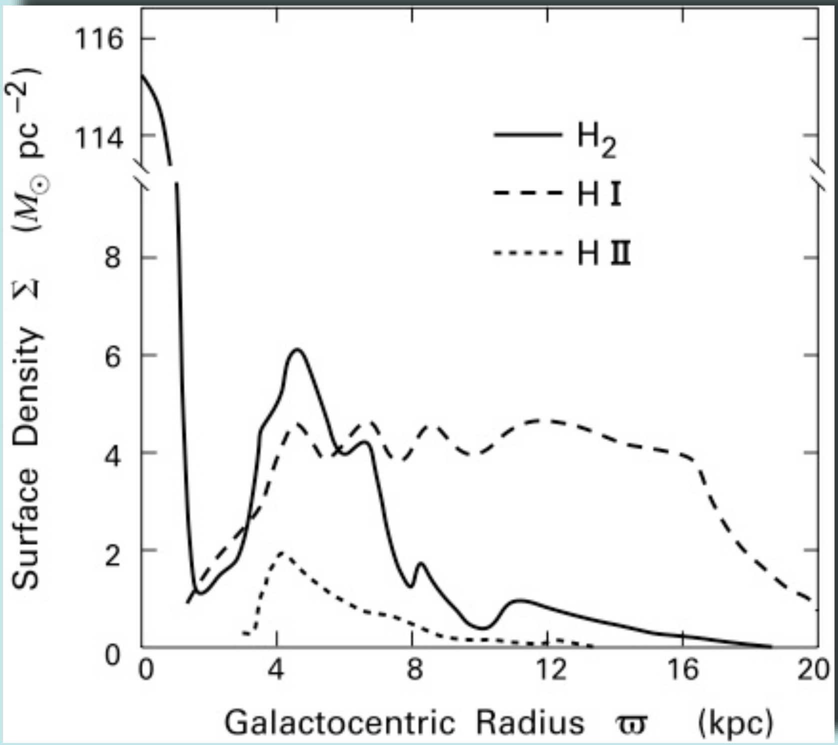
Inter-Stellar Medium (ISM)

- From diffuse clouds to dense cores
- HI, H_2, CO lines
- Interstellar dust
- Transfer of radiation
- Heating and cooling

Distribution of gas in the Milky Way



Warm Neutral Medium:

•HI gas: $n_H \sim 0.5$ cm^{-3}, T ~ 8x10^3 K, M ~ 4x10^9 $M_\odot$

Cold Neutral Medium:

•HI clouds: $n_H \sim$ 10-100 cm^{-3}, d ~ 1-100 pc, T ~ 80 K, M ~ 3x10^9 $M_\odot$

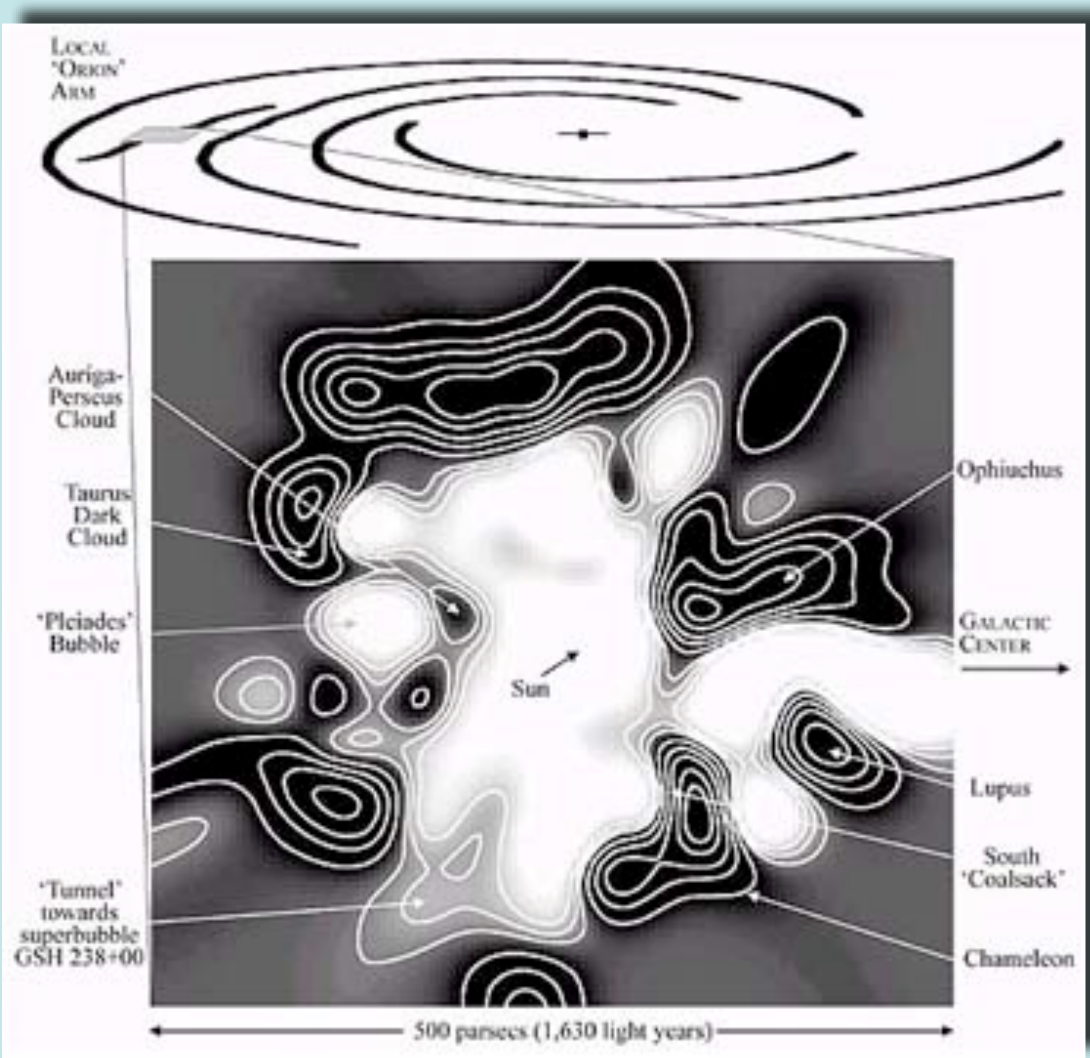
•H_2 gas: $n_H > 300$ cm^{-3}, T ~ 10 K, M ~ 2x10^9 $M_\odot$

Phases of the ISM

	Phase	n_{tot}	T	M	f
		(cm^{-3})	(K)	$10^9\ M_\odot$	
COLD	molecular	>300	10	2.0	0.01
COLD	Cold Neutral	50	80	3.0	0.04
WARM	Warm Neutral	0.5	$8x10^3$	4.0	0.30
WARM	Warm Ionized	0.3	$8x10^3$	1.0	0.15
HOT	Hot Ionized	$3x10^{-3}$	$5x10^5$	-	0.50

Field, Goldsmith and Habing (1969); McKee & Ostriker (1977)

The Sun is located in the (warm) Local Bubble, which may have been carved out by a supernova that exploded nearby some 300,000 years ago.



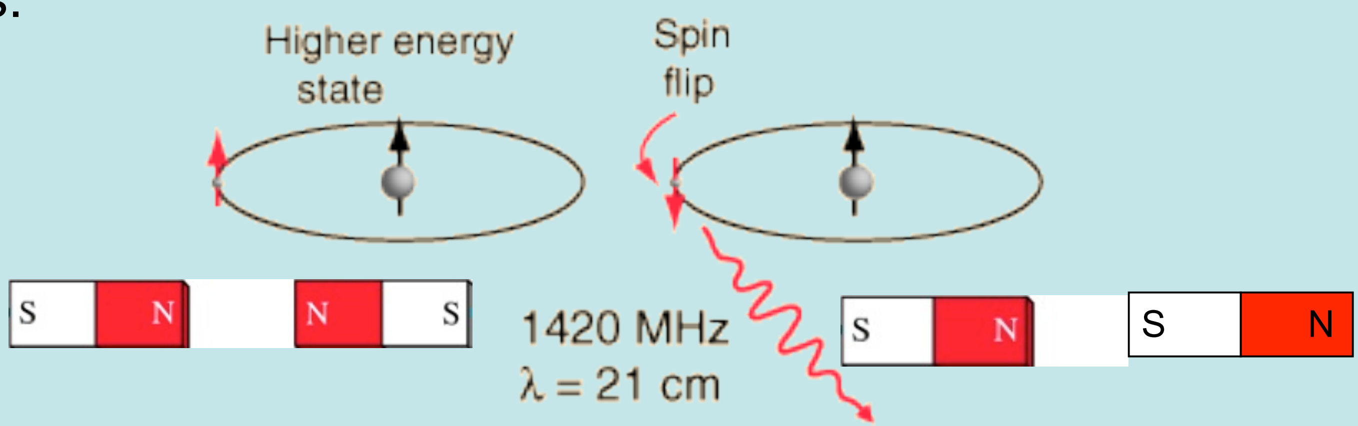
Map of the cold, dense interstellar gas surrounding the Local Bubble in the plane of the Galaxy. White areas represent regions of extremely low gas density (which are partially filled with plasma); dark areas reveal where large condensations of cold, dense gas occur. Notice that the local cavity is surrounded by many of these condensations, but this "wall" is broken in several places by low density interstellar tunnels that link the local cavity with other nearby bubble cavities such as the Pleiades and GSH 238+00+09.

A detailed understanding of the structure of the galactic disk had to wait until the development of **radio astronomy**. Thanks to their long λ, radio waves can penetrate the interstellar medium even more easily than IR light.

Fortunately for us, hydrogen, the most abundant element in the Universe, emits radio waves even in cold clouds. To understand this, we need to consider the structure of protons and electrons.

Particles such as protons and electrons possess **spin**. Because electric charges in motion generate magnetic fields, a proton or electron behaves like a tiny magnet with a north pole and a south pole.

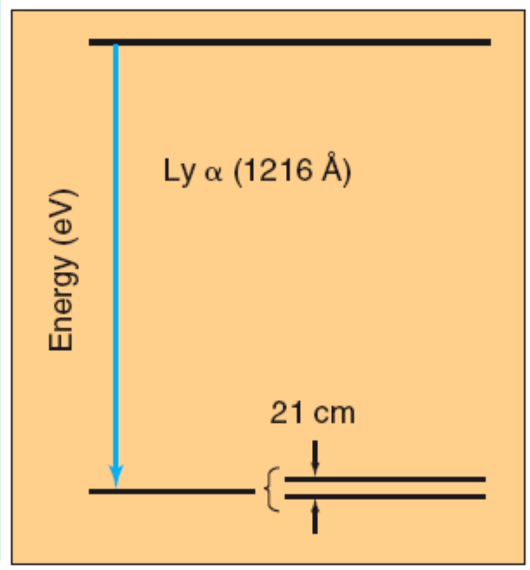
As in the case of two magnets, the energy of a hydrogen atom is slightly different depending on whether the spins of **p** and **e$^-$** are in the same or opposite directions.

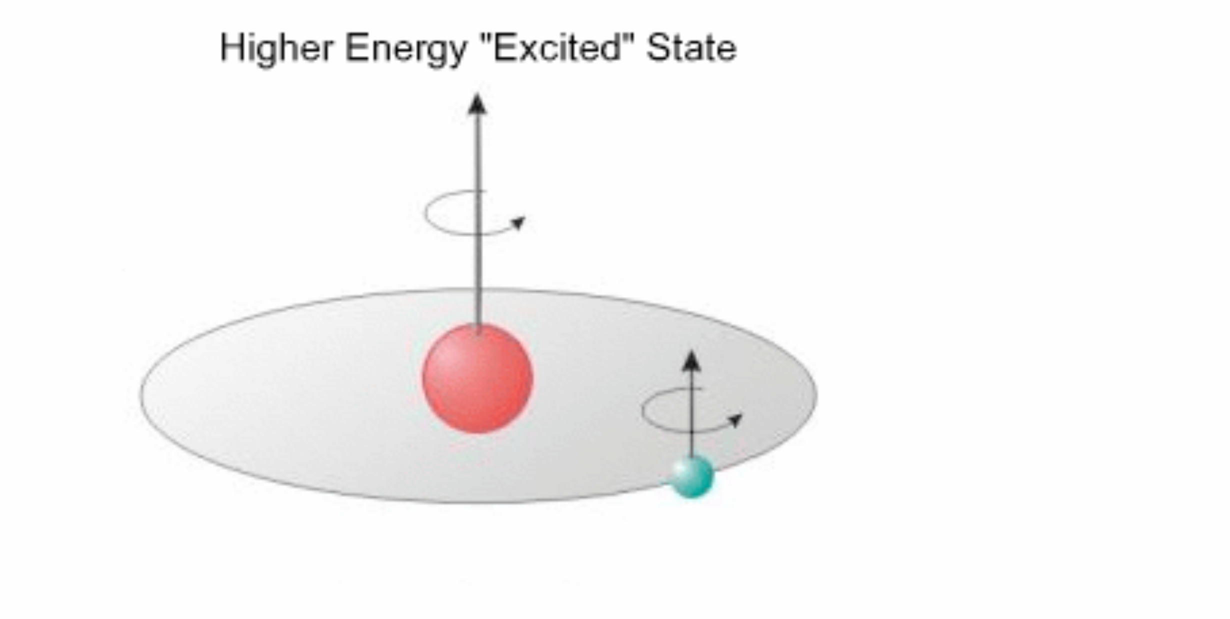


If the spin of the electron changes its orientation from the higher-energy configuration to the lower energy one (**spin-flip transition**), a photon is emitted.

