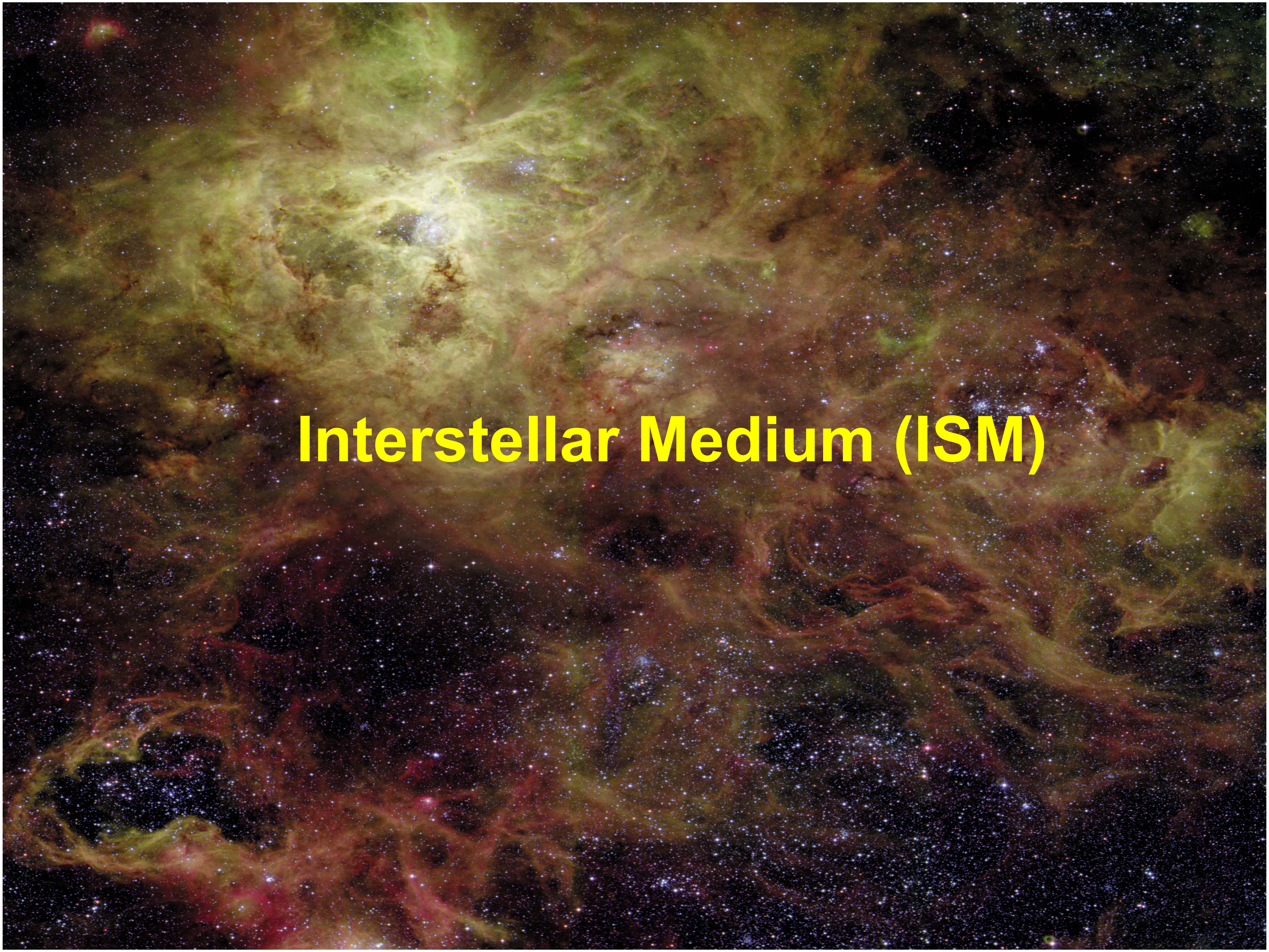
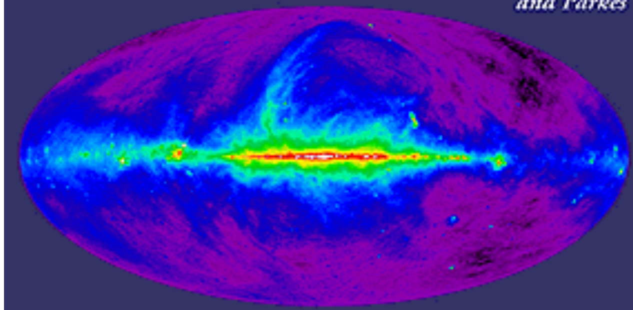
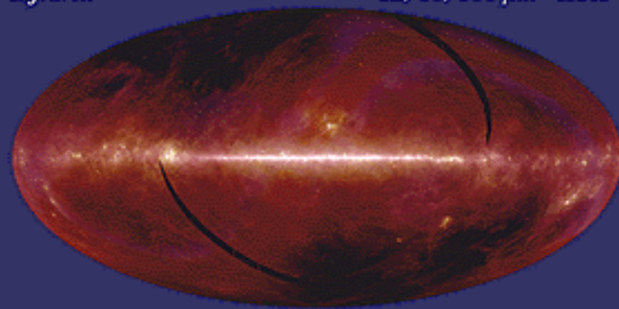

Interstellar Medium (ISM)

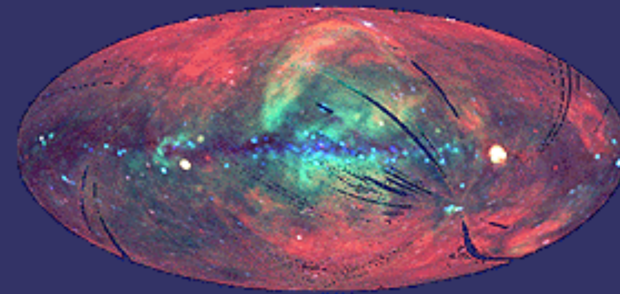
Radio Continuum (408 MHz) *Bonn, Jodrell Bank, and Parkes*



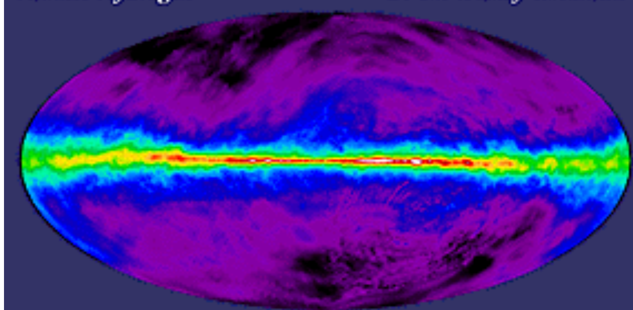
Infrared *12, 60, 100 μm IRAS*



X-Ray *0.25, 0.75, 1.5 KeV ROSAT/PSPC*

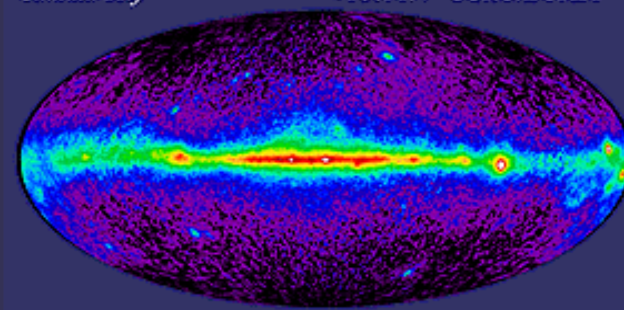


Atomic Hydrogen *21 cm Dickey-Lockman*

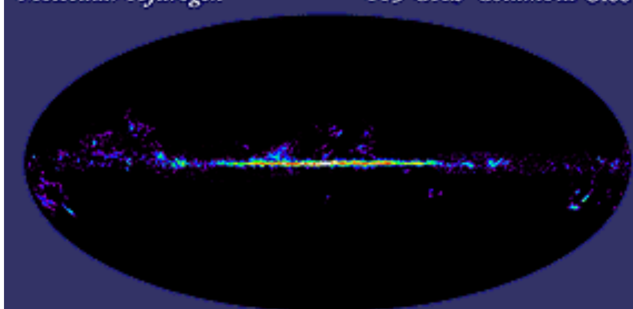


Interstellar gas and dust

Gamma Ray *>100MeV CGRO/EGRET*

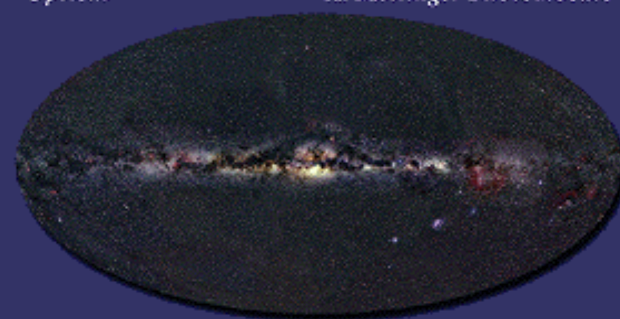


Molecular Hydrogen *115 GHz Columbia-GISS*



Near Infrared *1.25, 2.2, 3.5 μm COBE/DIRBE*

Optical A. Mellinger Photomosaic



Constituents of the ISM

	constituents of ISM in Milky Way	where	temperature density ...	how observed
Gas	atomic hydrogen HI	in disk, some in halo $\approx$ 60% of mass, 40% of vol.	$50...300$K $1...100$cm^{-3}	21cm radio line UV absorption lines
Gas	molecular hydrogen H_2	dark clouds in disk $\approx$ 15% of mass, 1% of vol.	$3...100$K $10^2...10^6$cm^{-3}	UV absorption lines IR emission lines
Gas	ionized hydrogen HII	near hot stars, ≈ 20% of mass, 10% of vol.	$5000...10000$K $10^2...10^4$cm^{-3}	optical and IR emission lines, radio continuum
Gas	hot gas	everywhere ≈ 1-2% of mass, 50% of vol.	$10^6...10^7$K 0.01cm^{-3}	X-ray emission
	dust grains	mostly in disk ≈ 1% of mass	$20...100$K size ≈ 2000Å	reddening/absorption of starlight, IR emission
	magnetic fields	everywhere	μGauss	polarization of stars, Zeeman effect, synchrotron radiation
	cosmic rays	everywhere	energies up to 10^{20}eV	air showers
	radiation field (CMB, starlight, dust)	everywhere	~ 1eV cm^{-3}	various

The total mass of the ISM in the Milky Way amounts to ≈ 15% of the mass in stars, which is a typical value for spiral galaxies in general.

