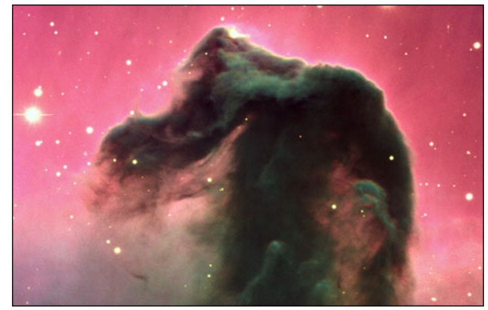
The interstellar medium (ISM)
(Section 18.2, bits of 18.7,18.8)

- Space between stars is not a vacuum but is filled with gas.
- Why is the ISM important?
  – Stars form out of it
  – Stars end their lives by returning gas to it
  – Evolution of ISM and stars is crucial to the evolution of galaxies

- The ISM has
  –a wide range of structures
  –a wide range of densities (10^{-3} -10^{7} atoms/cm^3; not dealing with g/cm^3 now!)
  –a wide range of temperatures (10 K - 10^7 K)
  –is dynamic

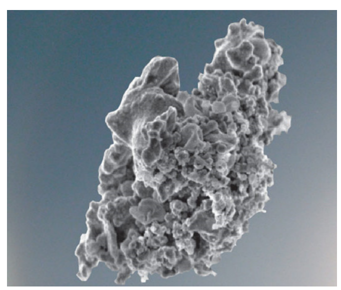
Overview of the ISM

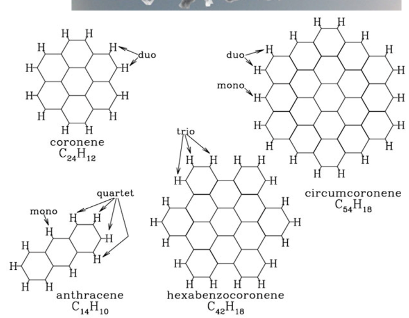
- The ISM consists of gas and dust. Dust comprises ~1% of the ISM mass. Total mass of Milky Way ISM about $5x10^9$ M⊙. About 10% as much mass in gas as in stars.
- Gas is in a few "*phases*", meaning different temperatures and densities.



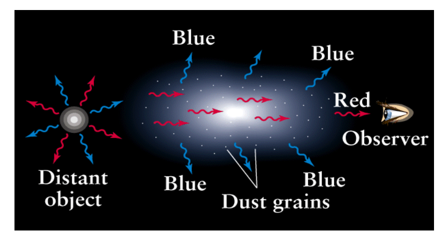
Dust particles

- Where there is gas, there is dust (except in hottest gas where dust may be destroyed).
- Larger grains with carbon, graphite, silicates, size ~ 10^{-8} -10^{-6} m (vast majority of dust mass)
- Small grains/large molecules of ~ 50 - 10^3 atoms (hydrocarbons)
- They cause "extinction" and "reddening", and emit infrared radiation





- Extinction is reduction in optical brightness due to absorption and scattering by dust.
- Strong wavelength dependence on absorption and scattering => reddening