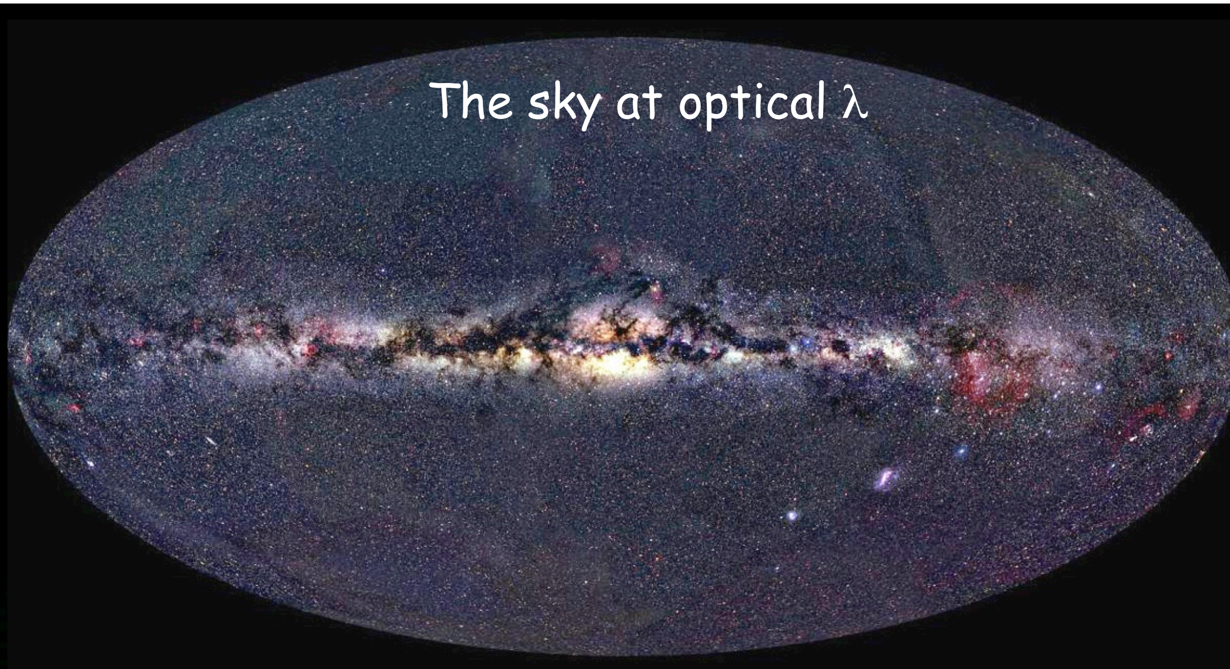
The energy difference between the two spin configurations is only ~10^{-6} as great as those between different electron orbits.

The corresponding wavelength is **21 cm** (radio).

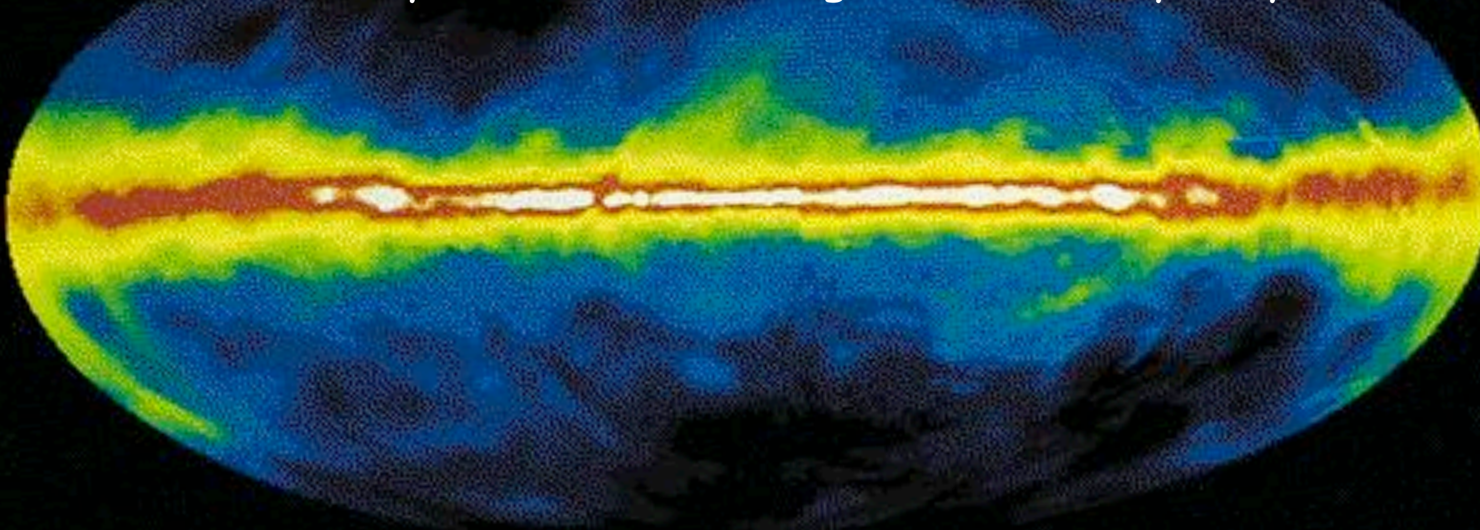




The spin-flip transition was first predicted in 1944 by the Dutch astronomer Henrik van der Hulst. Harold Ewen and Edward Purcell (Harvard) first succeded in detecting it.



The sky at 21 cm: atomic gas in the Milky Way

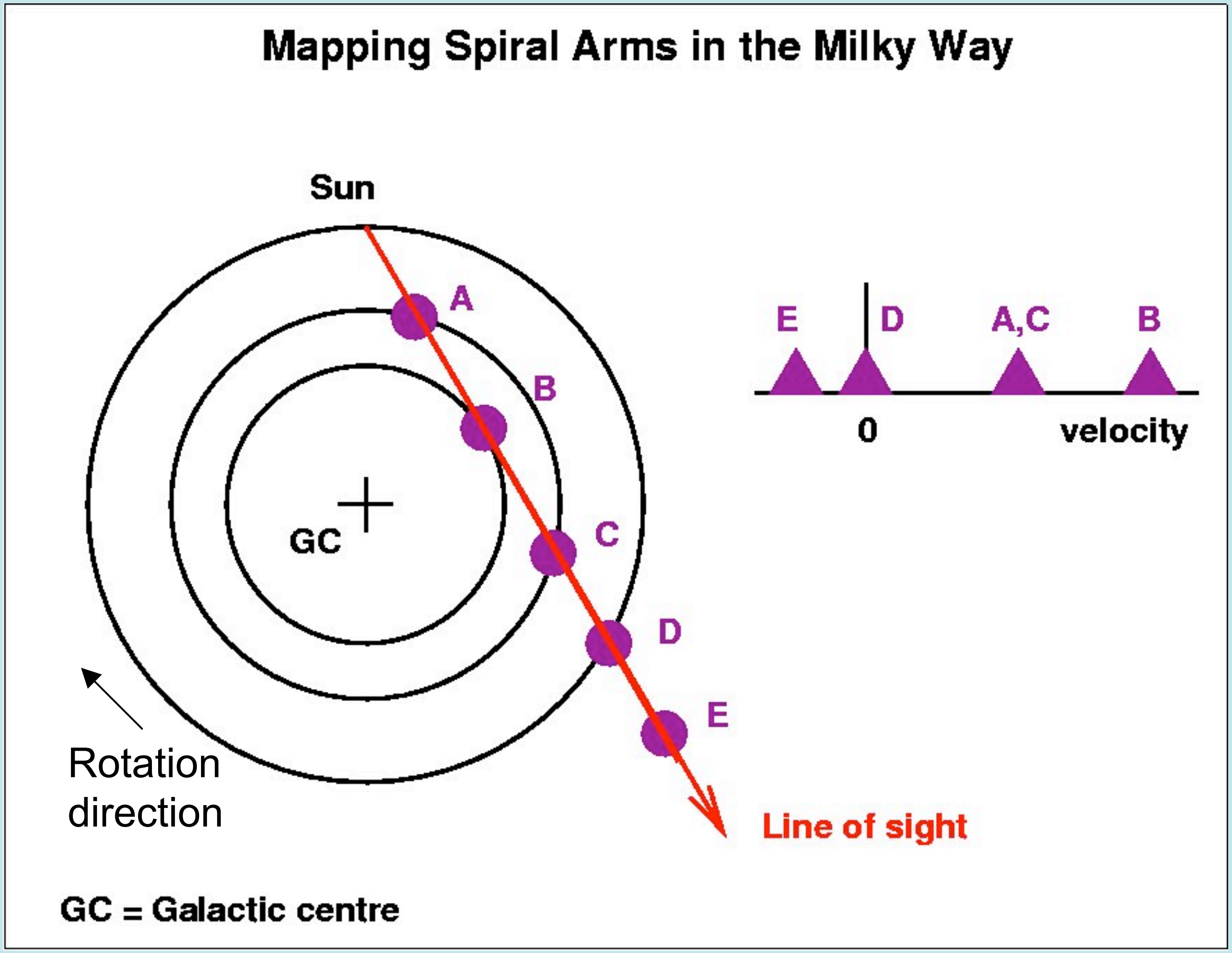


The 21 cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy

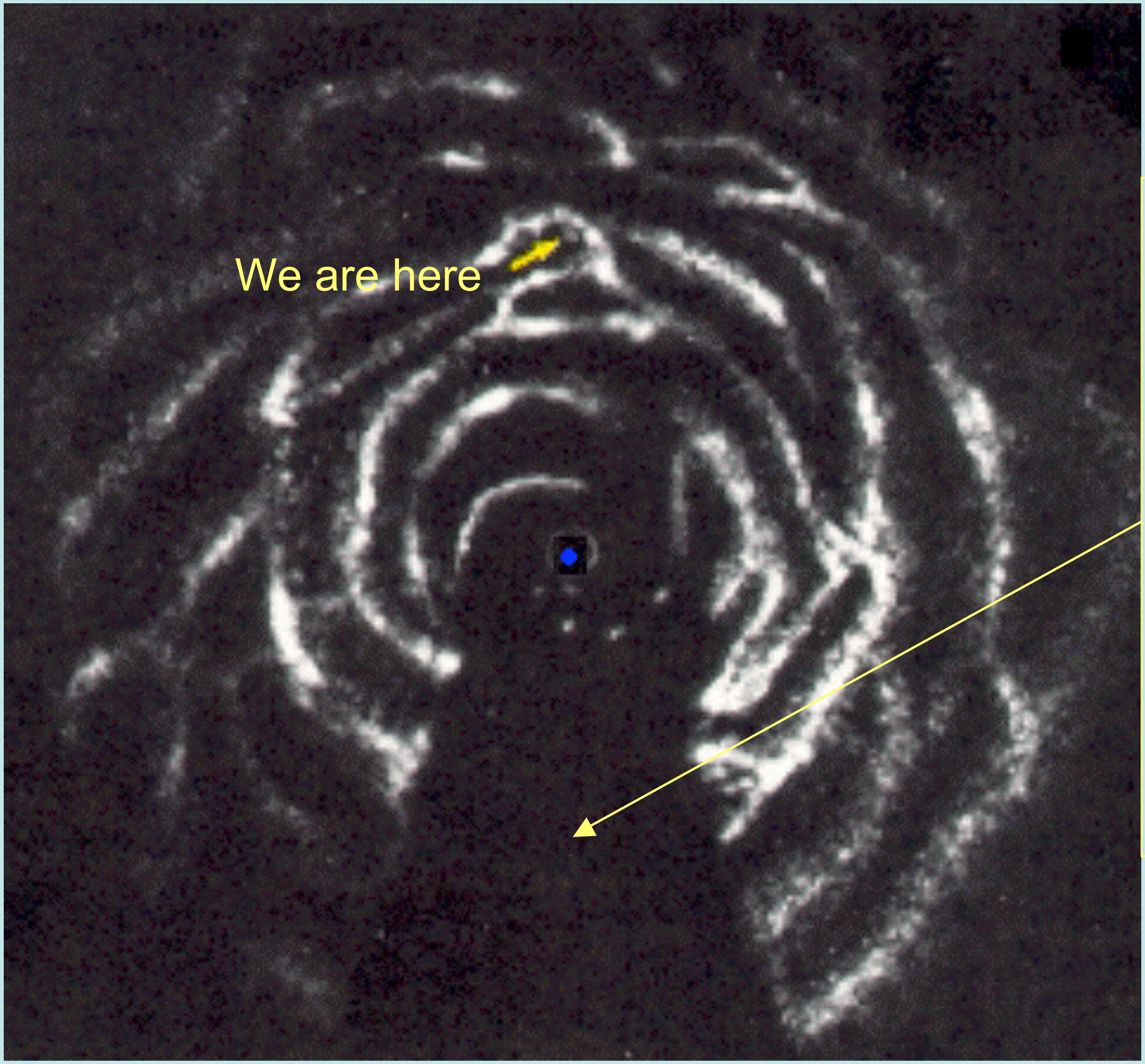
The detection of 21-cm radio radiation was a major breakthrough that permitted astronomers to probe the galactic disk.

