

GAS

The other baryonic component- sec 2.4 in S+G
Material scattered in sec 8-9 of MWB

**See web page of Alyssa Goodman at harvard
Astronomy 201b : Interstellar Medium and
Star Formation**

<http://ay201b.wordpress.com/>

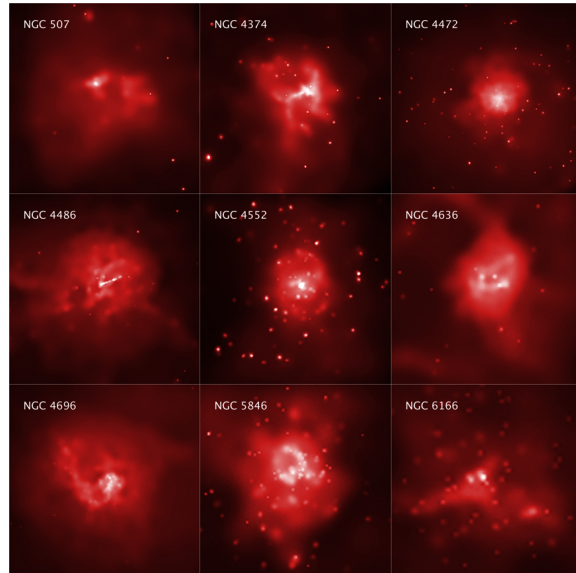
I will be going thru material a bit too fast for
derivations and strongly recommend looking at
the above page for details

Gas- Big Picture

- dark matter halos grow by merging and accretion (e.g. Galaxies can grow by accretion of gas, by merging with gas rich galaxies and by merging with gas poor galaxies)
- gas falls into these halos, cools and forms stars.
- How does this occur- the physics of gas accretion,
 - How and when did galaxies accrete their gas and what do they do with it (e.g. form ISM, stars, expel the gas, feed the supermassive black hole)

- ‘cold’ gas: dominates in **Spirals-many phases**
 - neutral hydrogen
 - molecular gas-Dense molecular clouds, have most of the total mass of the interstellar gas and are of key importance for star formation, occupy a negligible fraction of the total volume
 - warm ionized gas-has persistent transient states out of thermal pressure balance
 - Milky-Way-like galaxies cold gas mass $\sim 10\%$ of the stars
 - For lower mass galaxies the baryonic fraction in gas is larger; at $M_{\text{halo}} < 10^{11} M_{\odot}$ gas dominates the baryonic content
 - Hot gas ($T \sim 10^{6-7}$ k) dominant ISM in **elliptical** galaxies
- In spirals hot gas fills the volume but low total mass

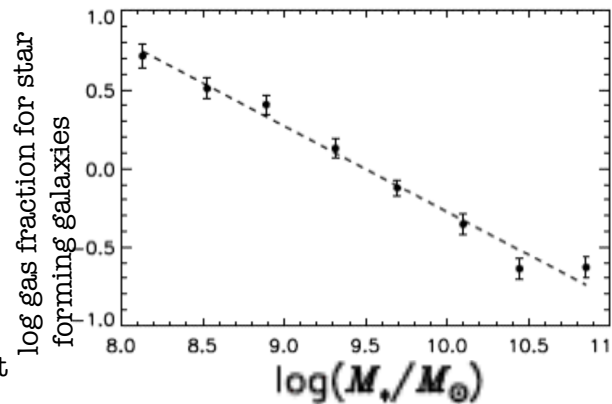
GAS-ISM



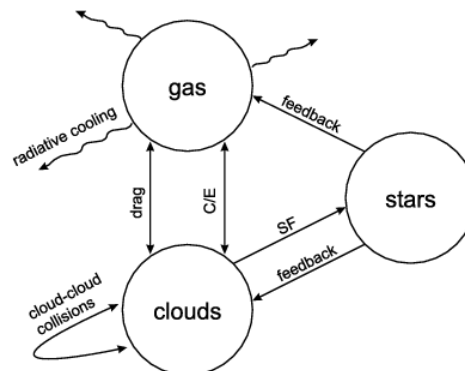
x-ray images of elliptical galaxies emphasizing structure

Gas

- Other than stars the baryons in galaxies lie in 3 forms
 - gas
 - rocks
 - dust (0.1% of mass)
- the % mass in rocks and dust is small
- There is an interplay between the stars and gas, with stars forming out of the gas and with enriched gas being ejected back into the interstellar medium from evolved stars.
- There exist a vast array of spectral diagnostics for the gas in both emission and absorption which can reveal
 - chemical composition
 - temperature
 - velocities
 - ionization mechanism

