ISM- Phases

- Hot ionized medium (e.g. X-rays)
- Warm ionized medium HII region(e.g. Hα)
- 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 (cm^{-3})	$10^2 - 10^5$	4–80	0.1–0.6	$\approx 0.2\ cm^{-3}$	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	≈ 8000	10^6–10^7
h (pc)	≈ 70	≈ 140	≈ 400	≈ 900	$\gtrsim 1$ kpc
f_{volume}	$< 1\%$	≈ 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

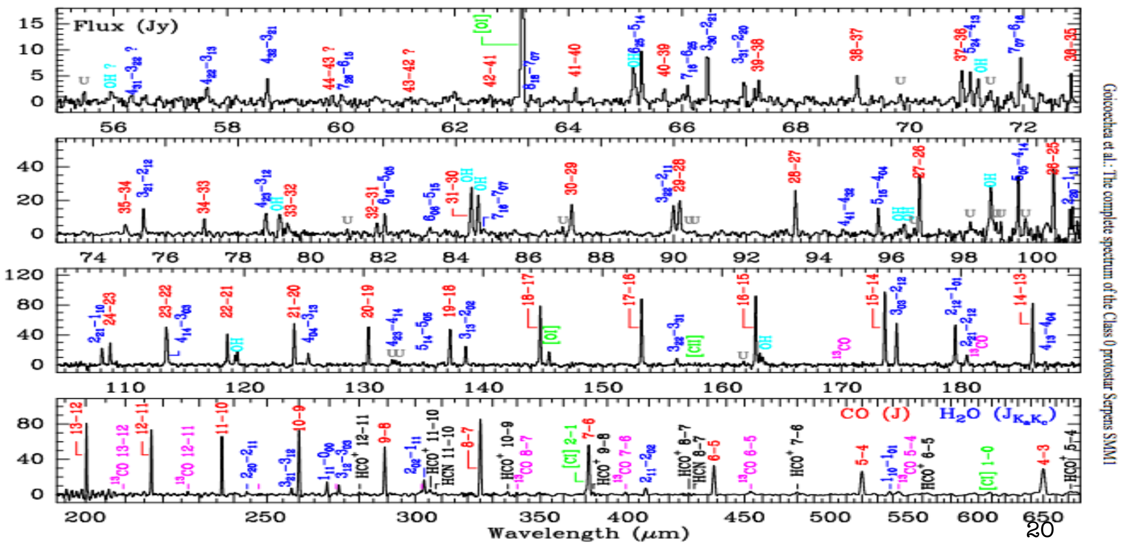
The ISM

- The 5 'states' are in dynamic interaction.
- the coldest and the densest clouds are molecular (hydrogen molecules, CO, NH_3 and other molecules)- **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 ~ 5μG, these fields provide a pressure comparable to the pressure of the gas. The magnetic fields therefore affects the dynamics of the ISM

- Book on the subject Bruce Draine ' Physics of the Interstellar and Intergalactic Medium' Princeton series on Astrophysics

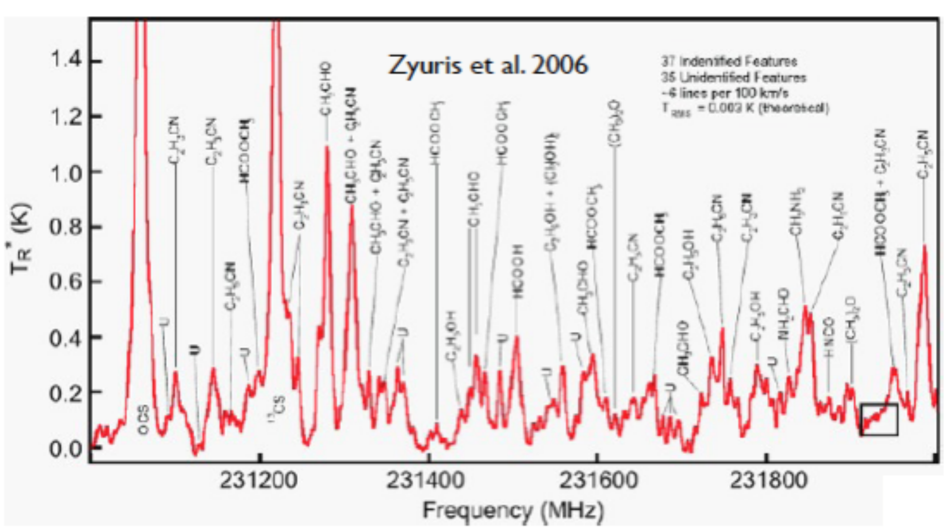
Far IR Lines

- More than 145 lines , most of them rotationally excited lines from abundant molecules:
- 38 lines ^{12}CO , 37 lines -H_2O,16 OH lines., 12 ^{13}CO lines and several HCN and HCO^+ lines Goicoechea et al 2012: brightest line is [OI] at 63μ

