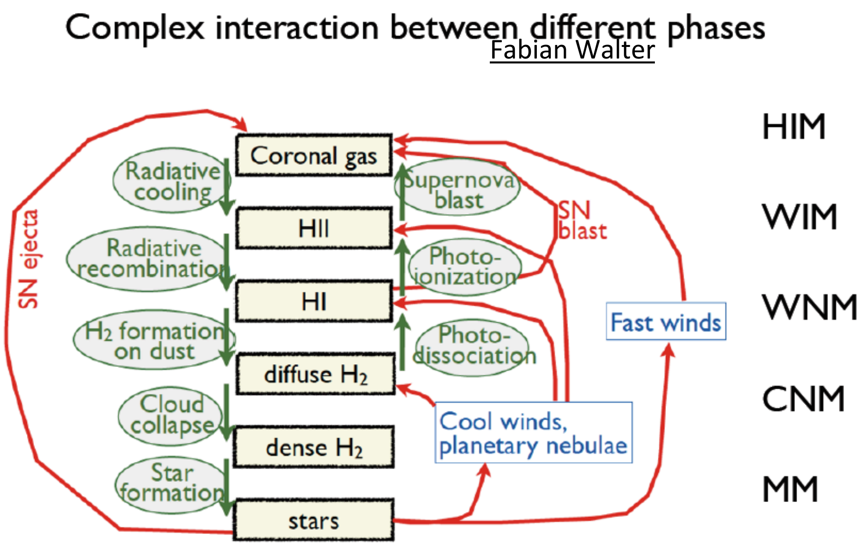
GAS Continued

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)

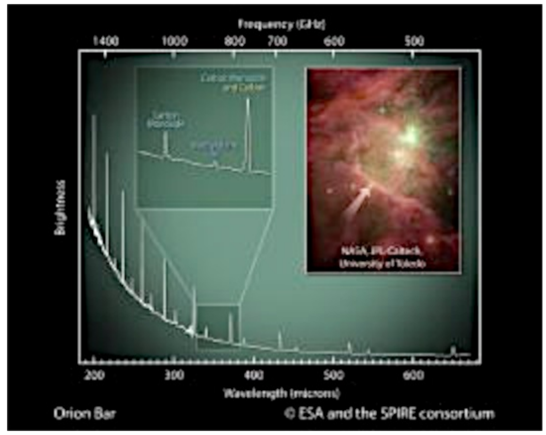


Fabian Walter

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



region in the Orion nebula - partly ionised by intense radiation from nearby hot young star

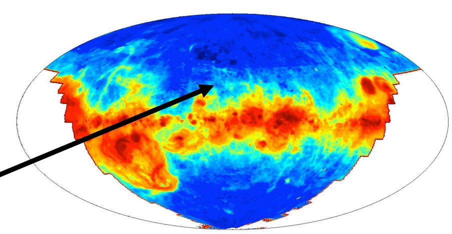
How Does One Observe the ISM (sec 5.2 in S&G)

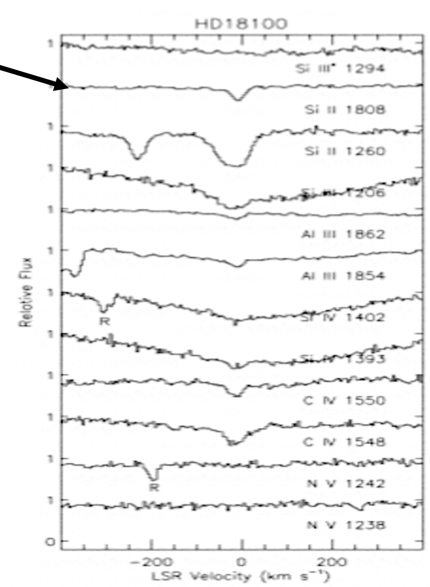
- Optical/UV
  - wide variety of emission and absorption lines from ionized metals (C,N,O etc) - gas is photoionized
- Soft x-ray
  - continuum and emission lines from T~10^6-10^7k gas (spirals and ellipticals) - gas is collisionally ionized