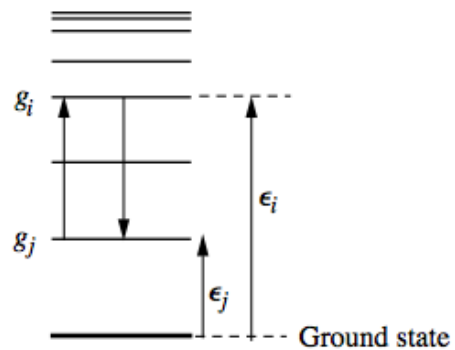


Peeples and Shankar 2011



A Bit of Physics

- Saha equation describes the ionization balance of the gas which depends on the temperature, quantum mechanical transition probabilities and densities
- An atom with multiple energy states in thermal equilibrium with a radiation field will find itself in one or another of these energy states.
- Frequent transitions to and from other states will occur as photons interact with the atoms.
- transitions from the upper of the states of figure take place by photo deexcitation and by induced deexcitation. Transition in the upward direction is by photoexcitation or collisional excitation

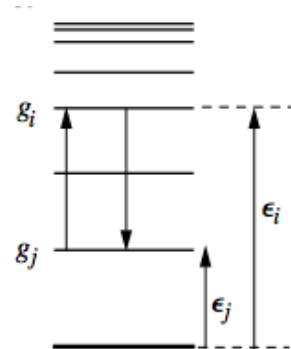


For lots of details see MBW appendix B

A Bit of Physics

- The rates of ionization and recombination are important (see eqs 2.21, 2.22 in S+G); e.g. $X^+ + e \rightarrow X + \gamma$
- the rate at which ions recombine thus clearly depends on the ion density n_{X^+} and the electron density and the recombination coefficient α , which depends on the ion, (e.g. the number of electrons it has and its atomic number)
- Thus recombination rate of electrons for a given ion X^+ is

$$dn_e/dt = n_{X^+} n_e \alpha(T_e);$$
- the recombination time is the # of electrons/ the rate : $n_e / dn_e/dt$
a few thousand years in a HII region - α the recombination rate depends on QM and Boltzmann's law



In steady state # of ionizations = # of recombinations

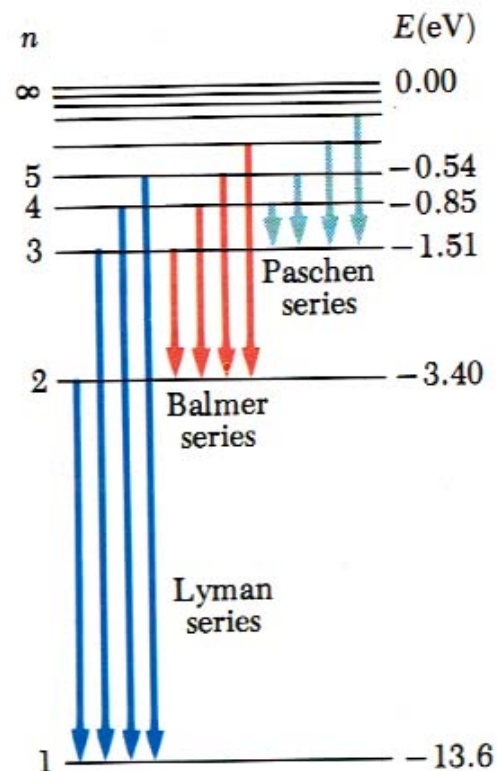
Ionization is from

- collisions with hot electrons

- photoionization from stars
- shocks

Atomic Lines

- The energy levels and transitions for hydrogen
- Each element and ionization set has a similar (but more complex) set of lines
- The probability of emitting a given line depends on the temperature and density of the gas



A Bit of Physics-Ionizing Photons

- One can estimate the number of ionizing photons from a star using the black body formula (e.g. 1.35 in S&G) and integrating over the photons more energetic than the ionization potential of the ion of interest (e.g. H with 13.6 eV)- effects of radiative transfer in stellar atmospheres of hot stars is VERY important
- These photons ionize and heat the gas
- The gas responds by emitting lines characteristic of the chemical composition, temperature, ionization state, density etc ...

Physics of Emission from Gas

- Gas is heated/excited/ionized by photons (stars, AGN), shocks (supernova) and gravity
- Atomic transitions reveal the ionization state, temperature, density, velocity structure and chemical composition of the gas.
- Photoionization: photon from source eject electron from ion- to do this photon needs to have energy greater than ionization potential (e.g. 13.6 eV for Hydrogen; O,B stars, AGN)
- Collisional ionization: gas is excited by collisions with 'hot' electrons (again electron energy has to be above threshold). Electrons have Maxwell-Boltzman energy distribution in equilibrium
- wide range of types of transitions: 2 'basic' types
 - permitted: fast transition rate, line is emitted before ions state is altered
 - forbidden: violate transition rule, ion can be collisionally de-excited when density exceeds critical density; presence of line thus places constraint on gas density. - jargon forbidden lines are indicated by [OII] (OII is the ionization state of the gas, once ionized oxygen).

