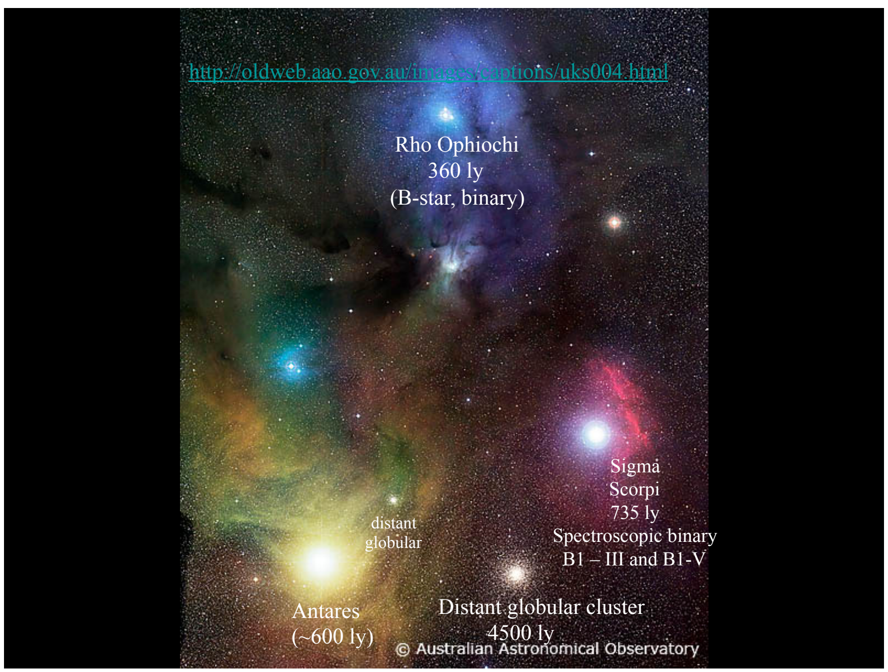




EMISSION NEBULAE

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.

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



ANTARES

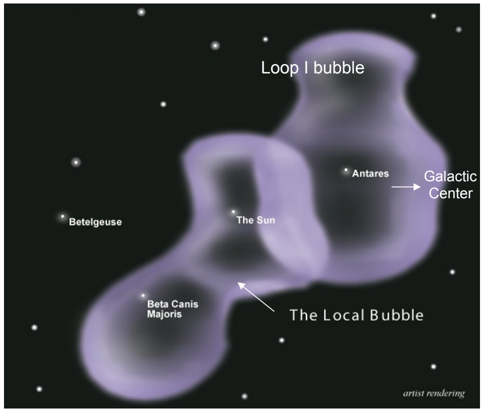
- Aka Alpha-Scorpius, a magnitude 1.06 star, about 15 times the mass of the sun
- Luminosity 10,000 times that of the sun; Spectral Class M I, T = 3100 K, not a main sequence star (B-V) = 1.83. Much like Betelgeuse.

.

- 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



The "Local Bubble" is a region of low density (~0.05 cm^{-3} and high temperature (~10^6 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 Asociation (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 ~100,000 years Antares will be a supernova.
- Total ~ 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

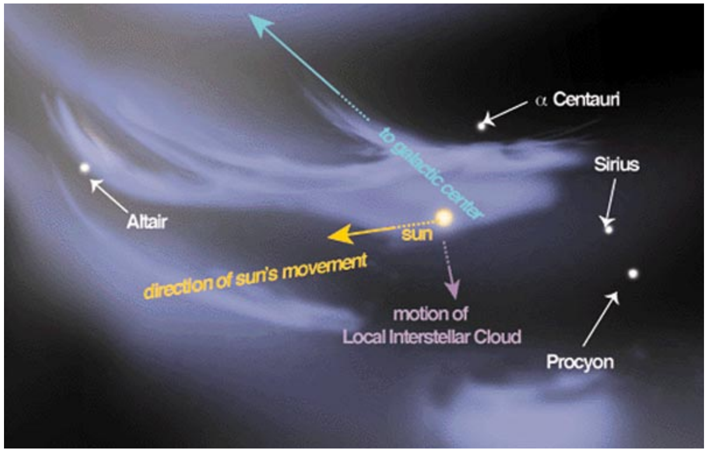
The Local Cloud, sometimes called the Local Fluff, is an interstellar cloud (roughly 30 light years across) through which our solar system is currently moving. The sun entered the Local Cloud between 45,000 and 150,000 years ago and is expected to remain within it for another 10,000 to 20,000 years. The cloud, which is inside the Local Bubble, has a temperature of 7000° 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 - ~ 10 pc

