GAS

The other baryonic component- **sec 2.4 in S+G**

Material scattered in Ch 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 pages for details**

See also

Molecular Gas in Galaxies ARA&A Vol. 29: 5811991J. S. Young and N. Z. Scoville

Dopita, M., & Sutherland, R.: Astrophysics of the Diffuse Universe 2005

Lequeux, J.: The Interstellar Medium, Springer, Berlin, 2003

Osterbrock, D.E., & Ferland, G.J.: Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, Palgrave Macmillan, 2006

Spitzer, L.: Physical Processes in the Interstellar Medium1978

Thronson, H.A., Shull, J.M. (Herausgeber) : The Interstellar Medium in Galaxies, Kluwer Academic Publishers, 1990

Todays Figure- Isochrones for Omega Cen

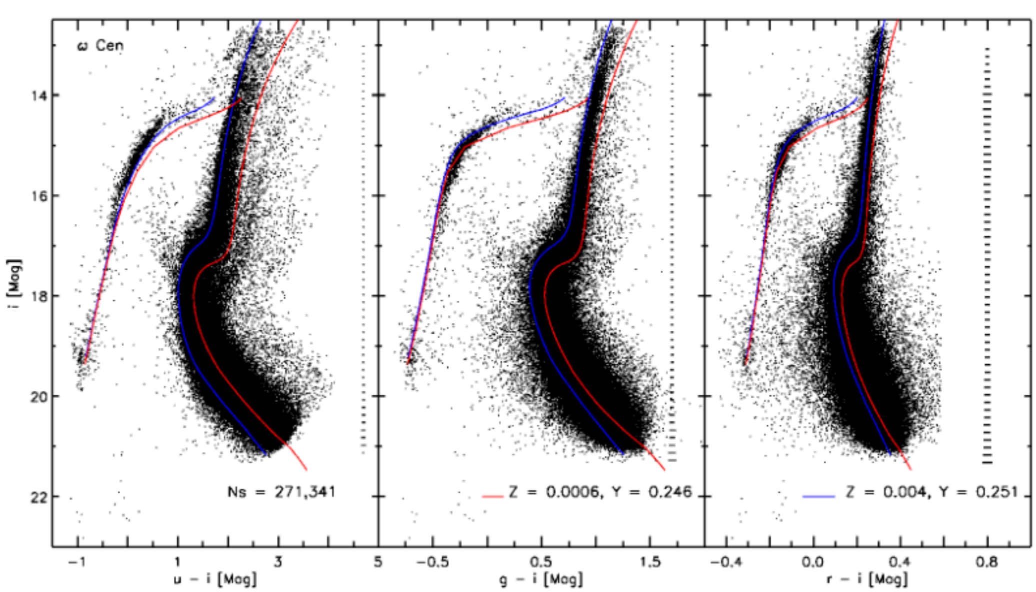
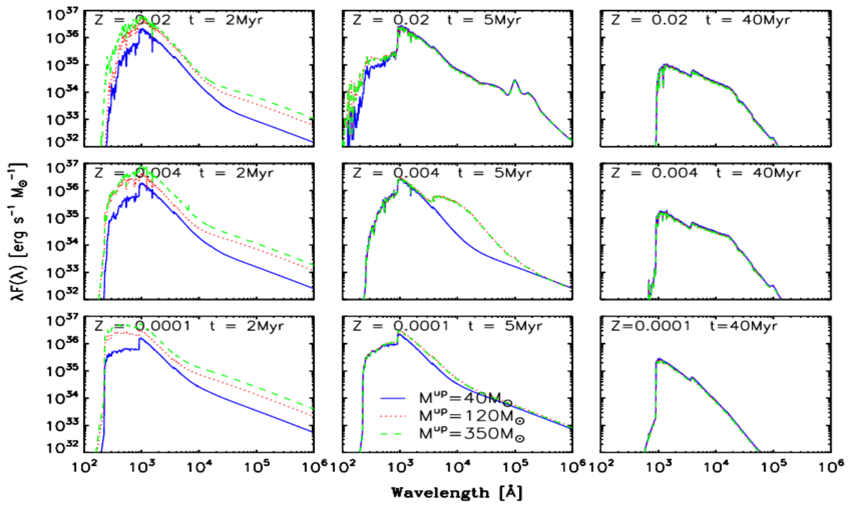