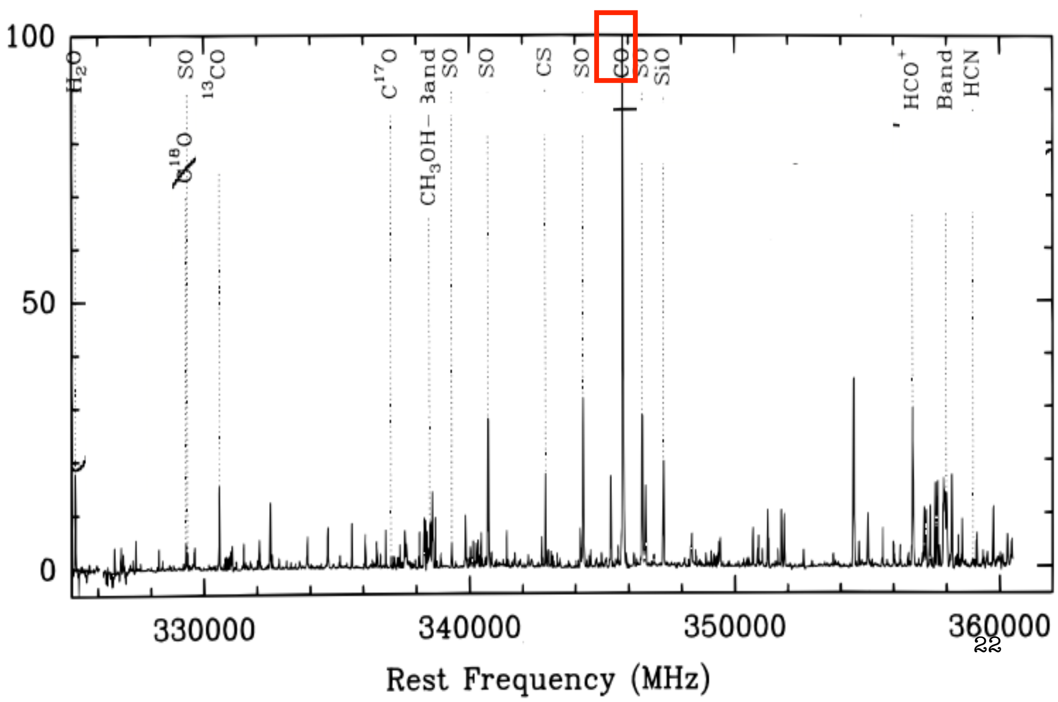


Molecular Lines

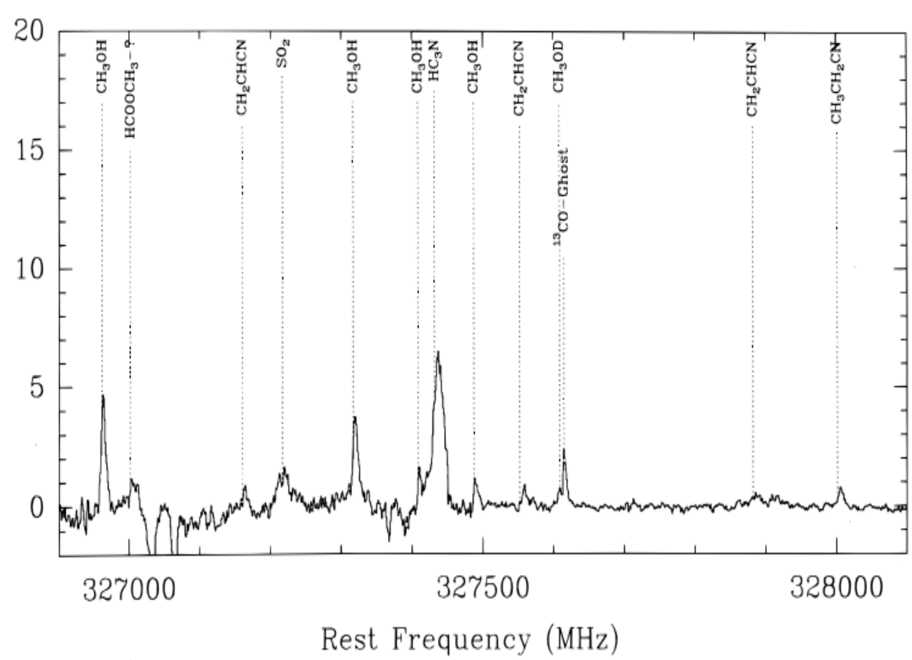
- Molecular clouds are very rich in spectral features from a wide variety of molecules- lots of information
- Some of the lines (CO) are so strong that they can be seen at high redshift



Millimeter Band Spectrum of Molecular Cloud

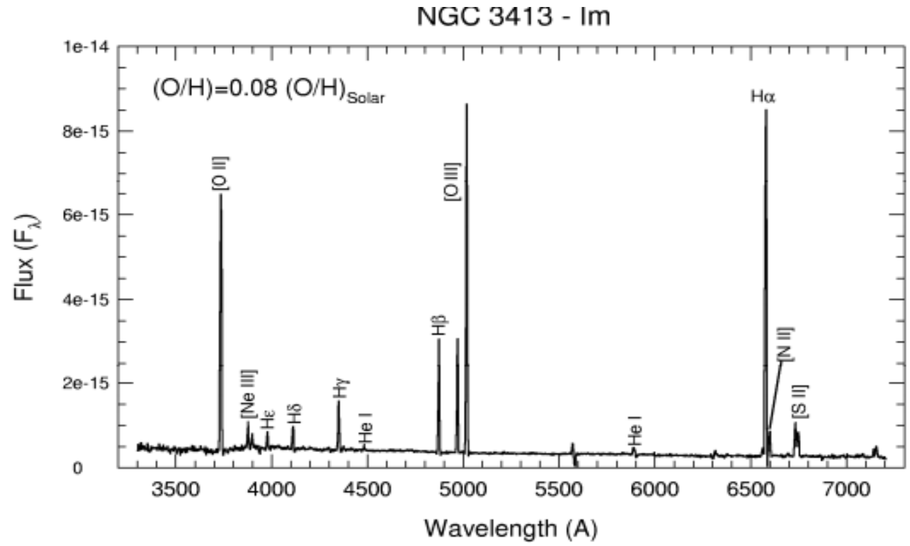


Millimeter Band Spectrum of Molecular Cloud



- zoom in on previous plot

Optical spectrum of HII Region



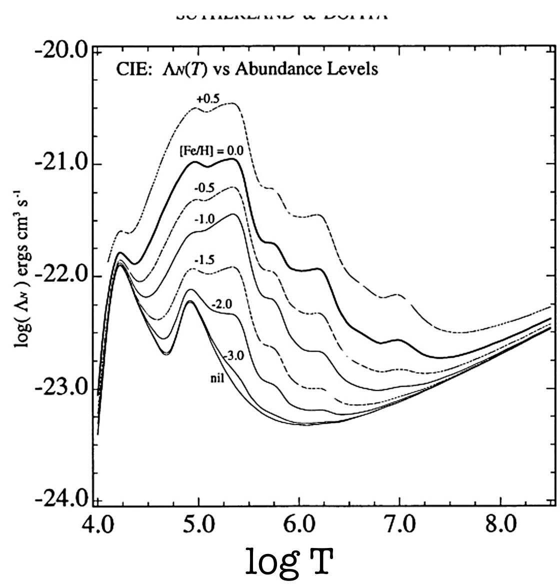
- Optical spectrum show lines due to [OII]. [OIII],Hα, [NII], etc
- the [...] symbol indicates 'forbidden' lines which come from low density gas

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**)
- Cooling via molecular vibrational and rotational lines and dust emission

Gas Cooling $L=n^2\Lambda(T)$ MWB sec 8.4, S&G sec 2.4.2 pg 105

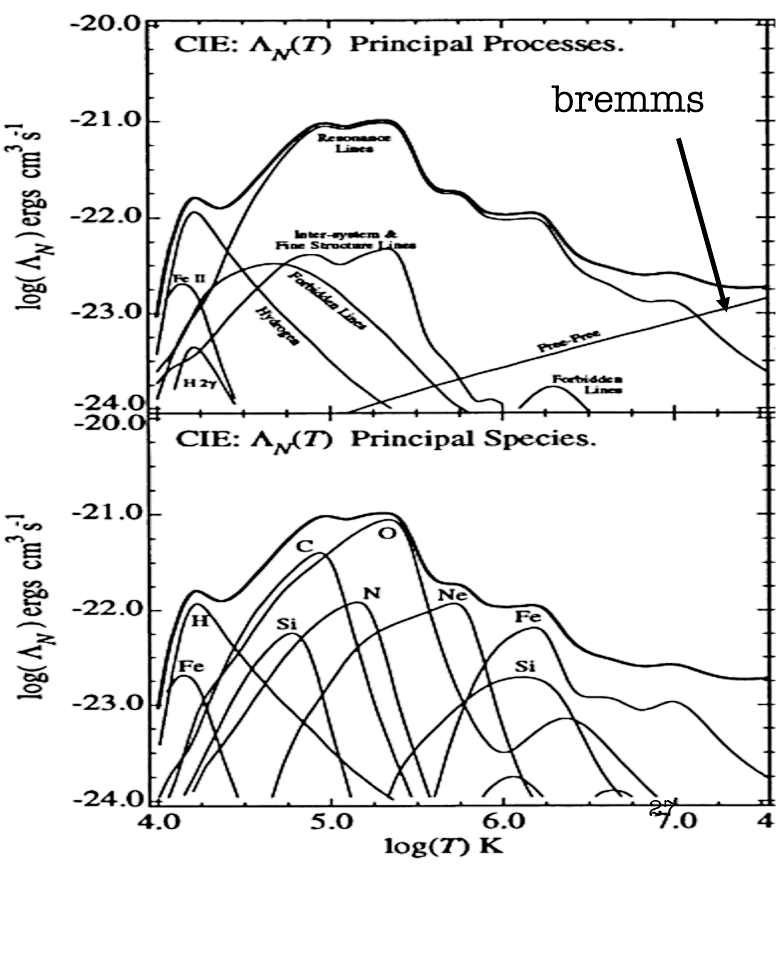
- $T>10^7$k thermal bremmstrahlung $L\sim n^2T^{1/2}$
- $10^7>kT>10^{6.3}$k Fe L lines
- $10^{4.5}>kT>10^{6.3}$k K and L lines of 'metals'
- $10^4>kT>10^{4.5}$k Hydrogen
- At lower temperatures fine structure and molecular lines lines dominate