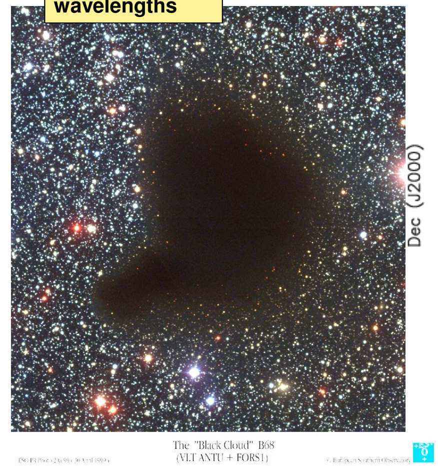


Orion at visible wavelengths

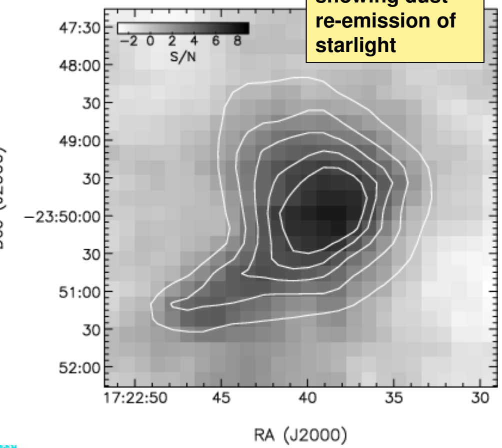
What happens to radiation absorbed by dust?

Orion at IR wavelengths (100μm): larger dust grains absorb UV/visible light and warm up to 10's-100's of K. Acting like blackbodies, they re-radiate in the IR. These dominate emission from dust and mass of dust.

Dark cloud Barnard 68 at optical wavelengths



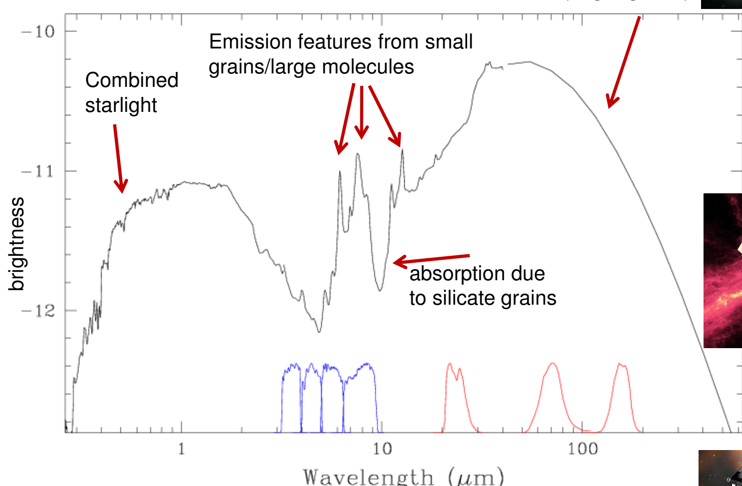
At 850 μm showing dust re-emission of starlight



Dust emission thus often indicates cold, dense, dark gas clouds, in which new stars are forming but can't be seen optically. Can help us understand the process, and determine the rate at which they form.

Optical and infrared spectrum of a whole galaxy (Messier 82)

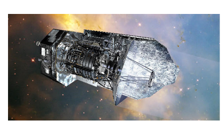
Combined dust infrared emission (larger grains)



Optical | <---------------- Infrared ----------------->

Spitzer Space Telescope

Herschel Space Telescope



The main ISM component: gas

- Interstellar gas is either neutral or ionized
- Neutral gas either atomic or molecular
- We refer to the gas by the state of H

number density of particles: atoms, molecules, or electrons (~ ions)

Component	Phase	T(K)	n(cm^{-3})
Neutral	Cold (molecular)	10-50	10^3-10^7
	Cool (atomic)	100	1
	Warm (atomic)	8x10^3	10^{-1}
Ionized	Warm	10^4	10^{-2},10-10^4
	Hot	10^6 - 10^7	10^{-4}-10^{-3}