~0.25/cm^3 7000 K

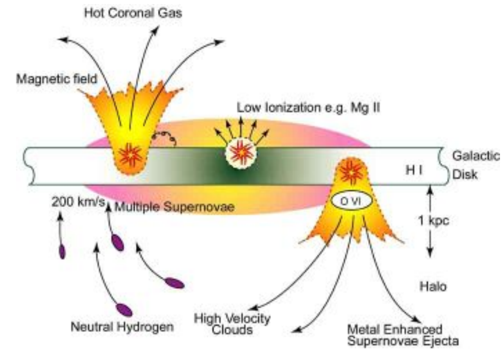
Local Bubble - ~100 pc

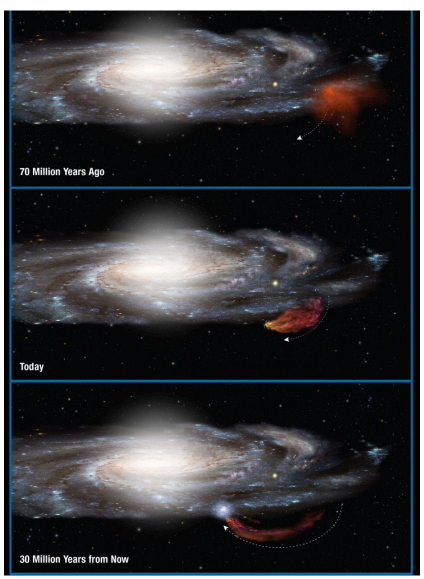
~0.01 - 0.05/cm^3 ~10^6 K

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

http://www.forbes.com/sites/startswithabang/2016/01/28/monstrous-cosmic-gas-cloud-set-to-ignite-the-milky-way/ - 632600660b74

THE (TOO) MANY PHASES OF THE INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
Molecular Clouds	< 1% but ~40% of mass	70	10 - 20	10^2 - 10^6	H_2	Radio and infrared (molecules)
Cold Neutral Medium (CNM)	1 - 5%	100 - 300	50 - 100	20 - 50	H I	21 cm
Warm Neutral Medium (WNM)	10 - 20%	300 – 400 (Local cloud)	5000-8000	0.2 - 0.5	H I	21 cm
Warm partly Ionized Medium (WIM)	20 – 50%	1000	6000 - 12000	0.2 - 0.5	H I, H II	H_α
H II Regions	<1%	70	8000	10^2 - 10^4	H II	H_α
Coronal Gas (Hot Ionized Medium (HIM)	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

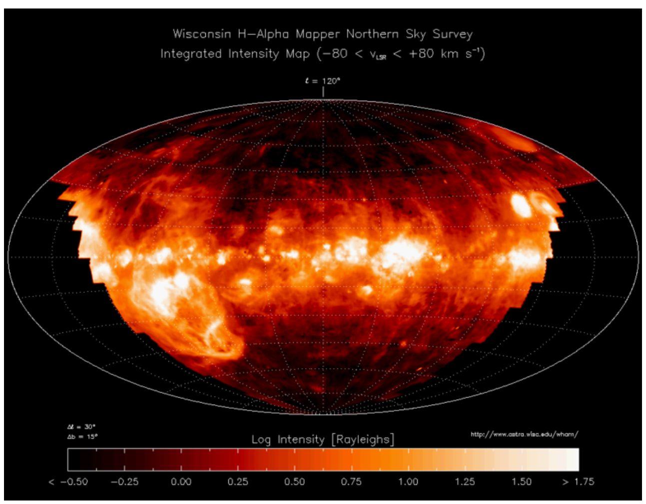
THE THREE COMPONENT INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
Cold dense Molecular Clouds	< 1% but ~40% of mass	70 - 300	10 - 100	10^2 - 10^6	H_2	Radio and infrared (molecules)
Warm Neutral Medium (WNM)	30-70% volume about 50% of mass	300 - 1000	100-10000	0.2 – 50	H I	21 cm
Coronal Gas (Hot Ionized Medium)	30 – 70% but <5% of mass	1000 - 3000	10^6 - 10^7	10^{-4} - 10^{-2}	H II metals also ionized	x-ray ultraviolet ionized metals recombination