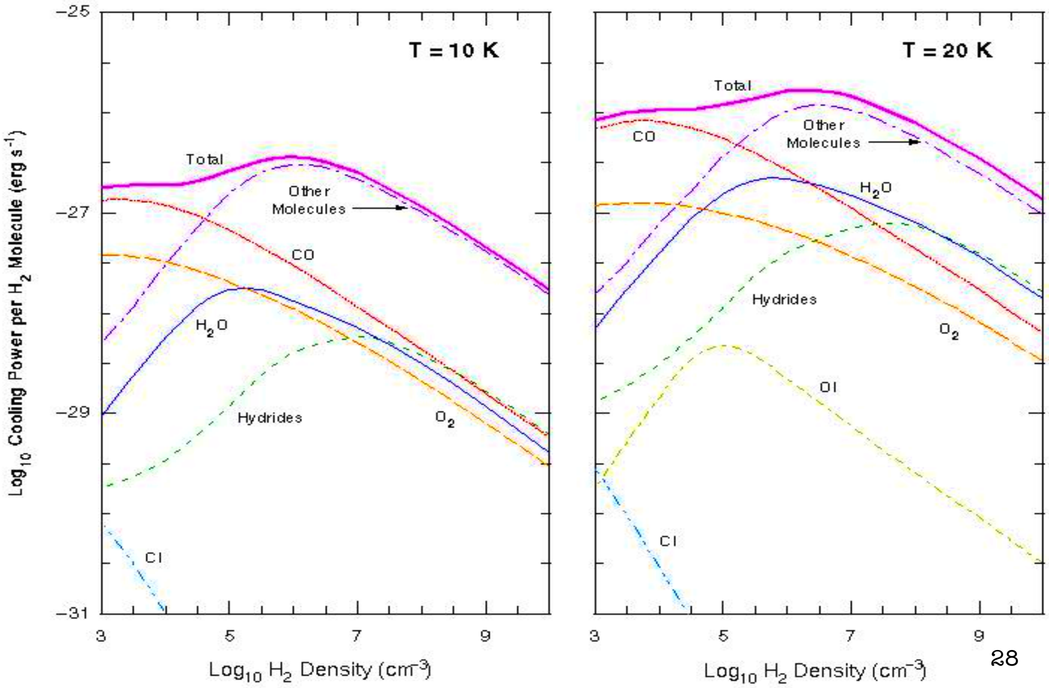
Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium
Sutherland and Dopita
table 2.5 in S&G

Gas Cooling

As the temperature changes the ions responsible for cooling change as do the physical processes
As the gas gets hotter the dominant elements/ions change

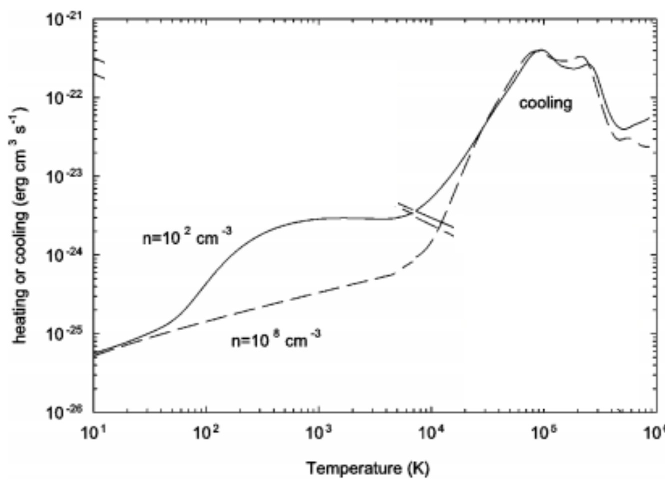


Molecular Cooling- Function of Density as well as T (not just n^2)



Gas Cooling

- The functions are very different for photoionized gas which is not in collisional equilibrium
- This depends on the shape of the photon spectrum and its intensity
- This is very important for studies of active galaxies and the *intergalactic* medium
- Things are of course more complex in a non-equilibrium system see ApJ Letters, 756:L3 2012 Avillez and Breitschwerdt



Physics of Photoionized Plasmas
G. Ferland
ARAA. 2003. 41:517

Cooling Time

- Dimensional analysis gives cooling time $t_{cool} \sim \varepsilon/(d\varepsilon/dt)$ where ε is the thermal energy in the gas ($L=d\varepsilon/dt$)

- $t_{cool} \sim \varepsilon\, \rho/\Lambda$; since energy release goes as ρ^2 ; $t_{cool} \sim \varepsilon/\rho$

- Alternatively (MWB e.q. 8.94)
- energy in gas per particle is ρE and cooling rate is Θ; $t_{cool} \sim \rho E/\Theta$
- for an ideal gas $\rho E_l \sim 3/2nkT$ and

by definition the cooling rate is $n^2\Lambda(T)$ so $t_{cool} \sim 3/2nkT/n^2\Lambda(T)$

- In general $\sim 3.3\times10^9\ (T/10^6K)/(n/10^3)\Lambda_{-23}$

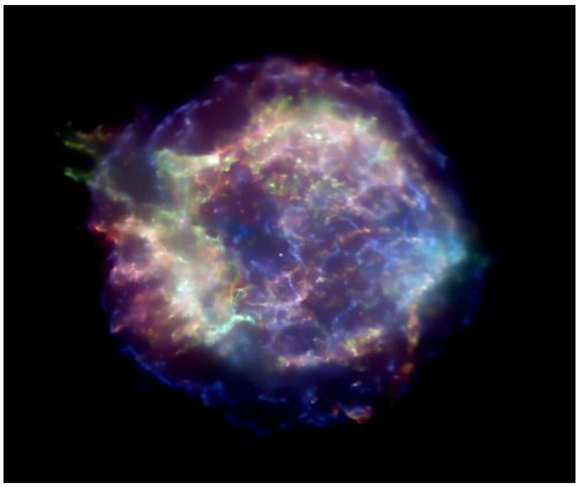
Λ_{-23} is the value of the cooling function in units of 10^{-23} ergcm^3/sec