A Bit of Physics-Relevant Velocities

Sound speed in gas $c_s = \partial P / \partial \rho$; P and ρ are the pressure and density

For isothermal gas $P = \rho k_B T / \mu m_H$

where k_B is Boltzmann's constant and μ is the mean molecular weight of the gas

$$c_s = \sqrt{k_B T / \mu}$$

Many astrophysical situations in the ISM are close to being isothermal, thus the isothermal sound speed is often used

Reason: sound crossing time is much higher than the (radiative) cooling time of the gas, an increase in temperature due to compression will be immediately followed by radiative cooling to the original equilibrium temperature.

Alfvén speed: The speed at which magnetic fluctuations propagate.

$v_A = B / \sqrt{4\pi\rho}$ Alfvén waves are transverse waves along the direction of the magnetic field.

ISM- Relevant Velocities

Some characteristic values

- galactic rotation gradient 18km/sec/kpc
- Thermal sound speed ideal gas for H, this is 0.3, 1, and 3 km/s at 10 K, 100 K, and 1000 K

Alfven speed- speed at which magnetic fluctuations propagate

$$v_A = B / \sqrt{4\pi\rho} \text{ - so for typical ISM values } B = 1\mu\text{G, \# density } n \sim 1 \text{ cm}^{-3}$$

$$v_A = 2 \text{ km/sec}$$

A Bit of Physics-TimeScales

In gas at temperature T, the mean particle velocity is given by the 3-d kinetic energy: $\frac{3}{2}mv^2 = kT$;

collision timescale $\tau \sim 1/v$; $l \sim n\sigma$; n is the NUMBER density of the gas and σ is a typical cross section (hard sphere approx for ions $\pi r^2 \sim 10^{-15} \text{ cm}^2$)

$$\text{and thus } \tau \sim \left\{ \frac{2}{3} \right\} \{kTm\}^{-1/2} / (n\sigma) = 4.5 \cdot 10^3 n^{-1} T^{-1/2} \text{ years}$$

for a typical place in the ISM $(n, T) = (1 \text{ cm}^{-3}, 10^4)$ the collision time is 45 years

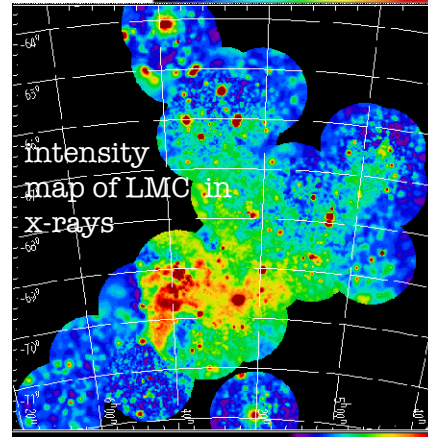
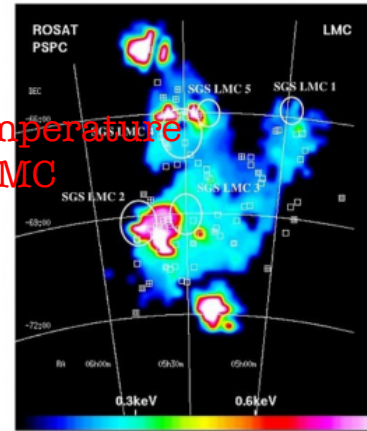
For a sphere of gas, where thermal pressure is balanced by self-gravity the timescale to collapse (the Jeans time) is $\tau_J \sim 1/\sqrt{4\pi G\rho}$ which is similar to the free falltime

$$\tau_{ff} = (3\pi/32G\rho)^{1/2} = 4.4 \times 10^4 \text{ yr} / \sqrt{\{n_H/10^6\}}$$

Big Questions

- What is the volume filling factor of the hot ISM?
- What is the distribution of the temperature, density, and velocity
- What are typical scales in the ISM and why?
- What is the effect of turbulence , magnetic fields and cosmic rays
- What causes density and pressure inhomogeneities in the evolution of the ISM
- How is the ISM related to star formation
- Why is the ISM in spirals and ellipticals so different in density and temperature?