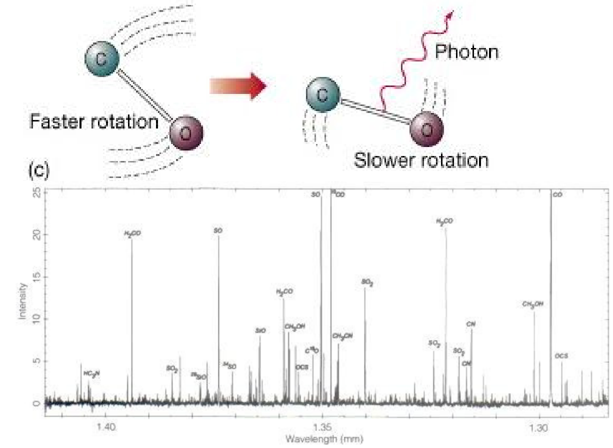
Molecular clouds

- Cold (~10 K), dense (n ~ 10^3–10^7 molecules/cm^3) well defined clouds
- Masses: 10^3 - 10^6 $M_\odot$
- Sizes: a few to 100 pc
- In the Galaxy: ~5000 molecular clouds, totaling 2×10^9 $M_\odot$, or nearly half the ISM mass
- Sites of star formation

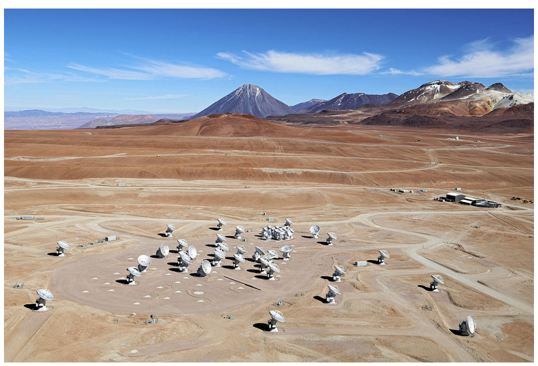
Molecular clouds have much dust, so are seen as dark clouds in the optical.

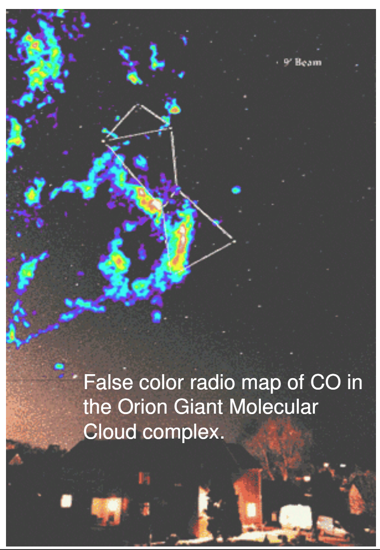
- Most abundant is H_2, but it radiates very weakly, so other "trace" molecules observed: CO, H_2O, NH_3, HCN etc, even glycine (C2H5NO2) the simplest of the amino acids (building bocks of proteins).

- These molecules undergo rotational energy level transitions, emitting photons at wavelengths of millimeters. Levels excited by low energy collisions at these low T's. e.g. CO, lowest transition at λ = 2.6 mm or 115 GHz.



Some emission lines from molecules in the Orion molecular cloud. This is only tiny part of mm-wave spectrum!





False color radio map of CO in the Orion Giant Molecular Cloud complex.

Molecular rotational transitions observed with mm-wave radio telescopes (or arrays), such as the ALMA array in Chile.

CO is most commonly observed tracer of molecular gas. Brightest emission.

CO map of Orion Molecular Cloud at 2.6mm or 115 GHz. 400,000 M⊙ of gas.

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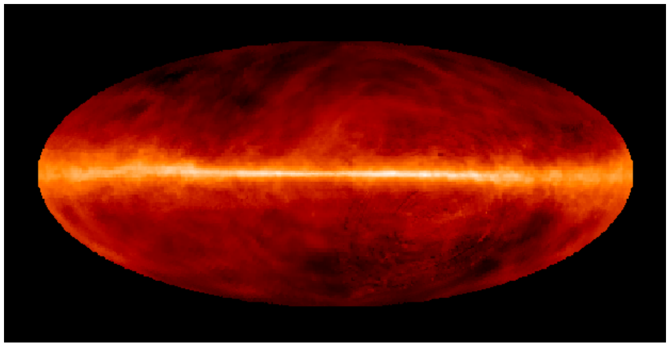
Atomic gas - HI

