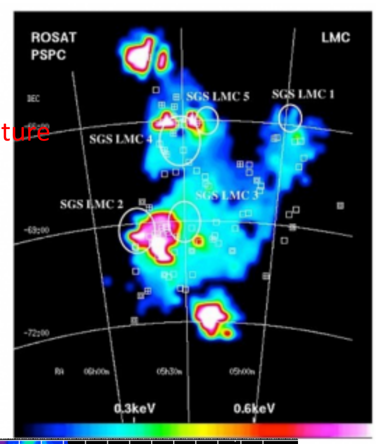
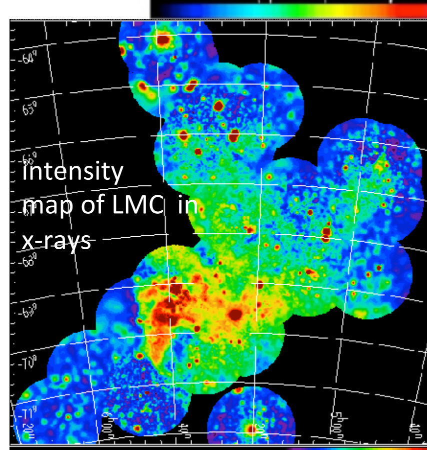
GAS Continued

ISM-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?
- How is the ISM related to star formation?
- Why is the ISM in spirals and ellipticals so different in density and temperature?
- What is the mass and chemical composition ?
- What is its 'dynamical' state?

x-ray temperature map of LMC





intensity map of LMC in x-rays

Importance of the ISM

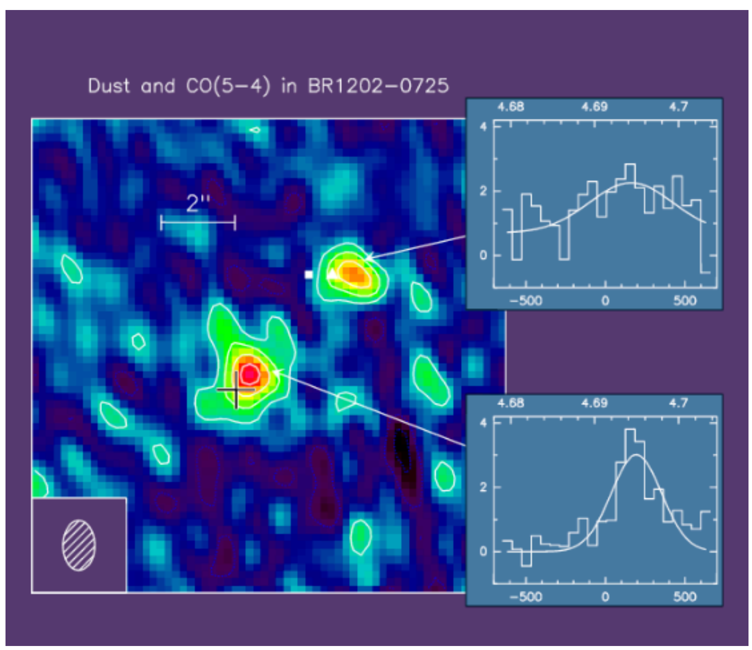
- **Despite its low mass, the ISM is very important**
- Crucial role in the star-gas cycle in spirals and irregulars,
  - it *facilitates* ongoing (& current) star formation
  - it is a repository for elements created in SNR and stars and therefore is a key to measure chemical evolution
- Because it can cool, its collapse is **dissipational**
  - **stars can form !!** hot gas → cold gas → stars:

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/ absorption lines
  - lines are bright and can be seen (relatively) easily at cosmological distances.

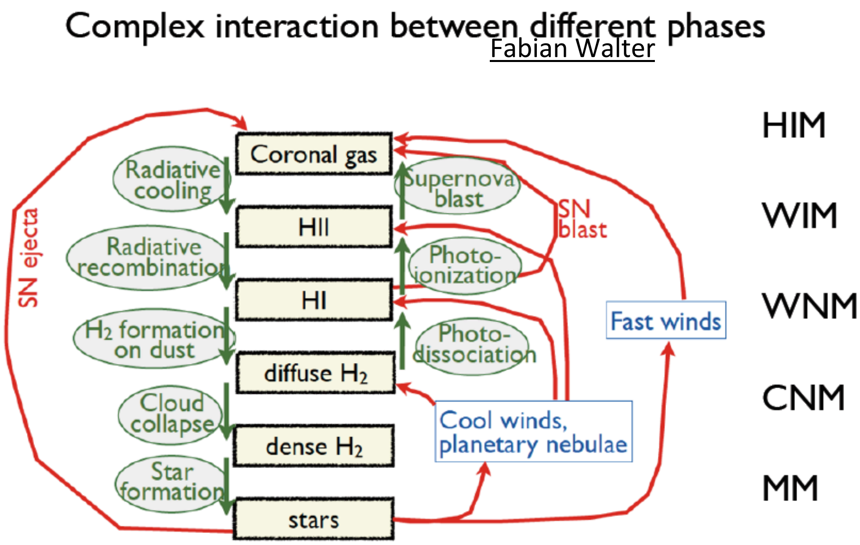
Molecular Gas at High Redshift

- Observations of CO at z=4.69 when the universe was 2.1 Gyrs old
- ALMA has the capability to detect molecular and atomic lines at very high redshift !



The ISM in Spirals is DYNAMIC- Driven by Star Formation

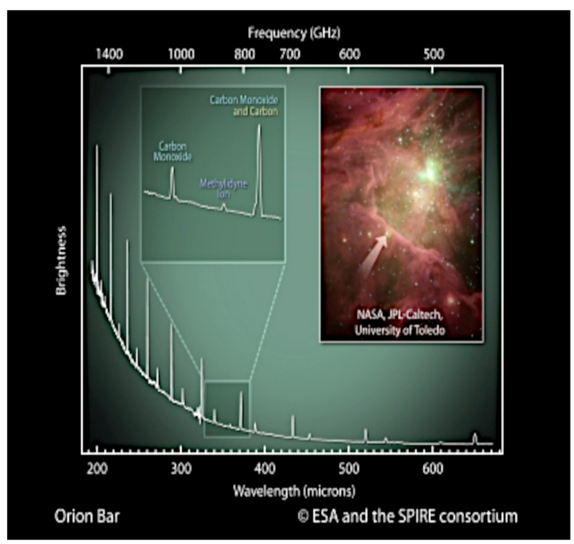
- There is strong interaction between the different phases of the ISM and feedback between star formation and the rest of the ISM
- There is lots of complex non-linear effects (and lots of jargon)



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
- Strong IR atomic spectral lines [OI]63,145μm [CII]158μm and [CI]370,609μm

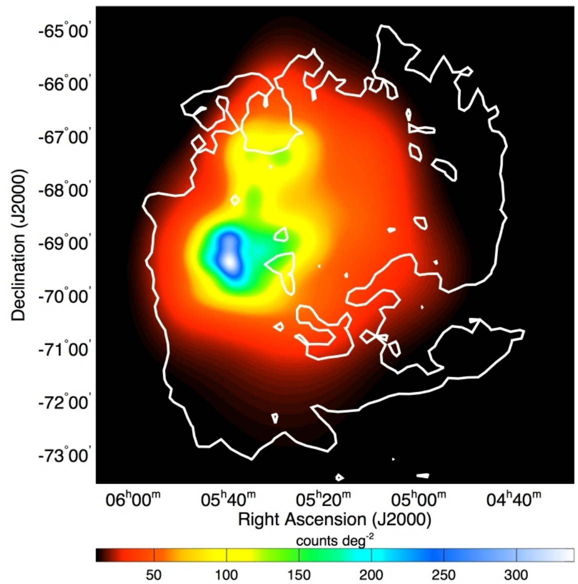


far IR spectrum of a region in the Orion nebula - partly ionised by intense radiation from nearby hot young star Dominated by a forest of CO lines herschel.esac.esa.int/FirstResultsSymposium/presentations/A54_HabartE_FTS_Orion_Bar.pdf

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

- 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 $T \sim 10^6$-10^7k gas (spirals and ellipticals) - gas is collisionally ionized
- Millimeter- molecular lines
- γ-ray
  - interaction of cosmic rays with gas