γ-ray

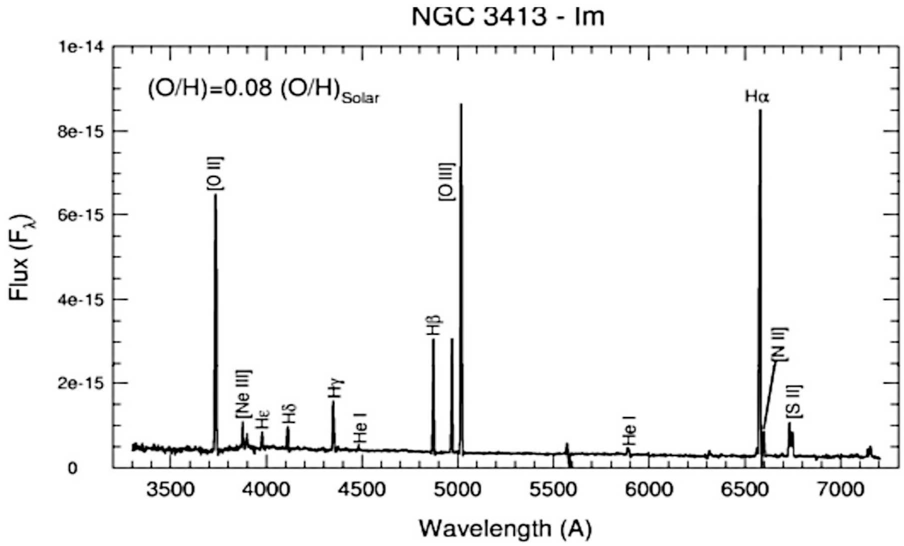
- interaction of cosmic rays with gas

Hα Emission from MW





Optical spectrum of HII Region



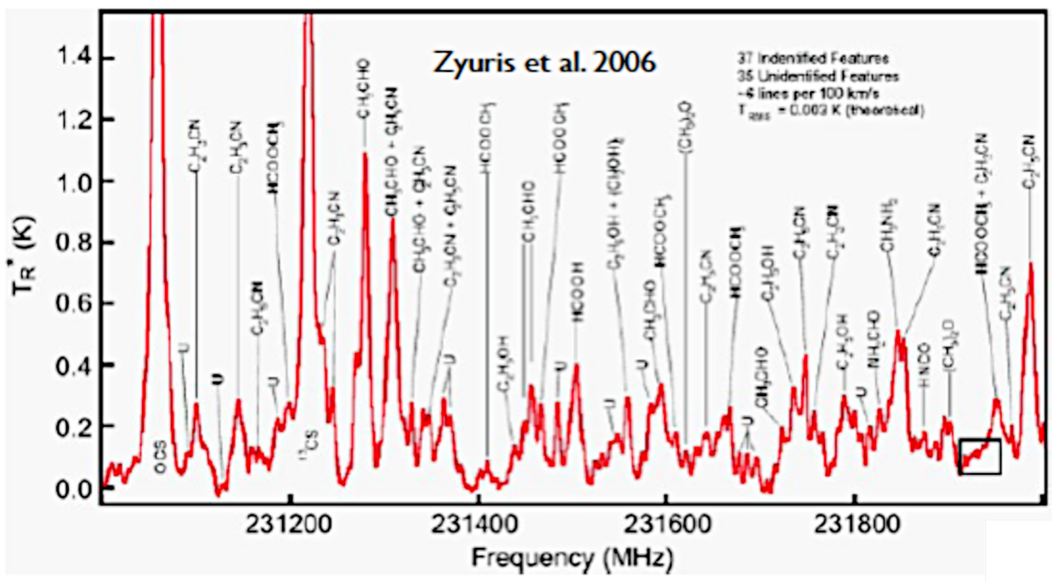
- Optical spectrum show lines due to [OII]. [OIII],Hα, [NII], etc
- the [..] symbol means a forbidden line which only arises in low density gas