FIG. 6.— DECam *ugri* color-magnitude diagrams of ω Cen cluster members. Isochrones for the same age, $t = 12$ Gyr, and different metallicities are over-plotted (see labeled values). The respective zero age horizontal branch (ZAHB) tracks are also shown. Error bars are marked.

And ...

- arXiv:1702.02230 Modelling the UV to radio SEDs of nearby star-forming galaxies: new Parsec SSP for Grasil I.A. Obi,et al
- By means of the updated PARSEC database of evolutionary tracks of massive stars, we compute the integrated stellar light, the ionizing photon budget and the supernova rates of young simple stellar populations (SSPs), for different metallicities and IMF upper mass limits

each color corresponds to a different maximum mass in the IMF



Gas- Big Picture

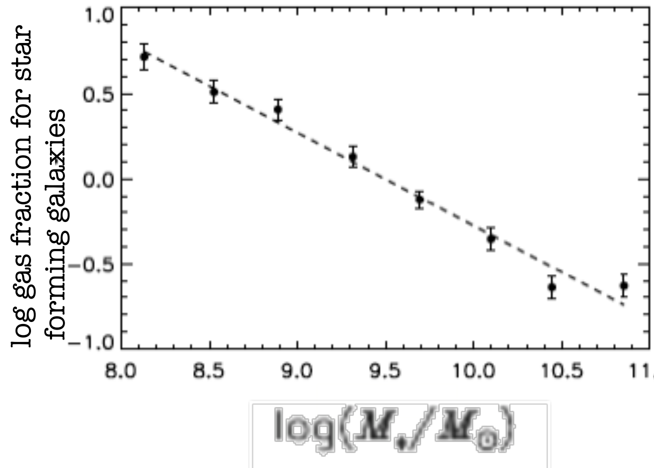
- Big Bang- its all dark matter, gas and radiation
- Dark matter halos grow by merging and accretion (e.g. Galaxies can grow by accretion of gas, by merging with gas rich galaxies and by merging with gas poor galaxies)

- 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 ....)

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- but lots of metals in dust
- A vast array of spectral diagnostics for the gas in both emission and absorption which can reveal
  - chemical composition
  - temperature
  - velocities
  - ionization mechanism
  - dark matter distribution