ISM is very dilute, far from LTE

Because the density of the ISM is extremely low, particles have a large mean free path

$$\lambda_{\rm mfp} \approx \frac{1}{n_H \sigma_c} \approx 10^{15} \left(\frac{1\ {\rm cm}^{-3}}{n_H} \right) {\rm cm}$$

Typical particle velocity: $m_H v^2 = k_B T$

The collision time scale is then:

$$\tau_c \approx \frac{\lambda}{v} \approx 1.3 \times 10^{11} \left(\frac{T}{\rm K} \right)^{-1/2} \left(\frac{n_H}{1\ {\rm cm}^{-3}} \right)^{-1} {\rm s}$$

Adopting T=100 K, n_H=1 cm^{-3}, we obtain about 1 collision in 500 years

Local thermodynamic equilibrium (LTE) requires all species, including ions, electrons neutrals, and photons collide with each other sufficiently frequently.

LTE applies inside the stars, NOT in the dilute ISM

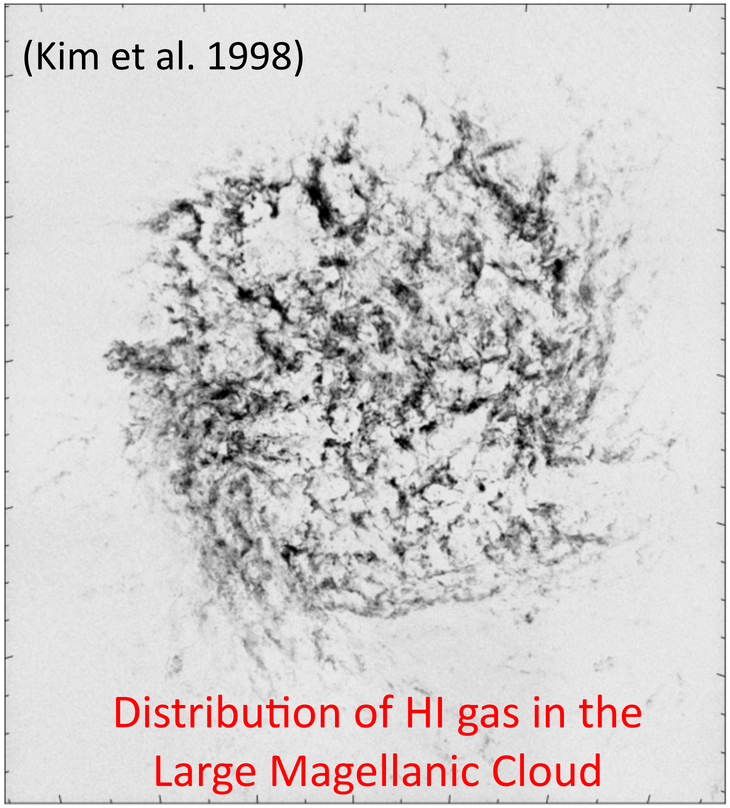
The multi-phase interstellar gas

• The various gas phases exist in pressure equilibrium:

$$n \cdot T \approx 10^3 - 10^4 \ \mathrm{K\ cm}^{-3}$$

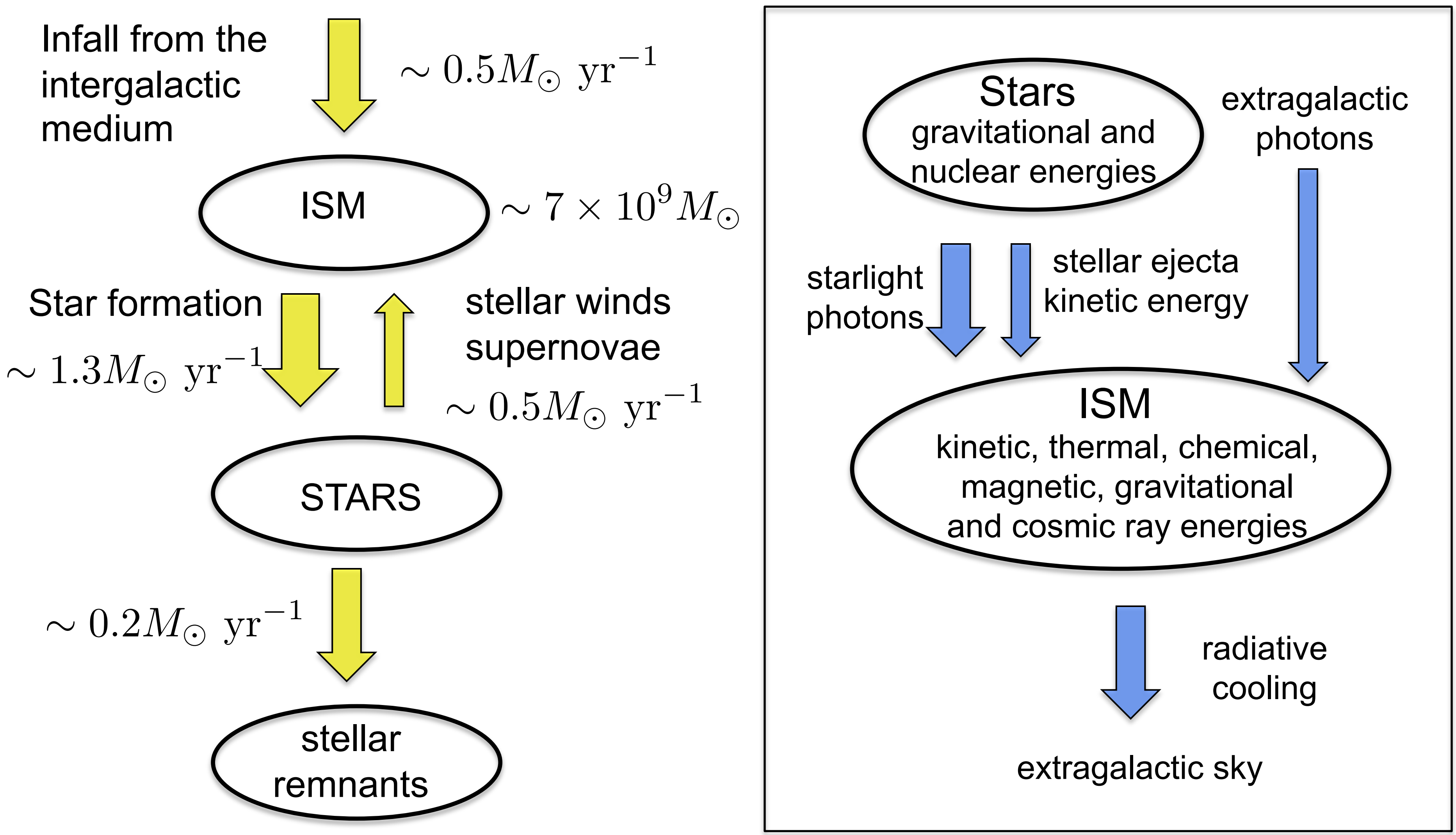
• The existence of a multi-phase medium requires that energy flows through the system, e.g., by injection of energy through supernova explosions and/or stellar winds

• The hot gas from SN explosions and stellar winds fills a large fraction of the interstellar space, compressing the HI and molecular gas into a filamentary, fractal structure.



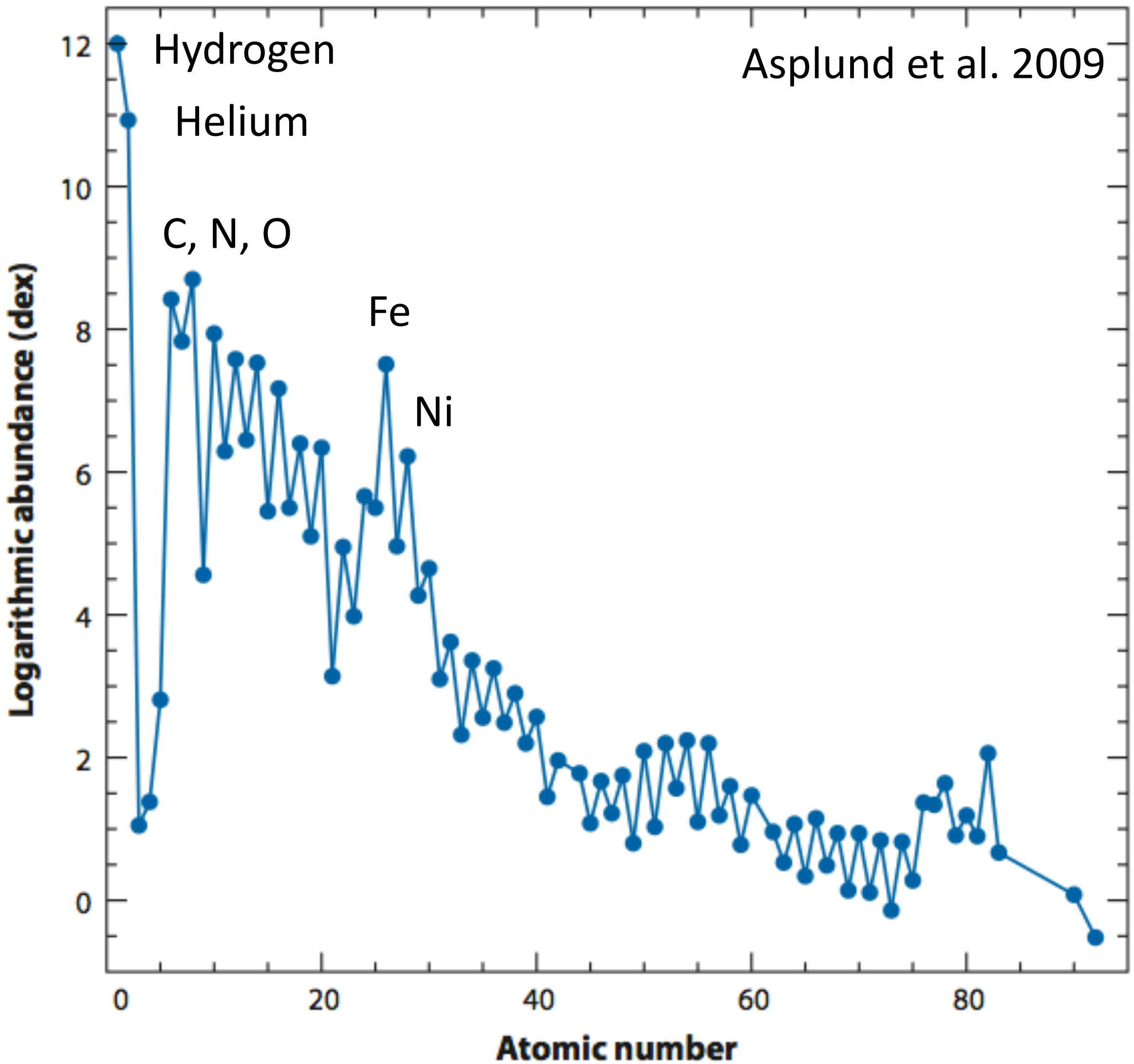
Distribution of HI gas in the Large Magellanic Cloud