γ-ray Map of LMC

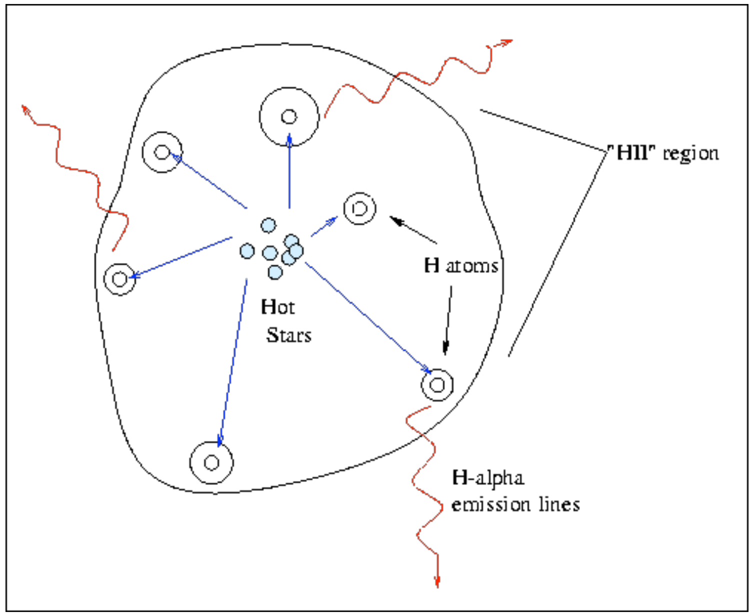


Spiral ISM 'States'- f is the filling factor

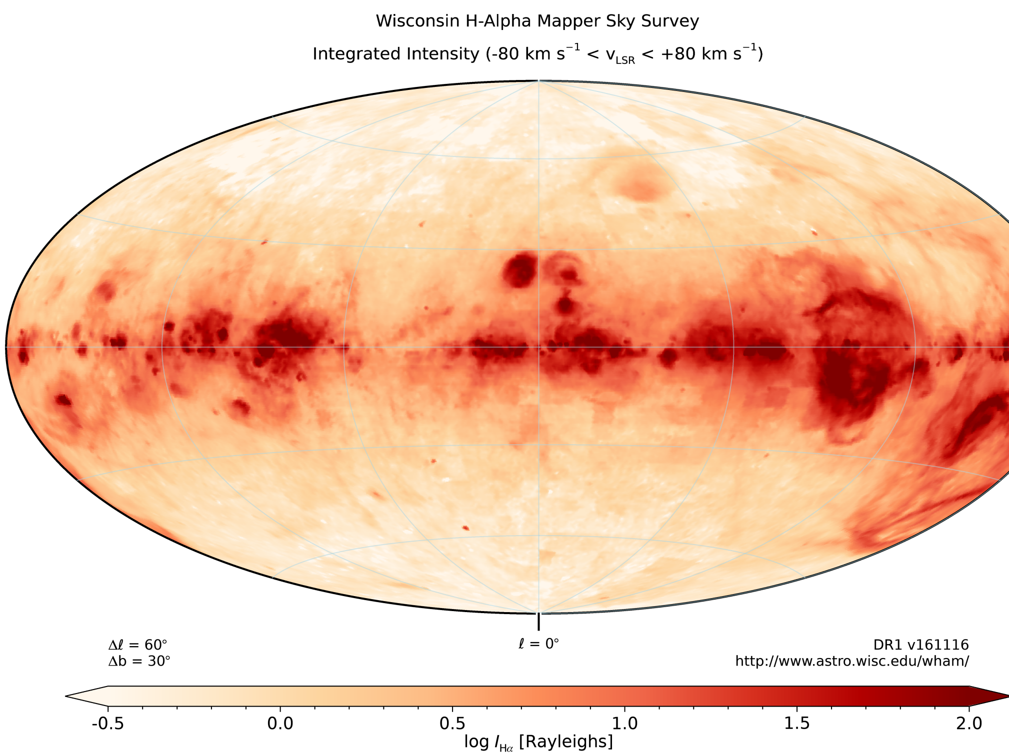
- Molecular Medium (MM): $T \sim 20$ K, $n > 10^3$ cm^{-3}, **f < 1%.**
  - The MM is mostly cold dense molecular clouds which are gravitationally bound. This phase contains much of the ISM mass, but occupies only a very small fraction of the ISM.
- Cold Neutral Medium (CNM; $T \sim 100$ K, $n \sim 20$ 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, $n \sim 0.3$ cm^{-3}, f~30%)
  - This phase provides the bulk of the **HI** seen in emission line surveys

HII Region

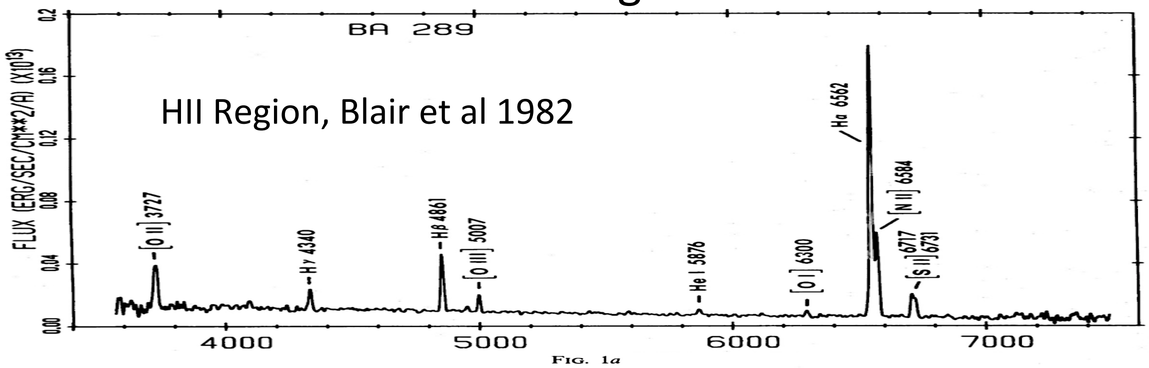
- Responsible for much of Hα emissions
- MW is highly structured
  - can be seen in external galaxies out to moderate redshifts
  - position sensitive spectra

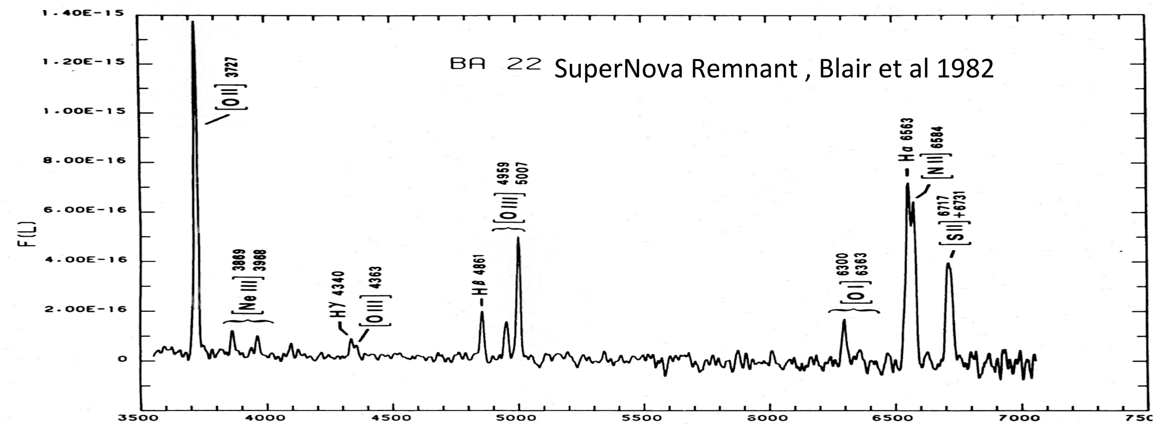


Hα Emission in the MW

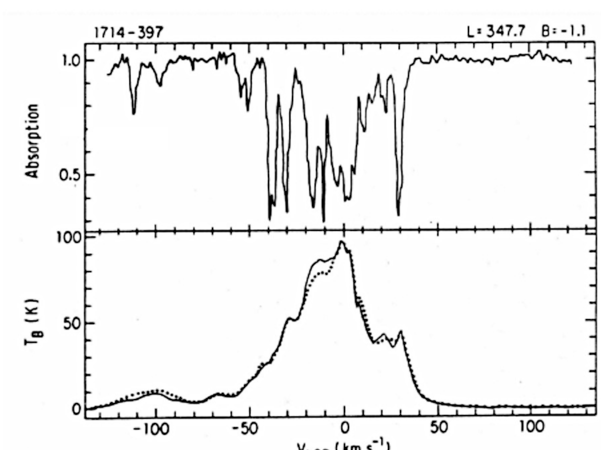


Other Strong Lines

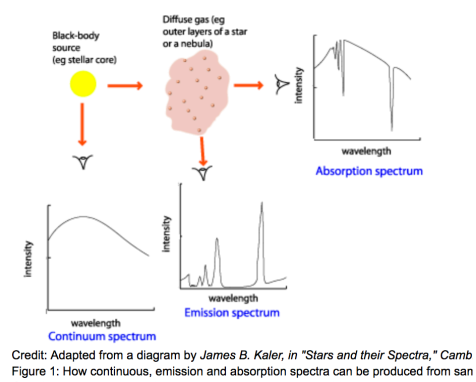




HI emission vs. absorption



Dickey et al. 1983



From H. Rix and F. Walter

Spectra taken towards same direction within our galaxy
This first suggested that the neutral ISM consists of 2 phases

Spiral ISM 'States'- f is the filling factor

- \- Warm Ionized Medium (WIM; T ~8000 K, n ~0.3 cm^{-3} f~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~10^6 K, n~10^{-3} cm^{-3}, f~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 but **low total mass**.