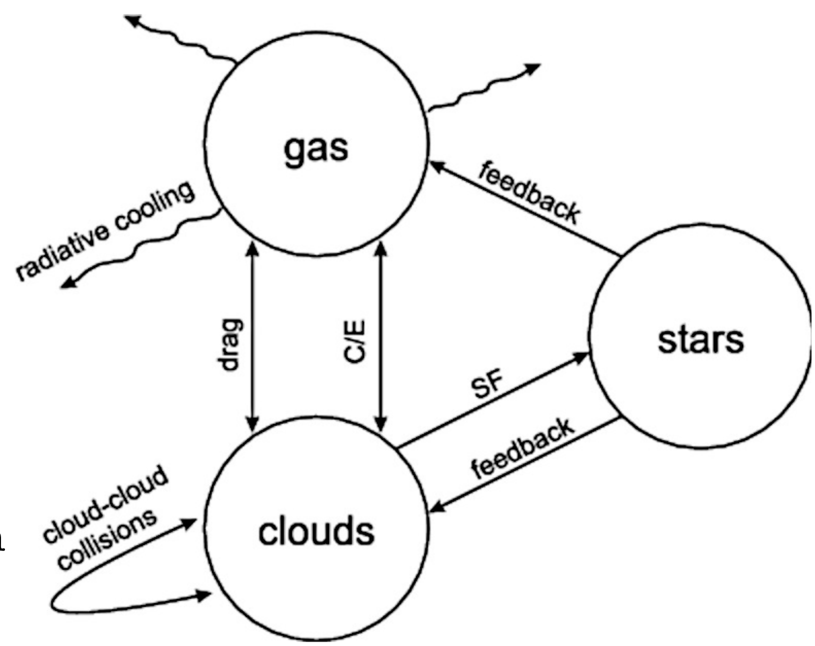


Peeples and Shankar 2011

As Stellar mass of galaxy increases, fraction of baryonic mass in gas decreases

Gas

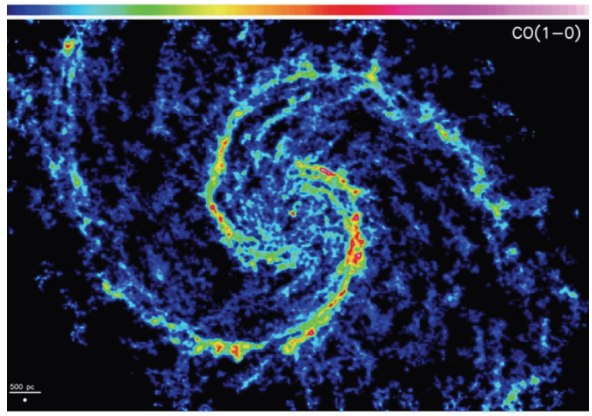
- interplay between the stars and gas
  - stars form out of the gas
  - enriched gas being ejected back into the interstellar medium from evolved stars.



Peeples and Shankar 2011

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
    - 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



CO Image of M51

Milky-Way-like galaxies cold gas mass~10% of the stars

CO is major tracer of molecular gas but ~ one CO molecule for every 10^4 of H_2.

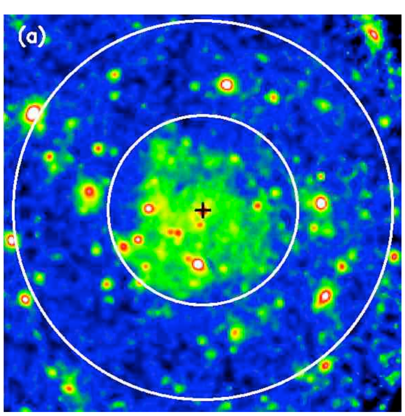
GAS-ISM

Hot gas (T~10^{6-7} k) dominant ISM in **elliptical** galaxies

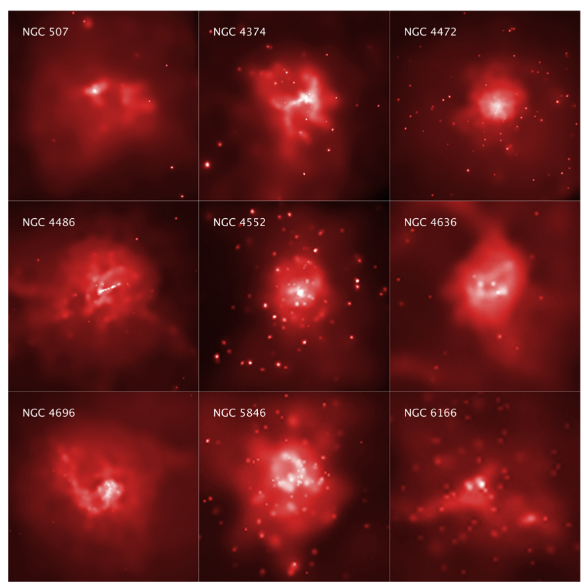
- seen via x-ray emission

In spirals

- hot gas volume filling (sponge-like topology) but low total mass



X-ray image of M101

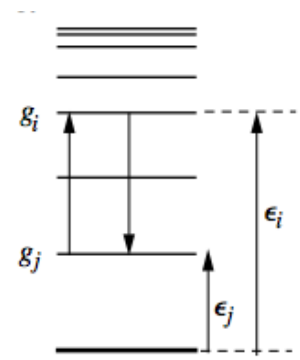


x-ray images of elliptical galaxies emphasizing structure

A Bit of Physics- see MBW

B1.3 Radiative Processes

- The rates of ionization and recombination are important (see eqs 2.21,2..22 in S+G); e.g. X^{+}+e ⟶ X+γ or
  $X^{0}+\gamma \rightarrow X^{-}$+e
- the rate at which ions recombine depends on
  - the ion density, X^{+} ,
  - the electron density
  - the recombination coefficient, α,
    - which depends on the ion, (e.g. the number of electrons it has and its atomic number)