If we look within the plane of our Galaxy from our position, hydrogen clouds at different locations (A, B, C, D, E) along our line of sight are moving at slightly different speeds relative to us.

As a result, radio waves from these various gas clouds are subjected to slightly different Doppler shifts. This permits radio astronomers to sort out the gas clouds and thus map the Galaxy.



This map, constructed from radio-telescope surveys of 21-cm radiation, shows the distribution of hydrogen gas in a face-on view of our Galaxy. The map suggest a spiral structure.



Details in the blank, wedge-shaped region at the bottom of the map are unknown. Gas in this part of the Galaxy is moving perpendicular to our line of sight and thus does not exhibit a detectable Doppler shift (Courtesy of G. Westerhout).

Molecular Hydrogen

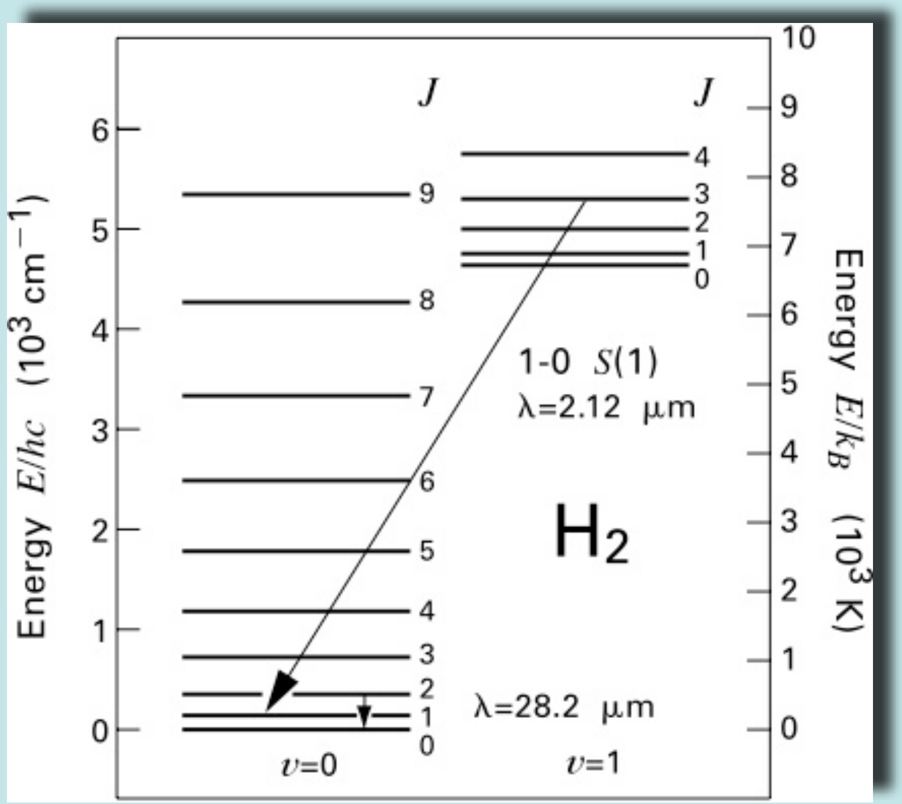
$$E_{rot} = \frac{J^2}{2I}$$

Rotational levels:

$$E_{rot} = \frac{\hbar}{2I} J(J+1) \equiv BhJ(J+1)$$

Rotational quantum number

Rotational constant (Hz)



The moment of inertia of H_2 is the smallest of any diatomic molecule ➔ its energy levels are widely spaced.

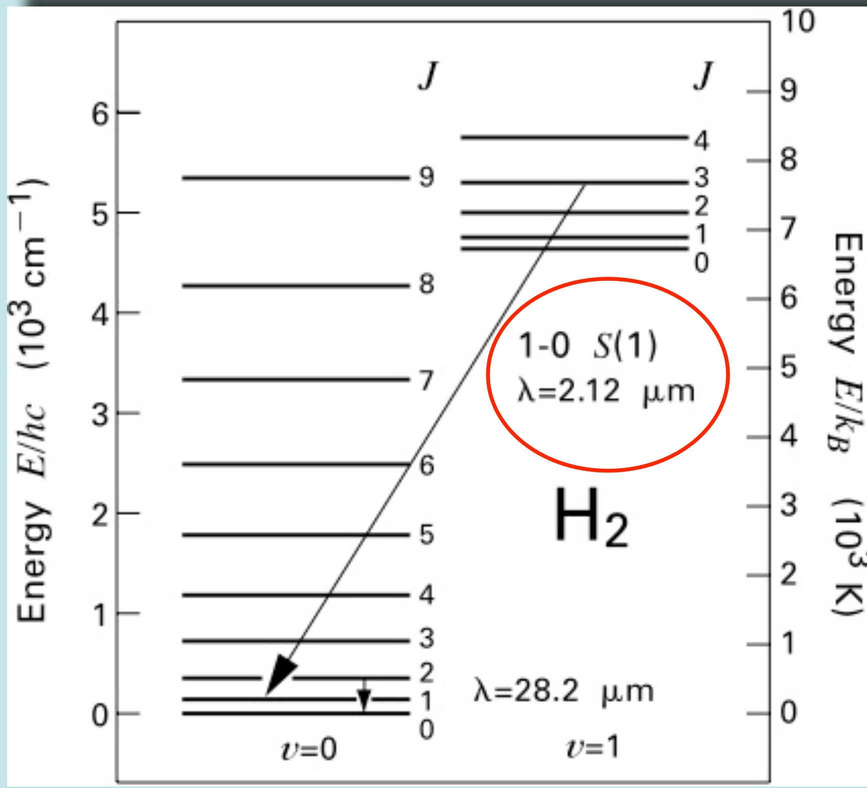
Rotational levels of H_2 decay through electric quadrupole transitions, in which J decreases by 2. J=2→0 has an associated energy change of 510 K (λ=28.2 μm).

H_2 total energy:

$$E_{tot} = E_{rot} + E_{vib} + E_{elect}$$

$$E_{vib} = h\nu_0(\mathrm{v} + 1/2)$$

Vibrational quantum number



In the hot environments where vibrational states are excited, H_2 relaxes through rovibrational transitions, in which J and v change (the change in v is unrestricted, while ΔJ =0 or ±2).

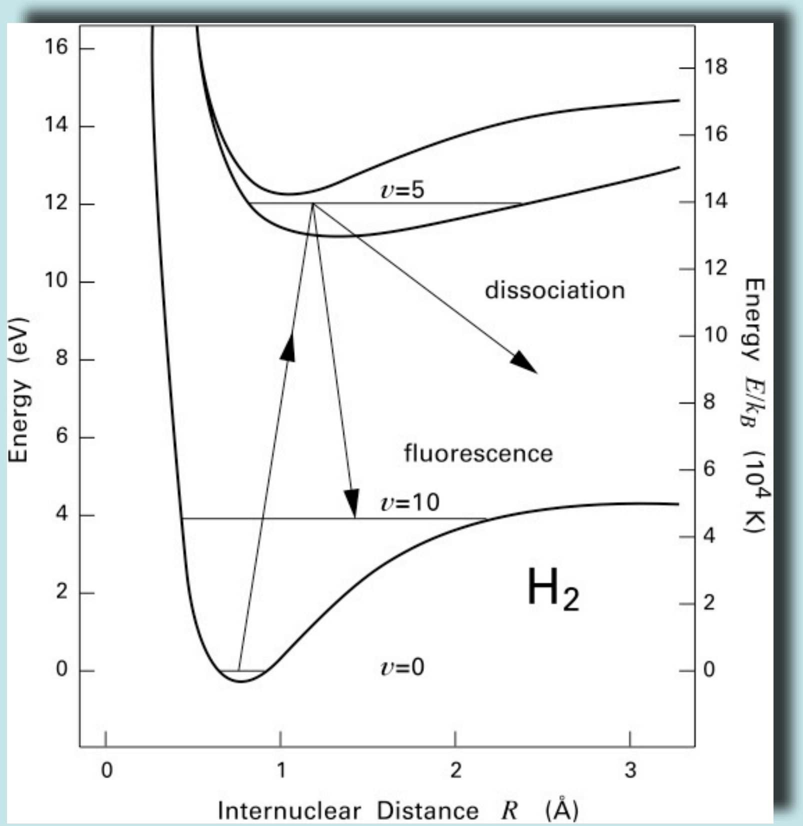
Designation: v' = initial vibrational state; v'' = final vibrational state:

v'-v''O(J'') if J''-J'=2
v'-v''Q(J'') if J''-J'=0
v'-v''S(J'') if J''-J'=-2

Electronic transitions have an energy separation of the order 10^5 K.

The ground electronic state contains 14 vibrational levels, plus a continuum of levels with E > ΔE_{diss} = 4.48 eV, the molecule's binding energy.

Indirect radiative dissociation: a photon with E > 11.2 eV excites H_2 to a higher electronic state. About 85% of the time, H_2 drops back to ground through electronic and rovibrational transitions (**fluorescence**). Emitted lines range from UV to IR.



Lyman band: cluster of transitions from first excited electronic state to ground state.
Werner band: from second excited electronic state to ground state.

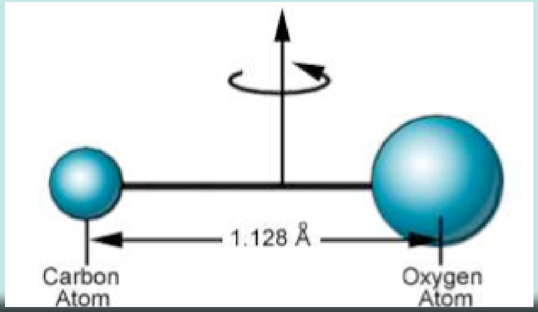
In order to dissociate, the molecule must decay from an excited electronic state to a vibrational continuum level lying above the v=14 level in the ground state.