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. 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 (h)

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	$\approx$8000	10^6–10^7
h (pc)	$\approx$ 70	$\approx$ 140	$\approx$ 400	$\approx$900	$\gtrsim$1 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

ISM in Spirals

- **The phases of the gas are distributed differently**
  - cold (molecular) gas is confined to a thin disk

$\rho(z)$~ 0.6 exp[-(z/80 pc)^2] and has a mean T~15k

  - 'warm' gas has a higher scale height density distribution

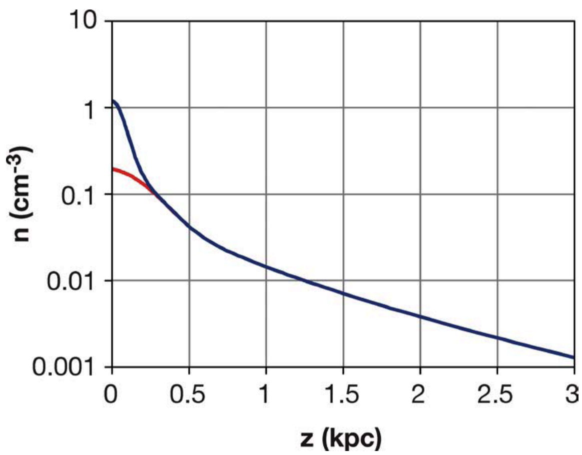
$\rho(z)$~ 0.55 * 0.2 exp[-(z/320 pc)^2]

where z is the distance above the disk midplane

has a mean T~5000k

Roughly magnetic, 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



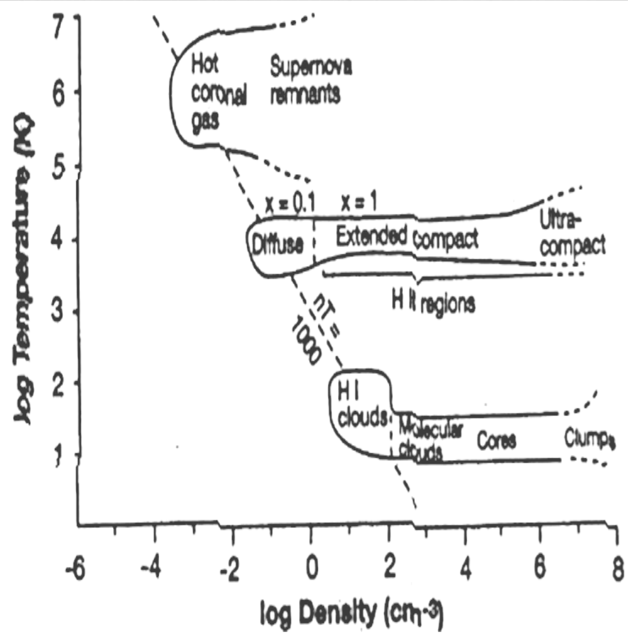
Cox+Reynolds ARA&A 1987 25,303

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

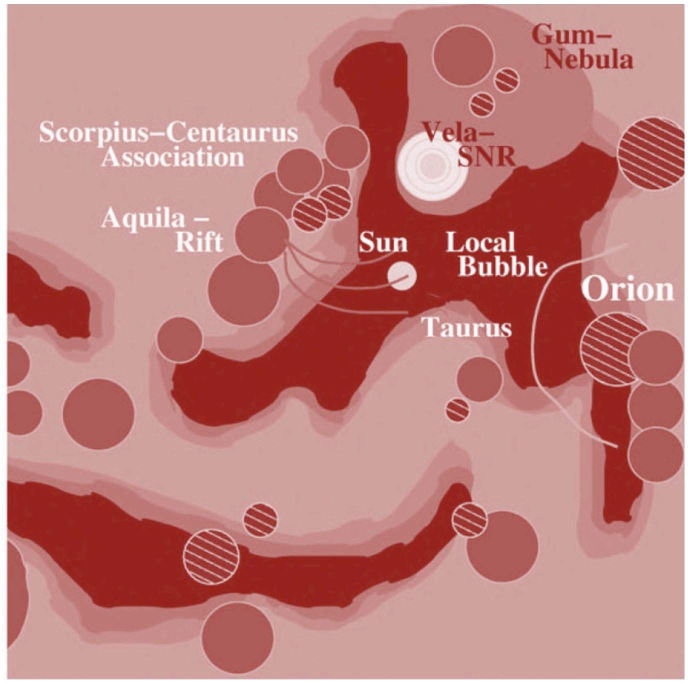
SN shocks heat/ionize/accelerate gas & are largely responsible for the ISM's complexity in spirals.



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

ISM 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, observable via X-ray emission (Cox ARA&A)



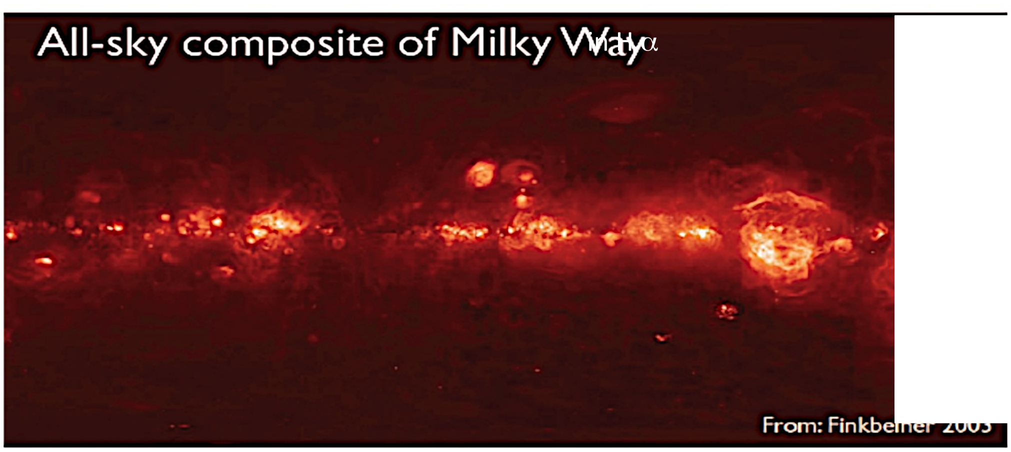
1500 ly

Norbert Schulz

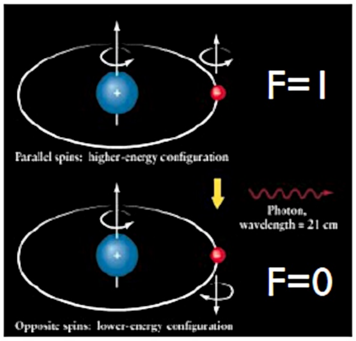
Warm Ionized Medium

Fabian Walter

- mainly traced by $H\alpha$
- 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}