H II Region

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

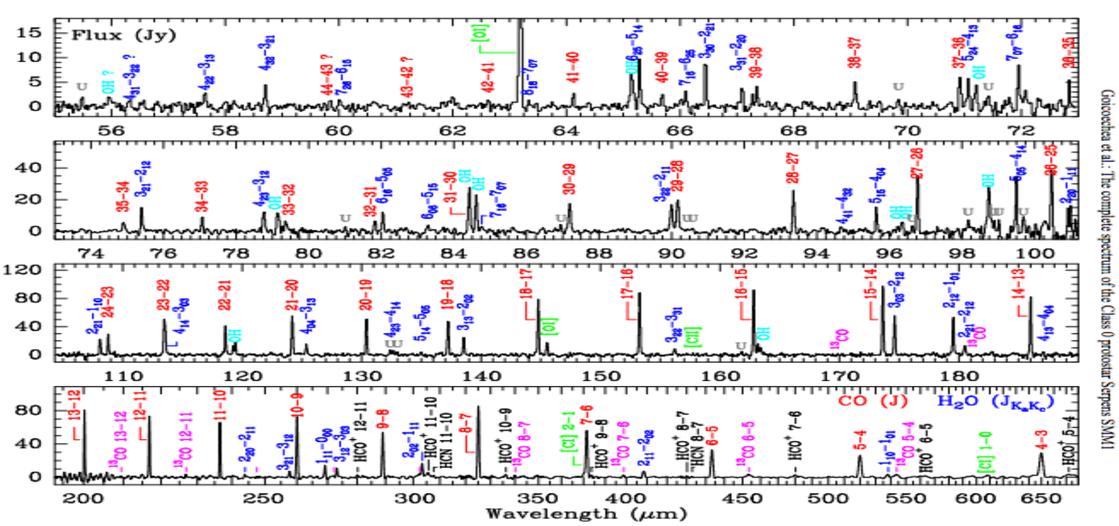
Molecular Lines

- 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

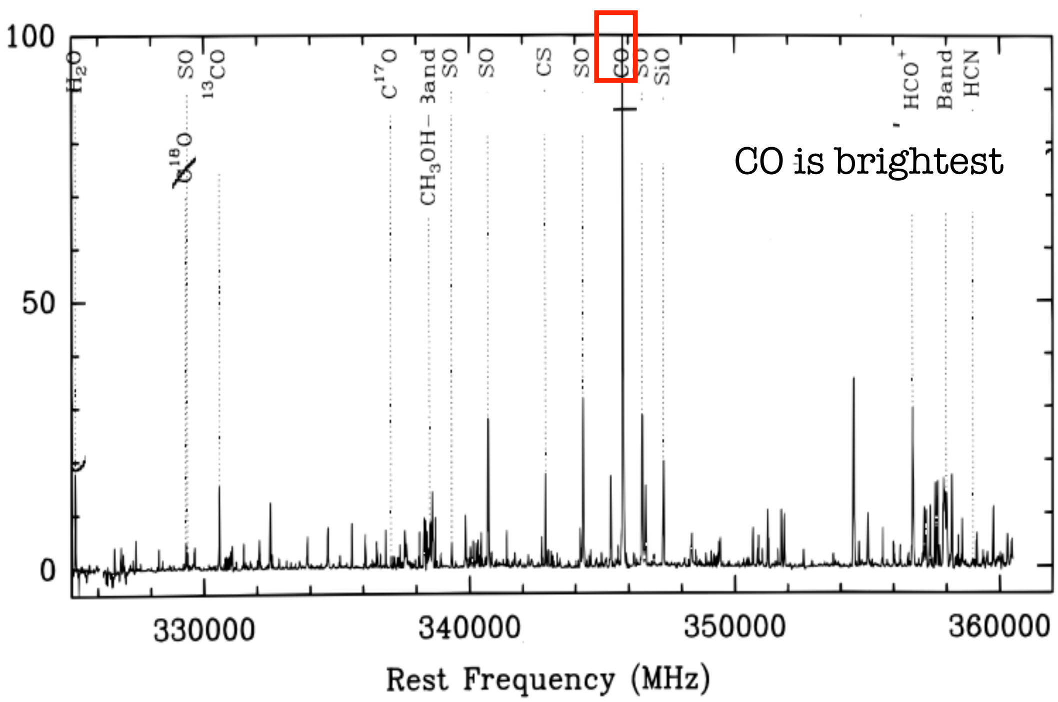


Richness of Far IR Spectra of ISM

- 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**



Millimeter Band Spectrum of Molecular Cloud



Spiral ISM 'States' - f is the filling factor

- Molecular Medium (MM): T~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~100 K, n~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 <u>absorption</u>.
- Warm Neutral Medium (WNM; T~6000 K, n~ 0.3 cm^{-3}, f~20%)

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**.

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	$\approx$8000	10^6–10^7
h (pc)	$\approx$ 70	$\approx$140	$\approx$ 400	$\approx$900	$\gtrsim$1 kpc
f_{volume}	$\lesssim$ 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

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

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

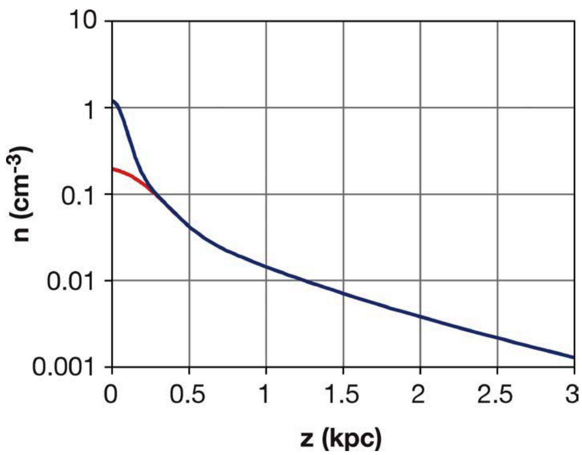
$\rho(z) \sim 0.55 * 0.2 \exp[-(z/320\ \mathrm{pc})^2]$

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

The ISM

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

How do Molecules Emit

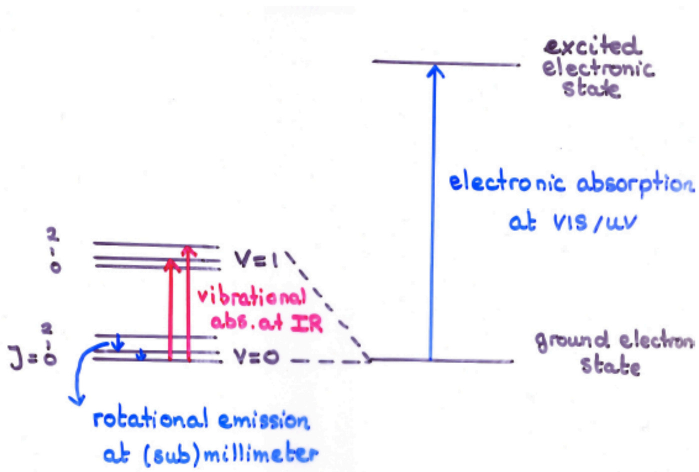
$$E = E^{el} + E^{vib} + E^{rot}$$

- 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

Gas Cooling- Physical Processes

- Collisional excitation: free electron impact knocks a bound electron to an excited state; it decays, emitting a photon.

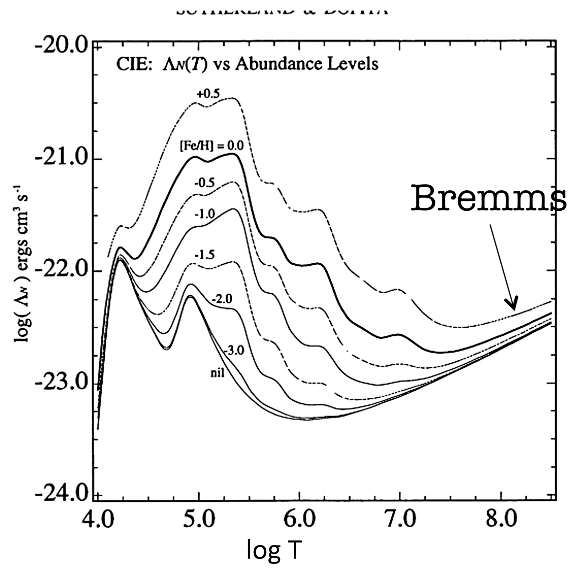
- Collisional ionization: free electron impact ionizes a formerly bound electron, taking energy from the free electron.