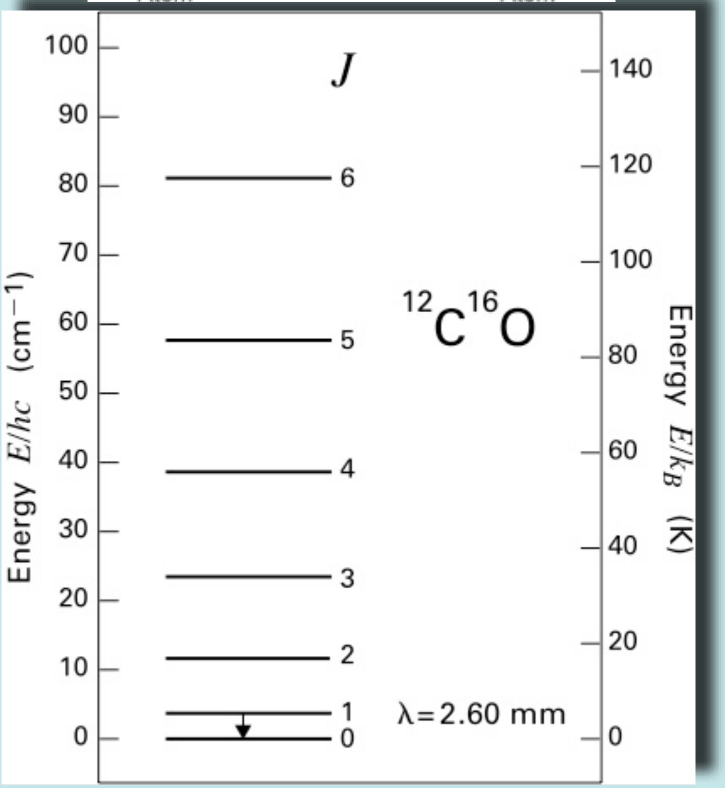
Carbon Monoxide (CO) rotation

$$E_{rot} = \frac{\hbar^2}{2I} J(J+1) \equiv BhJ(J+1) \qquad \Delta J = \pm 1$$

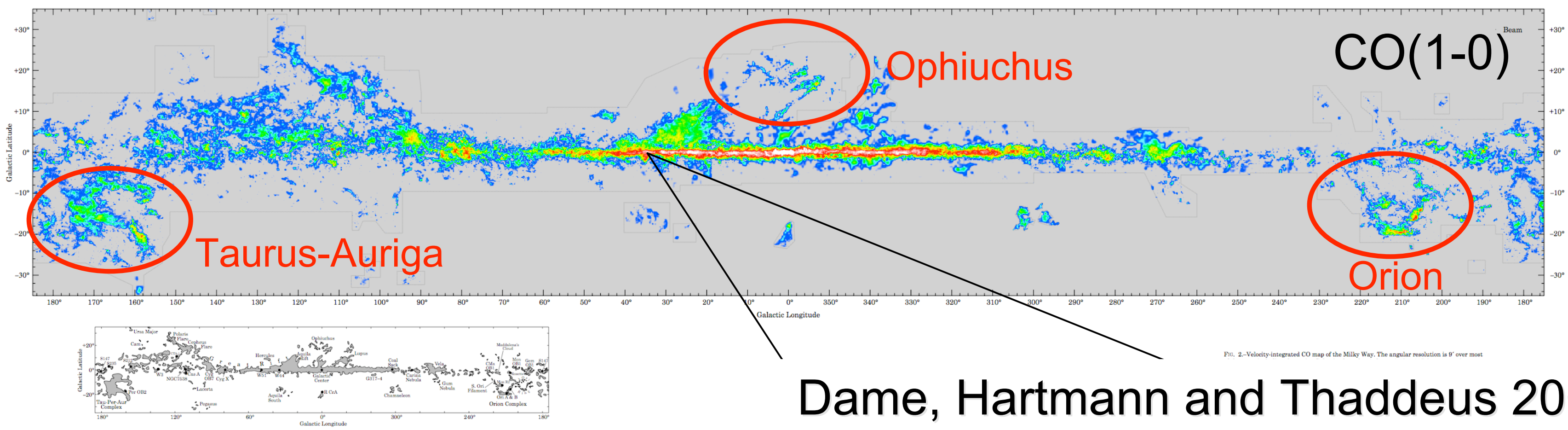
The J=1 state is elevated above the ground by 4.8×10^{-4} eV or, equivalently, 5.5 K ➔ easy to excite in a quiescent cloud.

Within a molecular cloud, excitation of CO to the J=1 level occurs primarily through collisions with the ambient H_2.

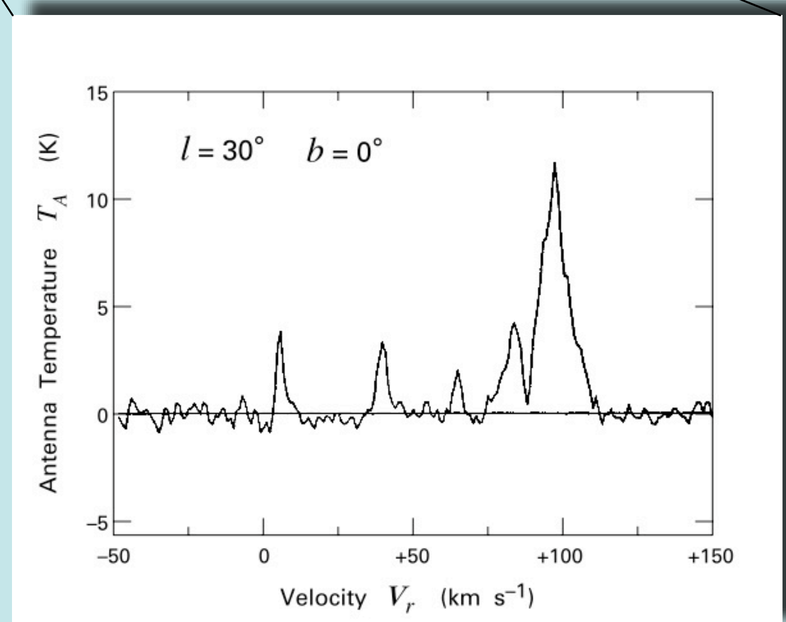




The distribution of molecular gas in the Milky Way



Dame, Hartmann and Thaddeus 2001



molecular gas mass ~ atomic gas mass: 2-4x10^9 $M_{\odot}$ (dust/gas mass ratio ~ 1%)

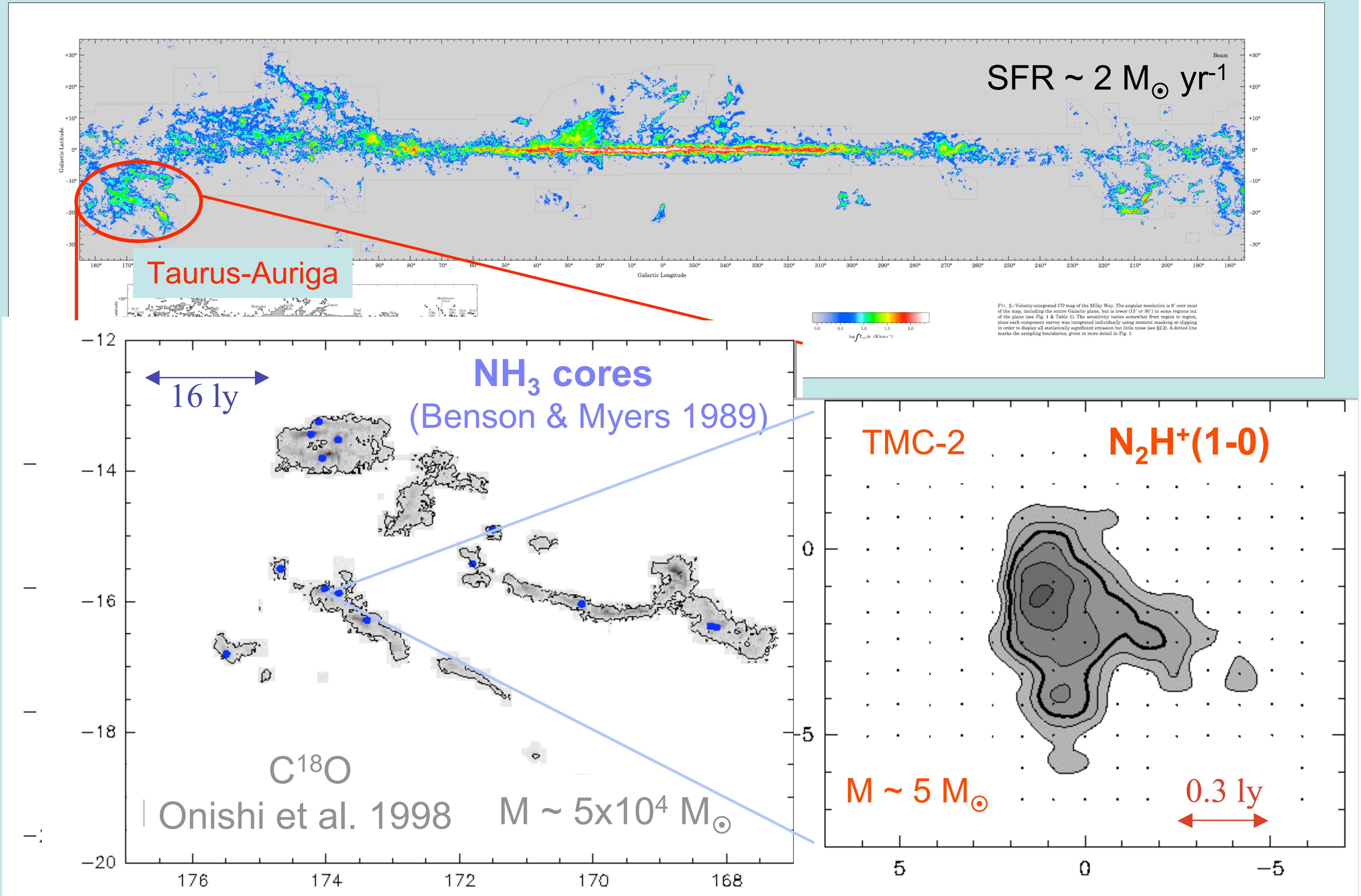
most of the molecular gas in Giant Molecular Clouds (≥10^5 $M_{\odot}$), confined in spiral arms

throughout the disk: small clouds and complexes (~a few 10^4 $M_{\odot}$)

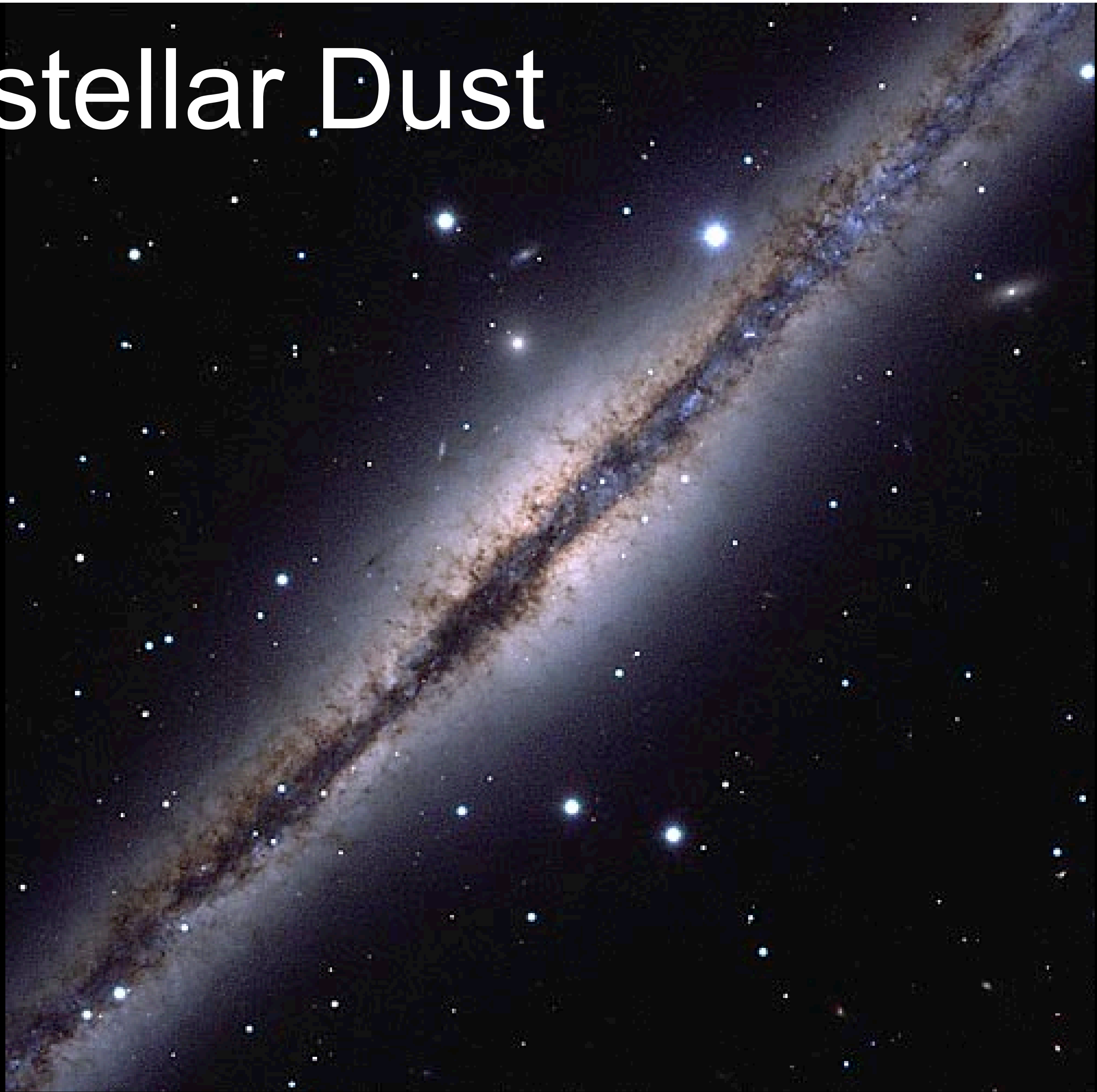
Physical Properties of Cold Clouds

Type	A_V	n_{tot}	L	T	M	Ex.
	(mag)	(cm^{-3})	(pc)	(K)	($M_\odot$)	
Diffuse	1	500	3	50	50	ζOph
GMC	2	100	50	15	10^5	Orion
Dark:						
complexes	5	500	10	10	10^4	Taurus
individual	10	10^3	2	10	30	B1
Dense cores	10	10^4	0.1	10	10	TMC-1 B335