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

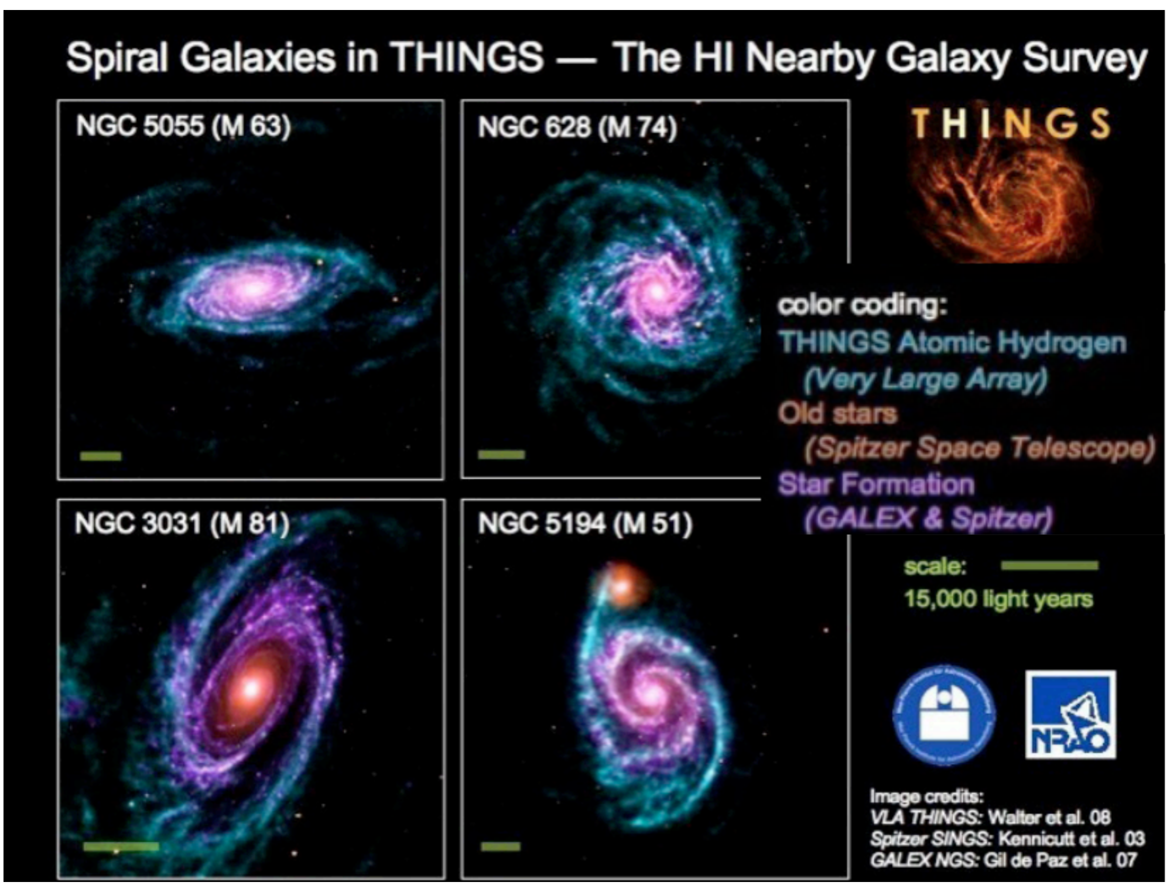


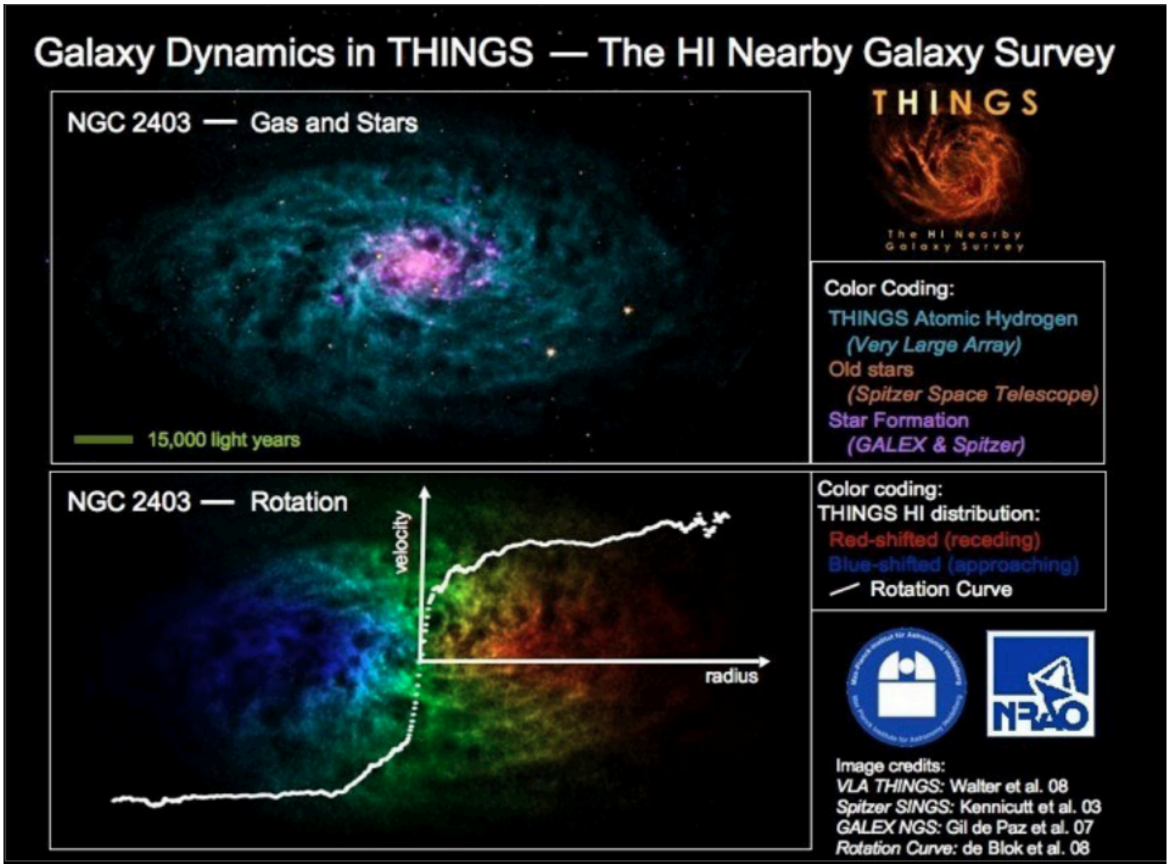
- H atom consists of 1 proton + 1 electron
  - Electron: spin S=1/2
  - Proton: nuclear spin I=1/2
  - Total spin: $F = S + I = 0, 1$
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $g_u = 2F+1 = 3$ $E = 5.87\times10^{-6}$ eV
  - $F = 0$ $g_l = 2F+1 = 1$ $E = 0$ eV

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

...but there is a lot of hydrogen out there!

From H. Rix and F. Walter



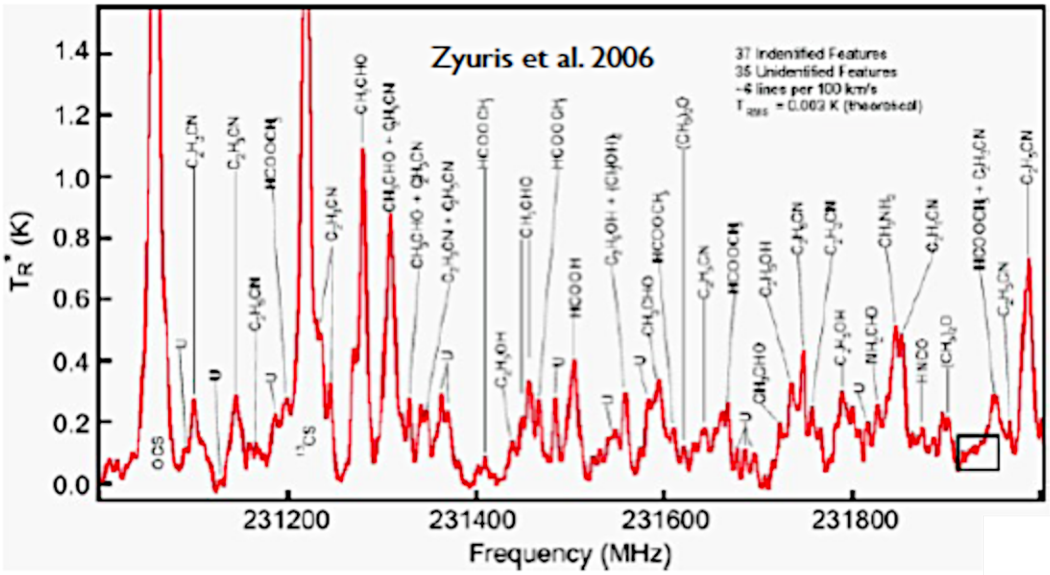


The ISM

- The 5 'states' are in dynamic interaction.
- The coldest, densest phase is molecular and the densest (hydrogen molecules, CO, NH_3 and other molecules)- **this is where stars form** .