- For bremmstrahlung

$t_{cool} \approx 3.3 \times 10^{10}\ (n\ cm^{-3})^{-1}\ (T/10^8K)^{1/2}$ yrs

Gas Heating Mechanisms in ISM

- heating by low-energy cosmic rays (dense MM)
- photoelectric heating by grains (CNM to MM)
- photoelectric heating by photoionization of atoms and molecules (HII regions)
- interstellar shocks (WNM, CNM, MM) due to supernova

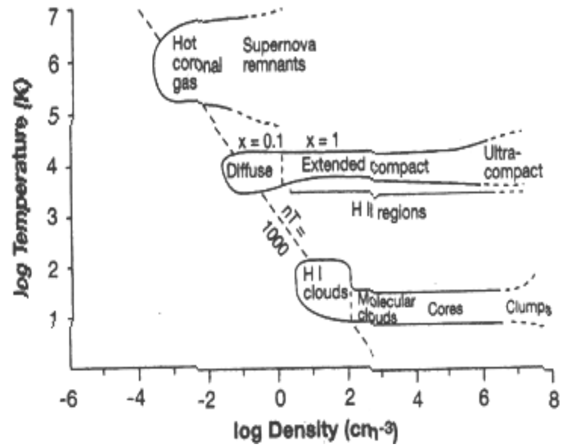


X-ray image of Cas-A youngest SNR in MW- color is energy of photons

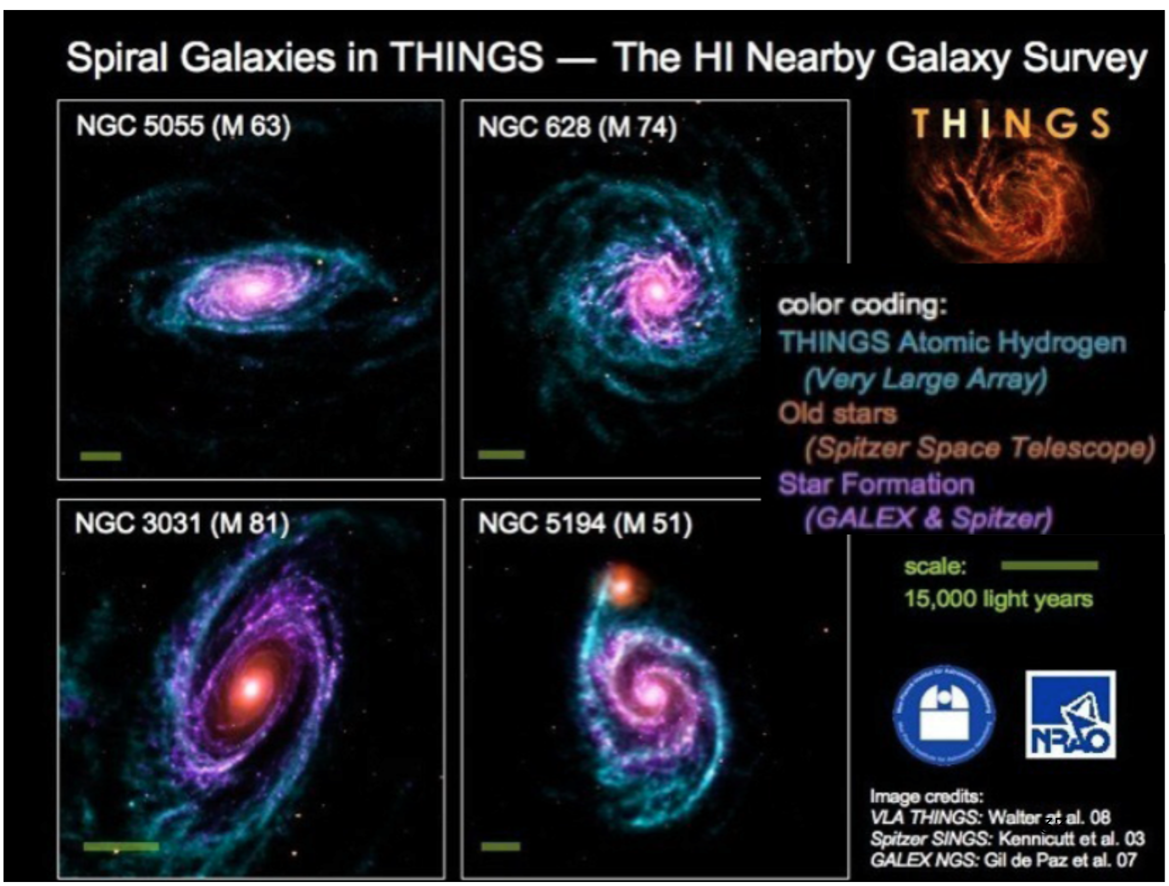
ISM in Spirals

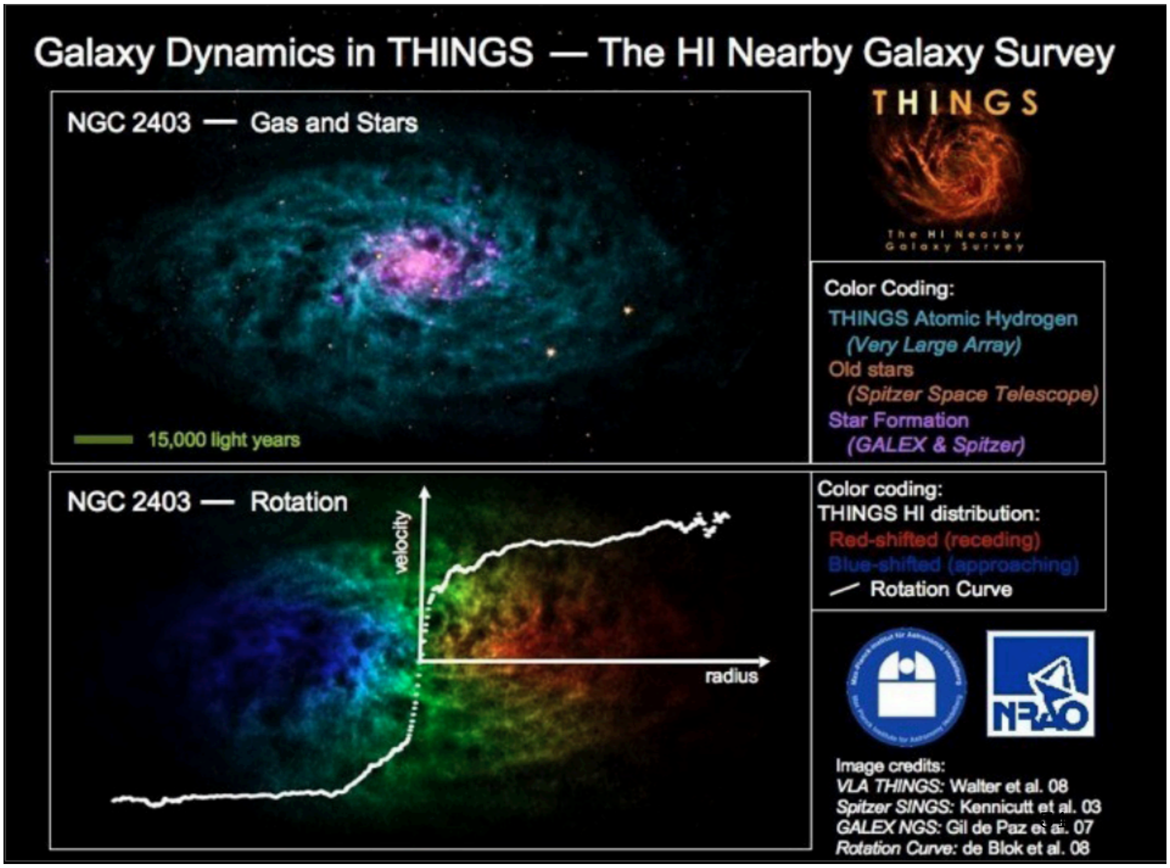
- The ISM is energized primarily by stars (starlight (dust), stellar winds, supernovae)
- UV starlight photoionizes atoms & dissociates molecules; photo-ejected electrons heat gas
- SN shocks heat/ionize/accelerate gas & are largely responsible for the ISM's complexity in spirals.