Molecular Clouds and Star Formation



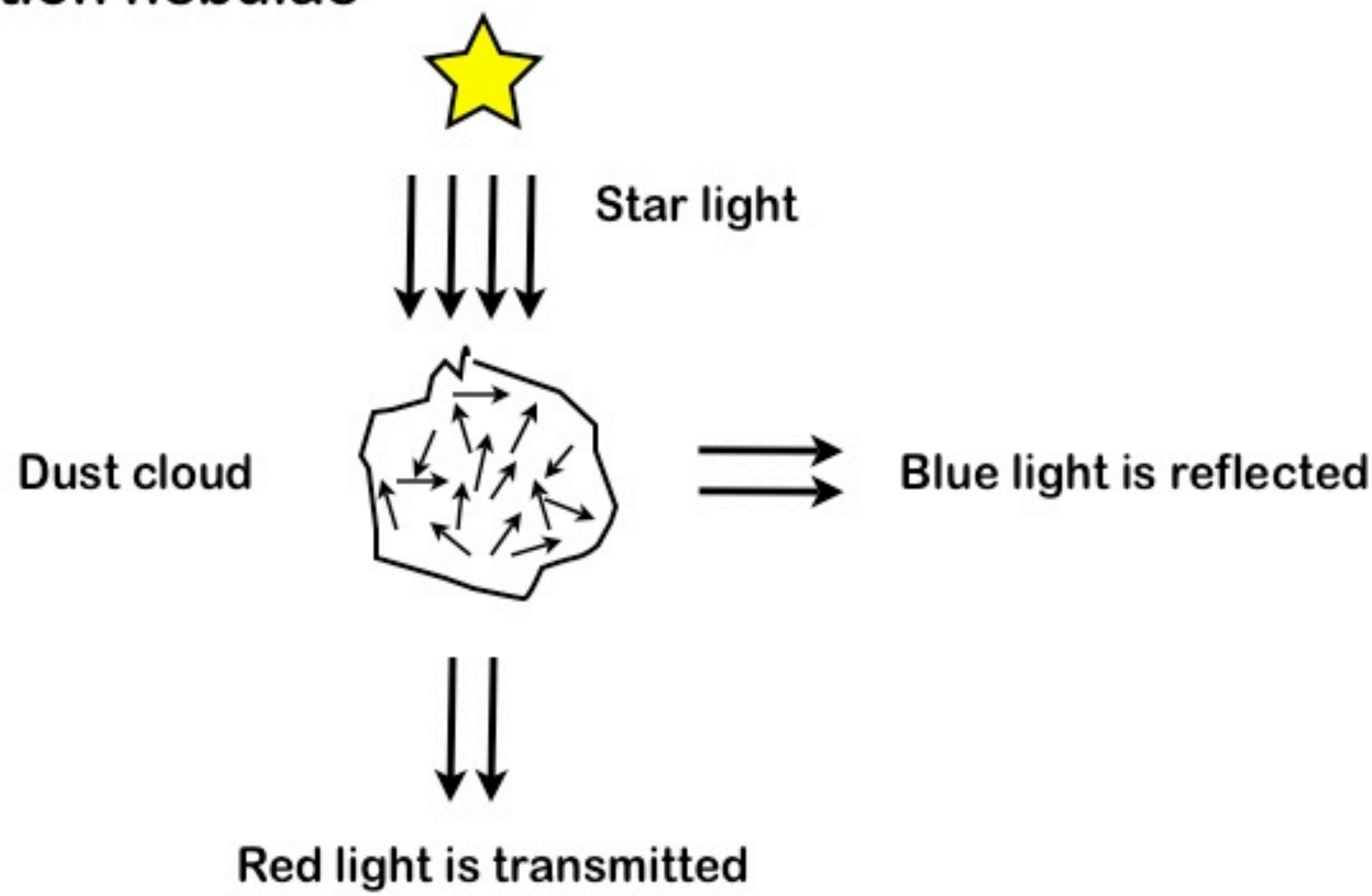
Interstellar Dust



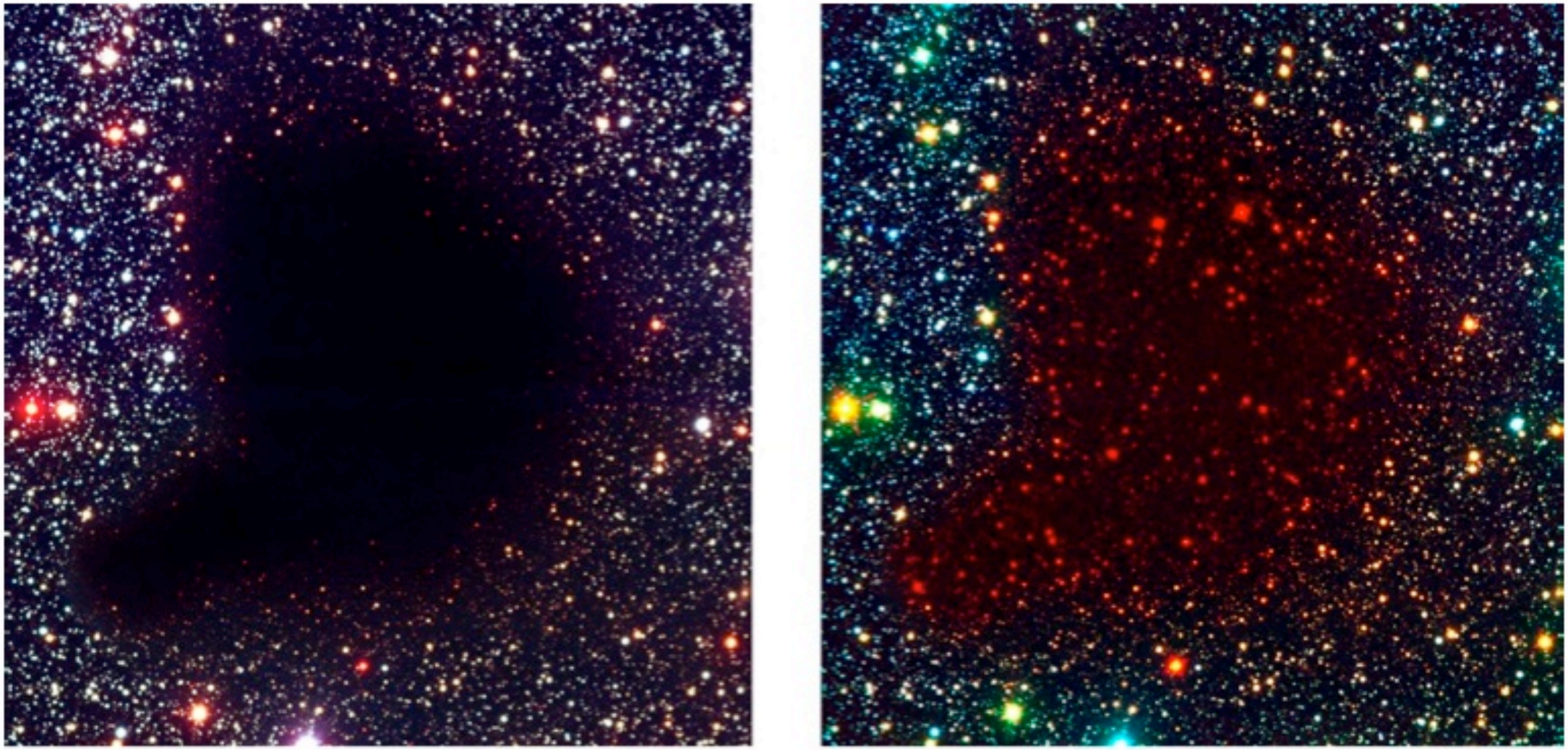
NGC 891

The effect of dust: scattering and absorption

- Diffuse light surrounding bright illuminating sources
- Same spectrum as illuminating source, but bluer
- 'Reflection nebulae'



An example of absorption…



B, V, I

B, I, K

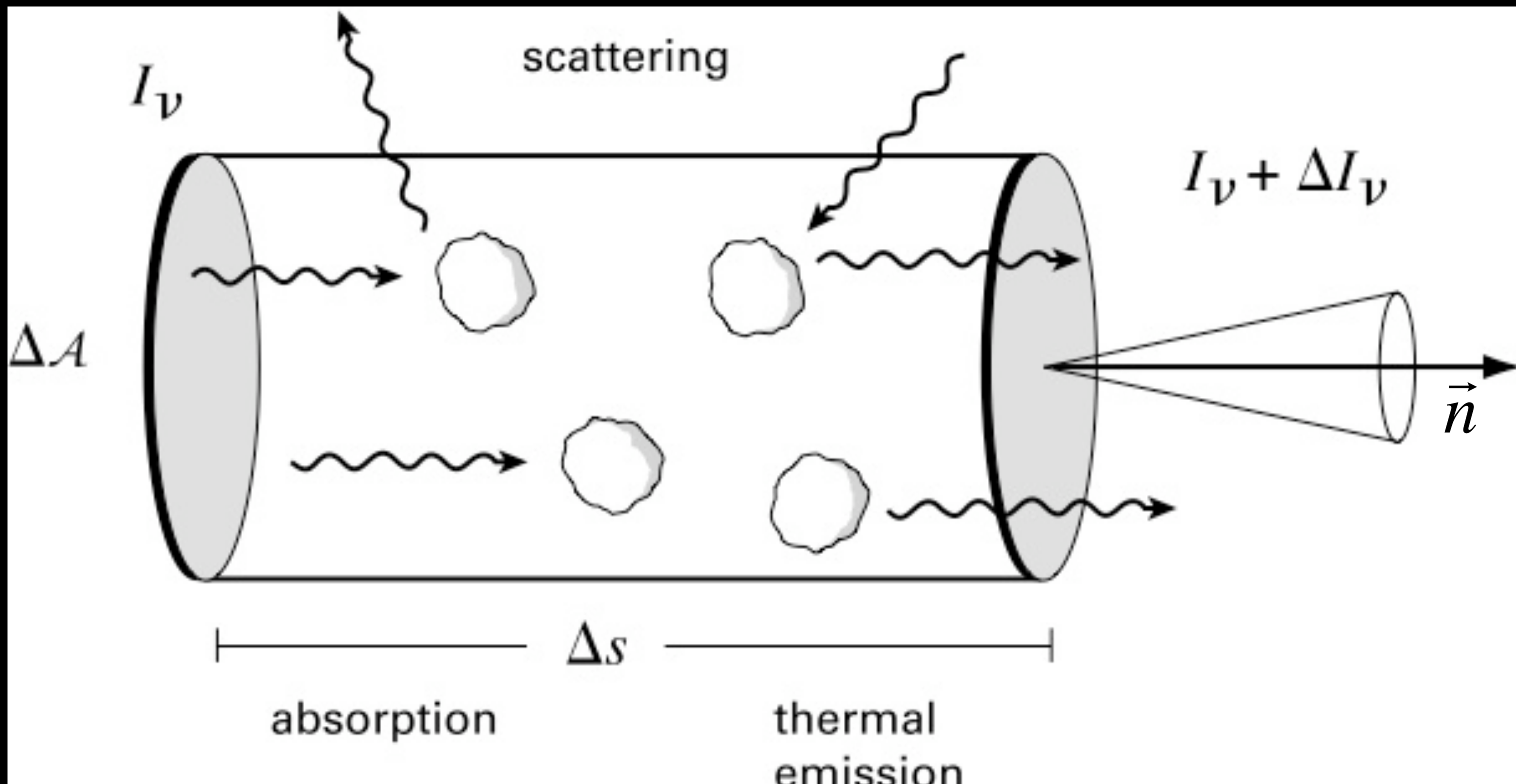
Pre-Collapse Black Cloud B68 (comparison)

(VLT ANTU + FORS 1 - NTT + SOFI)

An example of scattered light…

Witch Head reflection nebula

Transfer of radiation

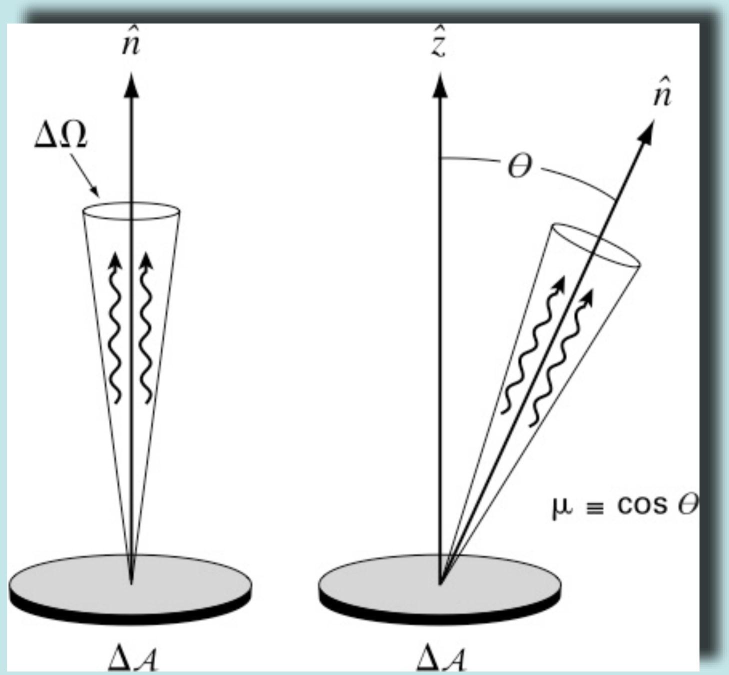


Intensity, Flux, Energy Density

- **Specific intensity I_ν**: $\Delta E = I_\nu \Delta A \Delta t \Delta\nu \Delta\Omega$