- Recombination: free electron recombines with an ion; the binding energy and the free electron's kinetic energy are radiated away

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

S&G 105,106 MWB sec 8.1.3, 8.4

- $T>10^7$k thermal bremmstrahlung $L\sim n^2T^{1/2}V$
- $10^7>kT>10^{6.3}$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 lines and molecules dominate

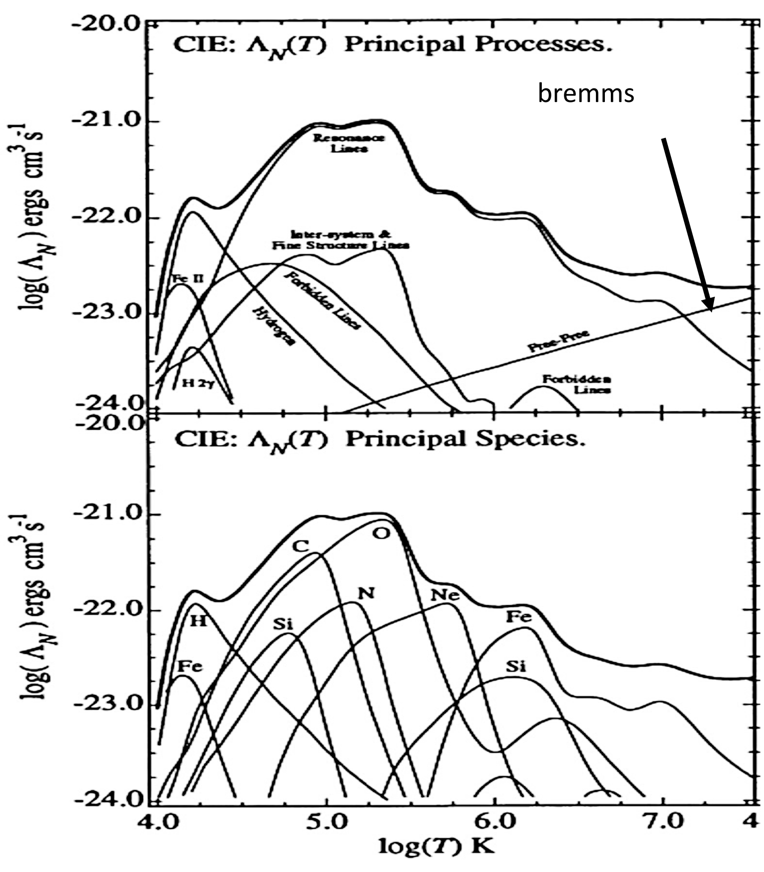


Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium Sutherland and Dopita table 2.5 in S&G

Gas Cooling

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

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



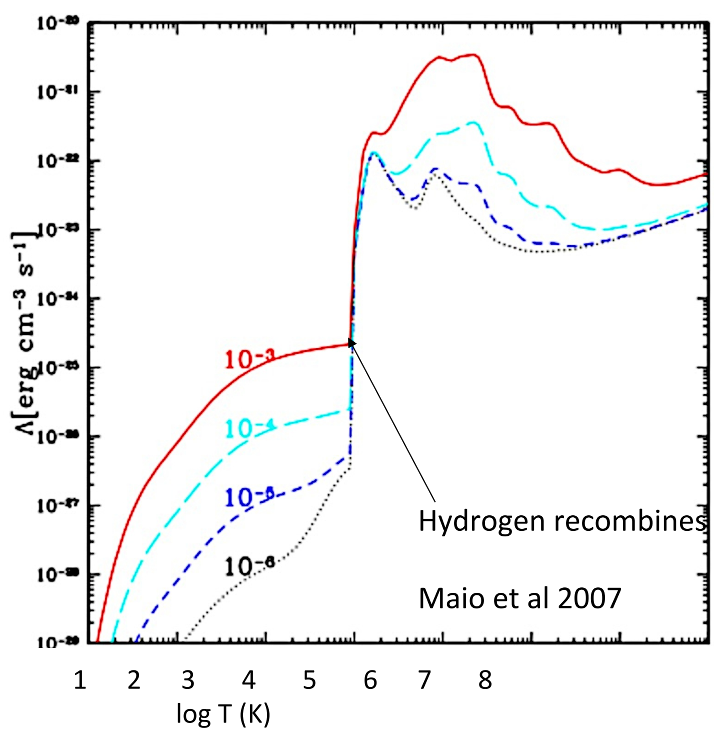
Cooling Processes

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

- Cooling function including hydrogen, helium, metals lines, H_2 and HD molecules as function of temperature- (appropriate for early universe)

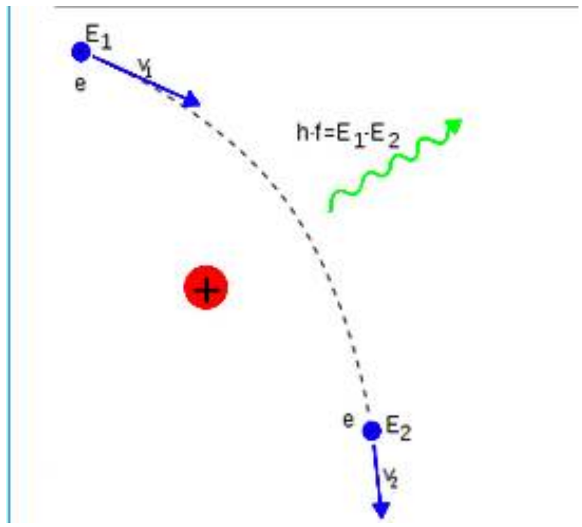


Different metallicities 10^{-3}-10^{-6} solar

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

$C_{ff} =\approx 1.4x10^{-23} T_8^{1/2} [n_e \mathrm{cm}^{-3}]^2$ ergs^{-1} 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)
- $t_{cool} \sim \varepsilon\, \rho/\Lambda$; since energy release goes as ρ^2 ;$t_{cool} \sim \varepsilon/\rho$

Cooling Time (BW 8.4.1)

- Alternatively (MWB e.q. 8.94)