- The interstellar medium near the Sun has large scale structures of bubble walls, sheets, and filaments of warm gas.
- The remainder of the volume is in bubble interiors, cavities, and tunnels of much lower density, hot enough to be observable via their X-ray emission (Cox ARA&A)



See lecture notes by Fabian Walter for lots more detail (on class web page)

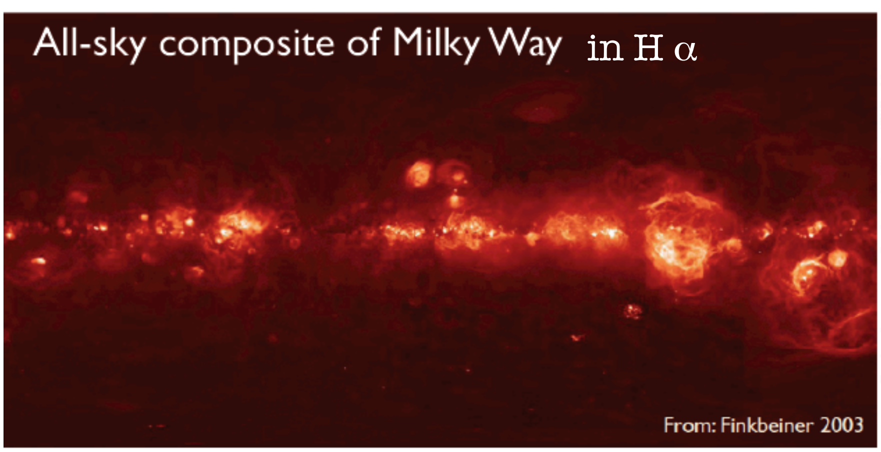


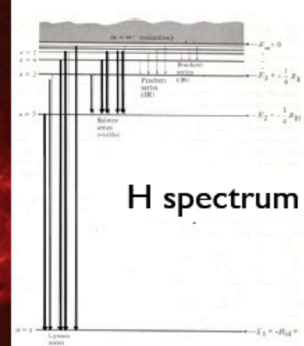


Warm Ionized Medium

Fabian Walter

- mainly traced by Hα
- most likely source: photoionization from OB stars
- scale height: 1kpc
- minimum energy rate: 3×10^5 kpc^{-2} s^{-1} (equiv. of 1 O4 star kpc^{-2})
- total energy requirement: 3×10^8 L_{sun}

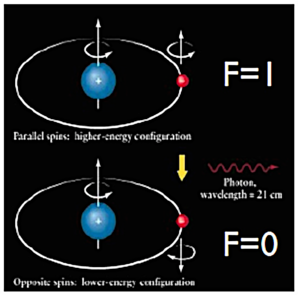




H spectrum

Most important tracer for warm/cold neutral medium:
HI 21cm line

pg 30 in S&G



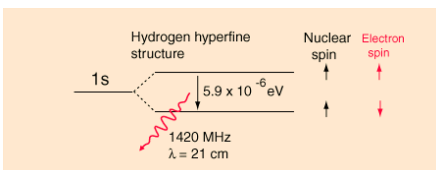
From H. Rix and F. Walter

- H atom consists of 1 proton + 1 electron
  - Electron: spin $S=1/2$
  - Proton: nuclear spin $I=1/2$
  - Total spin: $F = S + I = 0, 1$
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $\quad g_u = 2F+1 = 3$ $\quad E = 5.87\times10^{-6}$ eV
  - $F = 0$ $\quad g_l = 2F+1 = 1$ $\quad E = 0$ eV

'Spin flip' The 'flip' occurs spontaneously

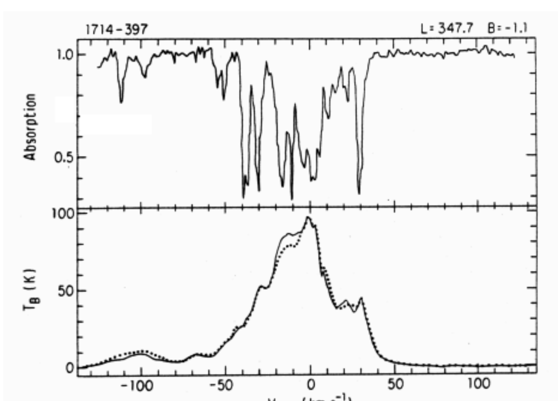
http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html

- Transition between $F = 0$ and $F = 1$:
  - $\nu = 1420$ MHz, $\lambda = 21.11$ cm
  - $\Delta E / k = 0.0682$ K
  - $A_{ul} = 2.869\times10^{-15}\,\mathrm{s}^{-1} = 1/(1.1\times10^{7}$ yr) (very small!)



H atoms excited by collisions to slightly higher energy level -- once per ~10^6 years per H atom
Average lifetime in excited state ~10^7 years...
...followed by spontaneous decay back to ground state, emitting radiation at λ = 21 cm
But ~ 10^{66} H atoms in MW plane ... hence observable line emission

HI emission vs. absorption



Dickey et al. 1983

$$j_\nu = \frac{h\nu}{4\pi}\frac{3n_H}{4}A_{10}\Phi(\nu),$$

$$\kappa_\nu = \frac{(h\nu)^2}{c}\frac{n_H B_{01}}{4kT_{ex}}\Phi(\nu)$$

emission and absorption coefficient of a 2-level system:

Spectra taken towards same direction within our galaxy

Suggested that ISM consisted of 2 phases

From H. Rix and F. Walter

Cosmic Rays – scattered in Sec 2.1-2.4 in S&G

- Cosmic rays, which are atomic nuclei electrons and protons which have been accelerated to nearly the speed of light- thought to be created in SNR shocks
- Gyroradius=r_g=p/qB

(p is the momentum of the particle, B the magnetic field, q the charge)

In handier units $r=3.3\times10^7\gamma/B$(gauss)cm ; γ is the relativistic factor sqrt($1/(1-v^2/c^2)$)

With B~5μG the gyroradius of a proton with $\gamma\sim10^4$ (a typical value) is $\sim10^{-4}$ pc.

so cosmic rays are trapped within the Galaxy by magnetic fields .