x-ray temperature map of LMC



Physics of Emission from Gas

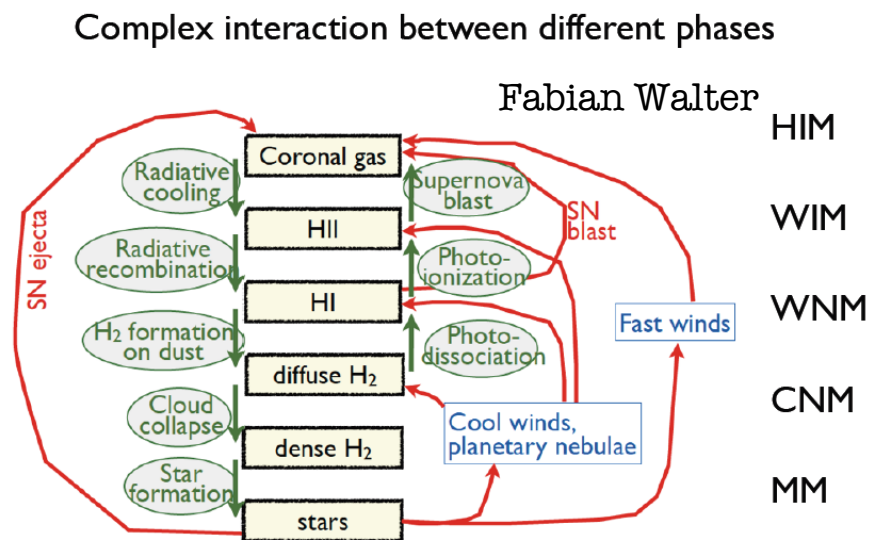
- Lines have enormous range of energies/wavelengths
 - molecular and fine structure lines in IR/radio band
 - atomic lines in the IR, optical, UV and x-ray
- Ionized gas also emits a continuum via thermal bremsstrahlung-
shape of which is a measure of temperature, intensity goes as density squared.
- Observed line energies give velocity information: redshift, velocity field
- Relative strength of lines determines ionization temperature, abundance of given element (corrected for ionization balance (go to board)).
- see Space Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008m astro-ph/0801.1011 for the background physics for low density, hot gas.

Importance of the ISM

- Despite its low mass, the ISM is very important
 - crucial role in the star-gas cycle in spirals and irregulars,
 - it facilitates ongoing (& current) star formation
 - it is a repository for elements created in SNR and stars and therefore is a key to measure chemical evolution
 - Because it can cool, its collapse is **dissipational**
 - stars can form !! hot gas → cold gas → stars:
 - galaxies are smaller than dark matter halos !
- its emission & absorption provides enormous diagnostic information
- Doppler motions reveal galaxy dynamics
 - Abundance measurements allow study of chemical evolution
 - physical conditions: density; temp; pressure; turbulence; gas column density; mass,
 - can all be derived from observations of emission lines
 - lines are bright and can be seen (relatively) easily at cosmological distances.

The ISM in Spirals is DYNAMIC

- There is strong interaction between the different phases of the ISM and feedback between star formation and the rest of the ISM
- There is lots of complex non-linear effects (and lots of jargon)



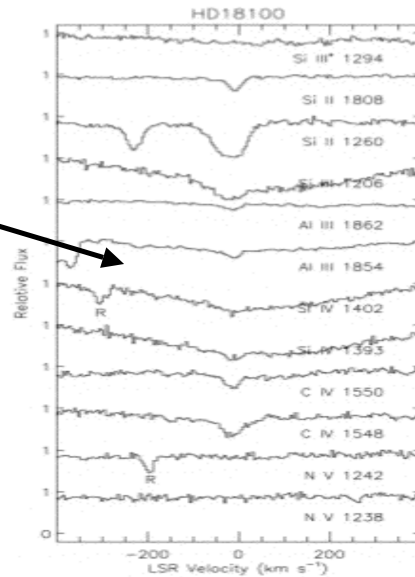
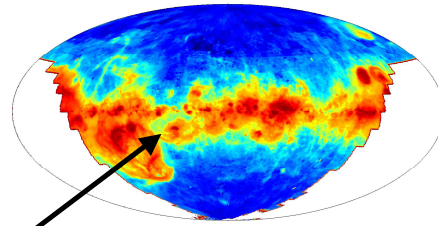
At low redshift ISM in spirals not affected much by AGN

Its not so clear if ISM in ellipticals is dynamic in the same way; AGN seem to be more important

How Does One Observe the ISM (sec 5.2 in S&G)