In steady state # of ionizations= # of recombinations

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

Collisional Excitation (Pg 28 S&G)

- When atom A collides with atom B (or an electron) to form the excited state A*, can have the reaction
- A + B –⟶ A* + B, A* –⟶ A + $h_P \nu$.
- However, photon is emissited only if state A* decays before colliding yet again.
- Either the decay must be rapid, or the gas density quite low (e.g. probability of collision low).

(h_P= Plancks constant)

Ionization +Excitation Mechanisms

- Collisional Ionization and Collisional Excitation
  - 'hot' electrons collide with atoms/ions
- Photoionization and excitation
  - photons interaction with atoms/ions
- Shocks

Motions that are faster than the local speed of sound, give rise to *shocks.* energy of motion is converted into heat which excites/ionizes gas

A Bit of Physics

- Recombination rate for a given ion X⁺+ is (S&G eq 2.21)
- $-dn_e/dt = n^2_e \alpha(T_e)$

$\alpha(T_e) \approx 2 \times 10^{-13}(T_e/10^4)^{-3/4}$ cm^3 s^{-1} (temperature sensitive)

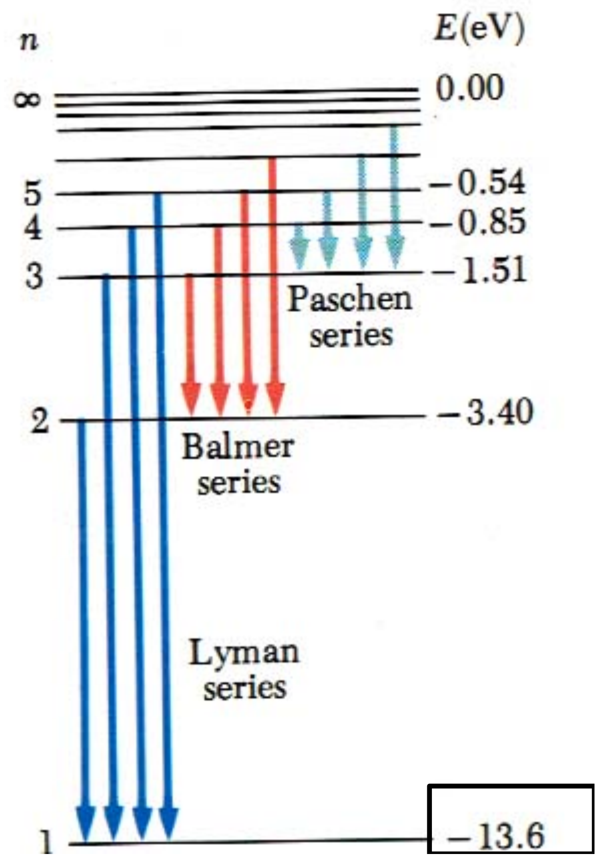
Recombination time (eq. 2.22) is
$t_{rec} = n_e|dn_e/dt| = 1/n_e\alpha(T_e) \approx 1500$ yr x $(T_e/10^4)^{-3/4}(100$ cm$^{-3}/n_e)$

n_e is the number density
the recombination time is the #of electrons/ the rate
$n_e/dn_e/dt$ ~ a few thousand years in a HII region- without continual ionization input gas recombines rapidly