- energy in gas per particle is nE and cooling rate is Λ;
- $t_{cool} \sim nE/\Lambda$
- for an ideal gas $nE_{ll} \sim 3/2nkT$ and

by definition the cooling rate is $n^2\Lambda(T)$

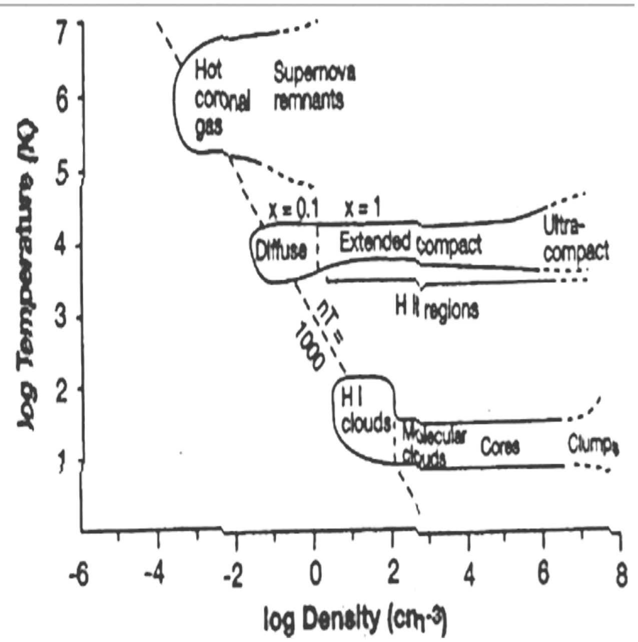
$t_{cool} \sim 3/2nkT/n^2 \Lambda (T)$

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

ISM in Spirals

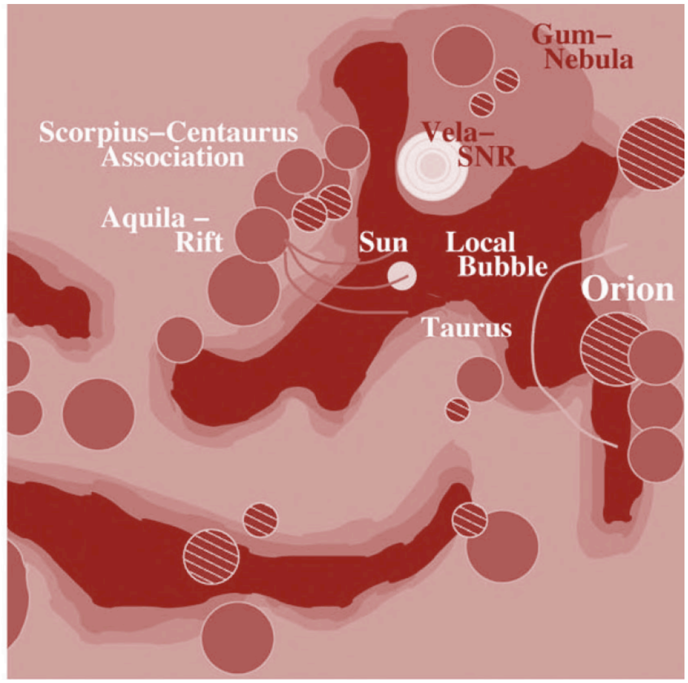
- The ISM is energized primarily by stars (starlight (dust), stellar winds, supernovae

- UV starlight photoionizes atoms & dissociates molecules; photo-ejected electrons heat gas