Energy density in cosmic rays comparable to other components of ISM

- Thermal IR from dust
- Starlight
- Thermal kinetic energy (3/2 nkT)
- Turbulent kinetic energy
- Magnetic fields ($B^2/8\pi$)
- Cosmic rays

.

The ISM **can dominate a galaxy's integrated SED** -in the far IR and radio

- Mid-IR to Sub-mm is dominated by emission from dust, molecular lines and fine structure lines
- radio comes either from HII regions or a relativistic plasma radiating via synchrotron radiation

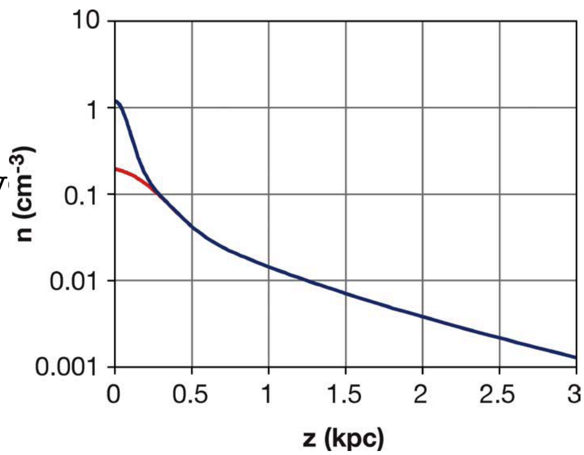
certain emission lines (eg Lyα ; [CII] 158μ) can be major coolants

ISM in Spirals

- The phases of the gas are distributed differently
  - cold (molecular) gas is confined to a thin disk
    $\rho(z) \sim 0.58 \exp[-(z/81 \text{ pc})^2]$
    and has a mean T~15k
  - 'warm' gas has a density distribution
    $\rho(z) \sim 0.57 * 0.18 \exp[-(z/318 \text{ pc})^2]$
    where z is the distance above the disk midplane
    has a mean T~5000k

Roughly magnetic (~5μG), cosmic ray, and dynamical pressures are equal ~10^{-12} dyne mid-plane

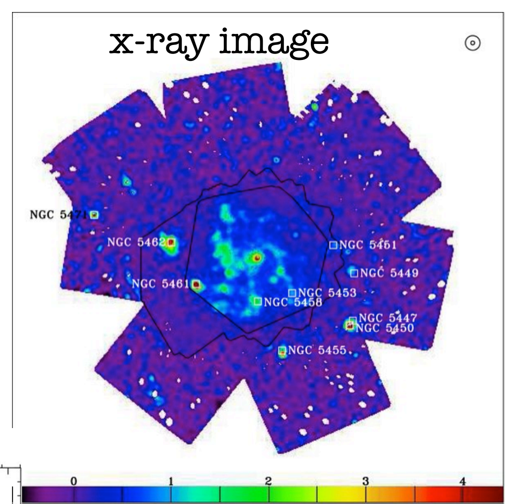
total gas density in MW vs height above the disk (blue)
warm gas in red



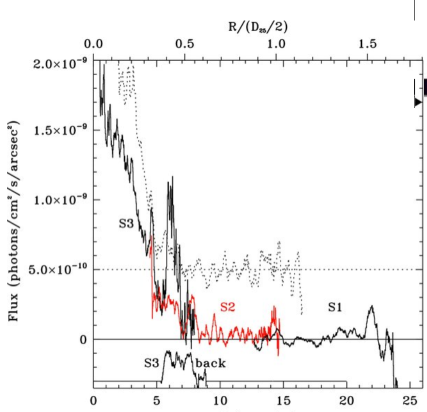
Cox Ann Rev A&A

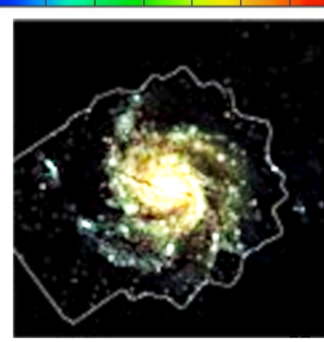
X-ray ISM in M101

- Hot phase of ISM in M101- dominated by ionized oxygen OVII/ OVIII and T~2×10^6k is the temperature of the dominant component.
- The emission is centrally concentrated
- Such data exists for only a few objects



x-ray surface brightness

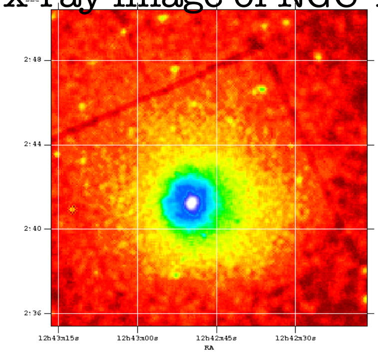




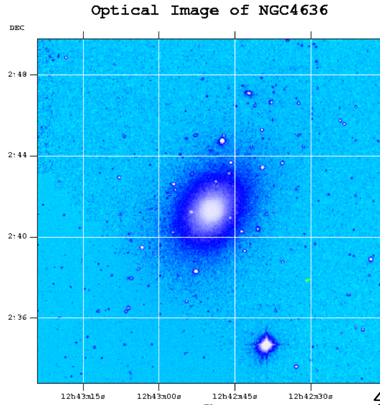
ISM In Ellipicals-pg 272 in S+G

- Predominately hot $kT \sim 10^6$-10^7K and thus visible only in the x-ray
  - the temperature is set, predominantly by the depth of the potential well of the galaxy (if it were hotter it would escape, if colder fall)
  - The metallicity of the gas is roughly solar

x-ray image of NGC 4636



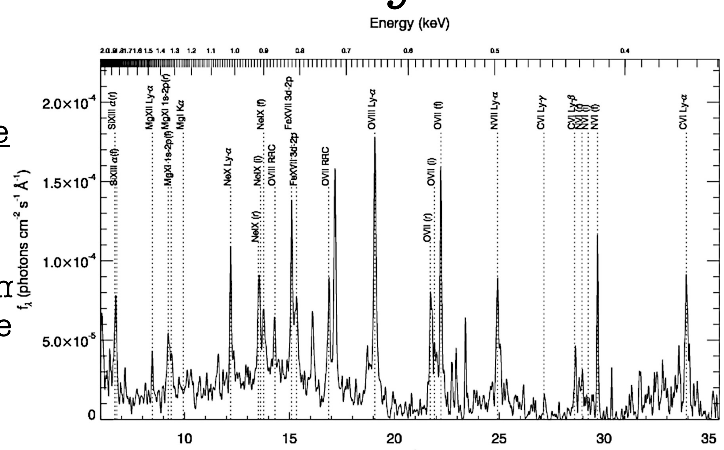
Optical Image of NGC4636



Hot Gas and Metallicity

- In elliptical galaxies , clusters of galaxies and star forming galaxies <u>the ISM is hot</u> and emits primarily via thermal bremmstrahlung with strong emission lines from abundant elements (O, Ne Si, S, Fe)

