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

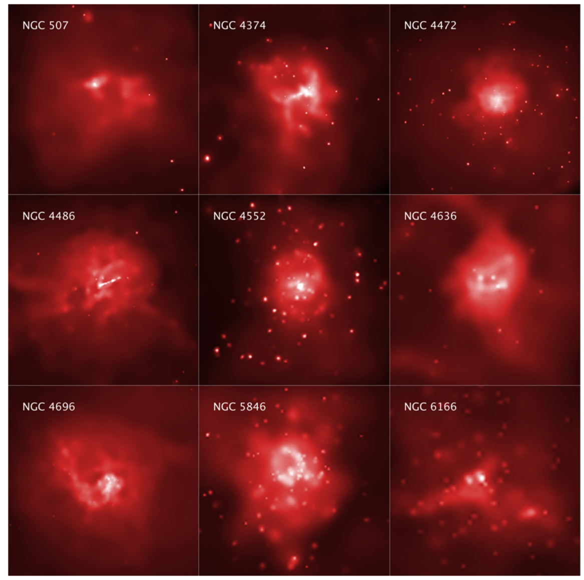
Gas- Big Picture

- 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 ....)
- Once a galaxy has 'formed' the gas content of the galaxy is related to its star formation rate.
  - the interstellar medium (ISM) is the reservoir of material lost by stars (supernova, stellar mass loss etc)

GAS-ISM

- '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~10% of the stars
- For lower mass galaxies the baryonic fraction in gas is larger; at $M_{halo}<10^{11}M_\odot$ gas dominates the baryonic content
- Hot gas (T~10^{6-7} k) dominant ISM in **elliptical** galaxies

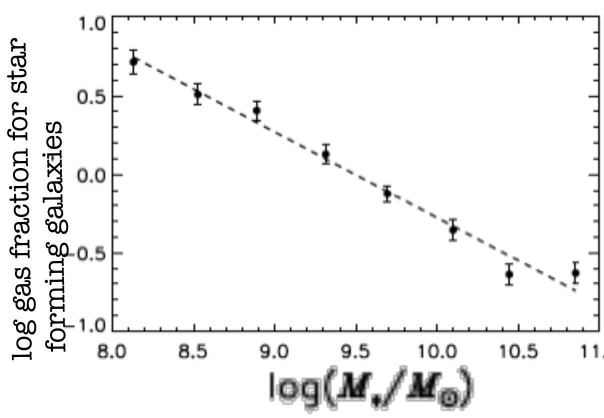
In spirals hot gas fills the volume but low total mass



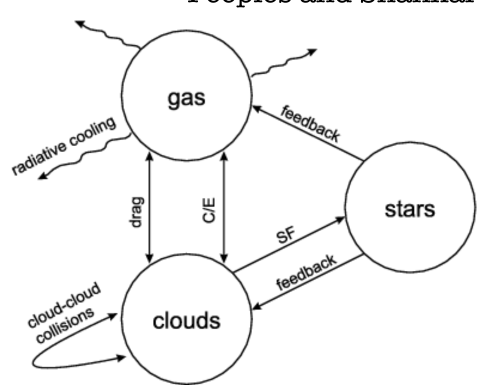
x-ray images of elliptical galaxies emphasing structure

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+chemistry
  - temperature
  - velocities
  - ionization mechanism