Material Flow and Energy Balance of the ISM



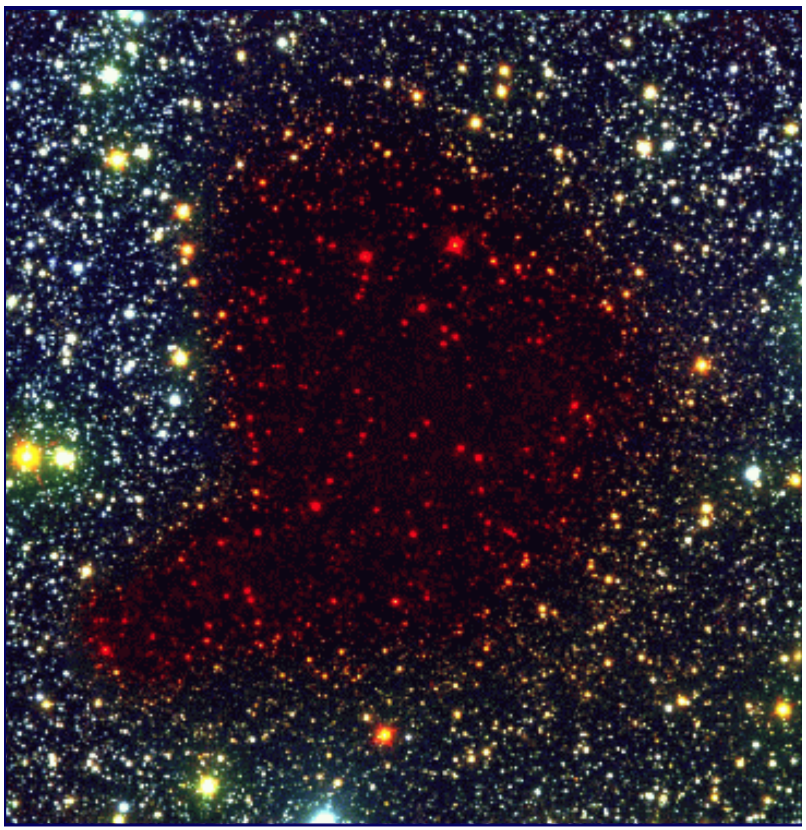
Abundance of elements in the solar neighborhood

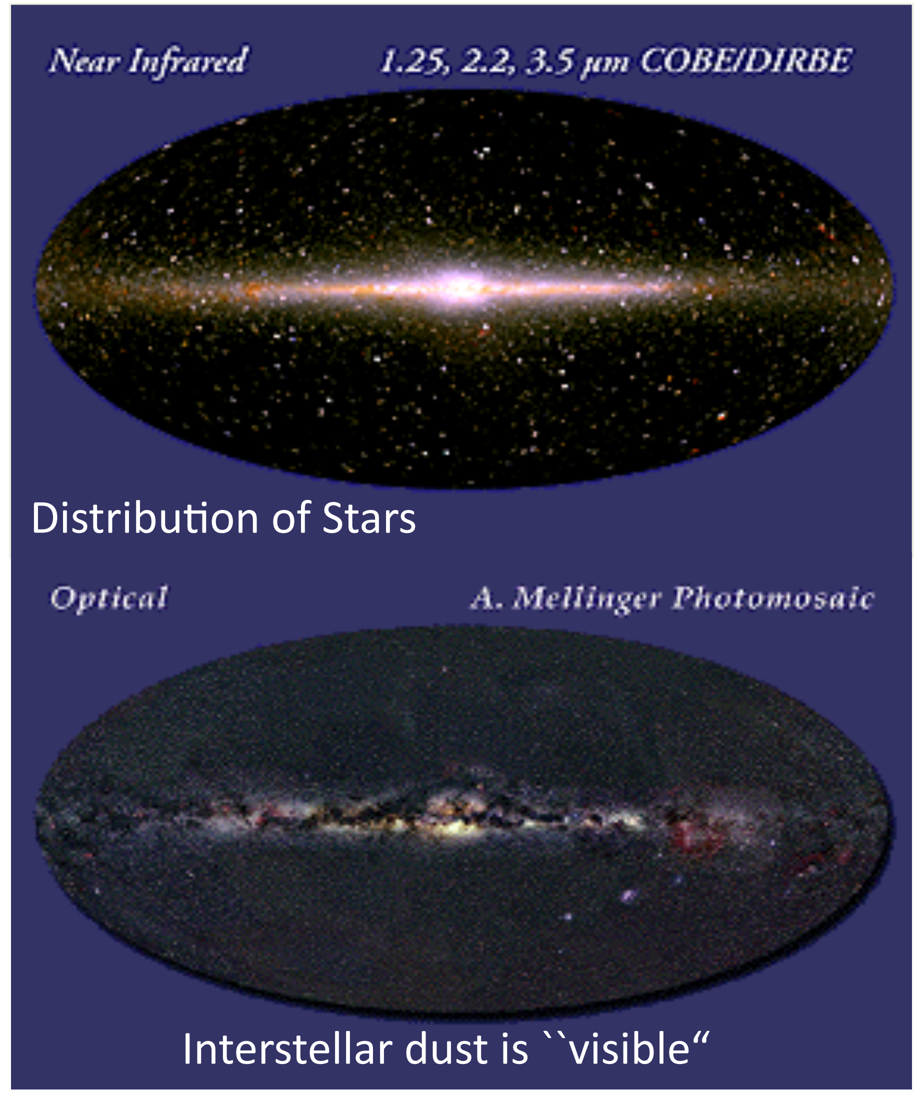
Log scale!



Interstellar Dust

- Extinction and reddening



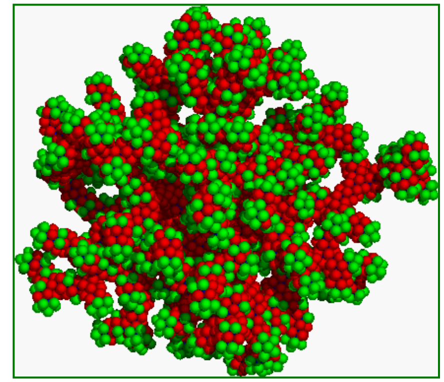


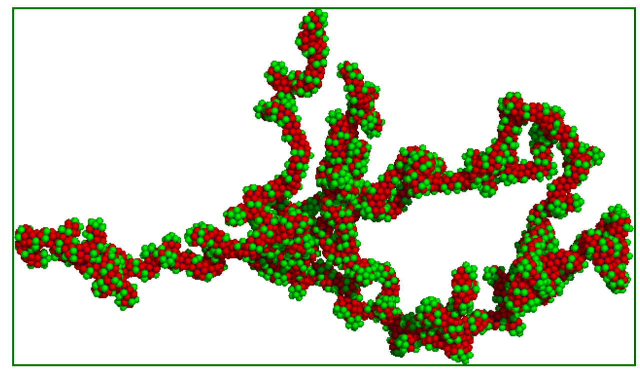
Distribution of Stars

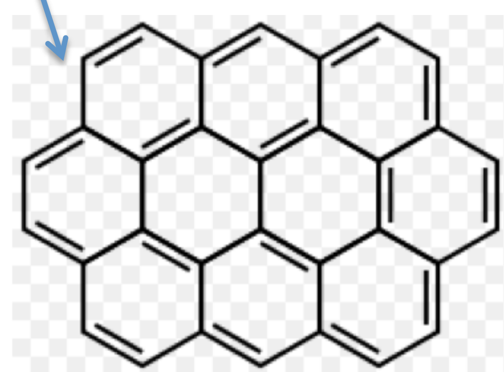
Interstellar dust is ``visible“

Dust grains: physical properties

- Abundance: ~ 1% in mass
- Location: well-mixed with gas (roughly)
- Composition: C, Si, O, Mg, Fe
- Size: sub-micron, down to nm sized PAHs (polycyclic aromatic hydrocarbon)
- Shape: mostly amorphous rather than crystalline, can be very irregular







Dust grains: extinction

- Absorb and scatter optical and UV photons very efficiently, re-emit in longer wavelength.

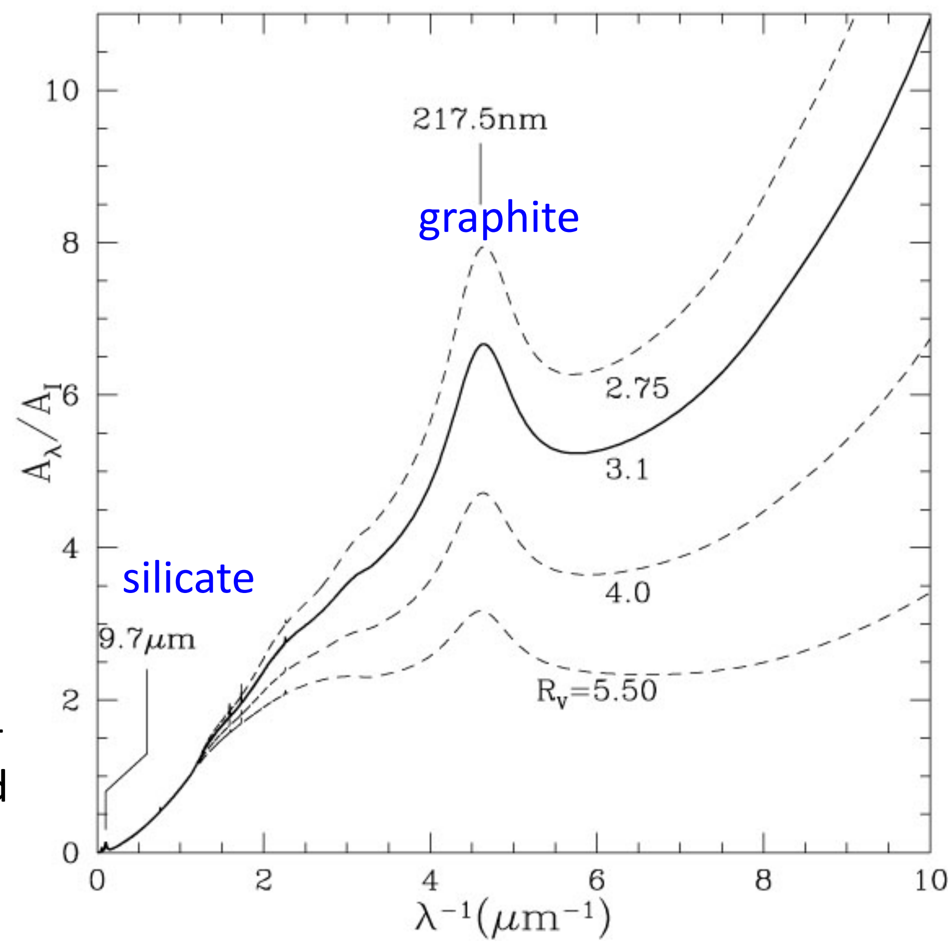
$$\frac{A_\lambda}{\text{mag}} = 2.5\log_{10}\left(\frac{F^0_\lambda}{F_\lambda}\right)$$
$$= 2.5\log_{10}(e^\tau) = 1.086\tau_\lambda$$

$$R_V \equiv \frac{A_V}{A_B - A_V} \equiv \frac{A_V}{E(B-V)}$$
$$= \frac{1}{\tau_B/\tau_V - 1}$$

Color Excess
(Reddening)

R_V depends on dust properties, and is determined by observations, which is in turn used to constrain dust models.