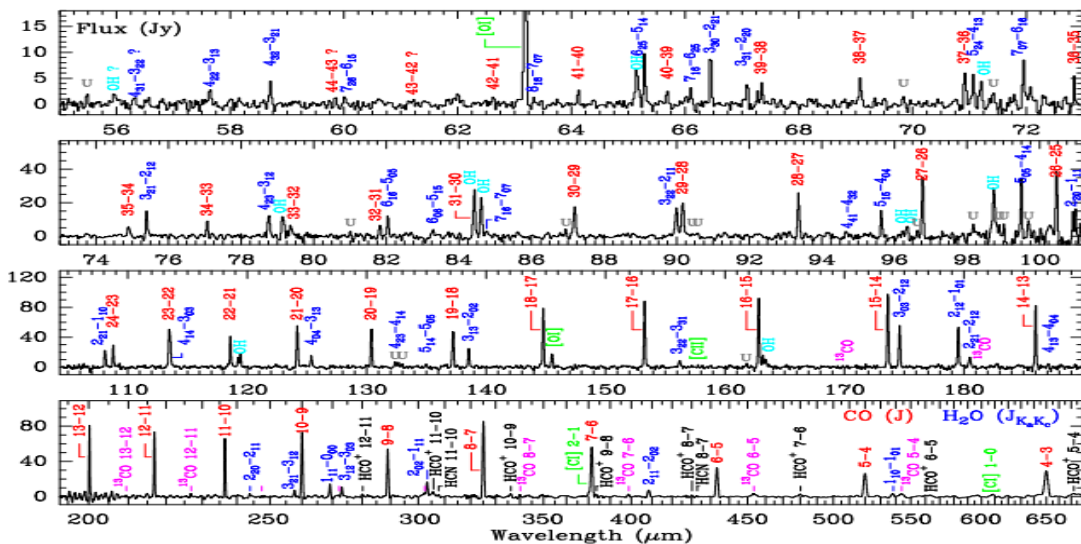
- **Because of the wide range in temperatures and densities a wide variety of techniques are needed**
- Radio:
 - free-free emission and 21cm for HI
 - high freq radio-far IR (CARMA,ALMA,Herschel) wide variety of molecular lines
- IR spectral lines [OI]63,145um and [CII]158 and [CI]370,609um
- Optical/UV
 - wide variety of emission and absorption lines from ionized metals (C,N,O etc) - gas is photoionized
- Soft x-ray
 - continuum and emission lines from $T \sim 10^6-10^7$ k gas (spirals and ellipticals) - gas is collisionally ionized
- γ -ray
 - interaction of cosmic rays with gas

H α Emission from MW



Far IR Lines

- More than 145 lines, most of them rotationally excited lines from abundant molecules:
- 38 ^{12}CO lines (up to $J=42-41$) 37 lines of both o- H_2O and p- H_2O (up to 818-717), 16 OH lines 12 ^{13}CO lines (up to $J=16-15$) and several HCN and HCO+ lines Goicoechea et



Goicoechea et al.: The complete spectrum of the Class 0 protostar Serpens SMM1

Spiral ISM 'States'- f is the filling factor

- Molecular Medium (MM): $T \sim 20$ K, $n > 10^3 \text{ cm}^{-3}$, $f < 1\%$. The MM is mostly cold dense molecular clouds which are gravitationally bound. this phase contains \sim as much mass as the atomic hydrogen, but occupies only a very small fraction of the ISM.
- Cold Neutral Medium (CNM; $T \sim 100$ K, $n \sim 20 \text{ cm}^{-3}$, $f = 2 - 4\%$). The CNM is distributed in rather dense filaments or sheets, occupying a minor fraction of the ISM. The CNM is most readily traced by HI measured in absorption.
- - Warm Neutral Medium (WNM; $T \sim 6000$ K, $n \sim 0.3 \text{ cm}^{-3}$, $f \sim 30\%$). This phase provides the bulk of the HI seen in emission line surveys.
- - Warm Ionized Medium (WIM; $T \sim 8000$ K, $n \sim 0.3 \text{ cm}^{-3}$, $f \sim 15\%$). associated with HII regions, but a considerable fraction of the ISM outside of HII regions is also filled with ionized gas.
- - Hot Ionized Medium (HIM; $T \sim 10^6$ K, $n \sim 10^{-3} \text{ cm}^{-3}$, $f \sim 50\%$). The hot gas produced by supernova explosions and their after effects (in spirals, other physics in ellipticals) - long cooling time, a **large fraction of the ISM** is filled with this component.
- <http://ned.ipac.caltech.edu/level5/March01/Brinks/Brinks4.html>

ISM- Phases

- Hot ionized medium (e.g. X-rays)
- Warm ionized medium HII region(e.g. $H\alpha$)
- Warm neutral medium (e.g. HI emission)
- Cold neutral medium (e.g. HI absorption)
- Molecular medium (e.g. CO)

These phases have different distributions perpendicular to the plane-scale height

TABLE 2.1— The different phases of the ISM.