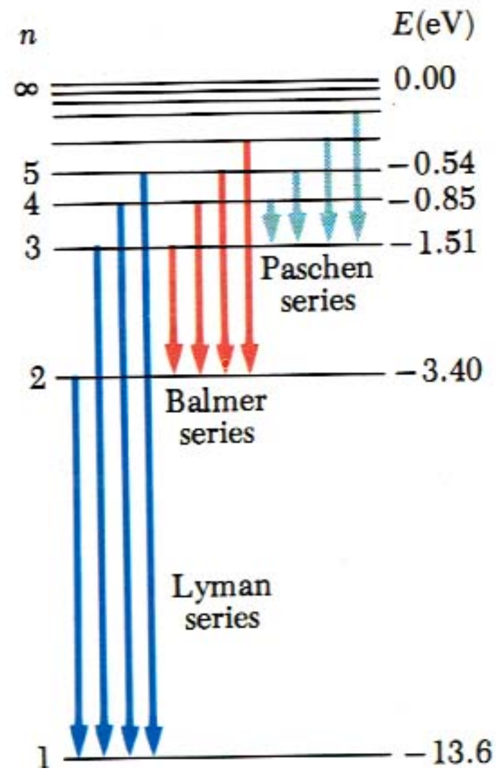


Peeples and Shankar 2011



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.q. 1.35 in S&G) and integrating over the photons more energetic than the ionization potential of the ion of interest (e.g. H with13.6 eV)

- 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 ejects an 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 Quantum 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 and m_H is the mass of the hydrogen atom.

$c_s=\mathrm{sqrt}(k_B T/\mu)$

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

Reason: if the sound crossing time is much larger 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.

ISM- Relevant Velocities

Some characteristic values

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

A Bit of Physics-TimeScales

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

collision timescale $\tau \sim l/v$; $\ell \sim n\sigma$; n is the NUMBER density of the gas and σ is a typical cross section (hard sphere approx for ions $\pi r^2 \sim 10^{-15}$ cm^{-3}); ℓ is a typical length and v a typical velocity

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

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

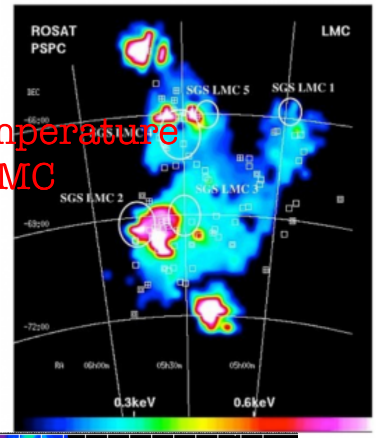
For a sphere of gas, where thermal pressure is balanced by self-gravity the timescale to collapse (the Jeans time) is $\tau_J \sim 1/\mathrm{sqrt}(4\pi G\rho)$ which is similar to the free falltime

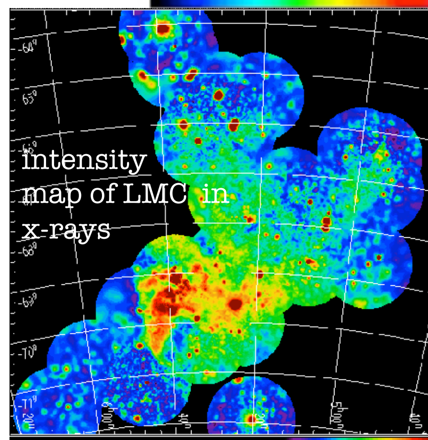
$\tau_{ff}=(3\pi/32G\rho)^{1/2} = 4.4 \times 10^4$ yr /sqrt{n_H /10^6)

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





intensity map of LMC in x-rays

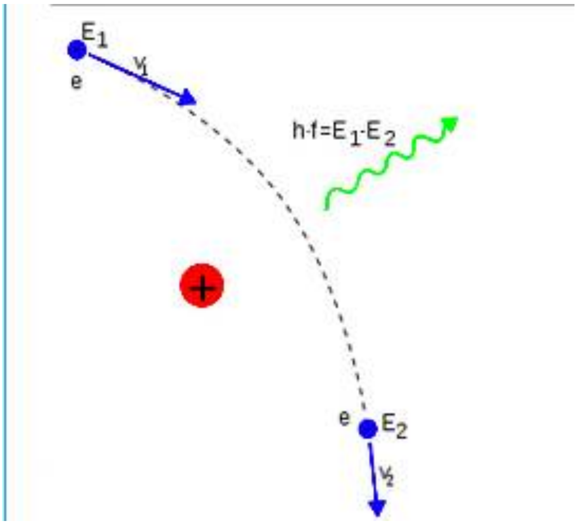
Physics of Emission from Gas

- 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 bremmstrahlung*- 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)