- **Specific flux F_ν**, or flux density, the monochromatic energy per area per unit time passing through a surface of fixed orientation z (W m^{-2} Hz^{-1} or erg s^{-1} cm^{-2} Hz^{-1} or Jansky=10^{-26} W m^{-2} Hz^{-1}):

$$F_\nu \equiv \int I_\nu \mu d\Omega$$



- **Total energy density u_ν**, per unit frequency at a fixed location (J m^{-3} Hz^{-1} or erg cm^{-3} Hz^{-1}):

$$u_\nu \equiv \frac{1}{c} \int I_\nu d\Omega$$

- **Mean intensity J_ν**, i.e. the average of I_ν over all directions:

$$J_\nu \equiv \frac{1}{4\pi} \int I_\nu d\Omega = \frac{c}{4\pi} u_\nu$$

Blackbody Radiation

Blackbody radiation is radiation in *thermal equilibrium* and it is *isotropic*, i.e. the specific intensity $I\nu$ is independent of direction:

$$u_\nu \equiv \frac{1}{c}\int I_\nu \, d\Omega \quad \Rightarrow \quad I_\nu = c u_\nu / 4\pi \equiv B_\nu$$

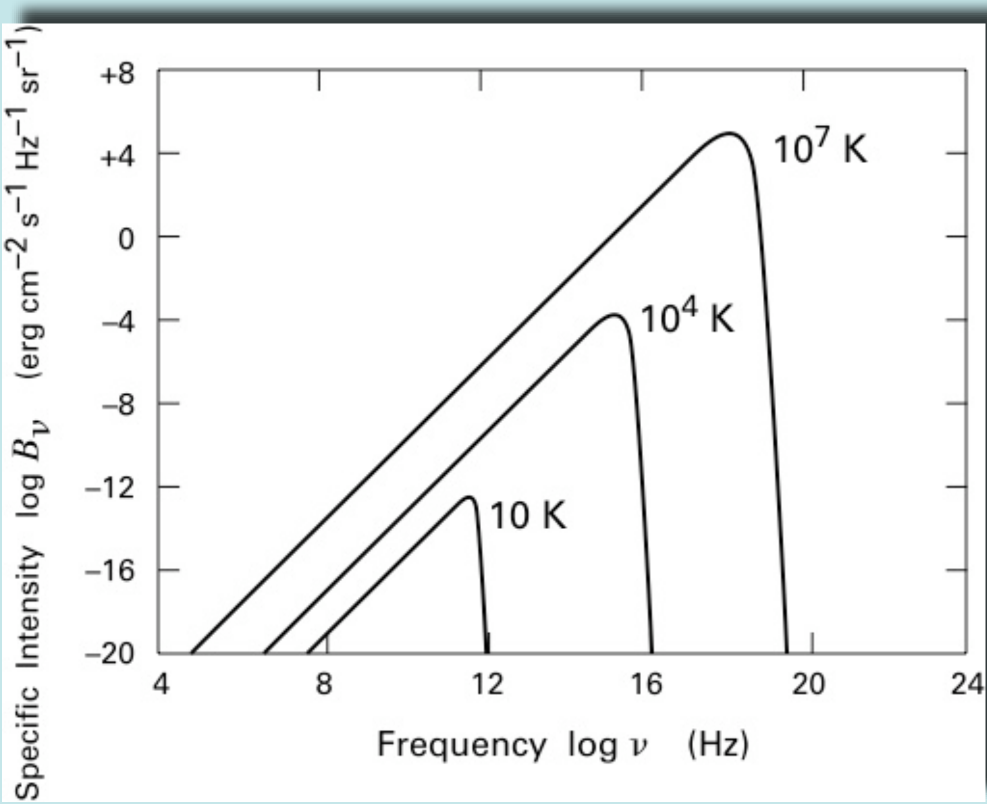
Planck Function

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/k_B T) - 1}$$

$$B_\lambda = B_\nu \left(\frac{d\nu}{d\lambda}\right) = -\left(\frac{c}{\lambda^2}\right) B_\nu$$

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda k_B T) - 1}$$

Blackbody Radiation



Much of a person's energy is radiated away in the form of infrared light.

Wien's displacement law:

$$\frac{\nu_{\max}}{T} = \frac{2.82 k_B}{h} = 5.88 \times 10^{10}\, Hz\, K^{-1}$$

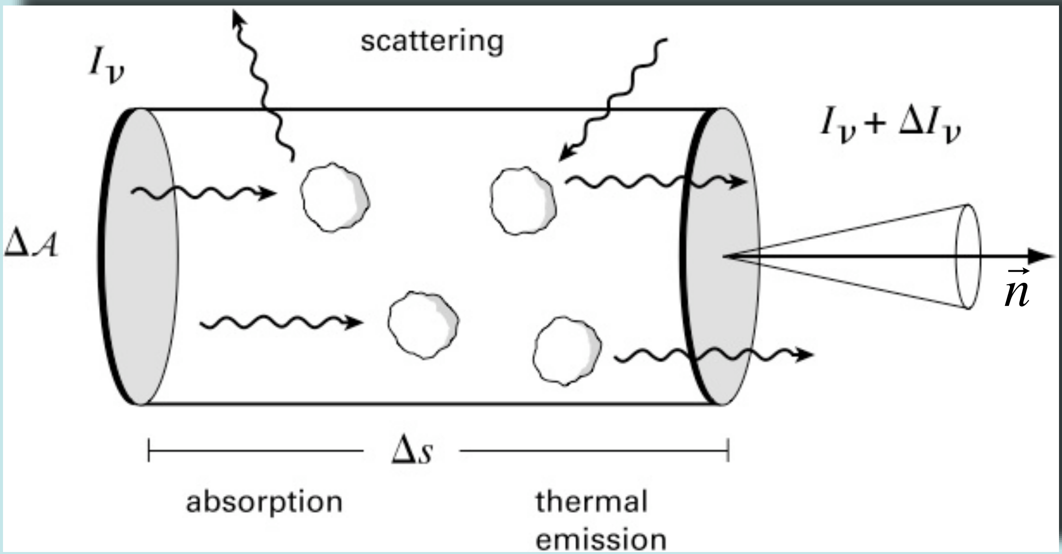
$$\lambda_{\max} T = 0.29\, cm\, K$$

Starlight warms the dust grains to T ~ 10 to 90 K. Thus, from **Wien's Law:**

$$\lambda_{\mathrm{max}} = \frac{0.0029 \text{ K m}}{T}$$

the dust emits predominantly at λ ~ 30 to 300 μm. These are **far-infrared (FIR)** λ. At these λ, interstellar dust radiates more strongly than stars, so a FIR view of the sky is principally a view of where the dust is.

Transfer of radiation



Assume that the radiation field travels along a small distance Δs. I_ν can be absorbed (radiative energy is transformed to internal motion of the grain lattice) and scattered (a photon with the same frequency is reemitted in a different direction):

$$\Delta I_{\nu 1} = -\rho \kappa_\nu I_\nu \Delta s$$

κ_ν is the opacity ($cm^2\ g^{-1}$), a quantity that depends on the incident frequency ν, the relative number of grains and their intrinsic physical properties.

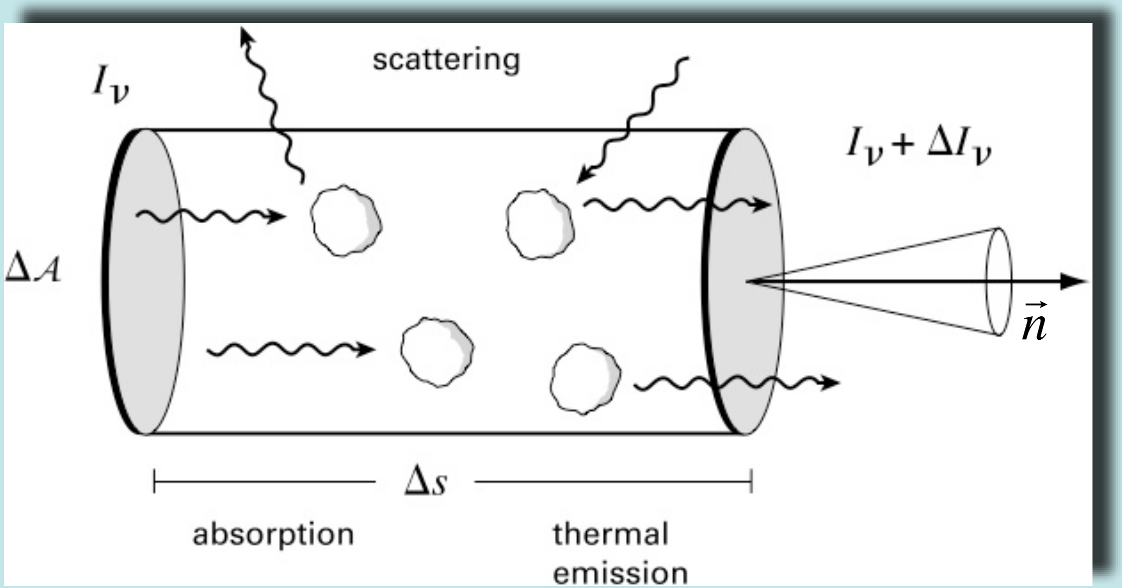
ρ is the medium total density ($g\ cm^{-3}$)

$1/\rho\kappa_\nu \equiv$ photon mean free path

$\rho\kappa_\nu \equiv$ absorption coefficient (cm^{-1})

The optical depth is defined by:

$$\Delta \tau_\nu = \rho \kappa_\nu \Delta s$$



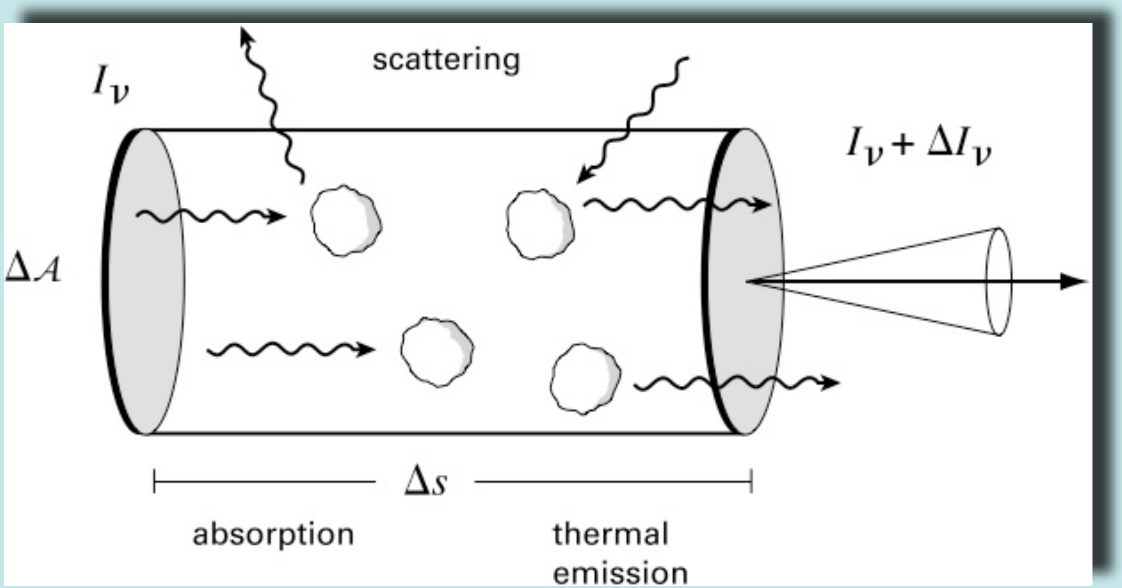
$$\Delta I_{\nu 1} = -\rho \kappa_\nu I_\nu \Delta s$$

I_ν can also increase due to the *thermal emission* from the dust:

$$\Delta I_{\nu 2} = +j_\nu \Delta s$$

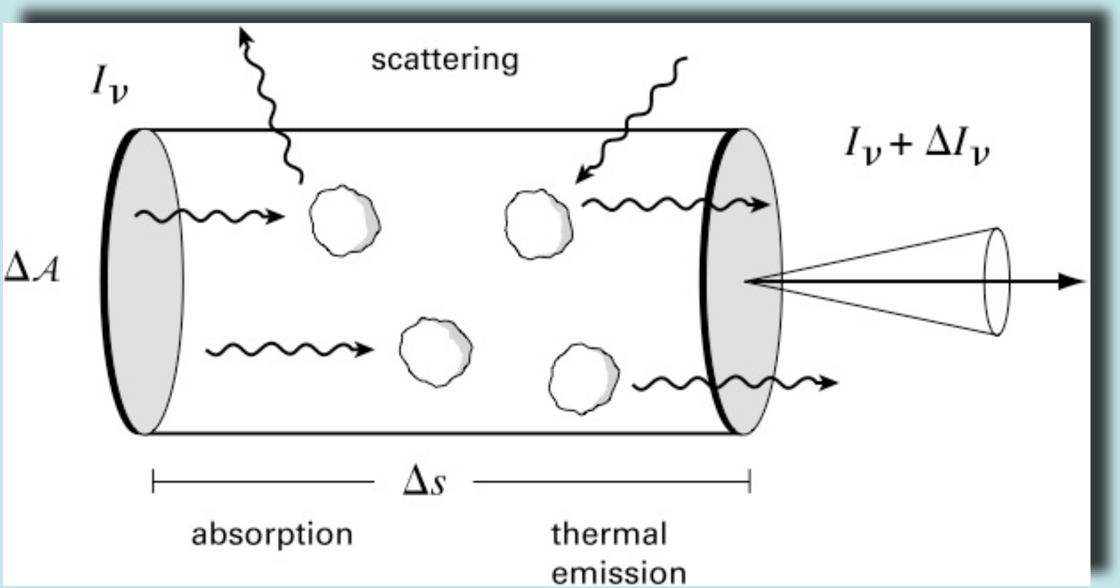
j_ν is the emissivity (W m^{-3} sr^{-1} Hz^{-1}), such that $j_\nu \Delta\nu \Delta\Omega$ is the energy per unit volume per unit time emitted into the direction $\vec{n}$.