R_V=3.1 in the solar neighborhood.



(Cardelli et al. 1989)

Dust grains: extinction

- Absorb and scatter optical and UV photons very efficiently, re-emit in longer wavelength.

extinction = absorption + scattering

(albedo = scattering / extinction)

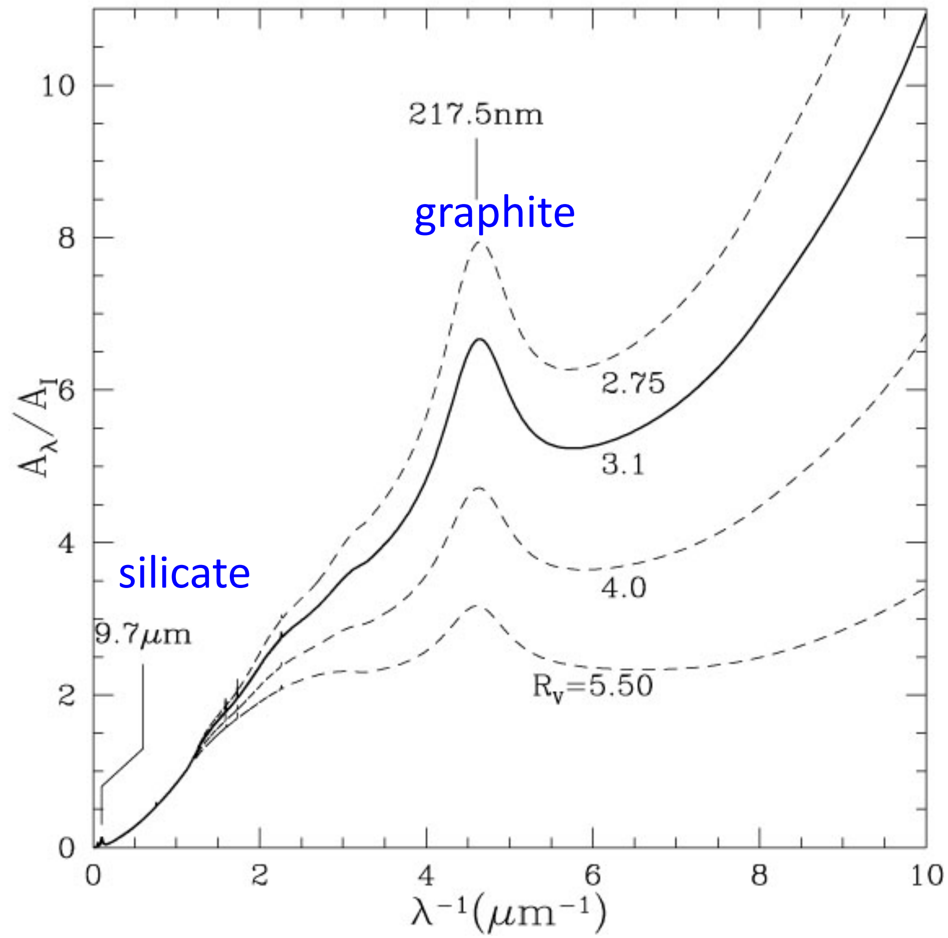
Extinction cross section for a single grain (**Mie theory**):

$$\sigma \approx \pi a^2 \quad \text{for} \quad \lambda \lesssim a$$

$$\sigma \propto 1/\lambda \quad \text{for} \quad \lambda > a$$

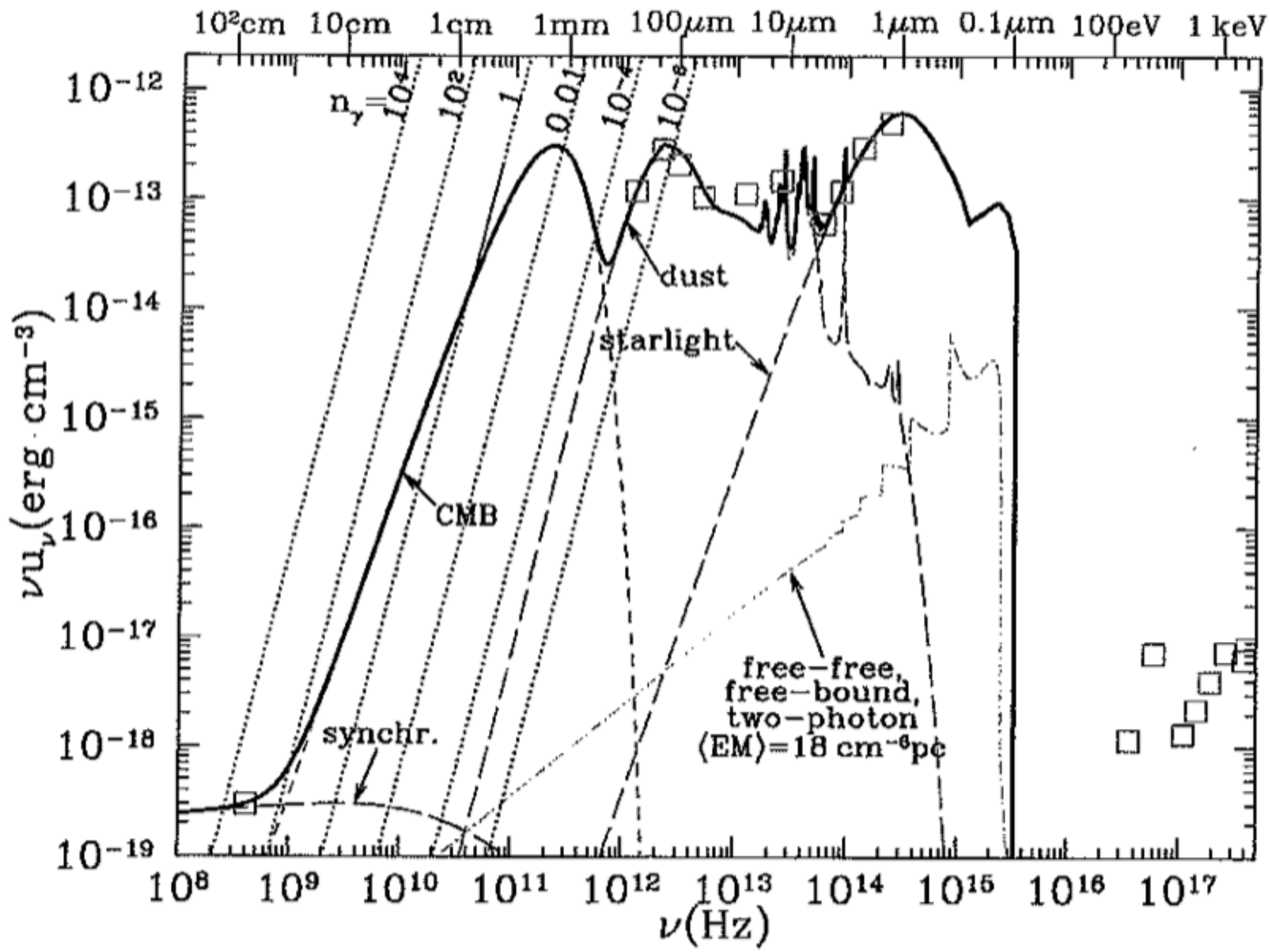
Extinction curve:

- Contains rich information about grain properties (composition, size distribution, etc.)
- Parameterized by R_V
- Of crucial importance for galactic and extragalactic observations



(Cardelli et al. 1989)

Dust grains: emission spectrum

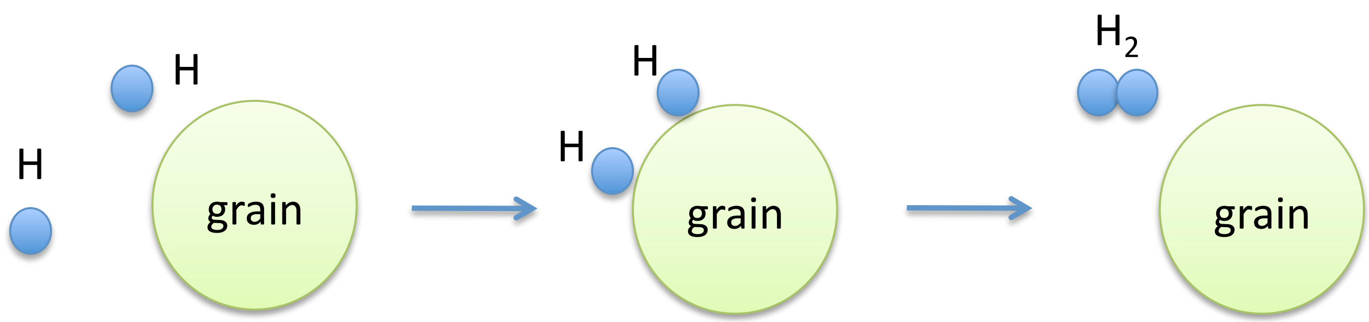


Dust grains: chemistry

- H_2 formation:

Direct formation of H_2 by collisions of two H atoms is very unlikely (unable to get rid of the excess energy efficiently).