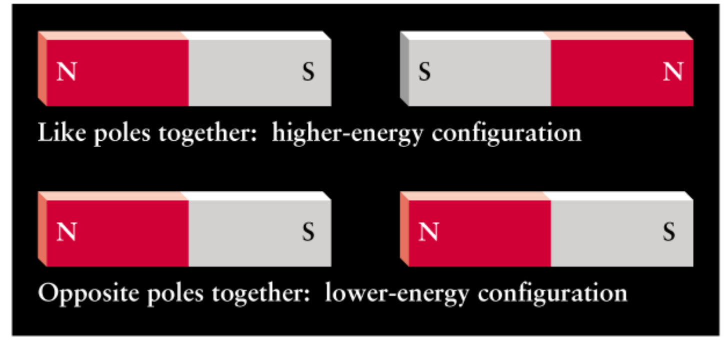
- Diffuse gas filling a large part (half or so?) of the interstellar space
- 2×10^9 $M_\odot$ in the Galaxy, making up nearly half the ISM mass



HI in the Milky Way. So what wavelength is this emission?

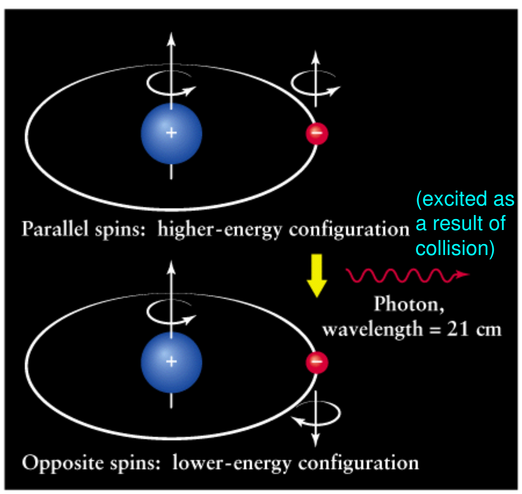
Gas too cold for collisions to excite H out of ground state. But H with electrons in n=1 level still emits energy through the "spin-flip transition".

How? Electrons and protons have a quantum mechanical property called spin. Classically, it's as if these charged particles are spinning. Spinning charged particles act like magnets:



a

The spin-flip transition produces a **21-cm** photon (1420 MHz).



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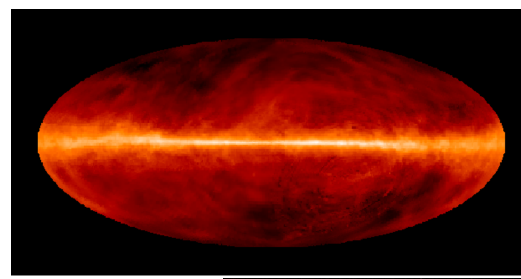
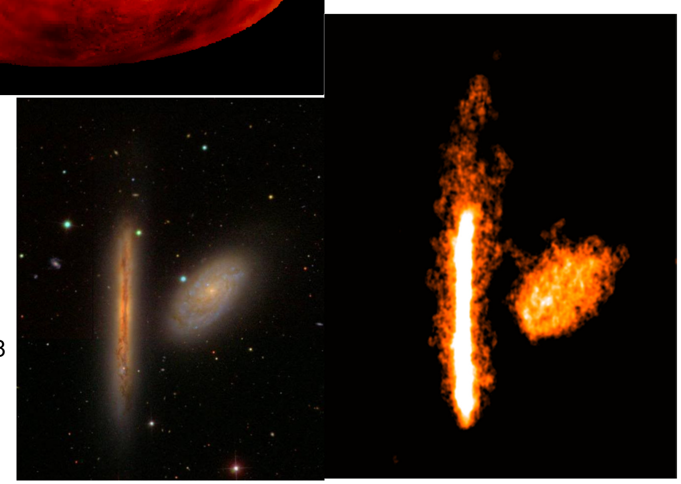
Low-frequency photon => transition happens even in cool gas