	MM	CNM	WNM	WIM	HIM
$n \text{ (cm}^{-3}\text{)}$	$10^2 - 10^3$	4-80	0.1-0.6	$\approx 0.2 \text{ cm}^{-3}$	$10^{-3} - 10^{-2}$
T (K)	10-50	50-200	5500-8500	≈ 8000	$10^5 - 10^7$
h (pc)	≈ 70	≈ 140	≈ 400	≈ 900	$> 1 \text{ kpc}$
f_{volume}	$< 1\%$	$\approx 2-4\%$	$\approx 30\%$	$\approx 20\%$	$\approx 50\%$
f_{mass}	$\approx 20\%$	$\approx 40\%$	$\approx 30\%$	$\approx 10\%$	$\approx 1\%$

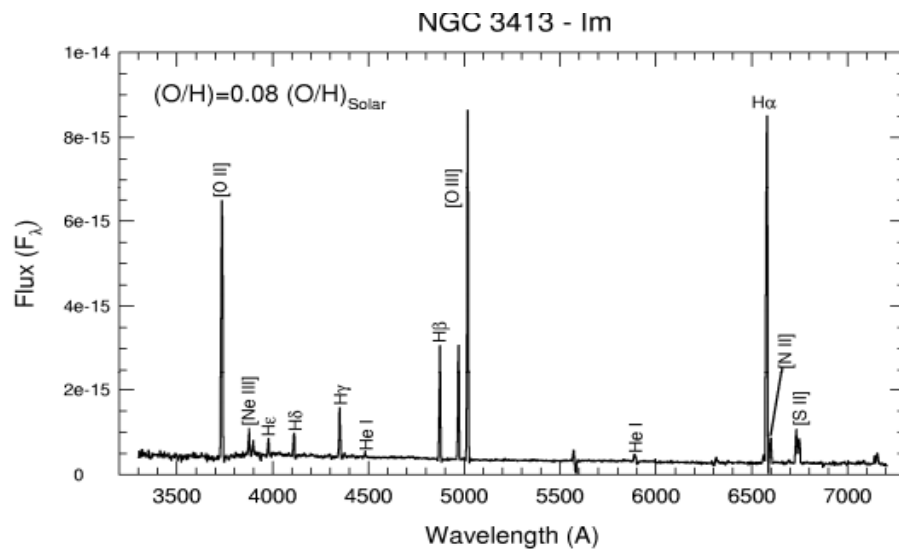
Note: the quoted numbers for each of the phases are only rough estimates. n is the particle density in cm^{-3} , T the temperature in K, h the scale height in pc, f_{volume} is the volume filling factors, and f_{mass} the mass fraction.

Fabian Walter

The ISM

- The 5 'states' are in dynamic interaction.
 - the coldest clouds are molecular and the densest (hydrogen molecules, CO, NH₃ and other molecule)s- **this is where stars form** .
 - The dust is composed of 'refractory' elements and molecules mainly carbon, silicon, iron and is responsible for most of the absorption of optical light in the galactic plane - the energy absorbed by the dust heats it and the dust re-radiates in the IR
 - The ISM is threaded by magnetic fields. At $\sim 5\mu\text{G}$, these fields provide a pressure comparable to the pressure of the gas . The magnetic fields therefore affects the dynamics of the ISM
-
- How dense (or not) is the ISM?
 - Dense molecular cores: $n \sim 10^5 \text{ cm}^{-3}$
 - Typical ISM: $n \sim 1 \text{ cm}^{-3}$
 - Best human-made vacuum: $3 \times 10^4 \text{ cm}^{-3}$