- The lines are fairly easy to measure and the amount of hydrogen is measured by the strength in the continuum.
- Problem is x-ray sources are weak and telescopes are small so not so many objects (~100's)

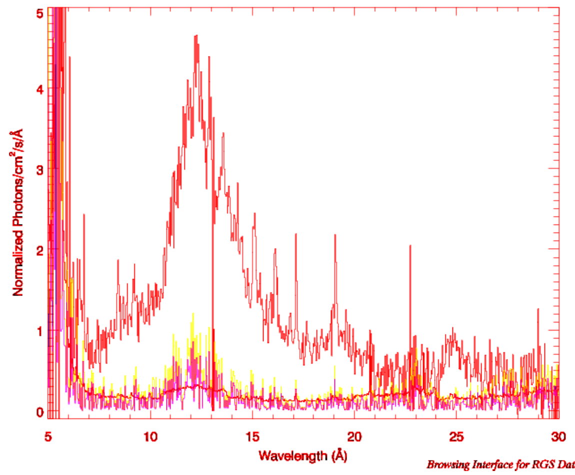


X-ray spectrum of hot gas in a star forming galaxy

Image of x-ray source determines the gas density since $L \sim \Lambda(T) n^2$

X-ray Spectra of NGC1399

- At certain temperatures (~4-16x10^6k) the spectrum is dominated by Fe lines from the L shell whose energy is very sensitive to temperature.
- Thus x-ray images and spectra (obtained simultaneously with CCDs) get the density and temperature and estimates of the chemical composition of the ISM in ellipticals

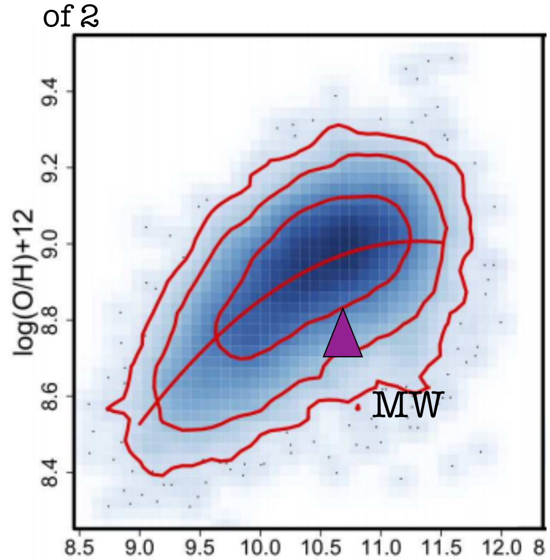


wavelength Å

Metallicity in Gas

- For star forming galaxies it is easier to measure the metallicity in the gas phase than in the stars-strong emission lines-but one measures different elements
- How does one do it ?- Use HII region spectra (ionized gas around hot young stars) : measure oxygen lines.
- O is an α-process element made in short-lived massive stars and is~50% of all the heavy elements by mass - **representative** of all the heavy elements made in type II SN
  - need to measure line strengths, electron temperature, density to get ionization structure of the gas
- More massive galaxies tend to be more metal rich

There are several methods to do this- but error of factor of 2



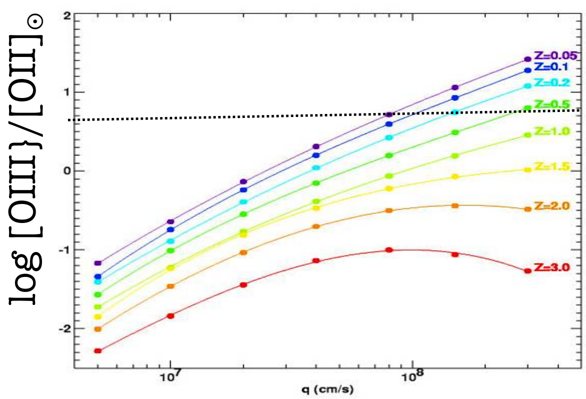
log $\text{Mass}_{\text{stars}}$

GAMA collaboration Foster et al 2012

Metallicity Issues for Distant Galaxies

Fundamental problem is that the ionization structure of the gas is unknown and the line strengths and hence the abundances depend on both

- chemical abundances,
- Free parameter is the ionization parameter (U) which is the ratio of ionizing photons density to gas density for photoionized gas ($U \sim L/n_e r^2$)



ionization parameter

each line corresponds to the predicted [OIII]/[OII] ratio for a different abundance (0.05-3x solar) and ionization parameter

A fixed line ratio can correspond to a factor of 20 range in abundance if ionization parameter if not constrained.

Metallicity Issues for Distant Galaxies

Since the electron temperature ,density and nature of stellar ionization field vary quite a bit over the galaxy these are 'irreducible' errors.

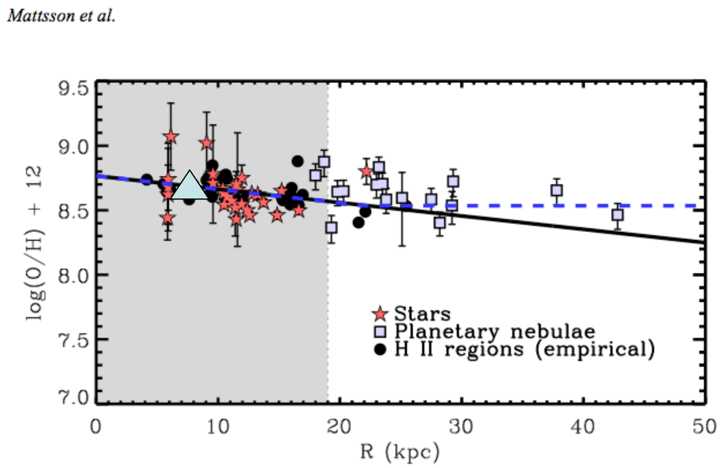
One resorts to calibrating the lower quality galaxy data against the excellent data for HII regions in the MW and some other nearby galaxies

Gas phase abundances are 'ok' for O,N and S (but not Fe)

Abundances determined in stars mainly measure 'Fe' via absorption lines in stellar spectra (Worthy et al 1994)- very very messy.

Why Metals are Important

- metals account for 1% of the baryonic mass, but they **dominate** most of the important chemistry, ionization, and heating/cooling processes.
- Comparison of the metal content of gas and stars compared to
  - what is expected from stellar evolution
  - cosmic star formation rates indicates whether galaxies expel metals and/or accrete gas.