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



How do Molecules Emit Radiation

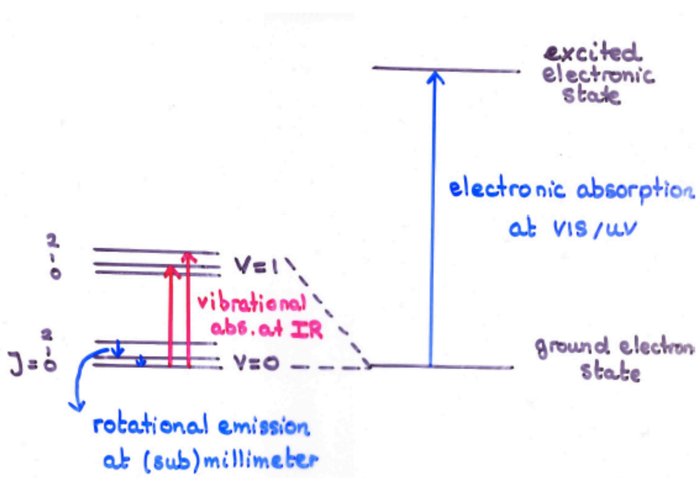
$$E = E^{el} + E^{vib} + E^{rot}$$

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

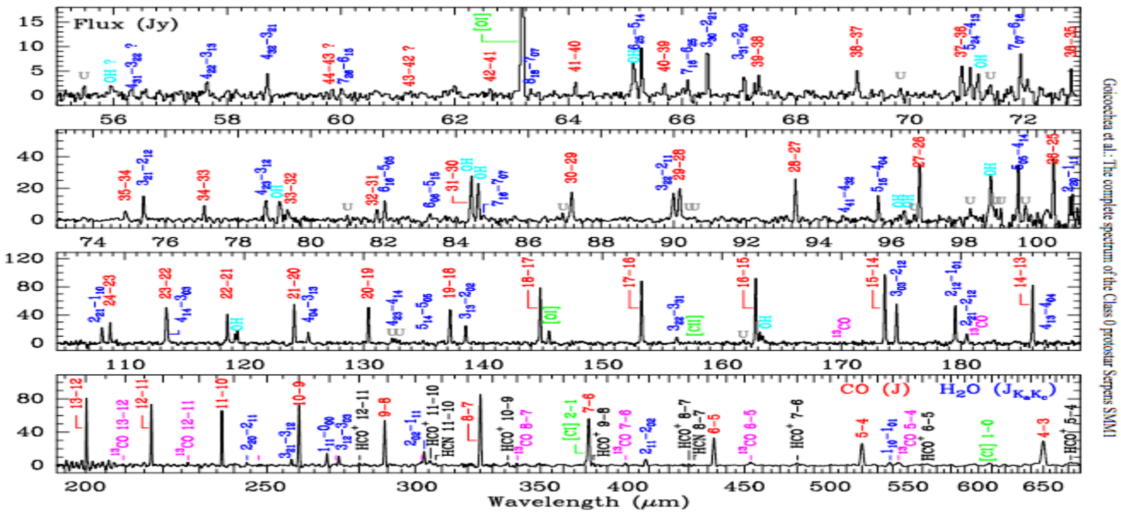


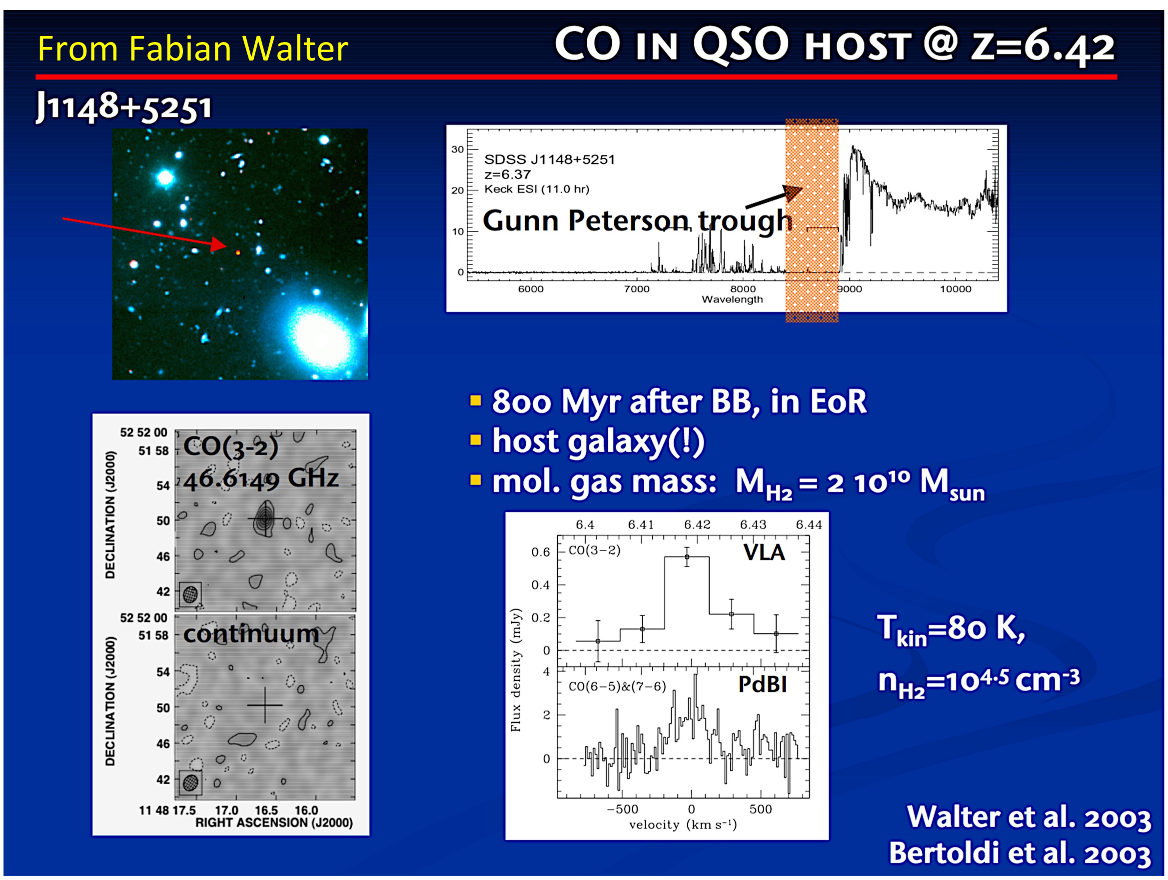
MM emission: Limitation: molecule must have permanent dipole moment => cannot observe H_2, C_2, N_2, CH_4, C_2H_2, …

Advantage: many molecules down to low abundances

Richness of Far IR Spectra of ISM

- 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 al 2015 ApJ 799 102 ; **brightest line is [OI] at 63μ**

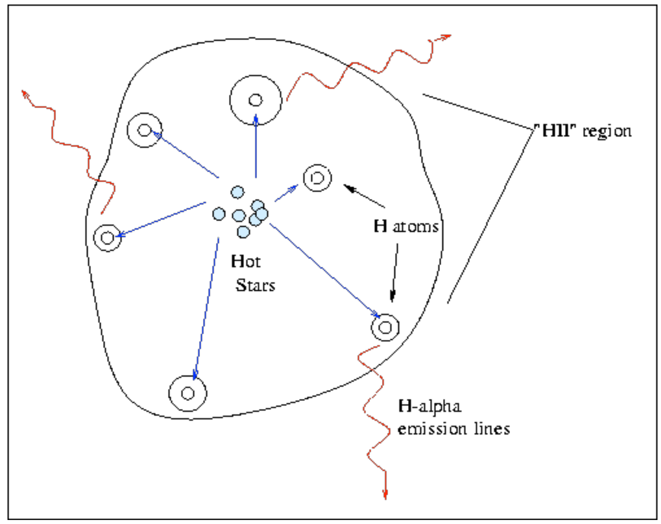




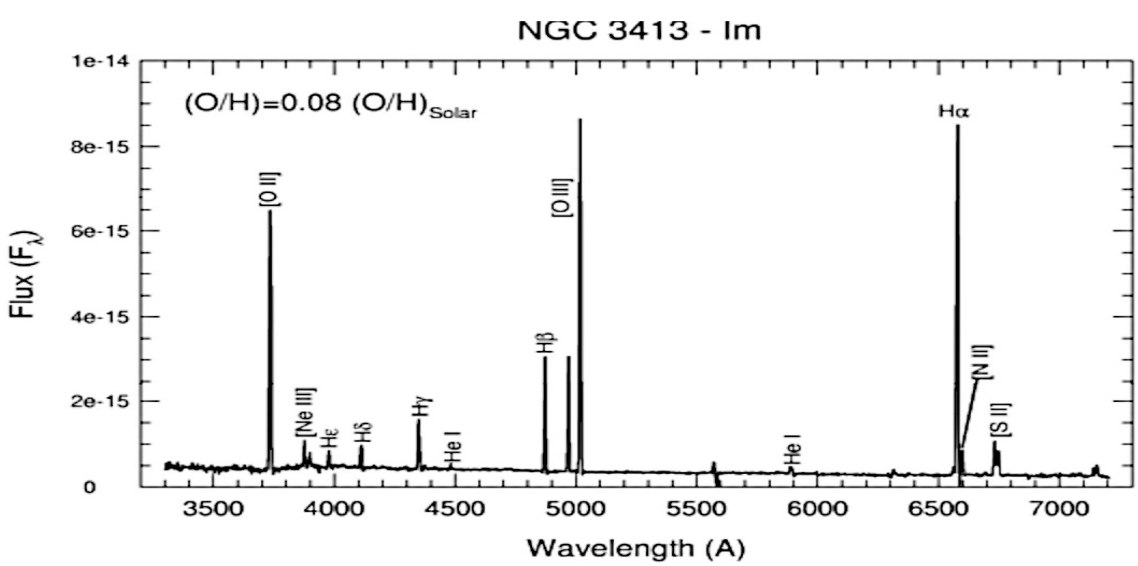
H II Region

- Regions of ionized gas around hot stars
- Complex relation to star formation (see pg 28 in S&G)