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

ISM in Spirals



1500 ly

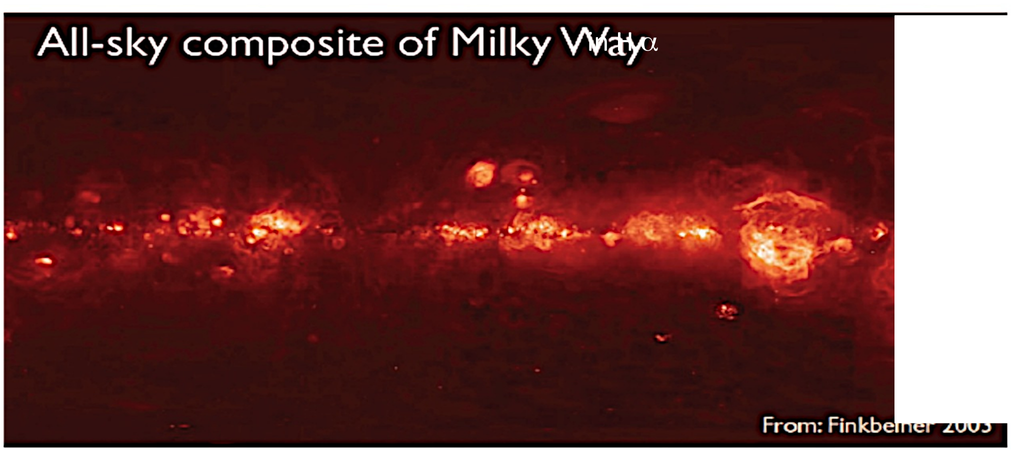
Norbert Schulz

- 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

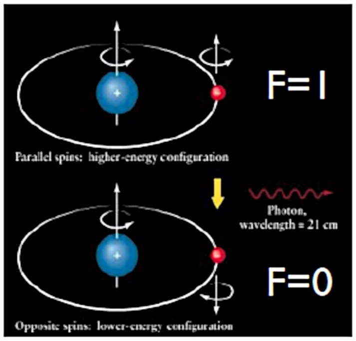
Warm Ionized Medium

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}



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



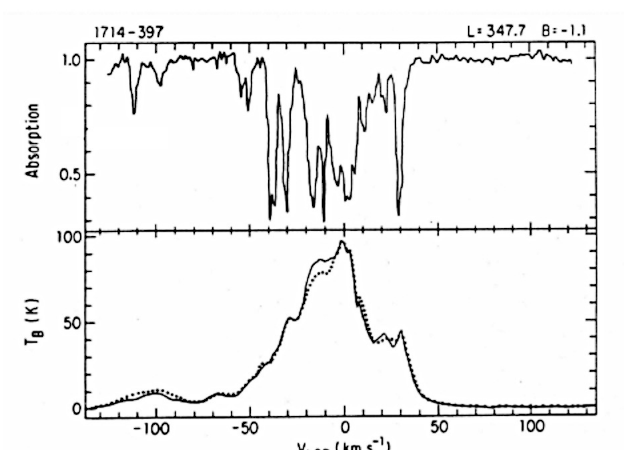
- H atom consists of 1 proton + 1 electron
  - Electron: spin $S=1/2$
  - Proton: nuclear spin $I=1/2$
  - Total spin: $F = S + I = 0, 1$
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $\quad g_u = 2F+1 = 3$ $\quad E = 5.87\times10^{-6}$ eV
  - $F = 0$ $\quad g_l = 2F+1 = 1$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