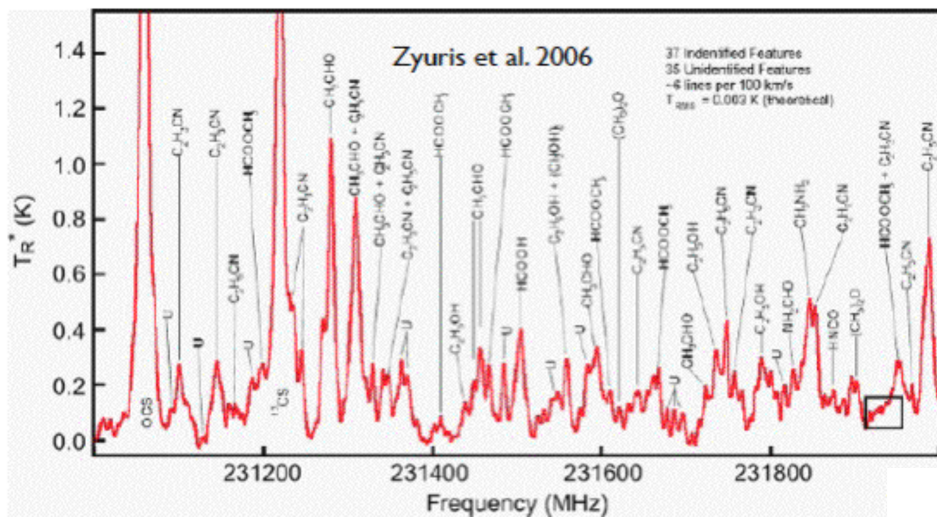
Optical spectrum of HII Region



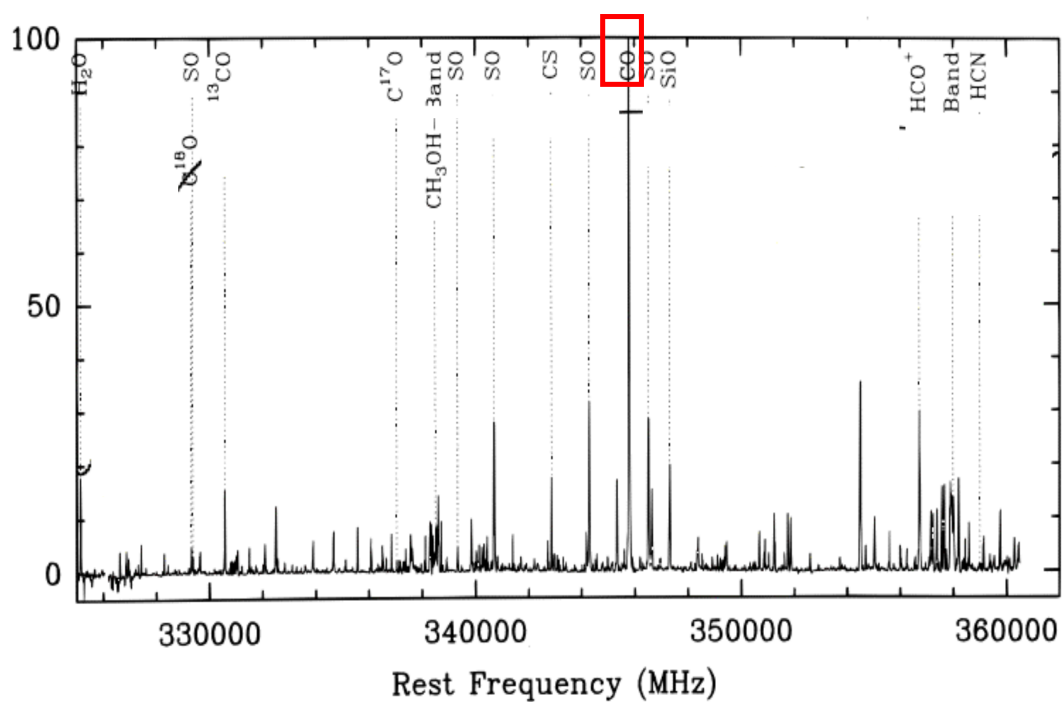
- Optical spectrum show lines due to [OII], [OIII], H α , [NII], etc

Molecular Lines

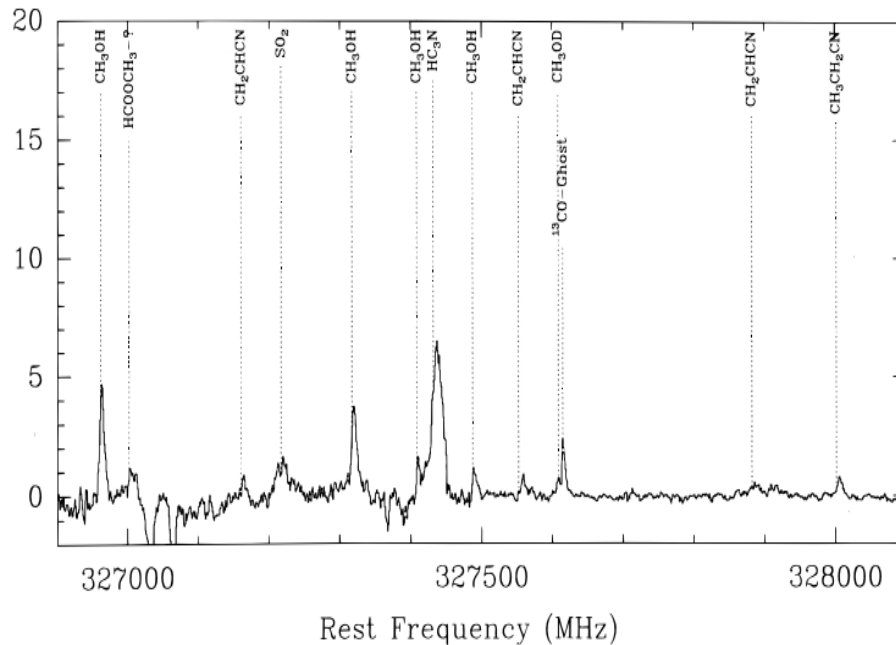
- Molecular clouds are very rich in spectral features from a wide variety of molecules- lots of information
- Some of the lines (CO) are so strong that they can be seen at high redshift