HII Region

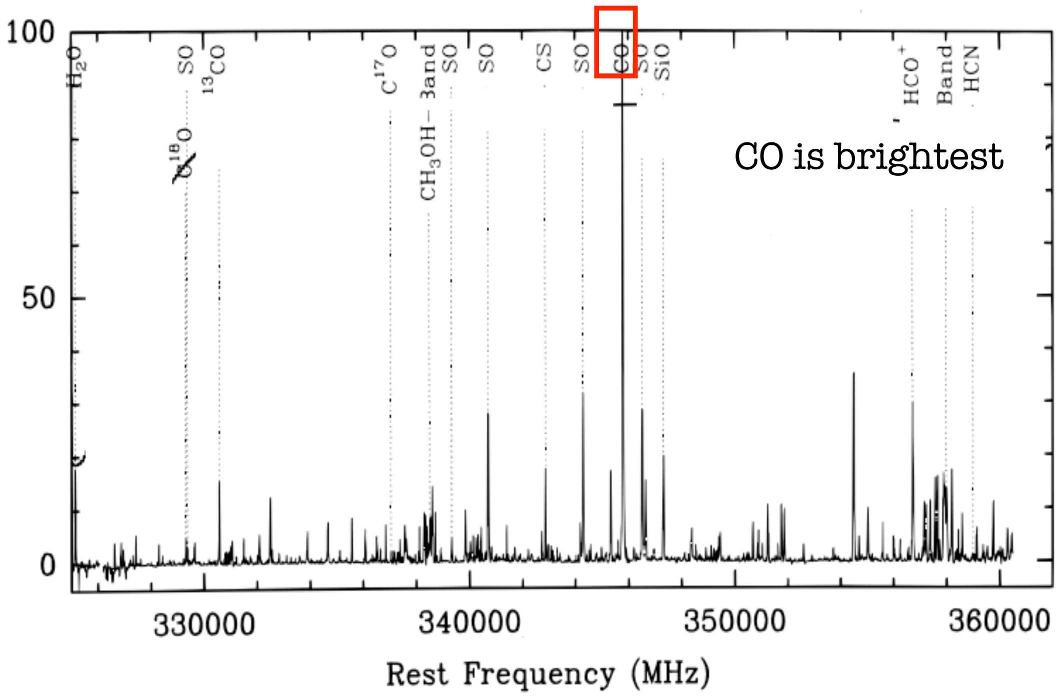


Optical spectrum of HII Region



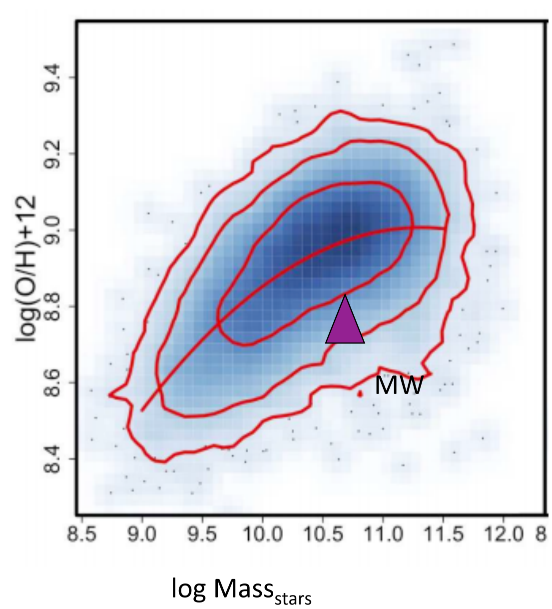
- Optical spectrum show lines due to [OII]. [OIII],Hα, [NII], etc
- the [..] symbol means a forbidden line which only arises in low density gas

Millimeter Band Spectrum of Molecular Cloud



Metallicity in Gas

- How does determine 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
    - thus **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**



GAMA collaboration Foster et al 2012

Gas Cooling- Physical Processes

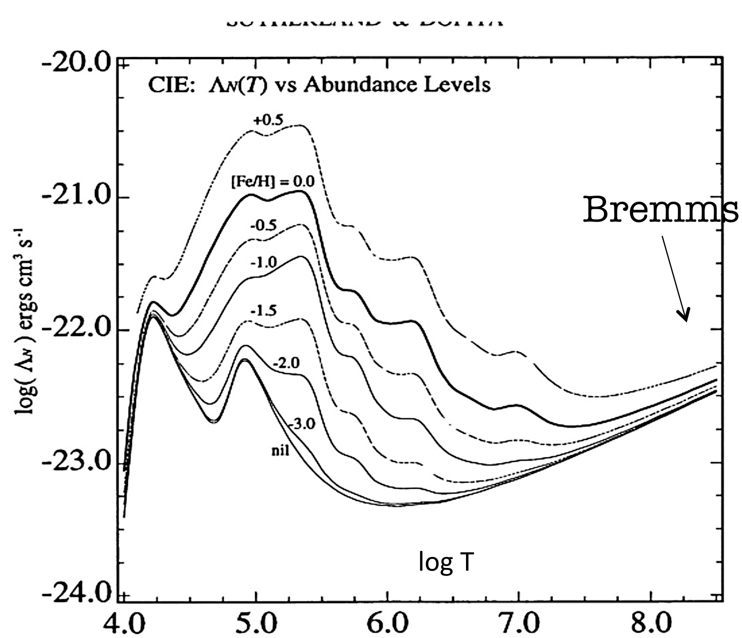
- Collisional excitation: free electron impact knocks a bound electron to an excited state; it decays, emitting a photon.
- Collisional ionization: free electron impact ionizes a formerly bound electron, taking energy from the free electron.
- Recombination: free electron recombines with an ion; the 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

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

S&G 105,106 MWB sec 8.1.3, **8.4**

- $T>10^7$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 fi structure lines and molecules dominate (and dust)



Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium Sutherland and Dopita 1993 table 2.5 in S&G

Cooling Processes

- Read S&G pg104-107

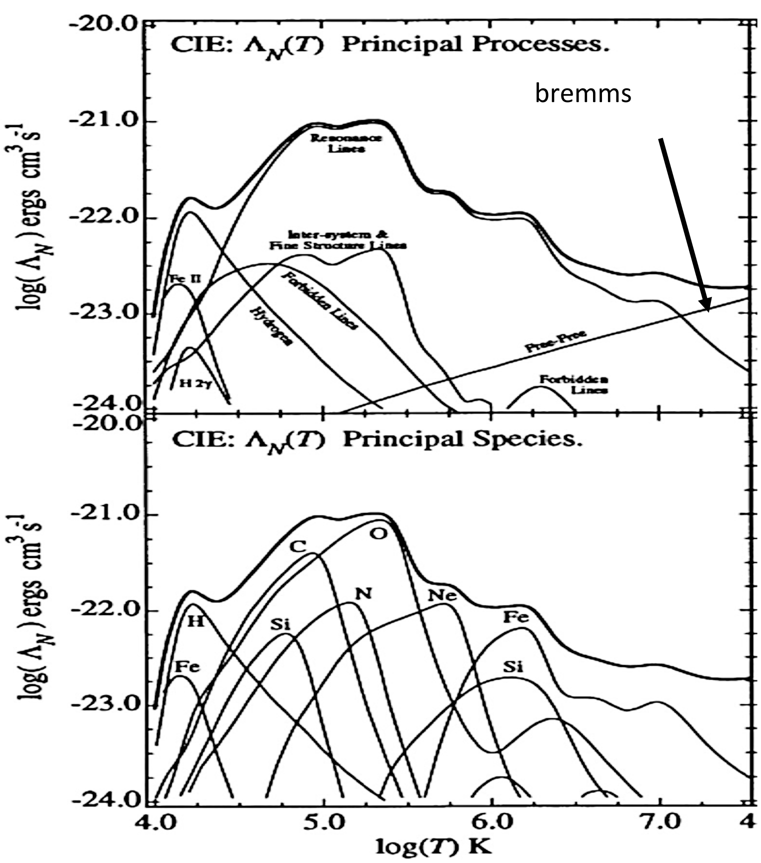
Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
$10^7 \text{ K} < T < 10^8 \text{ K}$	Iron resonance lines	X-ray
$10^5 \text{ K} < T < 10^7 \text{ K}$	Metal resonance lines	UV, soft X-ray
$8000 \text{ K} < T < 10^5 \text{ K}$	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~ 8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
$100 \text{ K} < T < 1000 \text{ K}$	[OI], [CII], H_2	Far IR: 63 μm, 158 μm
$T \sim 10–50$ K	CO rotational transitions	Millimeter-wave