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 Hα Map

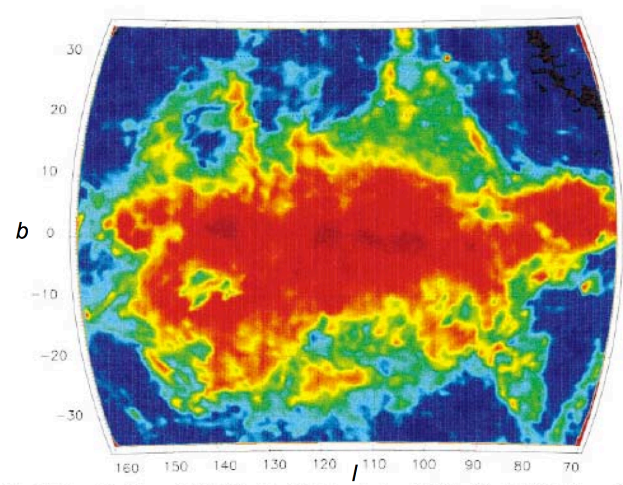


FIG. 6. High-resolution Hα map of a 90°×70° portion of the sky centered on (l=115°, b=0°) at velocities between −60 and 40 km s^{-1}, from the *WHAM* survey. Figure courtesy of L. M. Haffner. [Color]

90°x70° map centered at (l = 115°, b = 0°)

THE THREE COMPONENT INTERSTELLAR MEDIUM

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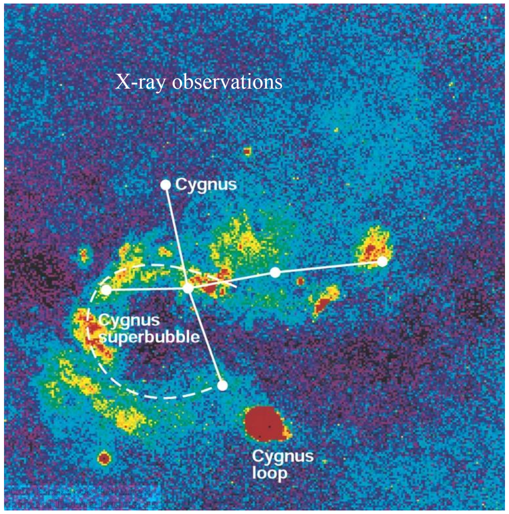
Coronal Gas Regions

- **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^3
  - 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



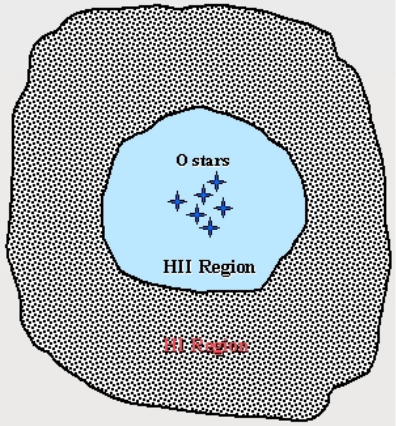
Called "coronal gas" because of its similarity to solar coronal gas, but very different origin.

Probably originates from supernova explosions and winds from very hot stars

Also recall the "Local Bubble"

HII Regions

- 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 ~ 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 Sagitarius – 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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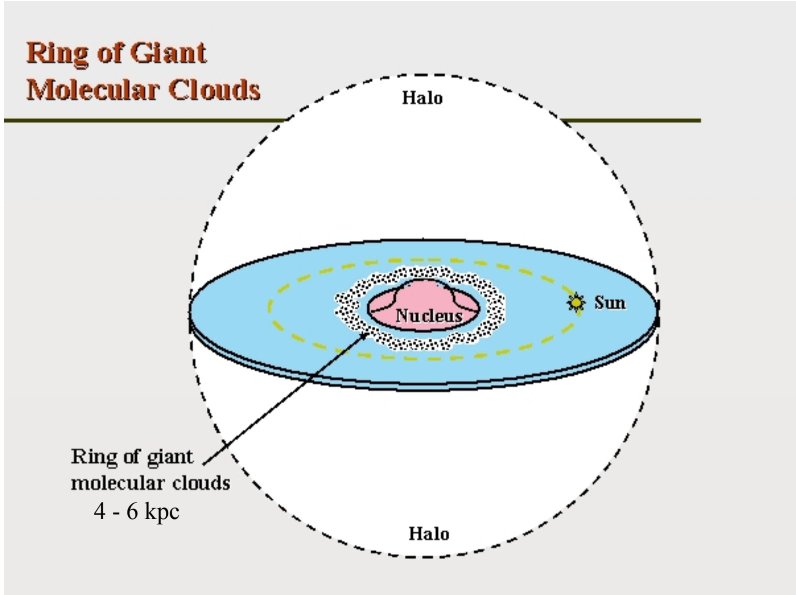
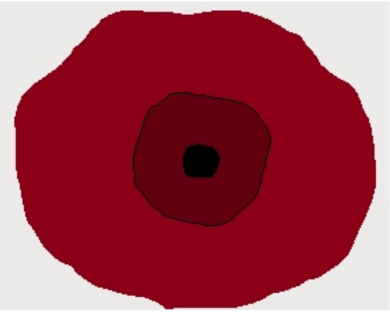
Molecular Hydrogen (H_2)