This is NOT the same as the cooling time

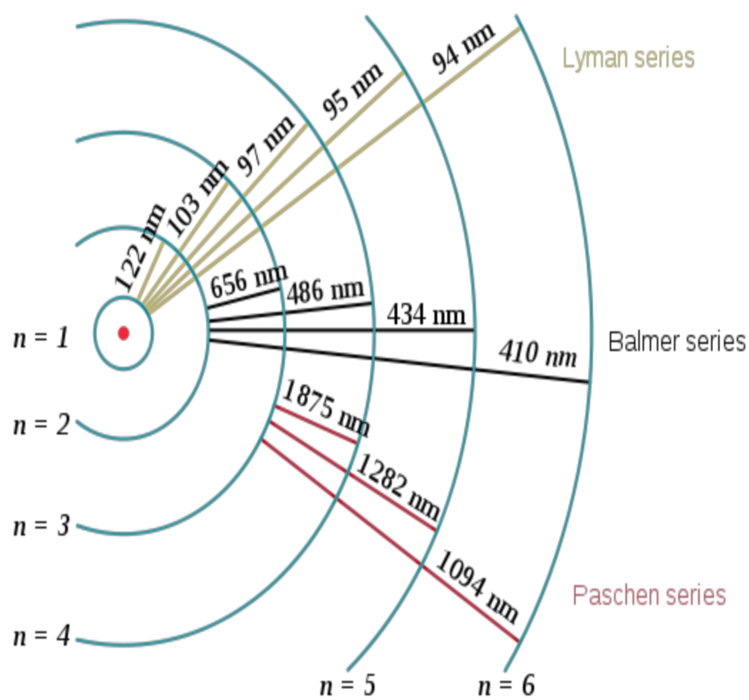
Atomic Lines

- The energy levels and transitions for **hydrogen**
  - **e.g Lyman is n⟶1**
  - Balmer is **n ⟶ 2**
- 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



Hydrogen Line Wavelengths

- Lyman lines are in the UV
- Balmer lines in the optical
- Paschen in the IR

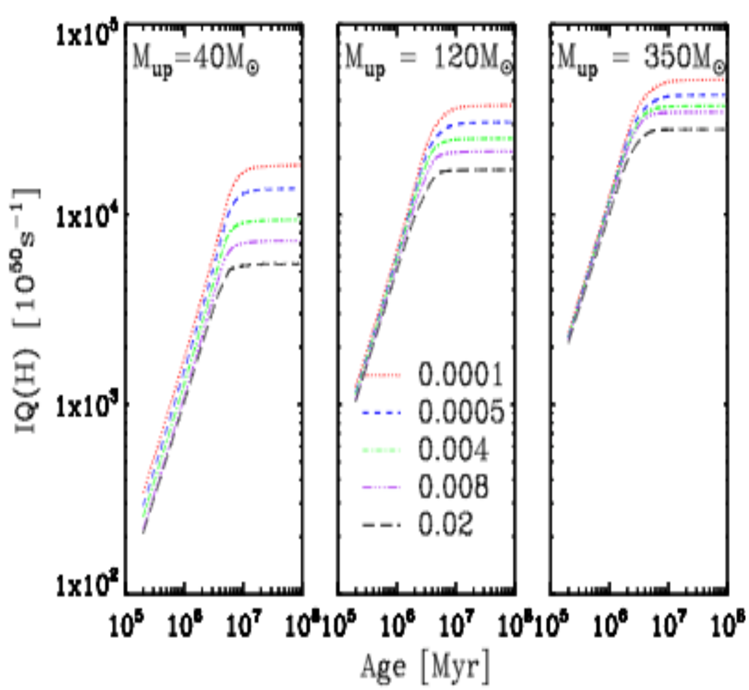


A Bit of Physics-Ionizing Photons

- 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 ...
- Pg 477 and ff in MWB also see https://ay201b.wordpress.com/2011/04/12/course-notes/#the_sound_speed for a LOT more detail (also covered in radiative processes course)

How Number of Ionizing Photons Changes

- The number of ionizing photons is VERY sensitive to the age of the system AND the maximum mass of the stars in the IMF (Obi et al 2017)
  - somewhat sensitive to metallicity (colored lines)