The equation of transfer



$$\Delta I_\nu = \Delta I_{\nu 1} + \Delta I_{\nu 2} = -\rho \kappa_\nu I_\nu \Delta s + j_\nu \Delta s$$

$$\frac{dI_\nu}{ds} = -\rho \kappa_\nu I_\nu + j_\nu$$



$$\frac{dI_\nu}{ds} = -\rho\kappa_\nu I_\nu + j_\nu$$

$$\Delta\tau_\nu = \rho\kappa_\nu \Delta s$$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

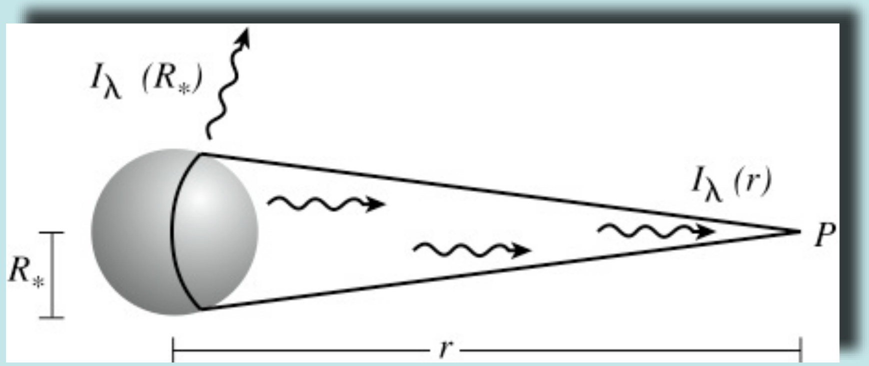
Source Function

$$S_\nu = \frac{j_\nu}{\rho\kappa_\nu}$$

Thermal emission: $\left[S_\nu = B_\nu \Rightarrow\right](j_\nu)_{therm} = \rho\kappa_{\nu,abs} B_\nu(T_{dust})$

Optical depth (τ_λ) and extinction (A_λ)

$$\frac{dI_\lambda}{d\tau_\lambda} = -I_\lambda + \frac{j_\lambda}{\rho\kappa_\lambda}$$



Let's use the equation of transfer to obtain the specific intensity at a point *P* located at a distance *r* from the center of a star. Assume that $j_\nu = 0$. Integrating the equation along any ray from the stellar surface to P, we obtain:

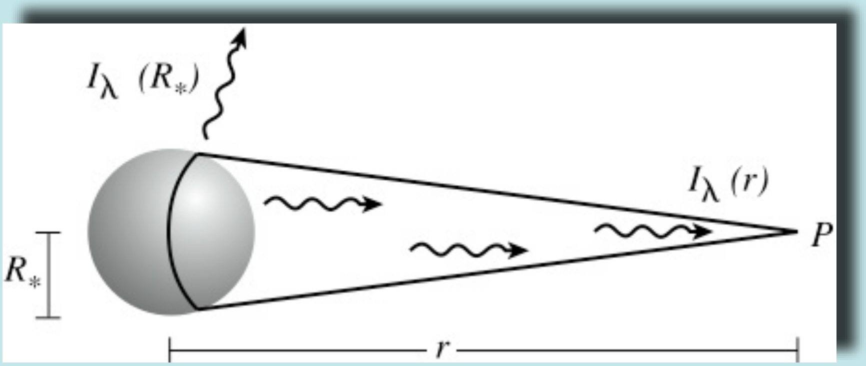
$$I_\lambda(r) = I_\lambda(R_*)\exp(-\Delta\tau_\lambda)$$

Let's now determine the Flux density ($\mu \approx 1$, and $\Delta\Omega = \pi R_*^2/r^2$):

$$F_\lambda \equiv \int I_\lambda \mu d\Omega$$

$$F_\lambda(r) = \pi I_\lambda(R_*)\left(\frac{R_*}{r}\right)^2 \exp(-\Delta\tau_\lambda)$$

Optical depth (τ_λ) and extinction (A_λ)



$$F_\lambda(r) = \pi I_\lambda(R_*)\left(\frac{R_*}{r}\right)^2 \exp(-\Delta\tau_\lambda) \quad \text{(a)}$$

Assume now that the same star is located at r_0 from P, with no intervening extinction:

$$F_\lambda^{\ *}(r_0) = \pi I_\lambda(R_*)\left(\frac{R_*}{r_0}\right)^2 \qquad \text{(b)}$$

Dividing (a) by (b) and taking the log:

$$-2.5\log F_\lambda(r) = -2.5\log F_\lambda^{\ *}(r_0) + 5\log\left(\frac{r}{r_0}\right) + 2.5(\log e)\Delta\tau_\lambda$$

$$m_\lambda = M_\lambda + 5\log(\frac{r}{10\,pc}) + A_\lambda$$

➔

$$A_\lambda = 2.5(\log e)\Delta\tau_\lambda$$

$$A_\lambda = 1.086\Delta\tau_\lambda$$

Heating and Cooling Mechanisms

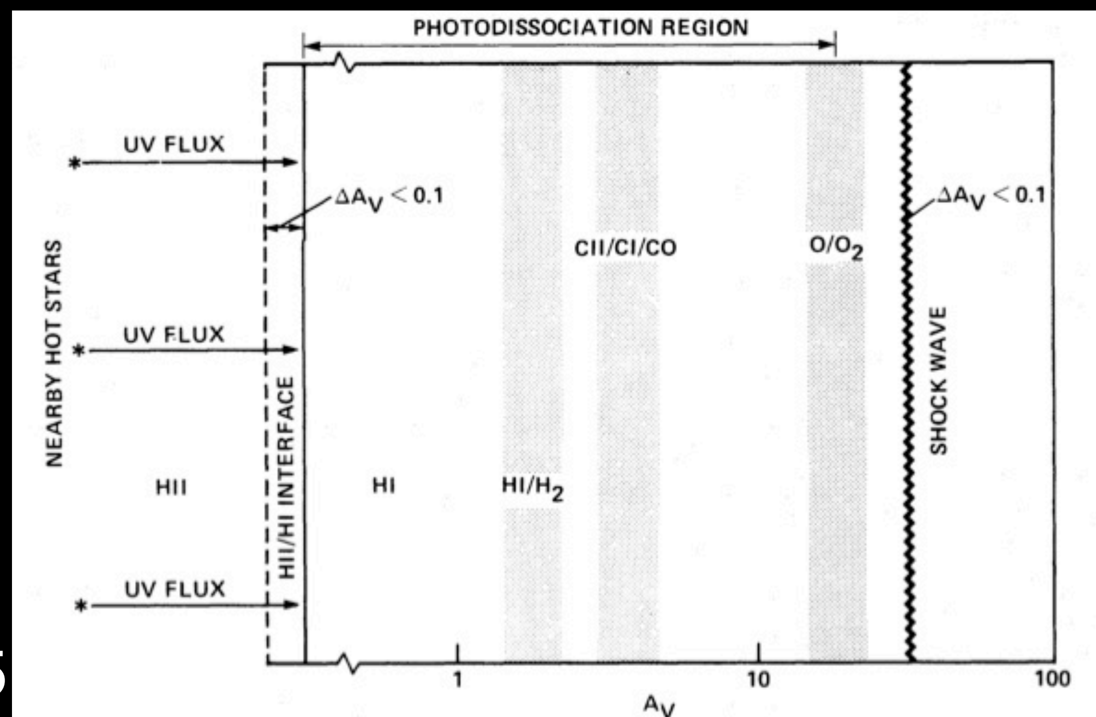
Photodissociation Regions (PDRs)

A PDR is a region where FUV (6 eV < $h\nu$ < 13.6 eV) radiation dominates the heating and/or some important aspects of the chemistry.

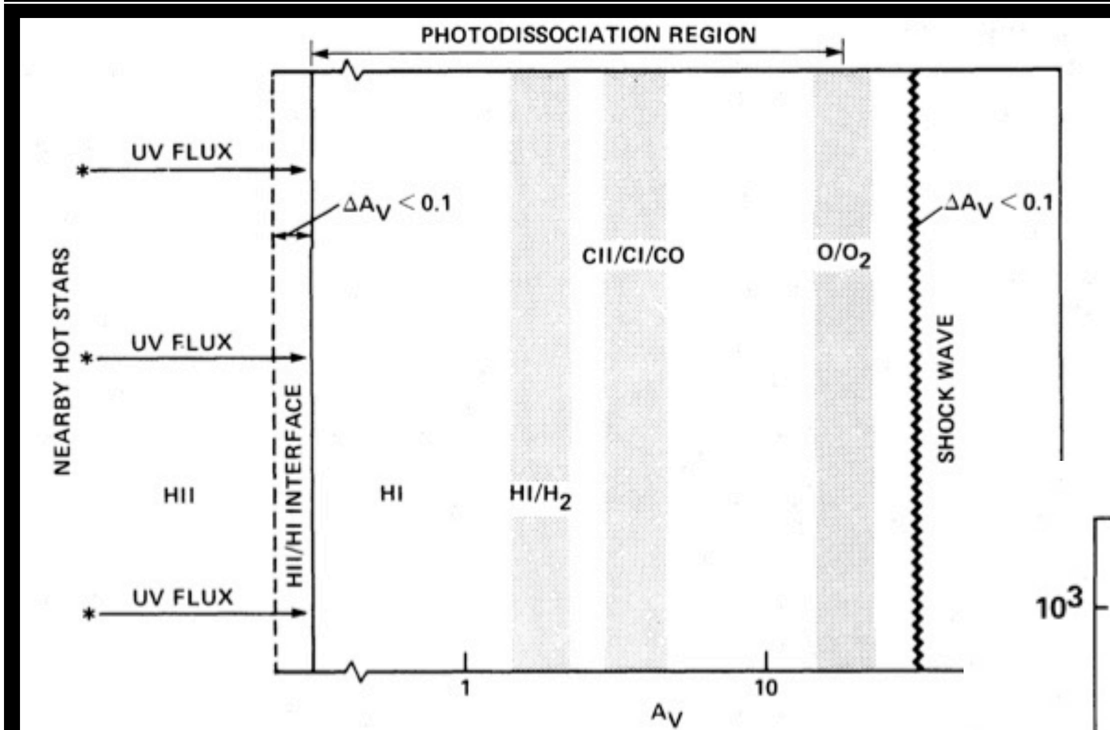
A large fraction of the volume of molecular clouds in our Galaxy has A_V < ~5 mag and FUV radiation plays an important role.