- 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

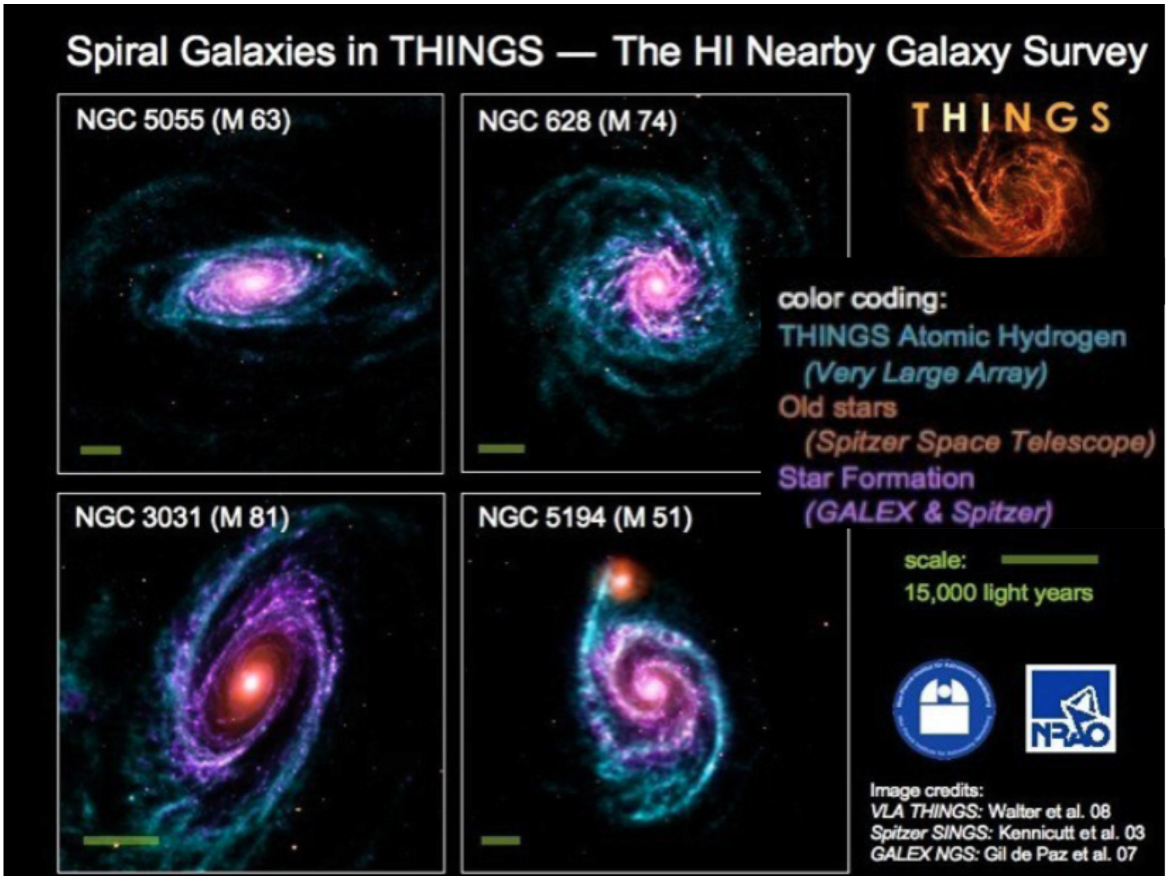
HI emission vs. absorption

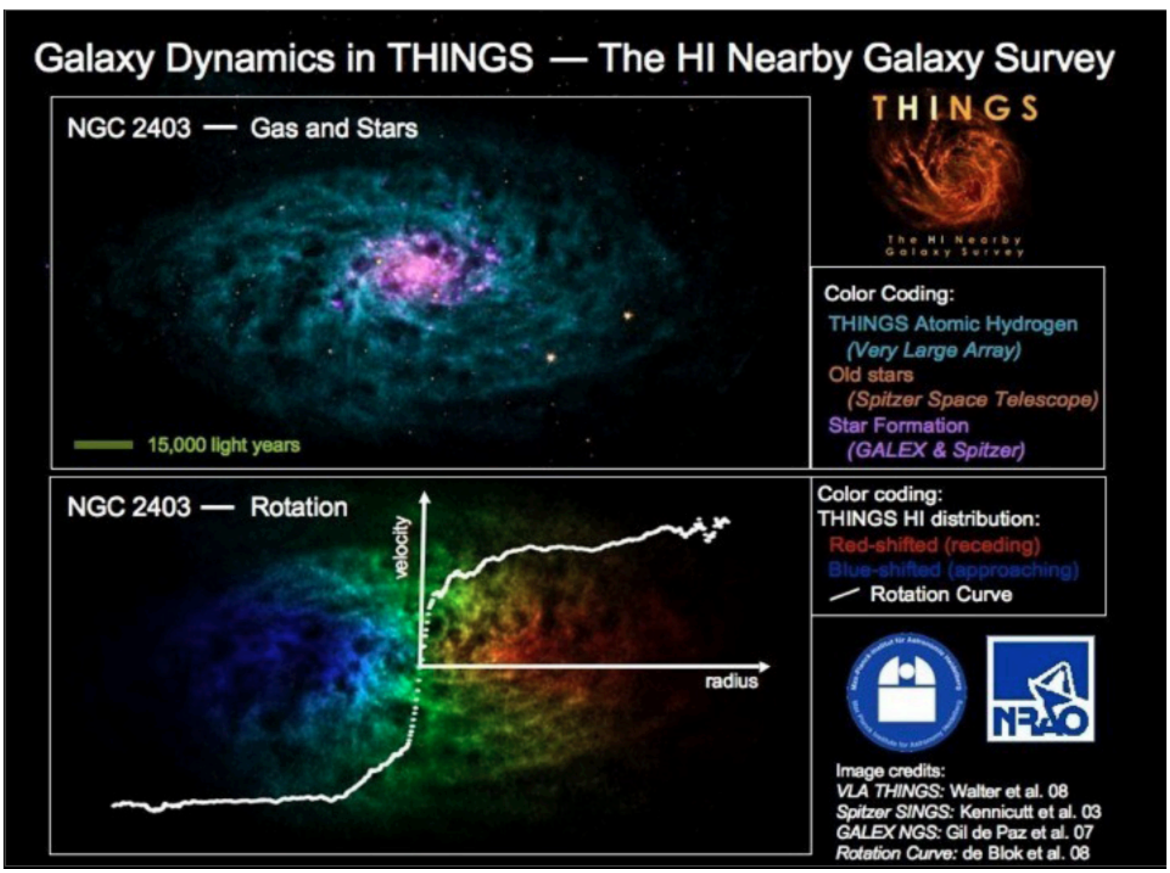


Dickey et al. 1983

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 Galaxies in THINGS — The HI Nearby Galaxy Survey
NGC 5055 (M 63)
NGC 628 (M 74)
THINGS
color coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)
NGC 3031 (M 81)
NGC 5194 (M 51)
scale:
15,000 light years
NRAO
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07


Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey
NGC 2403 — Gas and Stars
THINGS
The HI Nearby Galaxy Survey
Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)
15,000 light years
NGC 2403 — Rotation
velocity
radius
Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve
NRAO
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

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 $\gamma\sim10^4$ (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**

- 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

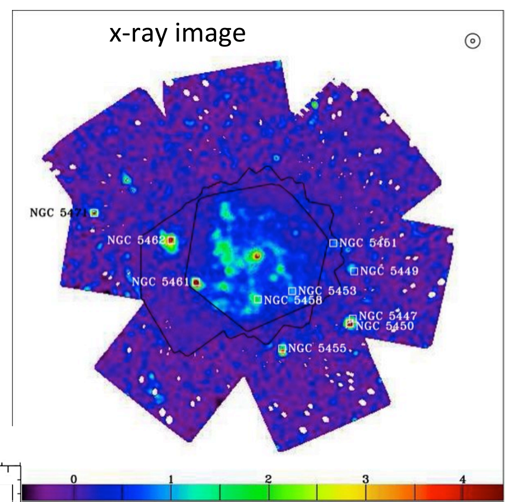
certain emission lines (eg Lyα ; [CII] 158μ) can be major coolants

X-ray Emission from Star formation

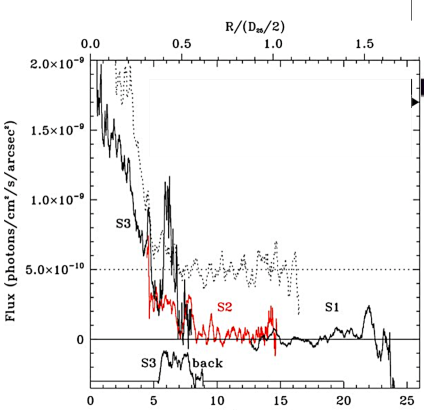
- Star forming region in M33 (Chandra in blue HST in red)
- X-rays from hot gas produced by young stars+ SNR.

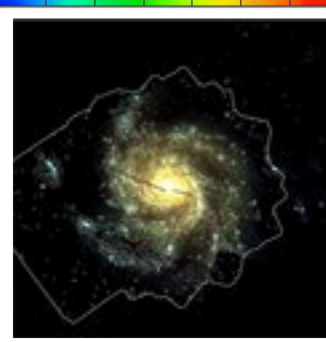
X-ray ISM in M101

- Hot phase of ISM in M101- dominated by ionized oxygen OVII/OVIII and $T \sim 2 \times 10^6$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