- 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



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)

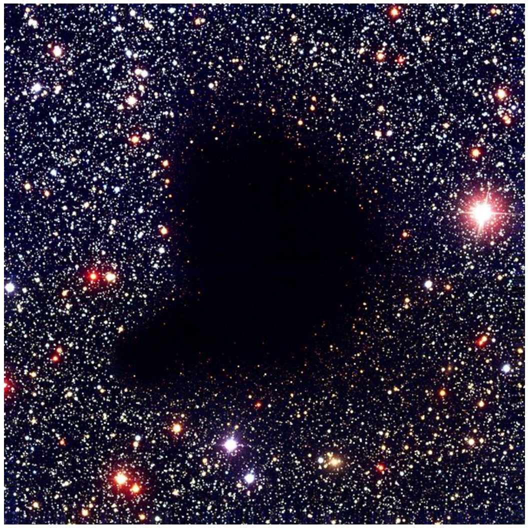


Molecular Clouds (continued)

- Live ~ few x 10^6

http://en.wikipedia.org/wiki/Molecular_cloud

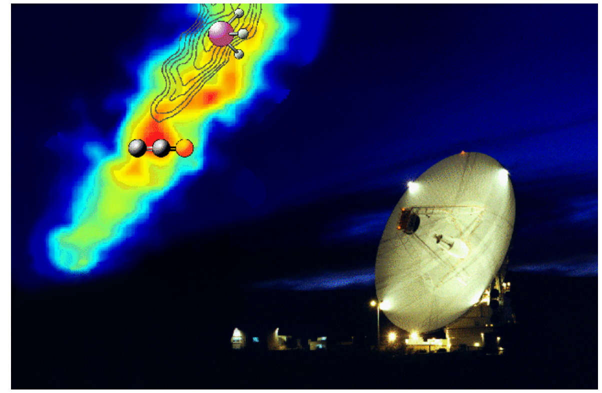
- Cold, dense, definitely regions of active star formation, but only about 2% of the cloud mass ends up as stars
- *Giant* molecular clouds may have masses M ~ 10^3 – 10^6 solar masses. [Taurus a few thousand solar masses; Orion 200,000] and sizes of 10's of parsecs (Orion ~ 70 pc - stretching several degrees from Belt to sword)
- Small molecular clouds are sometimes called "Bok globules", with highly variable masses ~ 1 - 100 solar masses. Found near H II regions. ~ 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". $HC_{11}N$ is the heaviest.

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



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

Molecules with Nine Atoms		
$(CH_3)_2O$ dimethyl ether	CH_3CH_2CN ethylcyanide	CH_3CH_2OH ethanol
CH_3C_4H methylbutadiyne	HCC-CC-CC-CN cyanohexatriyne	C_8H
$CH_3C(O)NH_2$ acetamide	C_8H^-	CH_3CHCH_2 propylene

Molecules with Ten Atoms	
$(CH_3)_2CO$ acetone	$HOCH_2CH_2OH$ ethylene glycol
$H_3C\text{-}CH_2\text{-}C(O)H$ propanal	$CH_3(CC)_2CN$ methylcyanodiacetylene

Molecules with Eleven Atoms		
HCC-CC-CC-CC-CN cyanooctatetrayne	CH_3C_6H methyltriacetylene	$HC(O)OCH_2CH_3$ ethyl formate