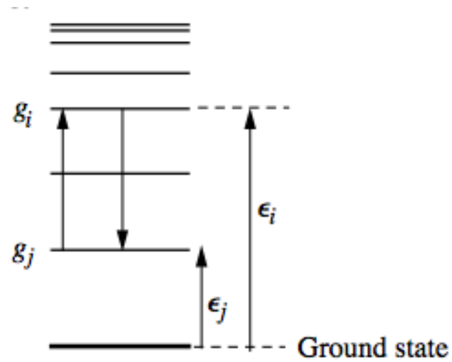
M31 metallicity vs galacto-centric radius- Mattsson et al 2014

Next Lecture – Dust

- Discussion of dust is in many places in S&G.
- Discussed in MBW pg 478-483

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



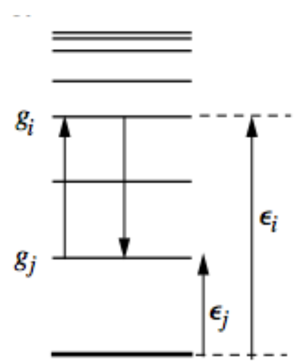
For lots of details see MBW appendix B

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 . 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 :$n_e/dn_e/dt$

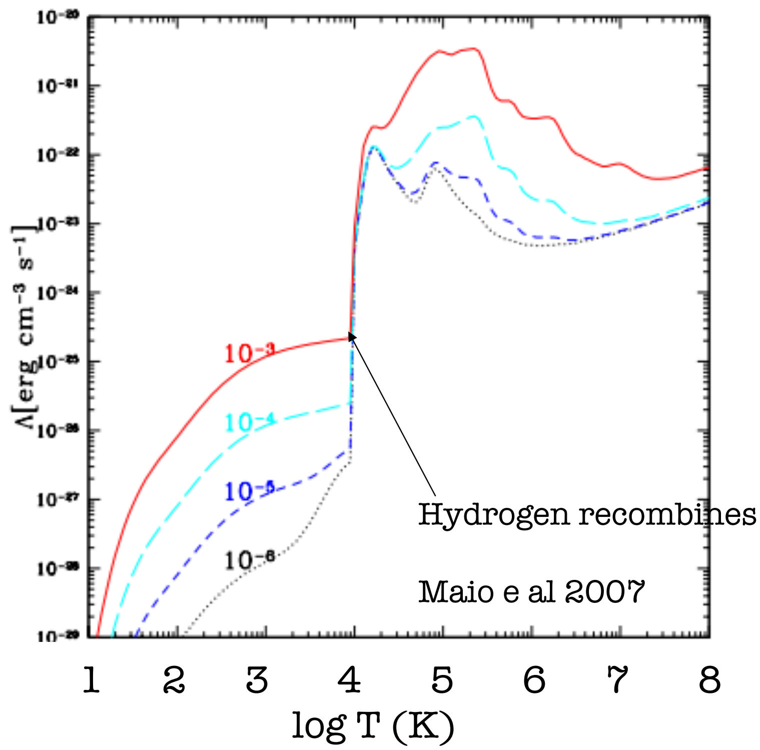
a few thousand years in a HII region - α the recombination rate depends on QM and Boltzmann's law



In steady state # of ionizations= # of recombinations

Ionization is from
- collisions with hot electrons
- photoionization from stars
- shocks

- Cooling function including hydrogen, helium, metals lines, H2 and HD molecules as function of temperature- (appropriate for early universe) but not including CO and other molecules (CO dominates the cooling for n < $10^5 cm^{-3}$, lowest rotational state about 5 K above ground state, so effective at low temperatures.



Different metallicities 10^{-3}-10^{-6} solar

How do Molecules Emit Radiation

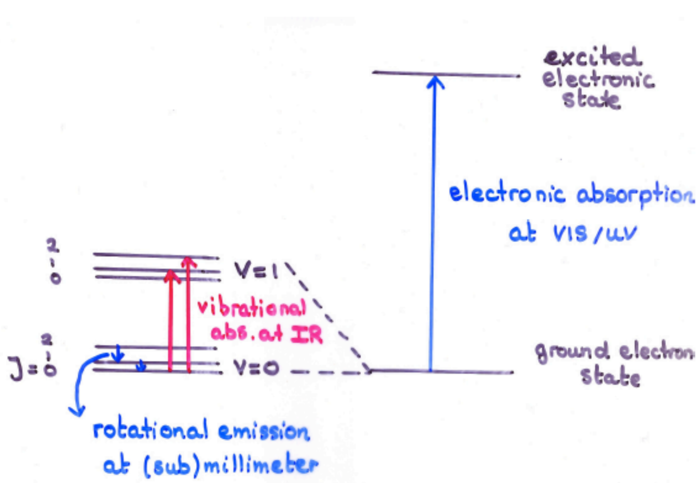
- Emission is primarily from rotational and vibrational levels
- Millimeter emission: rotational transitions
- Infrared absorption: vibrational transitions

Limitation: need background IR source => only info along line of sight

- Earth's atmosphere prevents observations of key
- molecules from ground: H_2O, O_2, CO_2

Ewine F. van Dishoeck

$$E = E^{el} + E^{vib} + E^{rot}$$



MM emission:Limitation: molecule must have permanent dipolemoment => cannot observe H2, C2, N2, CH4, C2H2, ...

Advantage: many molecules down to low abundances;

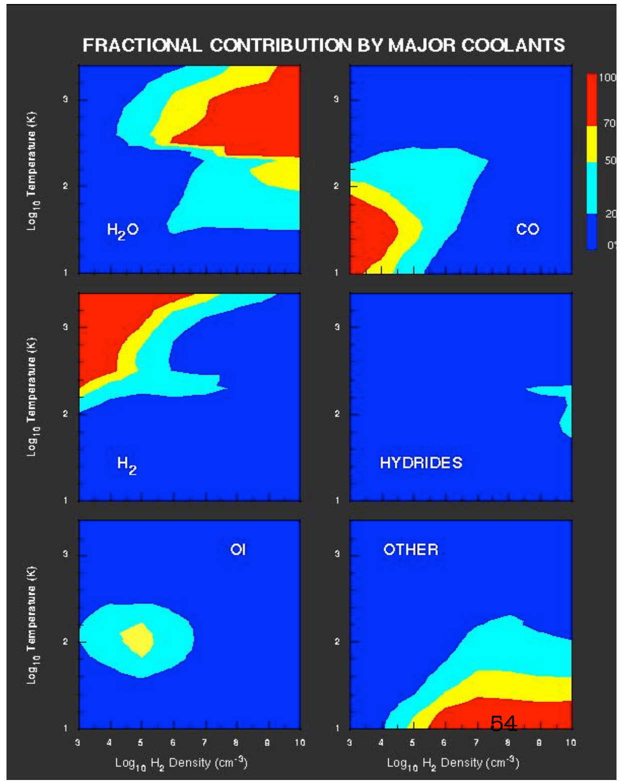
Gas Cooling

As the temperature changes the ions responsible for cooling change as do the physical processes

log T
3
2
1

http://www.cfa.harvard.edu/swas/swasscience/fig2.html

Major Molecular Coolants



54