Map of 21-cm emission from Milky Way



Optical image and VLA map of 21-cm emission from NGC 4302 and NGC 4298

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	Hot	10^6 – 10^7	10^{-4}-10^{-3}

- Well-defined structures: HII regions (or emission nebulae)
- Diffuse Ionized Gas (DIG)

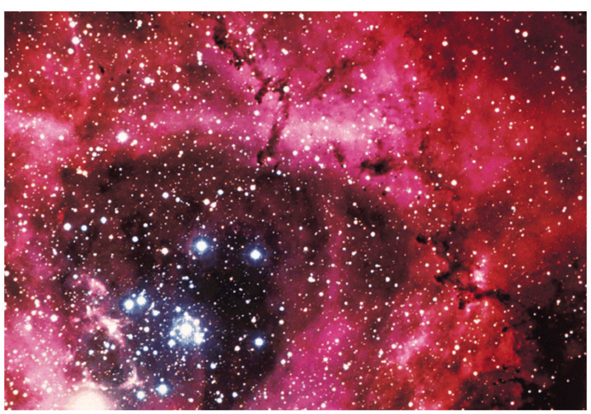
HII regions (or Emission Nebulae)

- *nebula* = cloud (plural *nebulae*)
- H essentially completely ionized
- n ~ 10 – 5000 cm^{-3}
- T≅10^4 K
- Sizes 1-20pc, well defined structures, small fraction of ISM mass
- associated with star forming regions, found within molecular clouds

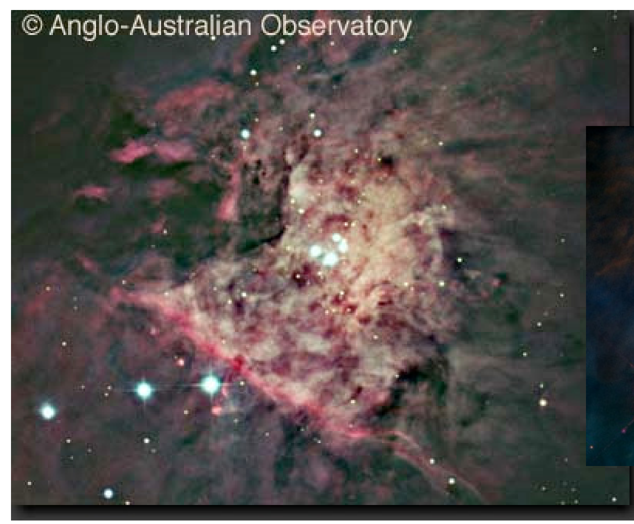
Rosette Nebula

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

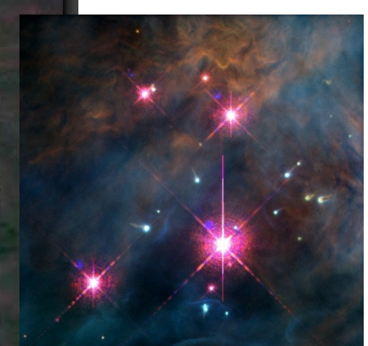
- UV energies are required to ionize the atoms
- Provided by hot and massive O, B stars (collisions rarely have enough energy to ionize at these temperatures). Gas warm and ionized only as long as these stars are there ~ 10^7 years. Low mass stars forming too, but short-lived high mass ones provide the best signposts of recent star formation.
- Dominant emission: Balmer α (i.e. Hα), at λ = 656 nm. Gives red color.



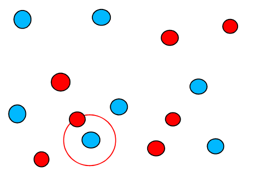
In the Orion Nebula, the Trapezium stars provide energy for the whole nebula. HII regions were once molecular gas, but molecules broken apart, then atoms ionized and heated by UV radiation from newly formed massive stars. Stellar winds can also disperse gas, but densities still high compared to most types of ISM gas.