Physics of Emission from Gas-MWB sec 10.3.7

- 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.
- Three 'main modes of excitation
  - 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 (S&G eq. 3.58)
  - Shocks due to supernova

Physics of Emission from Gas-MWB sec 10.3.7

- 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) (see page 28 in S&G, table 2.5)

Physics of Emission from Gas (MWB B1.3)

- 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 (S&G pg 33)- 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 **Thermal radiation processes** J.S. Kaastra, F.B.S. Paerels, F. Durret, S. Schindler, P. Richter

Space Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008 astro-ph/0801.1011 for the background physics

Line Emission from Hydrogen (MBW 476-478)

- Balance the flux $\mathcal{F}$ (number of photons per unit time) by the recombination rate.
- $\mathcal{F}=\alpha_B N_p N_e V$; α_B is the recombination coefficient, N_p is the proton density, N_e is the electron density, V is volume.

- If the region is *optically thin* the line emission corresponding to a transition between states 1 and 2 is
- $L_{12}=4\pi\varepsilon_{12}V=h\nu_{12}VN_pN_e\alpha$
- This gives for $T=10^4$K
- $\mathcal{F}=0.45hN_pN_eV\nu_{H\alpha}$ and $H\alpha/H\beta=3.8$
- **Thus, by measuring the luminosity of a *HII region* in a recombination line, one can in principle infer the rate which, in turn, can be used to infer the number of OB stars that generate the ionizing photons**

A Bit of Physics-Relevant Velocities

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

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

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

where k_B is Boltzmann's constant and μ is the mean molecular weight of the gas (See S&G problem 2.21)

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

ISM- Relevant Velocities

Some characteristic values

- galactic rotation gradient 18km/sec/kpc
- Thermal sound speed ideal gas for H: 0.3, 1, 3 km/s at 10 K, 100 K, and 1000 K- most of the velocities measured in galactic gas are supersonic (e.g. gas is turbulent)

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 $\tau \sim \ell/v$ ℓ is length , v is velocity

$\ell \sim 1/n\sigma$; 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^{-2})

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

ℓ is mean free path

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

A Bit of Physics-TimeScales

For a sphere of gas, if thermal pressure is balanced by self-gravity the timescale to collapse (the **Jeans time**)

- $\tau_J \sim 1/\mathrm{sqrt}(4\pi G\rho)$ which is similar to the free falltime (S&G eq 3.23)-The *free-fall time* t_{ff} is roughly the time that a gas cloud of density ρ would take to collapse under its own gravity (Also see MWB pg 14)

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

- *Jeans length* $\lambda_J = c_s$ Sqrt($\pi/G\rho$) *S&G 2.24*

n_H is the particle density

ρ is the mass density

https://en.wikipedia.org/wiki/Jeans_instability;

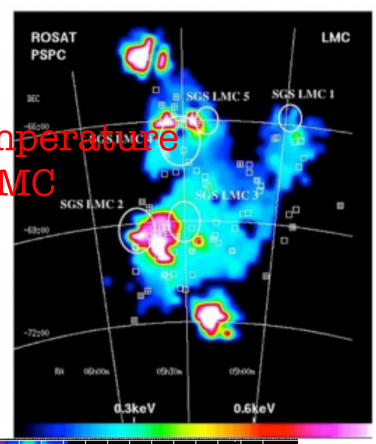
Simple Derivation of Jeans Collapse
S&G 8.5.1

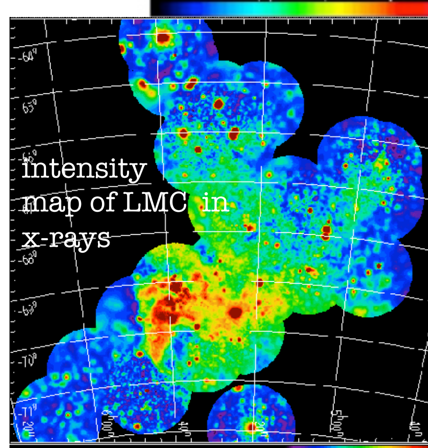
- Kinetic energy in cloud is $KE=(3/2kT)N$; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U=-3/5GM^2/R$ (uniform density sphere- derivation later in class)
- Using the viral theorem (lots more later)
  system is in equilibrium if $3NkT=(3/5)GM^2/R$
- So to collapse the internal energy <binding energy
- Assume all the mass is in hydrogen with a mass m per particle
- then to collapse $M_J>(5kT/Gm)^{3/2}(3/4\pi\rho)^{1/2}$ where ρ is the density (e.g. $(M/[4/3p\pi r^3])$)
- M is called the Jeans mass