In the present day universe most of the H_2 form by combining two H atoms after their adsorption by the surface of a dust particle:



- Recombination and grain charging

Grains can be charged by colliding with electrons and ions, with equilibrium net charge

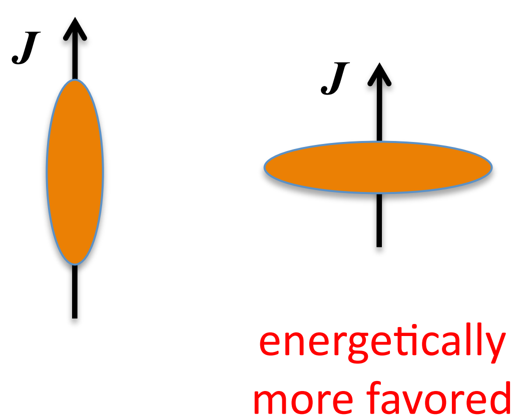
$$Z_{\rm gr} \approx -150 \left(\frac{a}{0.1\mu{\rm m}}\right)\left(\frac{T}{10^4{\rm K}}\right)$$

Dust grains: dynamics

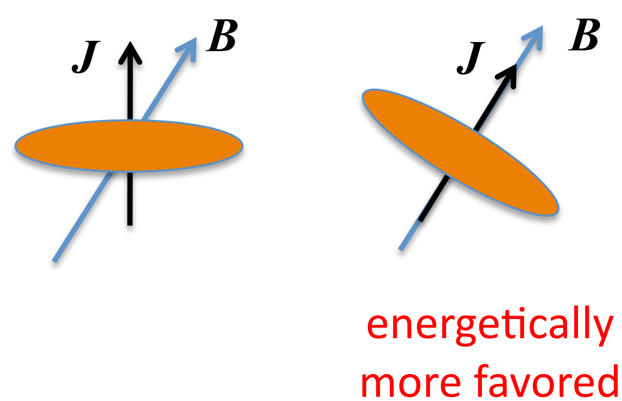
- Translational motion
  - Gas drag -> coupled to the gas
  - Lorentz force -> coupled to the magnetic field
  - Radiation pressure -> Poynting-Robertson effect (grains orbiting stars tend to spiral in)
- Rotation

  Grains can be spun up by absorption/emission of photons, H_2 formation, etc.
- Alignment of charged grains with magnetic field

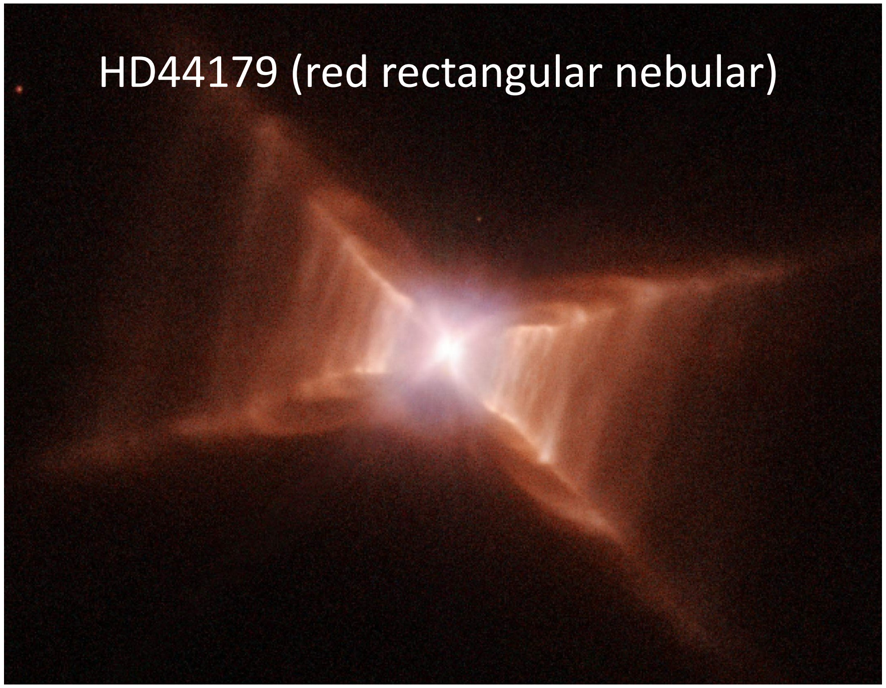
step 1:

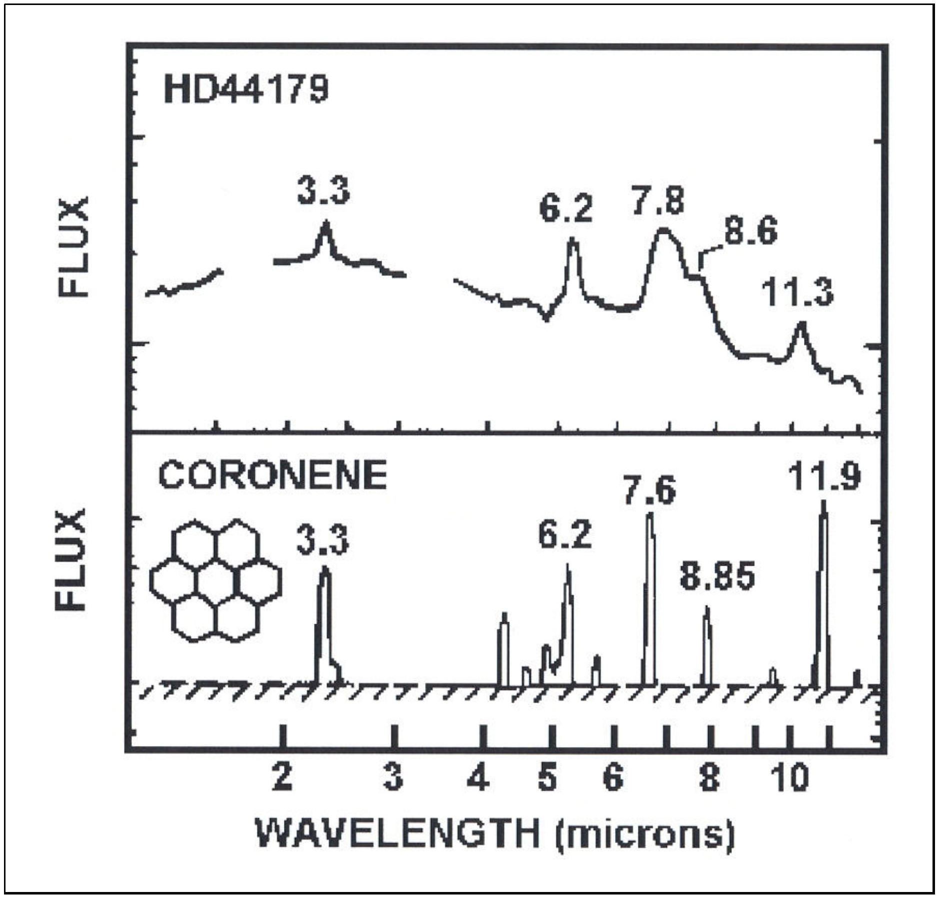


step 2:



Formation of interstellar dust

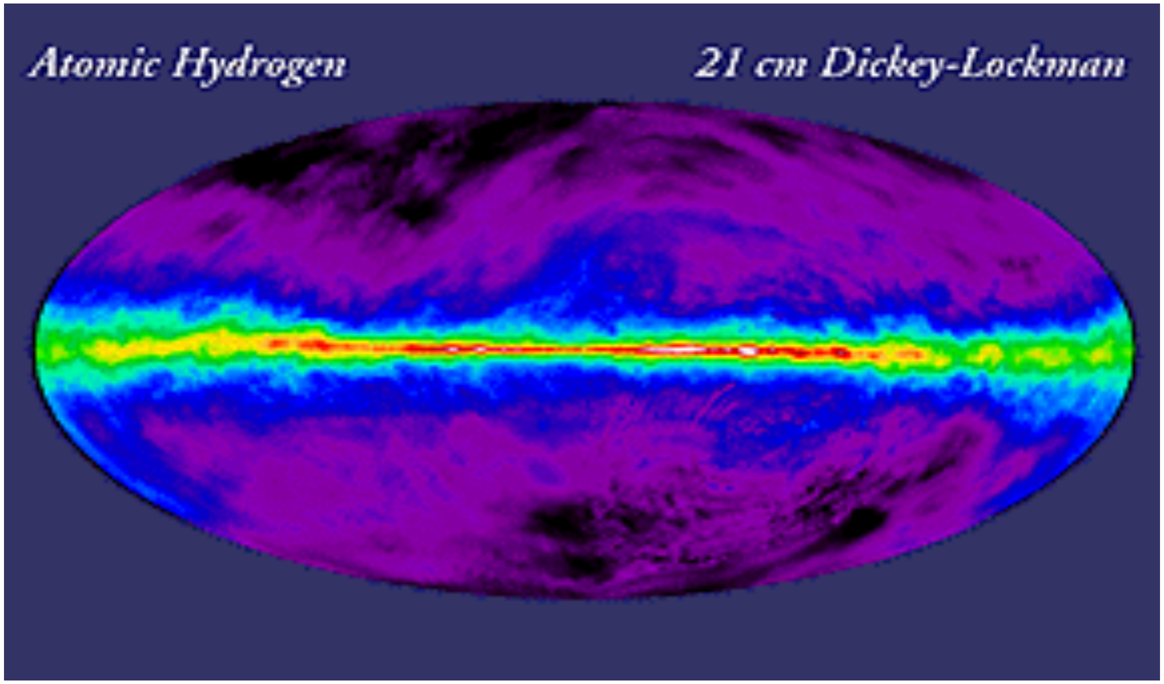




Interstellar dust is likely produced in the outer atmospheres of red giants.

Up: IR spectrum from the atmosphere of a red giant star.
Bottom: Laboratory spectrum of coronene, a type of PAH

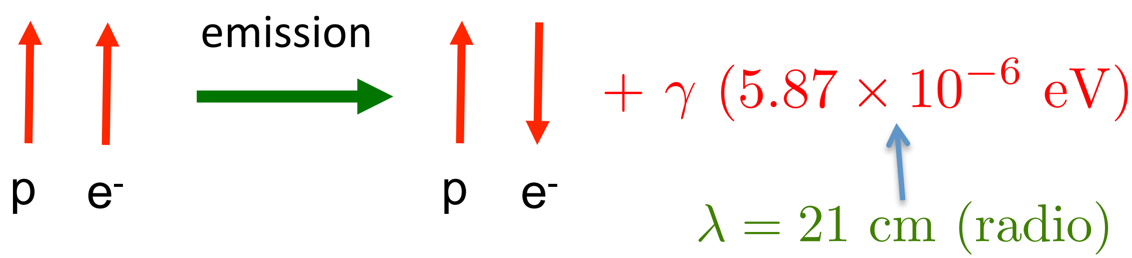
Atomic Hydrogen



- Atomic hydrogen comprises ~60% of the matter in the ISM
- Most diffuse H is in the form of HI in the disk with some in the halo
- HI gas is primarily heated by photoionization, and is cooled by line emission
- HI gas can be detected either by UV absorption lines or through the 21cm line

The 21cm line

- The 21 cm line is produced when the spin of the electron relative to the proton in the atom's nucleus reverses (hyperfine structure splitting)



- This transition is highly forbidden with a lifetime of 11 million years

- Still, the total number of hydrogen atom in a column of 1 cm area with 1 pc depth is >10^{18}, there are enough transitions.