Hubble Space Telescope

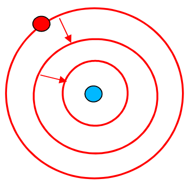


Hα requires H atoms, and isn't all the H ionized? Not quite.



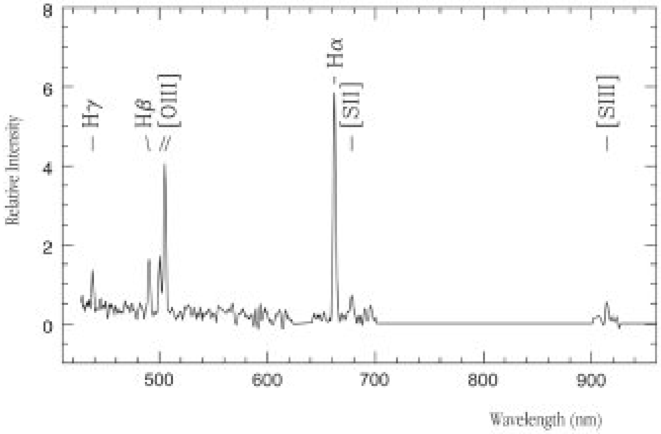
Sea of protons and electrons

Once in a while, a proton and electron will recombine to form H atom. Usually rejoins to a high energy level. Then electron moves to lower levels.



Emits photon when it moves downwards. 3-2 transition dominates optical emission. Atom soon ionized again.

Lines from other elements predominantly in ionized states. Radiation ionizes them, collisions cause emission line in ion (different from H, where lines are from recombining atoms).



Lagoon Nebula

Tarantula Nebula

Stellar winds, turbulence and supernova explosions give HII regions complicated structure.

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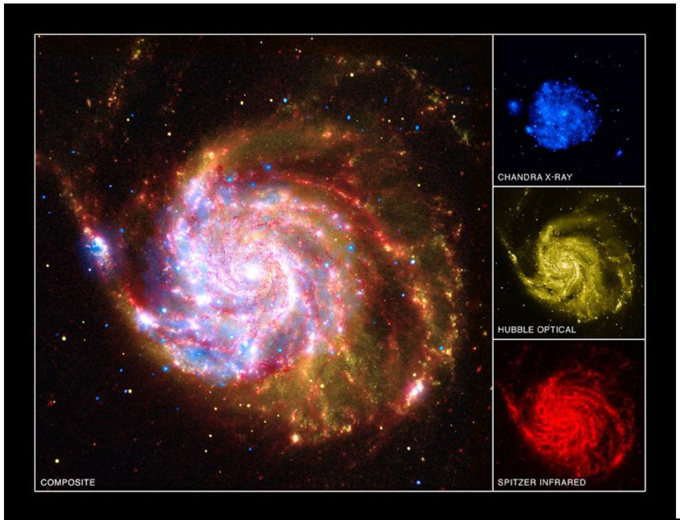
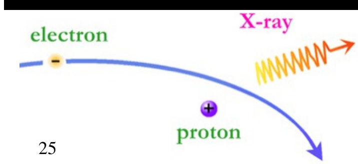


X-ray emission in galaxy Messier 101. ISM emission from “Bremsstrahlung” process (also some line emission from highly ionized elements). Hot regions probably heated by combination of many supernovae



Chandra X-ray observatory

Other ISM components

- Magnetic fields (10^{-9} -10^{-12} Teslas, widespread)
- Cosmic Rays (high energy particles, interact with magnetic fields ⇒ radio emission)
- Supernova remnants (radio, optical, x-ray – more later)
- Planetary Nebulae (isolated objects – more later)
- Reflection nebulae (light scattered by dust – blue)