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?

x-ray temperature map of LMC





intensity map of LMC in x-rays

Importance of the ISM

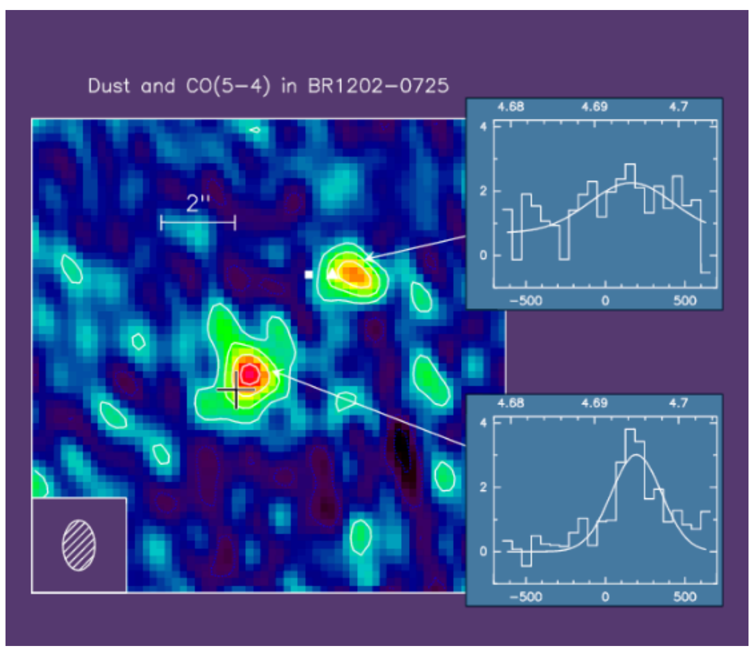
- **Despite its low mass, the ISM is very important**
- Crucial role in the star-gas cycle in spirals and irregulars,
  - it *facilitates* ongoing (& current) star formation
  - it is a repository for elements created in SNR and stars and therefore is a key to measure chemical evolution
- Because it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

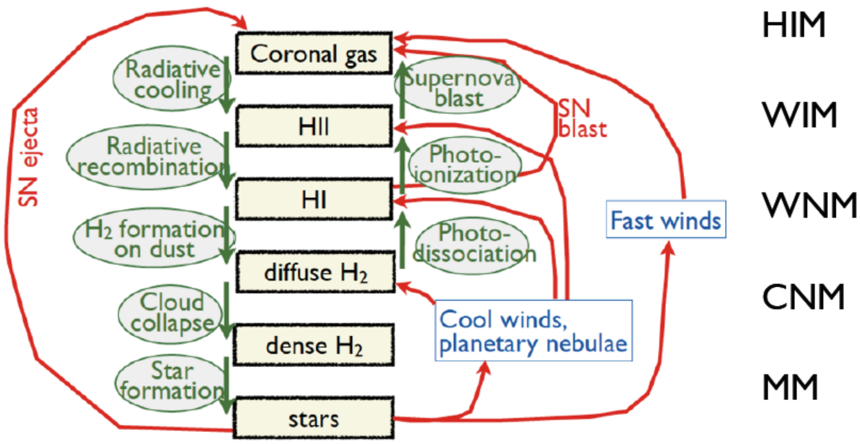


The ISM in Spirals is DYNAMIC-Driven by Star Formation

- 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)

Complex interaction between different phases

Fabian Walter



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