Millimeter Band Spectrum of Molecular Cloud



Millimeter Band Spectrum of Molecular Cloud



- zoom in on previous plot

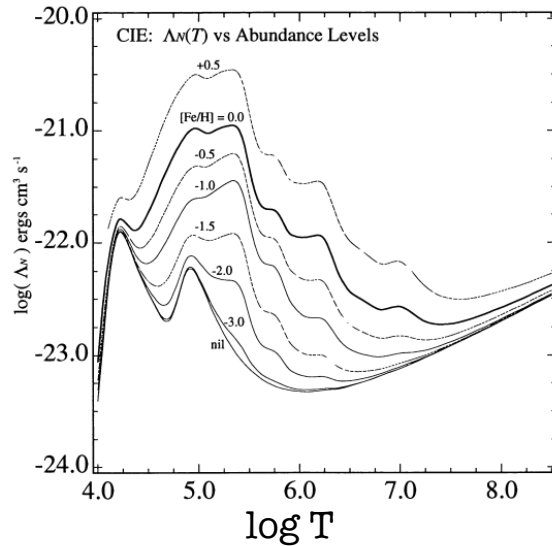
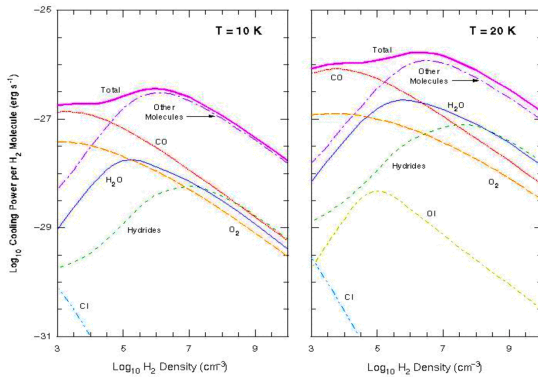
Gas Cooling

- Collisional excitation: free electron impact knocks a bound electron to an excited state; it decays, emitting a photon.
- Collisional ionization: free electron impact ionizes a formerly bound electron, taking energy from the free electron.
- Recombination: free electron recombines with an ion; the binding energy and the free electron's kinetic energy are radiated away
- Free-free emission: free electron is accelerated by an ion, emitting a photon. (A.k.a. Bremsstrahlung.)

Gas Cooling $L=n^2\Lambda(T)$

MWB sec 8.4

- $T > 10^7 \text{K}$ thermal bremsstrahlung $L \sim n^2 T^{1/2}$
- $10^7 > kT > 10^{6.3} \text{K}$ Fe L lines
- $10^{4.5} > kT > 10^{6.3} \text{K}$ K and L lines of 'metals'
- $10^4 > kT > 10^{4.5} \text{K}$ Hydrogen
- At lower temperatures fine structure lines and molecules take over



Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium Sutherland and Dopita table 2.5 in S&G

Cooling Time

- Dimensional analysis gives cooling time $t_{\text{cool}} \sim \epsilon / (d\epsilon/dt)$ where ϵ is the thermal energy in the gas
- $t_{\text{cool}} \sim \epsilon \rho / \Lambda$; since energy release goes as ρ^2 ; $t_{\text{cool}} \sim \epsilon / \rho$
- Alternatively (MWB e.q. 8.94)
- energy in gas per particle is ρE and cooling rate is Θ ; $t_{\text{cool}} \sim \rho E / \Theta$
- for an ideal gas $\rho E_1 \sim 3/2 nkT$ and by definition the cooling rate is $n^2 \Lambda(T)$ so $t_{\text{cool}} \sim 3/2 nkT / n^2 \Lambda(T)$
- In general $\sim 3.3 \times 10^9 (T/10^6 \text{K}) / (n/10^3) \Lambda_{-23}$
- Λ_{-23} is the value of the cooling function in units of $10^{-23} \text{ erg cm}^3 / \text{sec}$
- For bremsstrahlung $t_{\text{cool}} \approx 3.3 \times 10^{10} (n \text{ cm}^{-3})^{-1} (T/10^8 \text{K})^{1/2} \text{ yrs}$