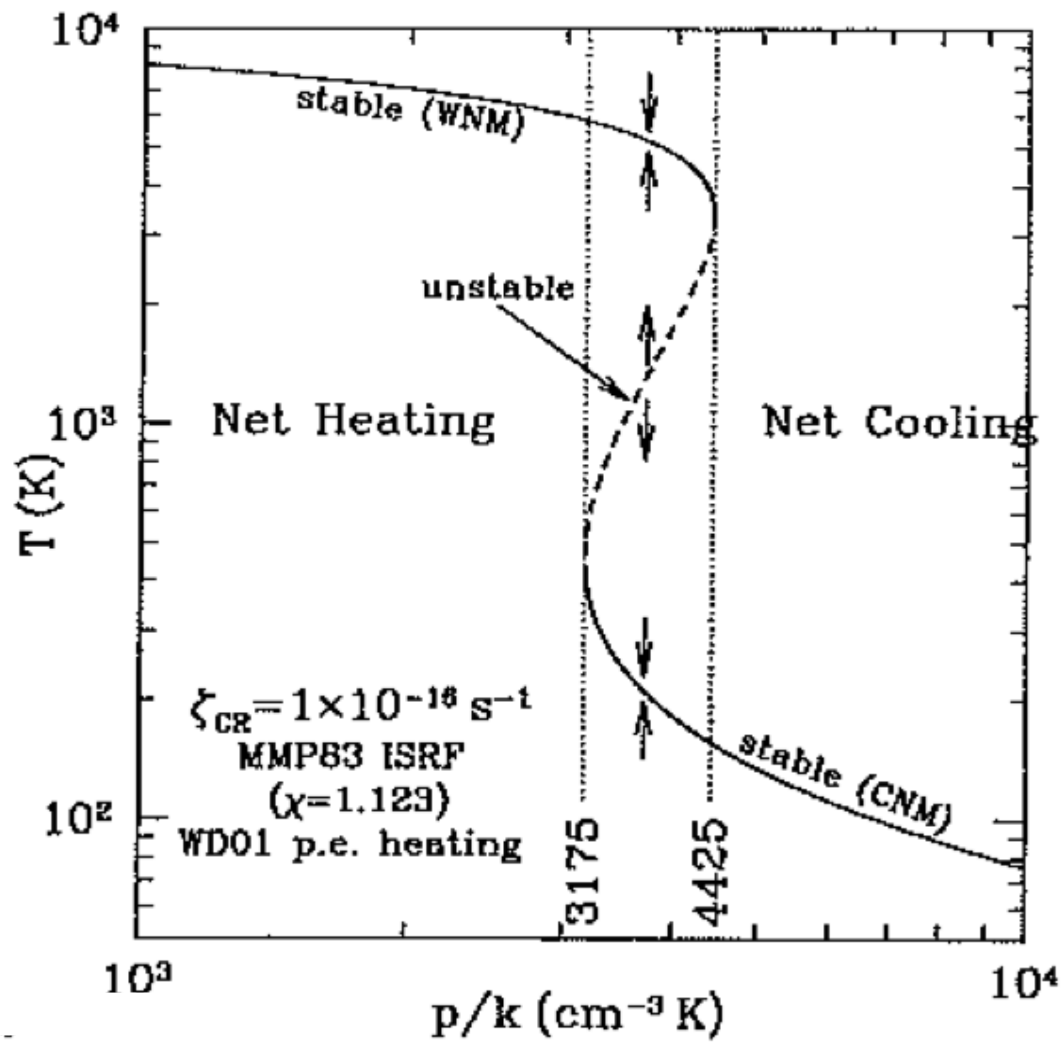
Two phases of HI

- Cold neutral medium (CNM)

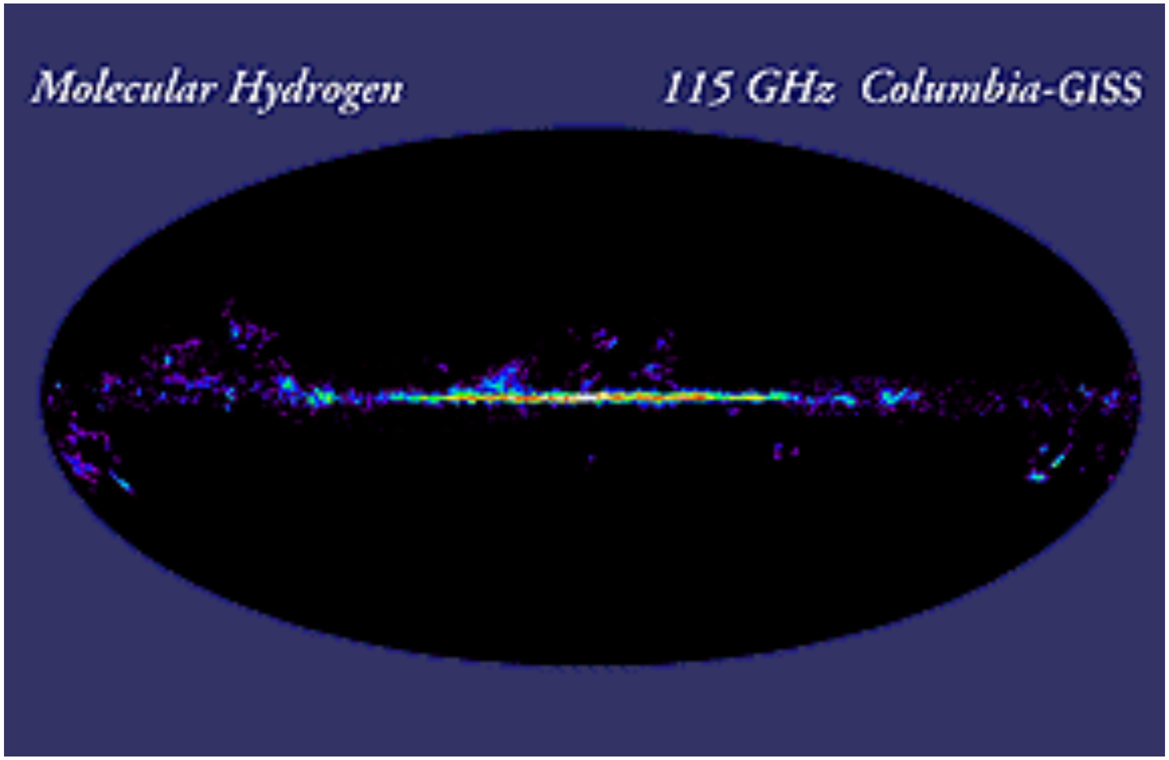
$$T \sim 100\text{K}$$
$$n_H \sim 30 \text{ cm}^{-3}$$
$$f_V \sim 0.01$$

- Warm neutral medium (WNM)

$$T \sim 5000\text{K}$$
$$n_H \sim 0.6 \text{ cm}^{-3}$$
$$f_V \sim 0.4$$

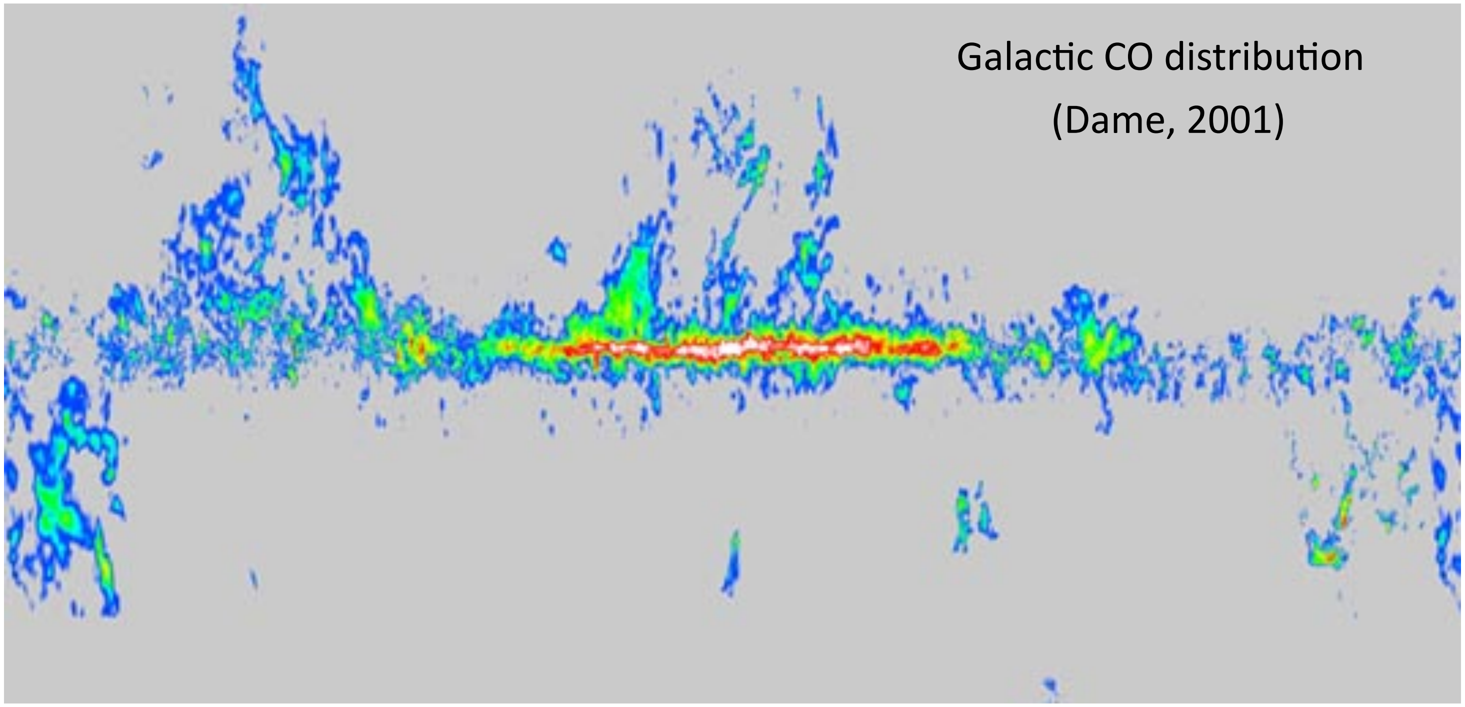


Molecular Clouds



- Associated with star-forming regions, concentrated in the galactic plane
- $\sim 20\%$ of mass in the ISM ($\sim 2\times 10^9 M_\odot$), H_2 being the dominant content
- Very opaque due to the dust
- Have a wide range of size and densities, from diffuse cloud ($A_V \sim 1$) to giant molecular cloud ($A_V \sim 20$ and up to 100)