Molecules with Twelve Atoms	
C_6H_6 benzene	$CH_3CH_2CH_2CN$ *n*-propyl cyanide

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

Selected Interstellar Molecules

Symbol	Molecule	Symbol	Molecule
H_2	molecular hydrogen	H_2S	hydrogen sulfide
C_2	diatomic carbon	N_2O	nitrous oxide
CN	cyanogen	H_2CO	formaldehyde
CO	carbon monoxide	C_2H_2	acetylene
NO	nitric oxide	NH_3	ammonia
OH	hydroxyl	HCO_2H	formic acid
NaCl	sodium chloride	CH_4	methane
HCN	hydrogen cyanide	CH_3OH	methyl alcohol
H_2O	water	CH_3CH_2OH	ethyl alcohol

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

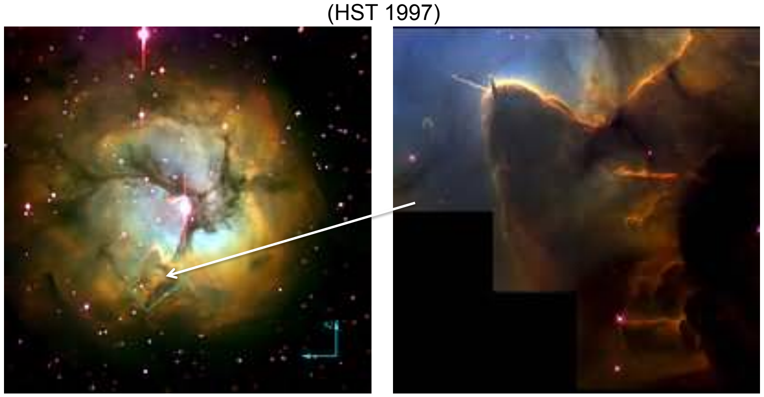
Nearest Example of a Giant Molecular Cloud: Orion

http://www.daviddarling.info/encyclopedia/O/Orion_Complex.html

- Size 70 pc (diameter)
- distance ~ 450 pc
- M ~ 200,000 solar masses
- Age ~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 Sagitarius, 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.

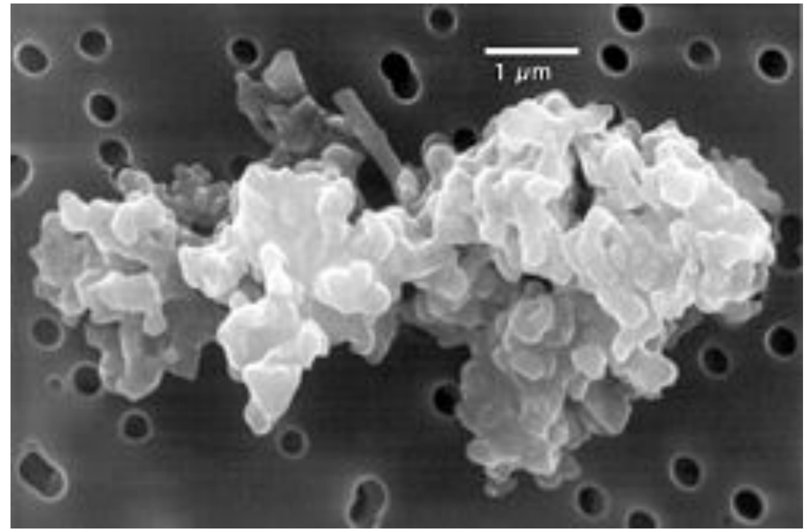
Star birth in the Eagle Nebula, 7000 light years away in the constellation Serpens.

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.

Interstellar Dust

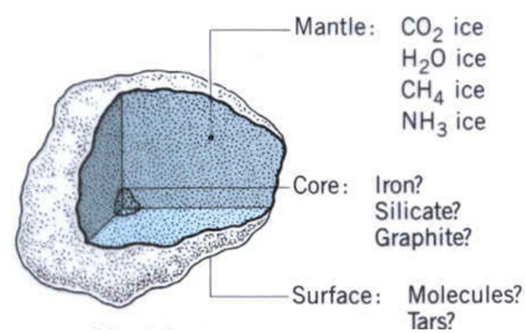
- **Interstellar dust** - microscopic solid grains containing large numbers of atoms that are concentrated in large dark interstellar clouds along plane of Galaxy
  - About 1% of mass of interstellar medium
  - Source of strong extinction of radiation along plane of Galaxy
  - Grain size is about 5 x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



Interplanetary dust in our solar system
Interstellar dust is much smaller (~0.1 - 1 micron = 1000 - 10000A)
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