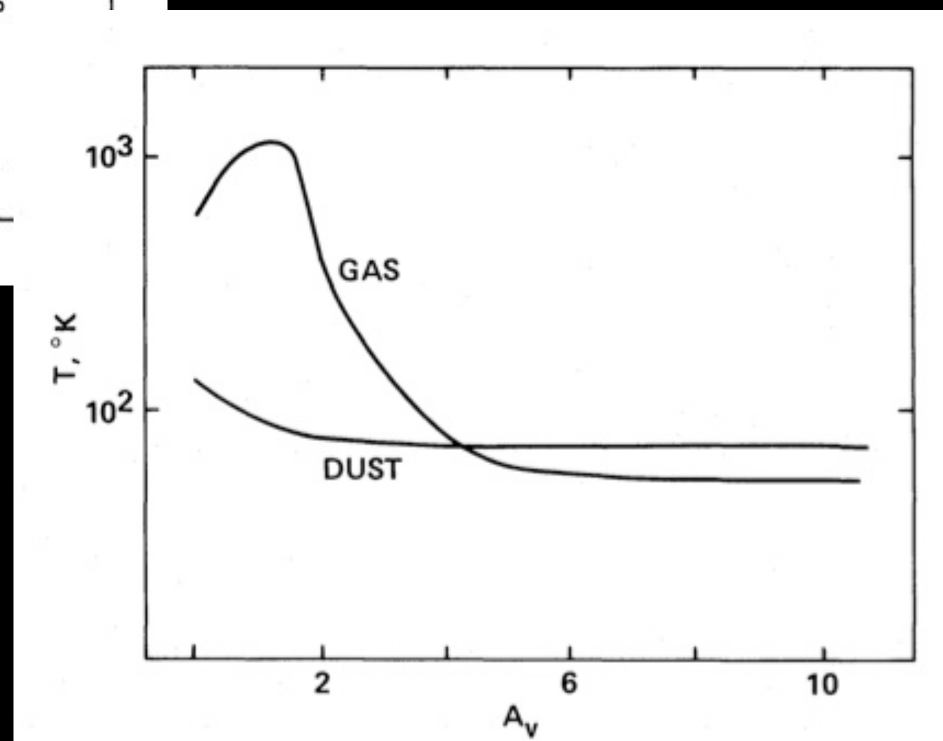
The Orion Bar:
$G_o \sim 10^5$ and $n_H \sim 10^5$ cm^{-3}

Tielens & Hollenbach 1985



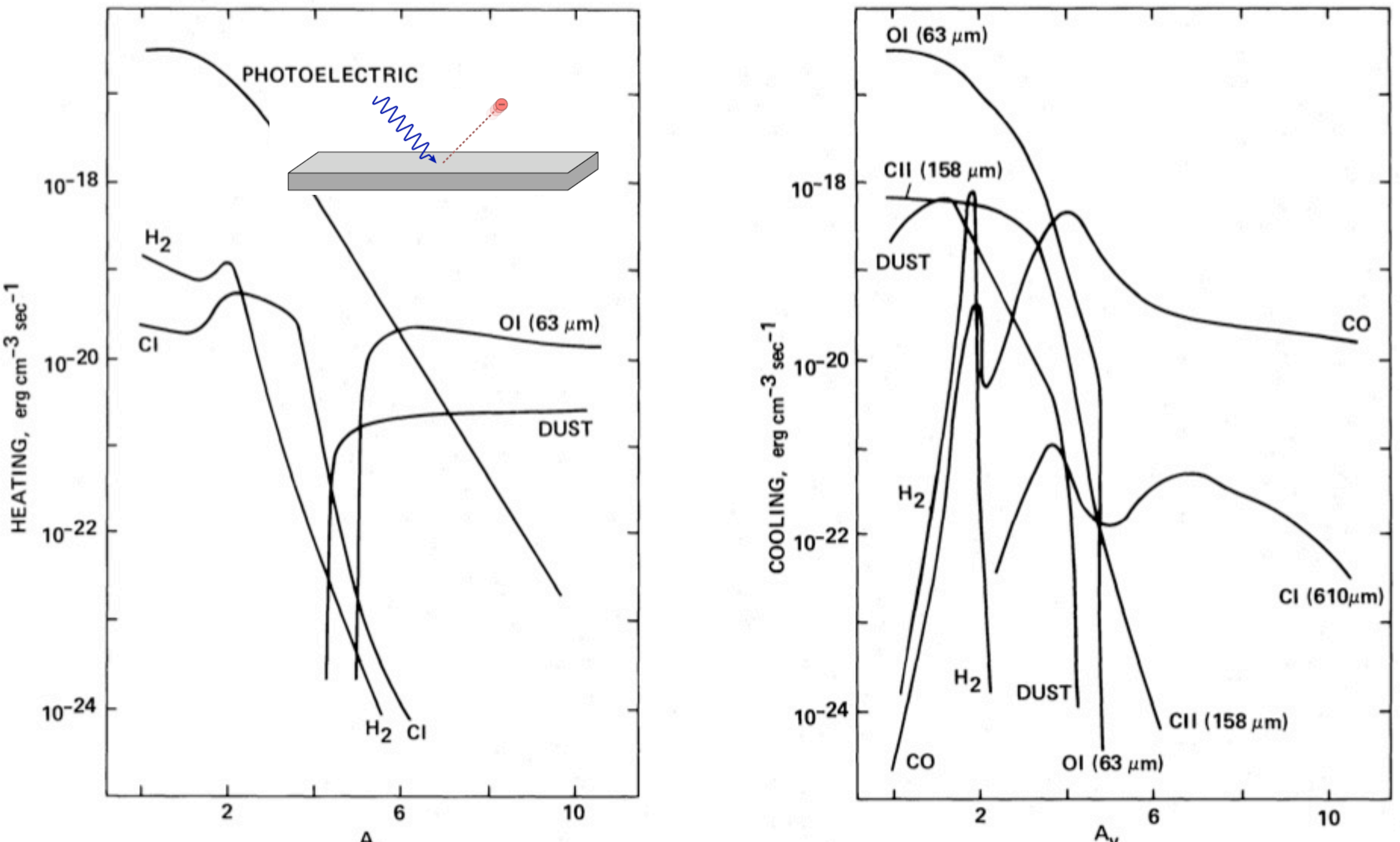
Photodissociation Regions (PDRs)





Tielens & Hollenbach 1985

Photodissociation Regions (PDRs)



Tielens & Hollenbach 1985

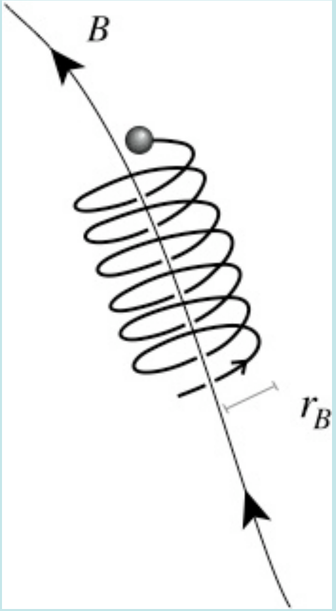
Photodissociation Regions (PDRs)

PDRs are the origin of much of the IR radiation from the ISM. The incident starlight is absorbed by dust grains and PAHs, and reradiated primarily as PAH IR features and IR continuum.

About 0.1-1% of the absorbed starlight is converted to gas heating via photoelectric ejection of electrons from grains.

Heating and Cooling of Gas in Molecular Clouds

Main heating process in dark clouds: ***Cosmic Rays on H_2:***



$$p^+ + H_2 \rightarrow H_2^+ + e^- + p^+$$

Cosmic rays mostly consist of relativistic protons, with an admixture of heavy elements and electrons. All the particles are electrically charged and thus subject to magnetic deflection.

Cosmic rays with energies up to 10^9 MeV are produced by particle acceleration within the magnetized shocks created by supernova remnants. More energetic particles are probably extragalactic in origin.

In a molecular cloud, a gyrating cosmic ray proton interacts with ambient nuclei and electrons through both the Coulomb and nuclear forces. The nuclear excitations ($E_p \geq 1$ GeV) principally decay through emission of γ rays.

The proton scatters inelastically with H_2, mainly ionizing it:

$$p^+ + H_2 \rightarrow H_2^+ + e^- + p^+$$

It is the secondary electron that provides heat though its subsequent interactions with ambient H_2. The *heat deposition in the cloud per unit volume (cooling rate):*

$$\Gamma_{CR}(H_2) = \zeta(H_2)\, n_{H_2} \Delta E(H_2)$$

Ionization rate (probability per unit time) = 1-10 × 10^{-17} s^{-1}

The most important means for the electron to provide heating is dissociation:

$$e^- + H_2 \rightarrow H + H + e^-$$

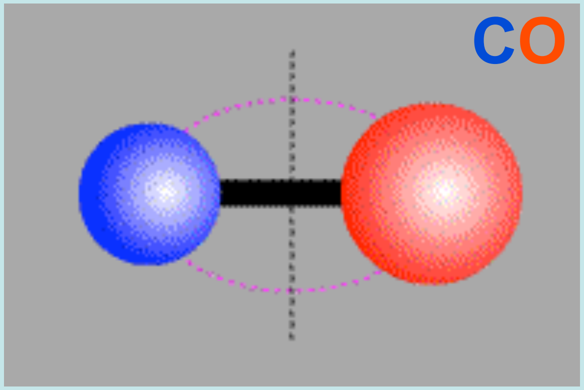
The energy of the incoming electron beyond that required to dissociate H_2 goes into motions of the two hydrogen atoms. Collisions quickly disperse this energy throughout the gas. In total, a 10 MeV proton provides:

$$\Delta E(H_2) \cong 7 \text{ eV}$$

$$\Downarrow$$

$$\Gamma_{CR}(H_2) \cong 3.4 \times 10^{-25} \left(\frac{\zeta(H_2)}{3 \times 10^{-17} s^{-1}} \right) \left(\frac{n(H_2)}{10^{10} m^{-3}} \right) \text{J s}^{-1} m^{-3}$$

What is the dominant cooling agent in molecular clouds ?



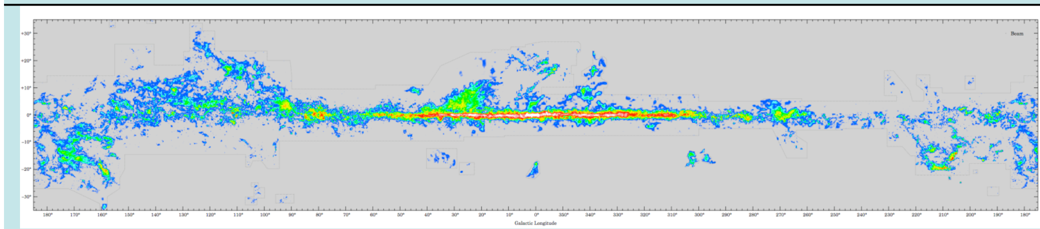
At T = 10 K and $n(H_2) = 10^{10}\ m^{-3}$:

$$\Lambda_{CO} \cong 4 \times 10^{-44}\, n^2$$

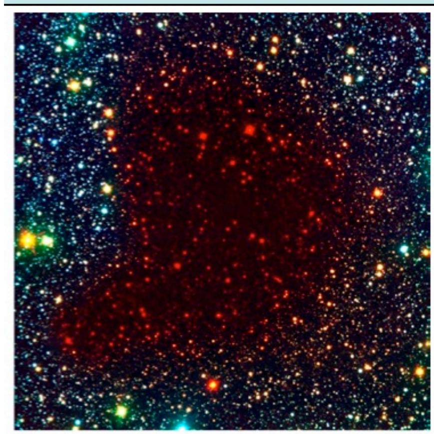
$$= 1.6 \times 10^{-23} \left(\frac{n}{2 \times 10^{10}\, m^{-3}} \right)^2 \text{J s}^{-1}\ \text{m}^{-3}$$

Λ_{CO} depends on the number density of CO molecules in the cloud, on the energy of the transition and on the optical depth of the emitted lines.

SUMMARY

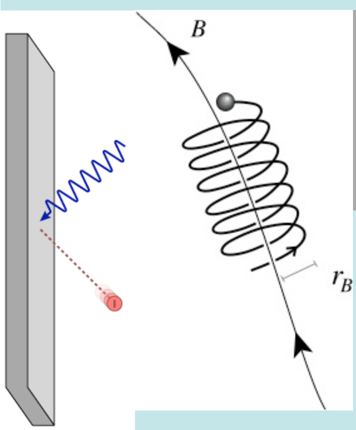


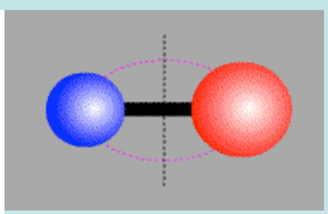
CO is a good tracer of molecular material in our Galaxy.
Molecular gas mass ~ atomic gas mass ~ 2-4×10^9 $M_{\odot}$
(dust/gas mass ratio ~ 1%)



Dust grains absorbs, scatter and emit radiation. The variation of the radiation field passing an interstellar cloud is given by the equation of radiative transfer:

$$\frac{dI_\nu}{ds} = -\rho\kappa_\nu I_\nu + j_\nu$$





Photoelectric heating and [OI], [CII] dominate the heating and cooling of diffuse regions and external layers of PDRs.
Cosmic rays impacting on H_2 and CO molecules dominate the heating and cooling of molecular clouds.