Molecular cloud: tracers



- H_2 can not be easily detected (lack of permanent electric dipole moment)
- Clouds are most often surveyed based on the CO molecule (rotational transition from J=1 to J=0, at wavelength of 2.6 mm)
- Other methods include observation of sub-mm continuum emission from the dust

Molecular cloud

- Because of high density, complex chemistry is possible:

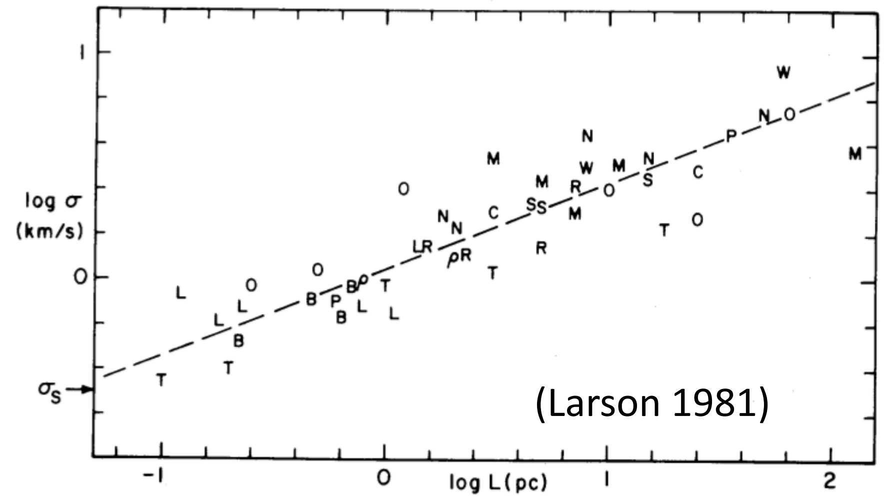
  Other molecules include but not limited to: H_2O, HCN (cyanide), OH (hydroxyl) and more complex molecules such as ethyl alcohol (CH_3CH_2OH)

- Giant molecular clouds are self-gravitating

  Velocity dispersion increases with cloud size

  Velocity dispersion is supersonic

  => supersonic turbulence



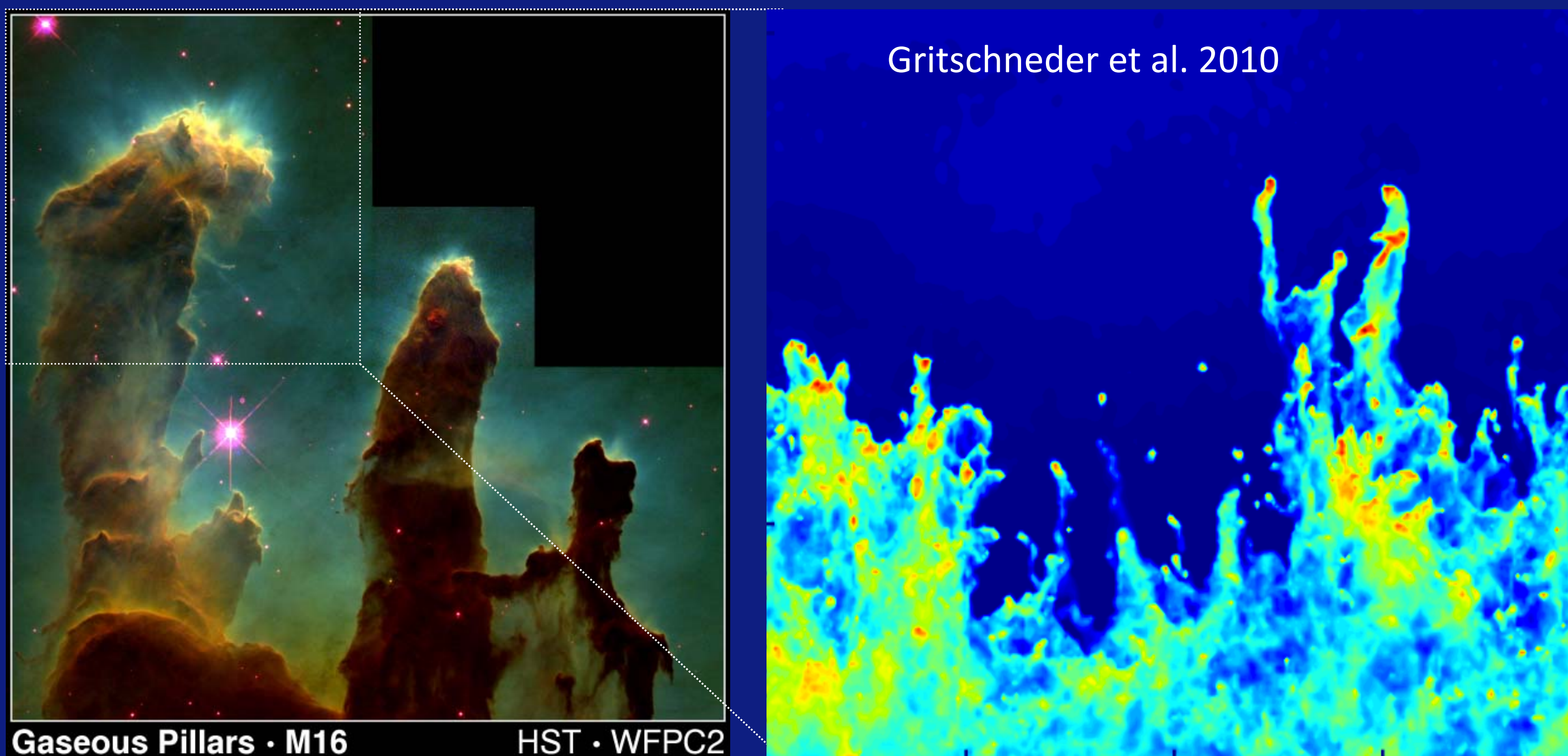
(Larson 1981)

- Presence of magnetic field

  Magnetic field of 5-1000 micro Gauss from Zeeman splitting measurement

  => magnetic energy comparable to the turbulent kinetic energy

“PILLARS OF CREATION” IN A STAR-FORMING REGION M16 - Eagle Nebula



Molecular clouds are clumpy and very irregular.

HII regions

- They are formed near molecular clouds where newly formed massive stars ionize hydrogen and heavier elements like O, N.

- $\sim 20\%$ of the mass in the ISM

- Heated to high temperature (7000-15000 K) by photoionization, cooled by optical and IR line emission, as well as free-free (bremsstrahlung) emission

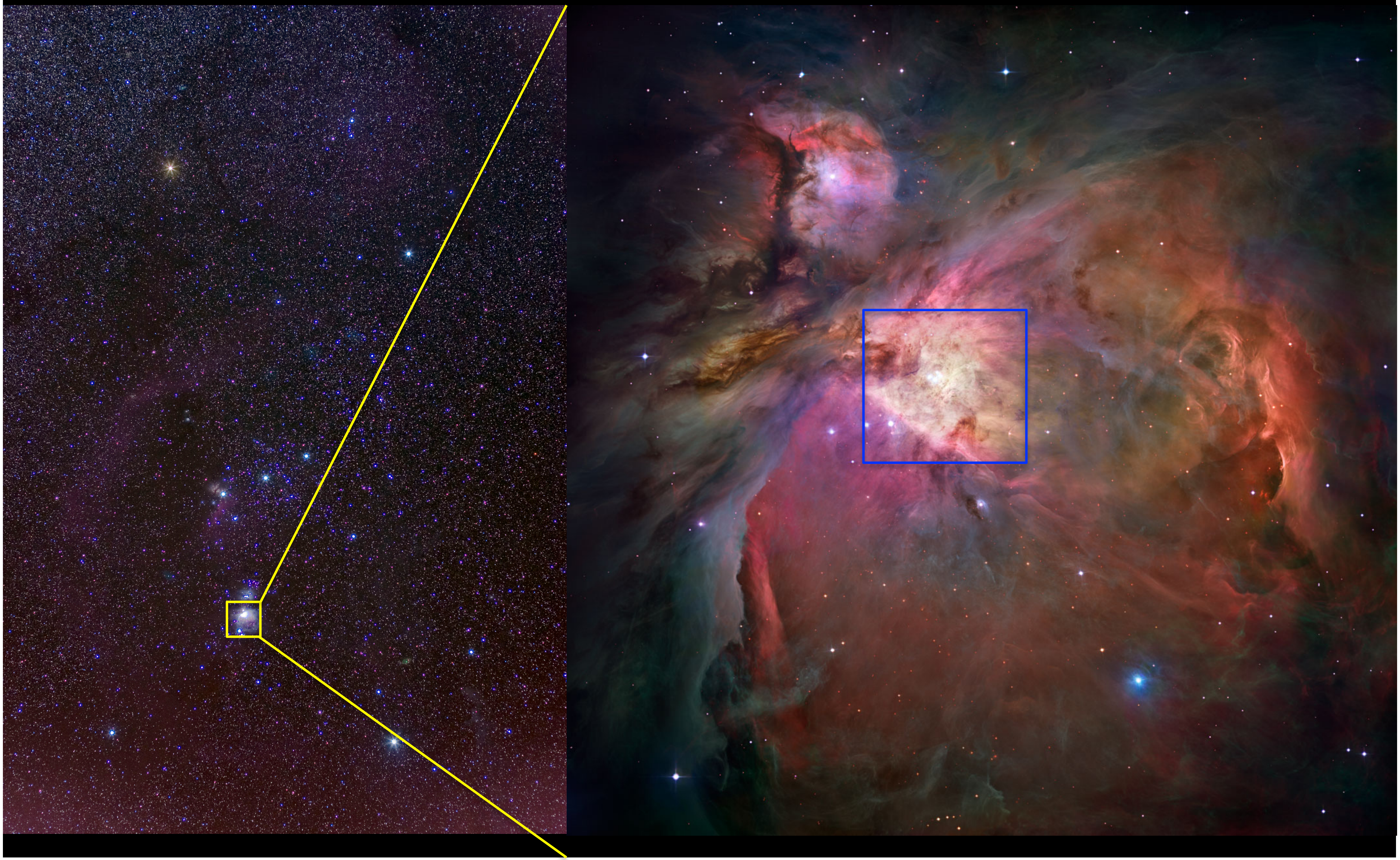
- Characteristic spectrum of HII regions are strong emission lines:

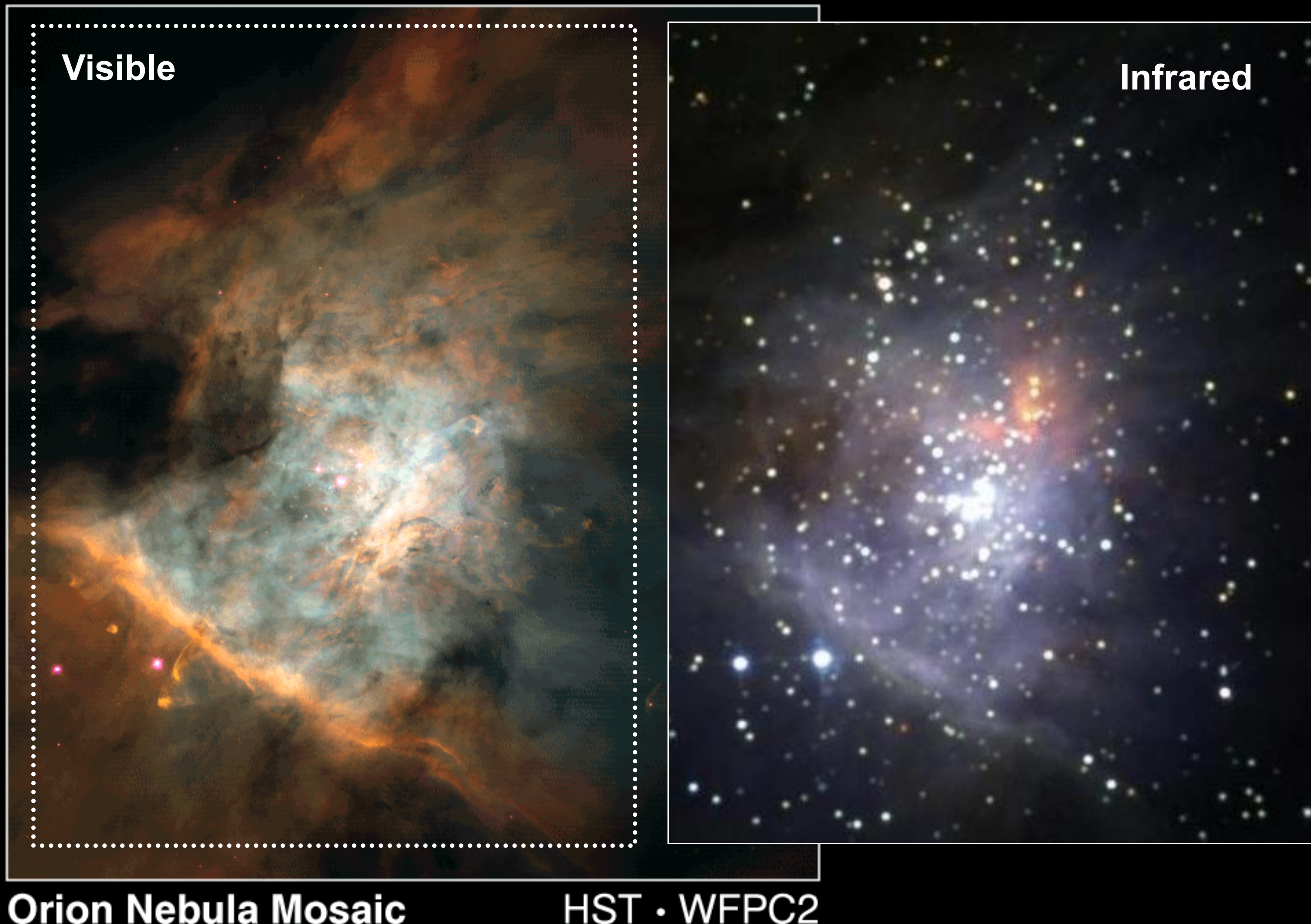
  Recombination lines: radiative recombination to upper energy levels followed by cascade. Most prominent: H balmer series, in particular the $\mathrm{H}\alpha$ line.

  Collisionally excited lines: collisions with electrons excite meta-stable levels resulting in forbidden line transitions such as [OIII]5008Å in optical, and fine-structure lines in mid-far infrared

- Line fluxes and their ratios used to diagnose temperature, density, abundances.

The Orion nebula





The gas in Orion glows because it is ionized by 4 hot stars: HII region

Strömgren sphere

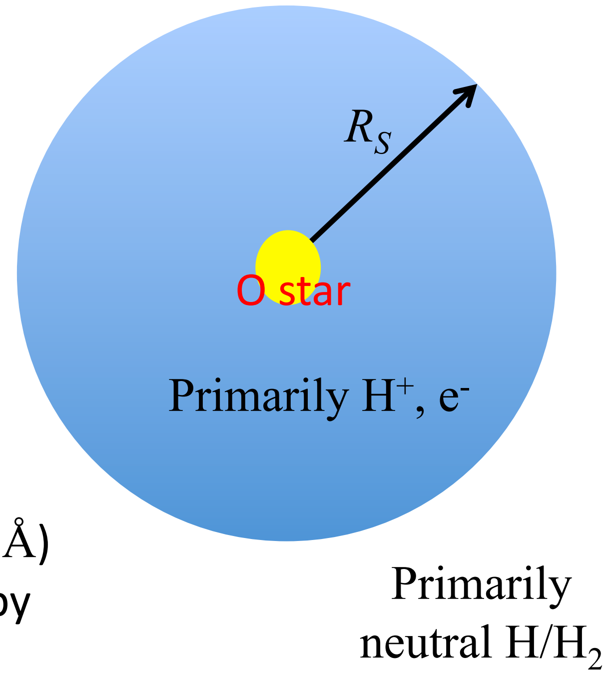
- The size of the HII region can be estimated by considering the requirement of ionization-recombination equilibrium

$$H \rightleftharpoons H^+ + e^-$$

Recombination rate per volume:

$$\dot{n}_{\rm recomb} = \alpha n_e n_p$$

In HII region, $n_e \approx n_p \approx n_H$ (fully ionized)



Let Q be the rate of ionizing photons (E>13.6eV or λ<912Å) produced by the O and B stars. They will all be absorbed by H in the region.

Rate of ionization = Rate of recombination

$$Q = \alpha(T) n_e^2 \times \frac{4\pi}{3} R_S^3$$

Strömgren radius

As long as equilibrium is not reached, the size of the region will grow.

Strömgren sphere

Strömgren radius: $R_S = \left(\frac{3Q}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}$

- At characteristic temperature T~8000K, $\alpha \approx 3.1 \times 10^{-13}\mathrm{cm}^3\mathrm{s}^{-1}$
- For massive O6 star, $Q \approx 10^{49}\ \mathrm{s}^{-1}$
- Typical number density in HII region: $n_e \approx n_H \sim 10^3\mathrm{cm}^{-3}$

$$\Rightarrow R_S \approx 0.7\ \mathrm{pc}$$

Note:

- Q *very sensitively* depends on effective temperature => only very massive stars (spectral type O and B) possess large HII regions
- The boundary of the Strömgren sphere exhibit as (thin) transition region called the photoionization front.

Hot gas in galaxies

• Hot gas ($T>10^6$K) is produced by fast stellar winds and by blast waves from novae and supernovae, and fills a large volume of the Galaxy.

• The hot gas produce X-ray radiation by free-free emission (bremsstrahlung), which is the major cooling mechanism.

• Hot gas is ejected into the halo (galactic fountains), or leaves the galaxy in a galactic wind.

M82, blue: X-ray; green:visible; red: IR

Magnetic fields

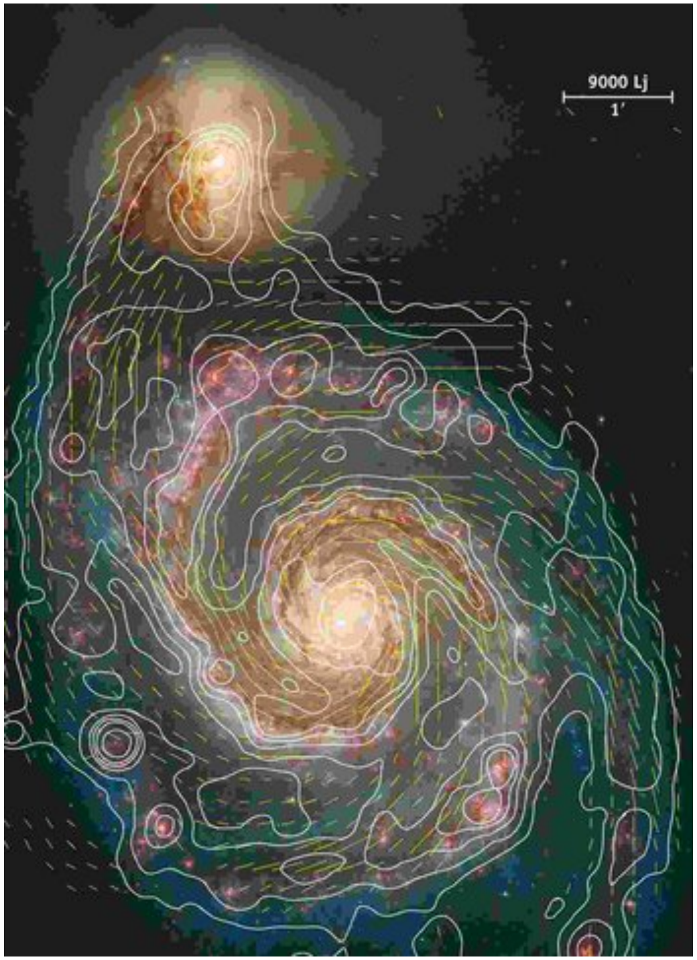
- Generated by galactic dynamo, with typical strength in the Galaxy 1-10 μG
- Exert magnetic pressure, comparable with (actually larger than) gas thermal pressure!
- Observed by polarized emission due to synchrotron / grain alignment
- Confine charged particles to Galactic disk:

For protons moving in 3 μG field, we find

$$\Omega_L = \frac{qB}{mc\gamma} = 0.02\ \gamma^{-1} s^{-1}$$

$$R_L = \frac{v}{\Omega_L} = \frac{mvc\gamma}{qB} = 0.1\ \frac{v}{c}\gamma\ AU$$

M51 with B field



Cosmic rays

- Collections of energetic protons, electrons, and nuclei
- Energy density comparable with other ISM components!
- At low energies confined to the Galaxy
- Important source of ionization
- Detected via air showers