Gas Cooling

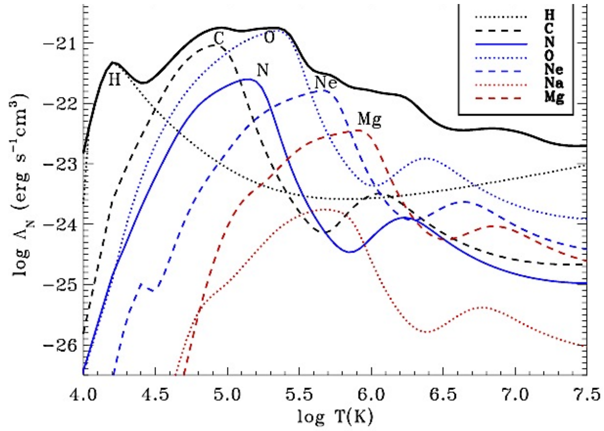
As the temperature changes the ions responsible for cooling
change as do the physical processes

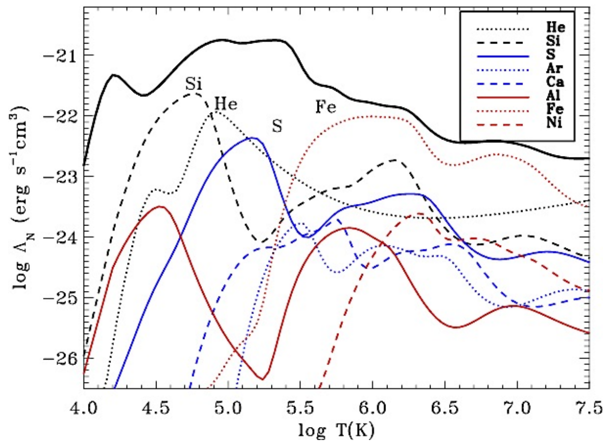
in the case of <u>primordial</u> gas, cooling below 10^4K is only possible if significant amounts of molecular hydrogen can form in the gas.



Which Ions 'Do' the Cooling

- Gas with different relative abundances cool differently at different temperatures

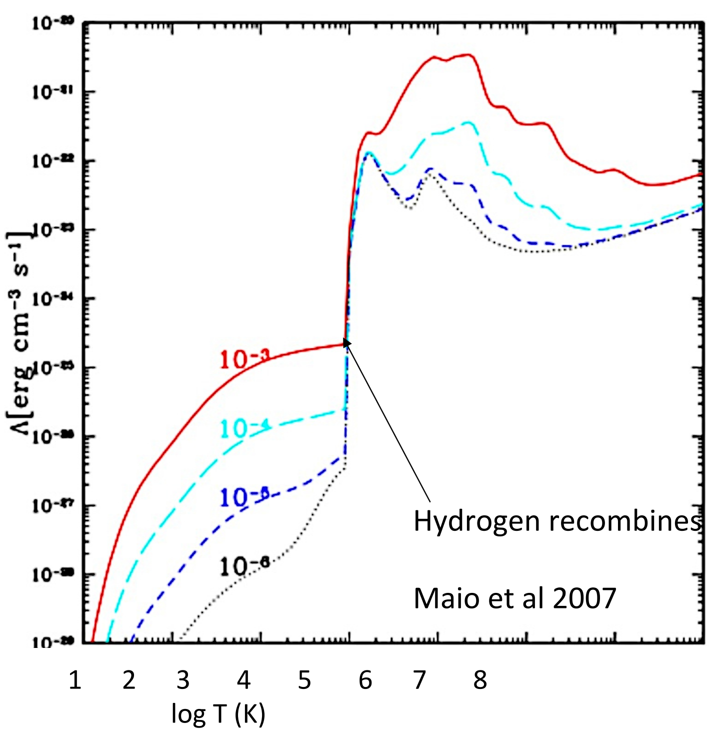




A new radiative cooling curve based on an up-to-date plasma emission code[*]

K. M. Schure - D. Kosenko,- J. S. Kaastra - R. Keppens - J. Vink

- Cooling function including hydrogen, helium, metals lines, H_2 and HD molecules as function of temperature- (appropriate for early universe)
- **Notice that even a tiny metallicity has a big effect on cooling**

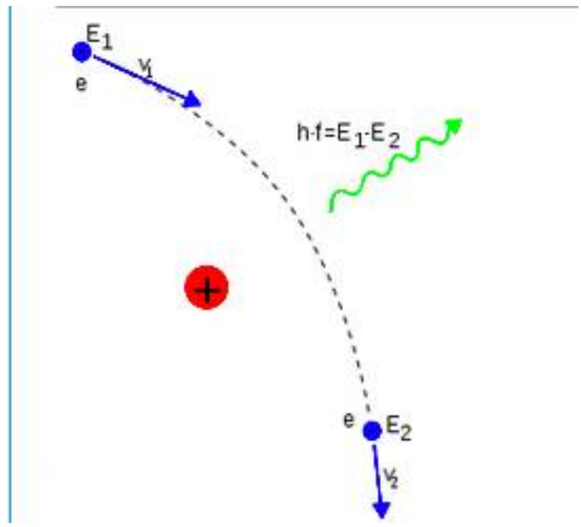


Different metallicities 10^{-3}-10^{-6} solar

Thermal Bremsstrahlung- Often Called Free-Free

- Electrons have a Maxwell-Boltzmann distribution
- electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus (wikipedia)
- Bremsstrahlung has a continuous spectrum, whose shape depends on temperature roughly $E^{-0.4}\exp(-E/kT)$
- Main non-line coolant- important at high temperatures or in gas with very low metallicity

$C_{ff} = \approx 1.4x10^{-23} T_8^{1/2} [n_e \mathrm{cm}^{-3}]^2$ $\mathrm{ergs}^{-1}\ \mathrm{cm}^{-3}$,



Cooling Time (MBW 8.4.1, S&G 2.23)

- Dimensional analysis gives cooling time $t_{cool} \sim \varepsilon/(d\varepsilon/dt)$ where ε is the thermal energy in the gas
- $L = n^2\Lambda(T)$, so $t_{cool} \propto T/[n\Lambda(T)]$:$\Lambda(T)$ depends only on the temperature, so denser gas cools more rapidly. (S&G 2.23)
- $\varepsilon=5/2nkT$; rate of cooling= luminosity
- $t_{cool}=(5/2nkT)/n^2\Lambda(T)$; this eq uses the gas enthalpy per volume, 5/2 $n\,k\,T$ instead of the thermal energy per volume 3/2 $n\,k\,T$ since the plasma is compressed as it cools which therefore effectively raises its heat capacity by a factor of 5/3
- if the cooling is due primarily to bremmstrahlung a good analytic approximation is
- $t_{cool} \sim 0.01(t_{Hubble}\ T_8)/n\Lambda_{-23}(T)$;
- where n is in units of cm^{-3} and is in units of 10^{-23}ergscm^3/sec and T is inunits of 10^8 k (Peterson and Fabian Physics Reports, Volume 427, Issue 1, p. 1-39, 2006.)