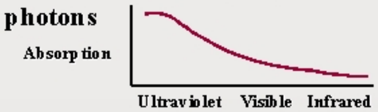
~0.5 μ

1 m= 10^{-6} m = 10^{-4}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

- **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



  - 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
Cold dense Molecular Clouds	< 1% but ~40% of mass	70 - 300	10 - 100	10^2 - 10^6	H_2	Radio and infrared (molecules)
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The Jean's Mass

$$\Omega \approx KE$$

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

$$\Omega \approx \frac{3}{5}\frac{GM^2}{R} \approx (\text{Number of particles})\left(\frac{3}{2}kT\right)$$

$$\approx \frac{M}{m_H}\frac{3}{2}kT \quad \text{(if made of pure hydrogen)}$$

$$= N_A M \frac{3}{2}kT \quad (N_A \text{ is Avogadro's Number, } 6.02 \times 10^{23})$$

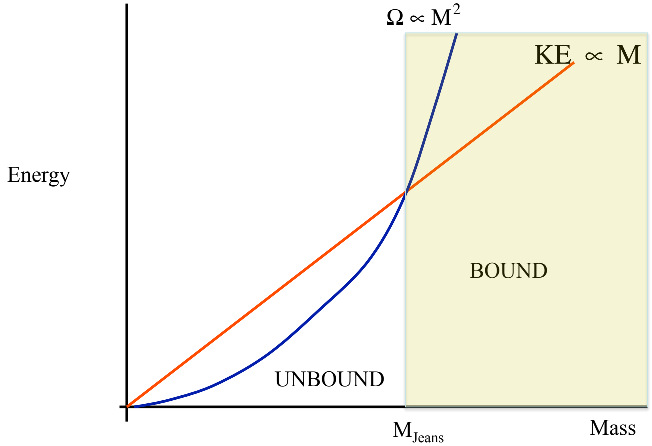
This can be solved for the "Jean's Mass", M_J

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

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

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

$$R = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

assume sphere, constant density $M = \frac{4}{3}\pi R^3 \rho$

previous page

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

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

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

$$= 8.5\times10^{22}\ \text{gm}\left(\frac{T^{3/2}}{\rho^{1/2}}\right) = 4.2\times10^{-11}\left(\frac{T^{3/2}}{\rho^{1/2}}\right)M_\odot$$

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

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

$$M_J = 8.5\times10^{22}\frac{T^{3/2}N_A^{1/2}}{n^{1/2}}\ \text{gm}$$

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

where n is the density in atoms cm^{-3}.

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 K, n = 10^4 atoms cm^{-3}

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

$$= 34\,\frac{(20)^{3/2}}{(10^4)^{1/2}} = 34\,\frac{89.4}{100}$$

$$= 30\ M_\odot$$

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

How long does the collapse take?

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

but, ρ, the density, is given by

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

so,

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

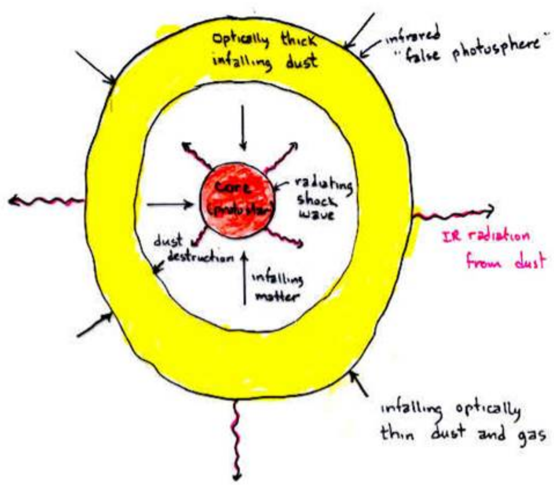
Denser regions collapse faster

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

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

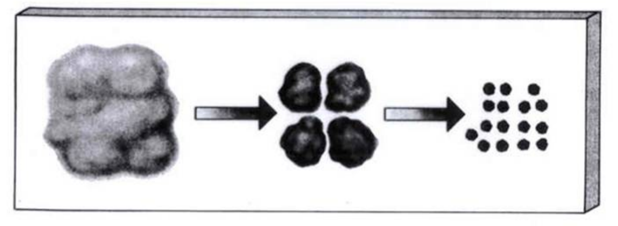
where n is the number of atoms per cubic cm.

1 million years if n = 10^4 atoms/cm^3



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.

Fragmentation



Complications:

Rotation

Magnetic fields