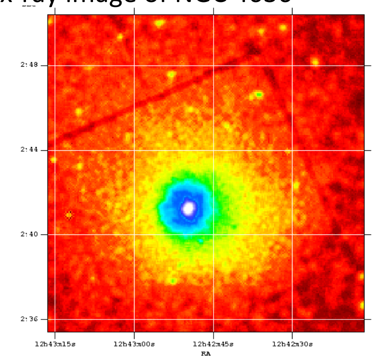




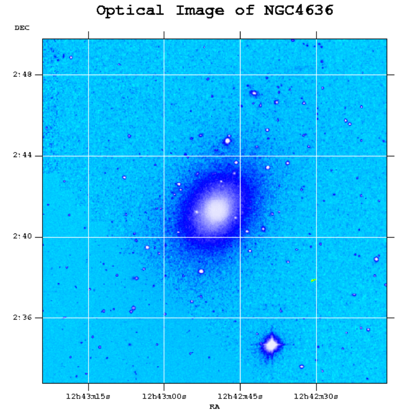
ISM In Ellipicals-pg 272 in S+G

- 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



Optical Image of NGC4636

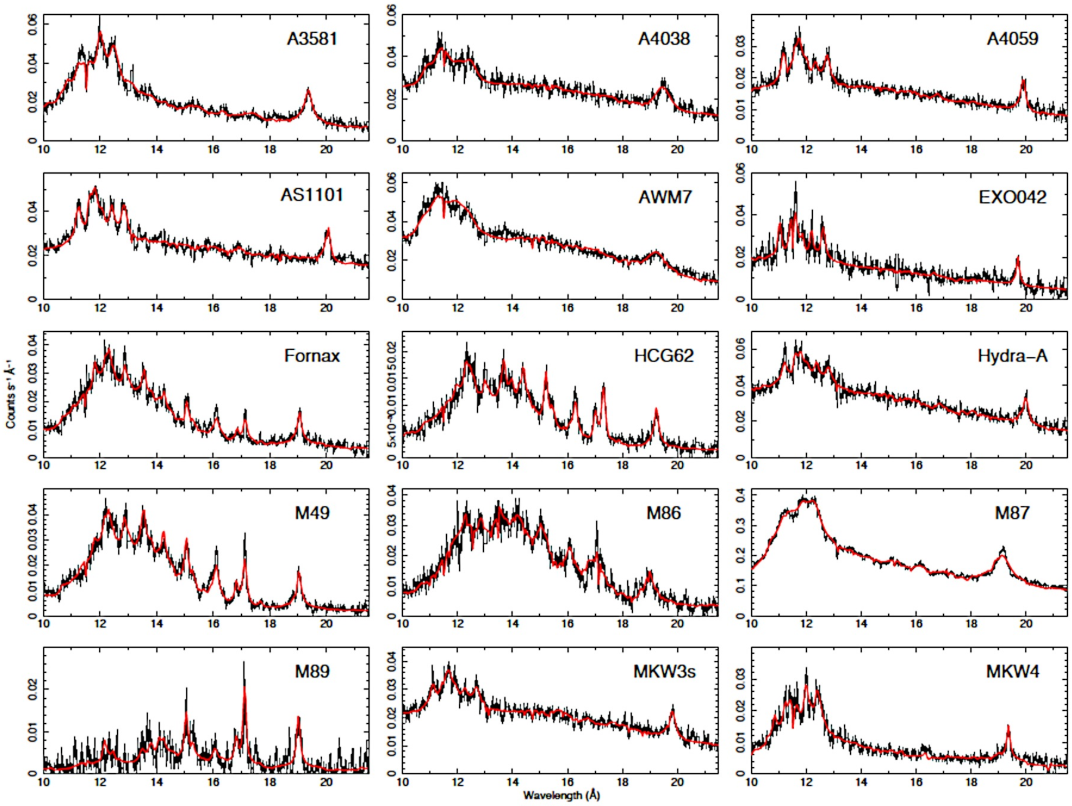


X-ray Spectral Diagnostics

- 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)

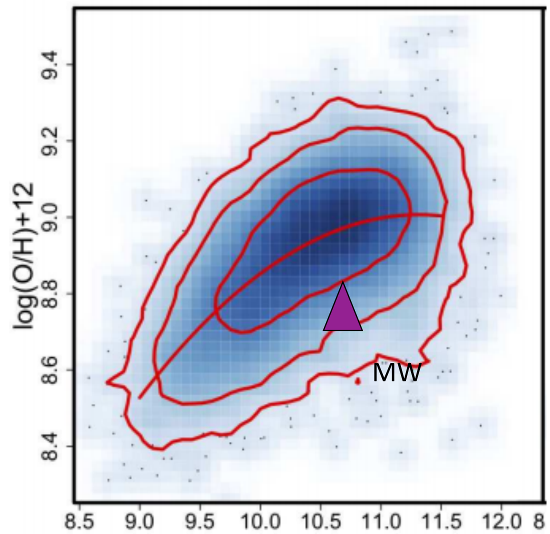
- While metals account for 1% of the mass, they **dominate** most of the important chemistry, ionization, and heating/cooling processes.

- 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.

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

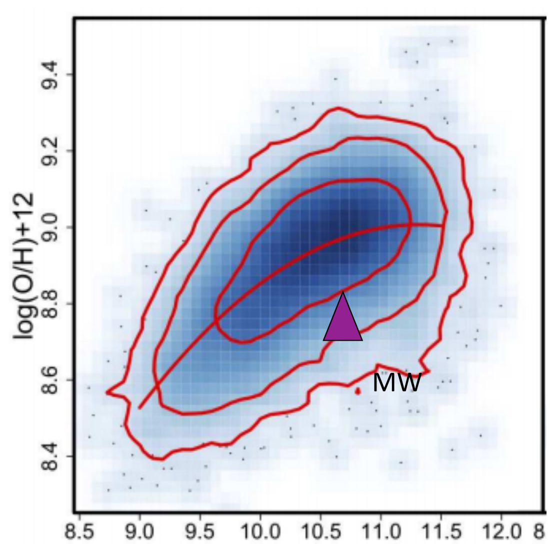


log $Mass_{stars}$

GAMA collaboration Foster et al 2012

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**



log $Mass_{stars}$

GAMA collaboration Foster et al 2012

Next Lecture- Dust

- Summary of ISM