*Bremmstrahlung (also called free-free) is radiation due to the acceleration of a charge in the Coulomb field of another

Thermal Bremmstrahlung- 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



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

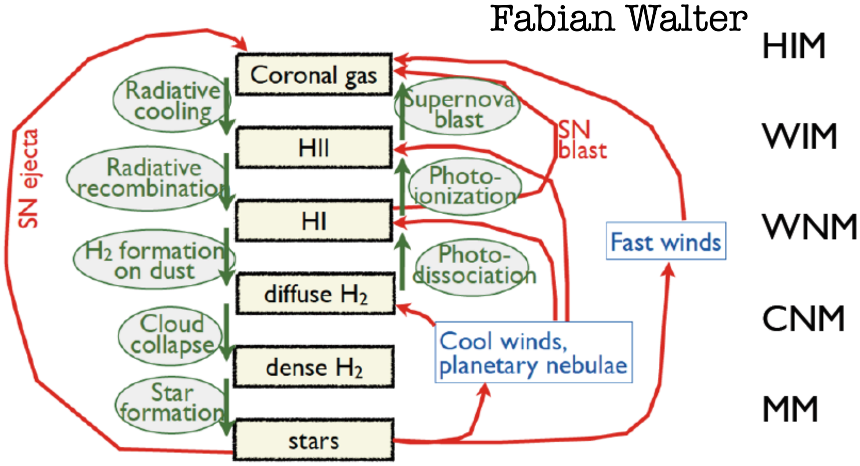
- Doppler motions reveal galaxy dynamics
- Abundance measurements allow study of chemical evolution
- physical conditions: density; temp; pressure; turbulence; gas column density; mass,
  - can all be derived from observations of emission/ absorption lines
  - lines are bright and can be seen (relatively) 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)

Complex interaction between different phases

Fabian Walter



At low redshift ISM in spirals not affected much by AGN

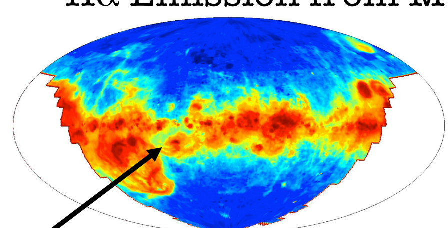
Its not so clear if ISM in ellipticals is dynamic in the same way; AGN seem to be more important in affecting the ISM

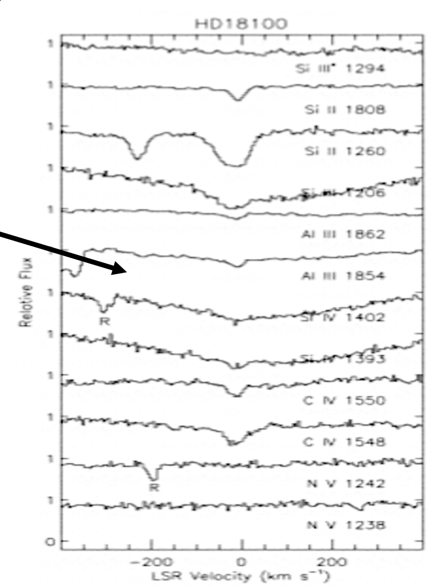
How Does One Observe the ISM (sec 5.2 in S&G)

- 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]63,145μm and [CII]158 and [CI]370,609μm
- 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





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 ~as much mass as the atomic hydrogen, 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 absorption.
- Warm Neutral Medium (WNM; T~6000 K, n~ 0.3 cm^{-3}, f~30%). This phase provides the bulk of the **HI** seen in emission line surveys.
- 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.
- 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

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	10^5–10^7
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.

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