Cooling Time (BBW,***8.1.3 Radiative Cooling*** 8.4.1)

- Alternatively (see MWB e.q. 8.94) ;t_{cool} $(d \ln T_g / dt)^{-1}$

$t_{cool} \sim 3/2nkT/n^2 \Lambda (T)$

Using energy per unit mass, θ=kT/m

the isobaric cooling time is $t_{cool}=5/2\ \theta/\rho\Lambda$

- In general $t_{cool} \sim 3.3x10^9\ T_6 / n_{-3}\Lambda_{-23}(T)$ yr*, MBW eq. 8.94*

with the cooling function $\Lambda = 10^{-23}\Lambda_{-23}$ erg cm^3 s^{-1}

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

n_{-3} is the density in units of 10^{-3} cm^{-3}

(cooling time calculation depends on whether cooling is occuring at constant pressure or density)

Cosmic Rays

- 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=3.3x10$^7\gamma$/B(gauss)cm ; γ is the relativistic factor γ=sqrt(1/(1-v^2/c^2))

If B~5μG the gyroradius of a proton with $\gamma \sim 10^4$ (a typical value) is ~10^{-4} pc.

so cosmic rays are trapped within the Galaxy by the 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 emission in the far IR and radio **can dominate a galaxy's integrated SED- see lectures on Dust (next)**

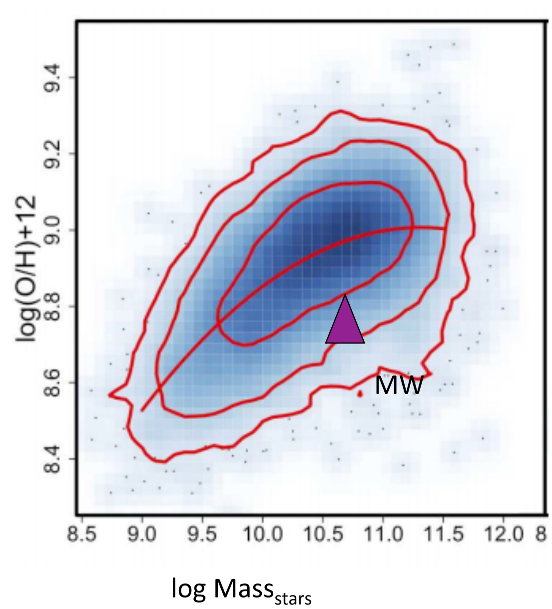
- Mid-IR to Sub-mm is dominated by emission from *dust*, molecular lines and fine structure lines
- radio comes either from HII regions (bremmstrahlung) or a relativistic plasma radiating via synchrotron radiation

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

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

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



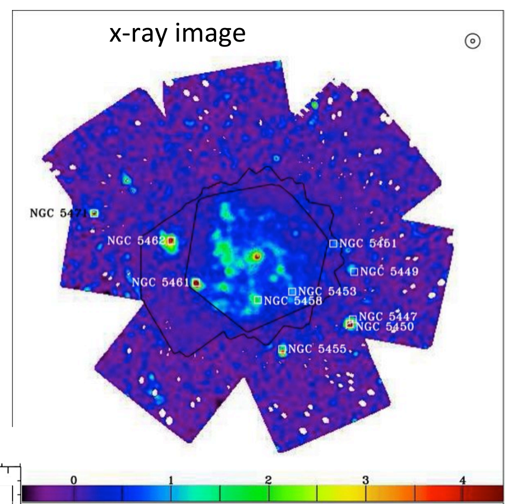
GAMA collaboration Foster et al 2012

X-ray Emission from Star formation

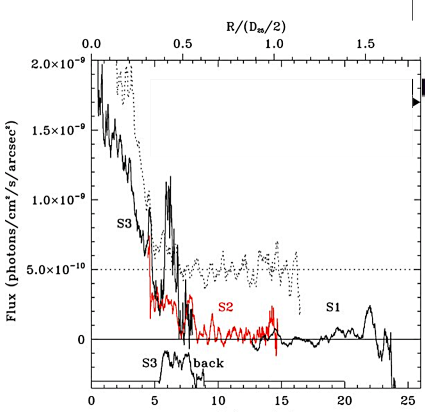
- Star forming region in M33 (Chandra in blue HST in red)
- X-rays from hot gas produced by young stars+ SNR.

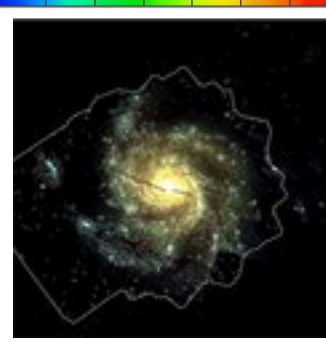
X-ray ISM in M101

- Hot phase of ISM in M101- dominated by ionized oxygen OVII/OVIII and T~2x10[6]k is the temperature of the dominant component.
- The emission is centrally concentrated
- Such data exists for only a few objects



x-ray surface brightness

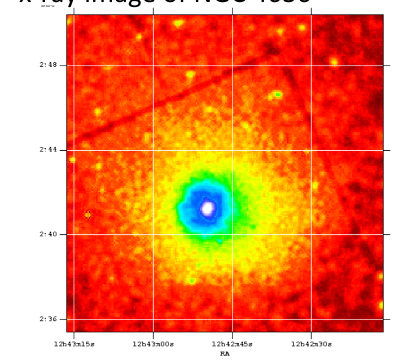


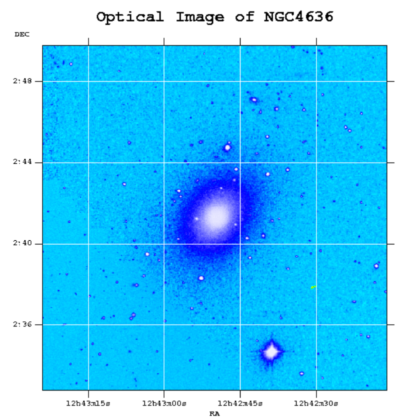


ISM In Ellipicals-pg 272 in S+G

- Predominately hot kT~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



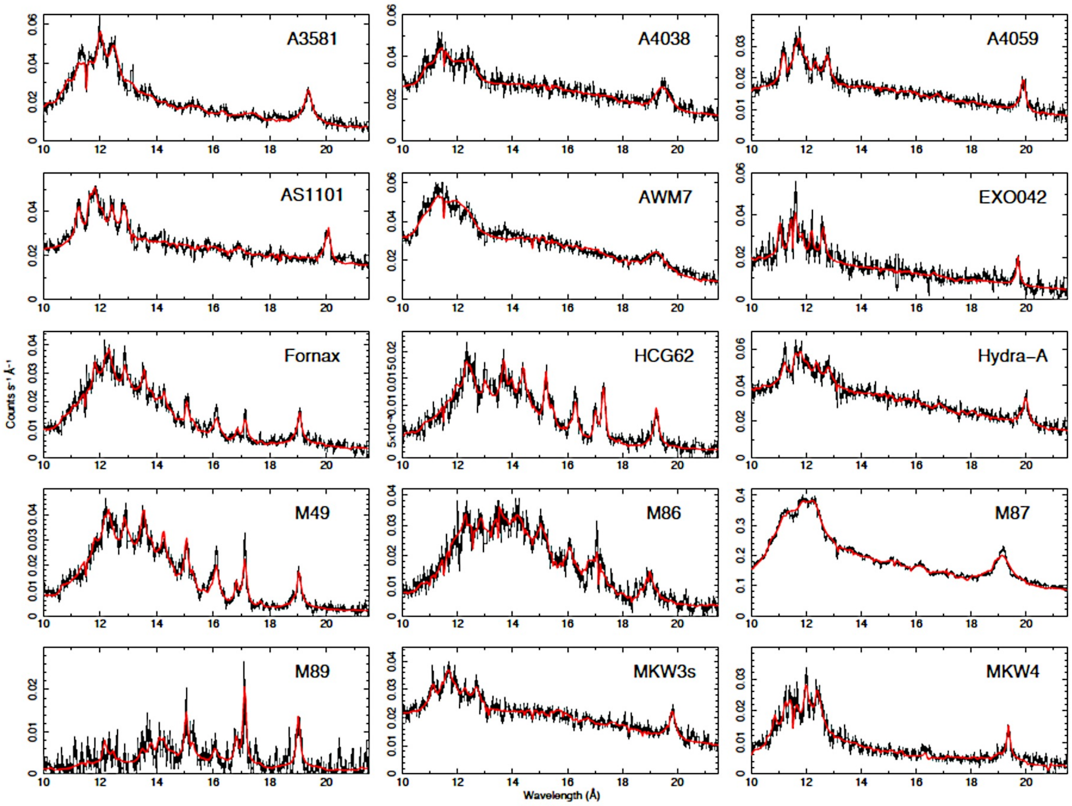


X-ray Spectral Diagnostics

- The strongest lines in the x-ray spectra of gas between 10^6-$2x10^7$ K are the L shell lines of Fe and the He-like triplets of N, O, Ne, Mg, Si,S

- The strength of the lines is very sensitive to temperature and roughly linearly sensitive to abundance

- Gas is optically thin and the electron temperature is derived by measuring the shape of the continuum (not possible in UV,optical, IR)



Why Metals are Important (sec 10.4 MBW)

- While metals account for 1% of the mass, 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.

Next Lecture- Dust

- Summary of ISM
- Multiphase
- Traced by many different spectral features sensitive to different temperatures, densities.
  - derive temperatures, abundances, densities, dynamics