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/

Also Interstellar and Intergalactic Medium

By

Richard Pogge and Barbara Ryden- Only $9.95

I will be going thru material a bit too fast for derivations and **strongly recommend looking at the above 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 3different colors, 2 models with different metallicities (z) and He abundance (Y)

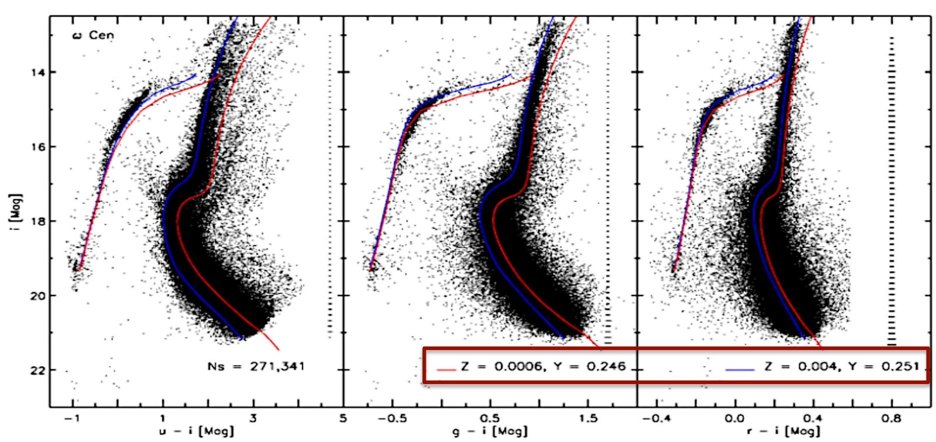
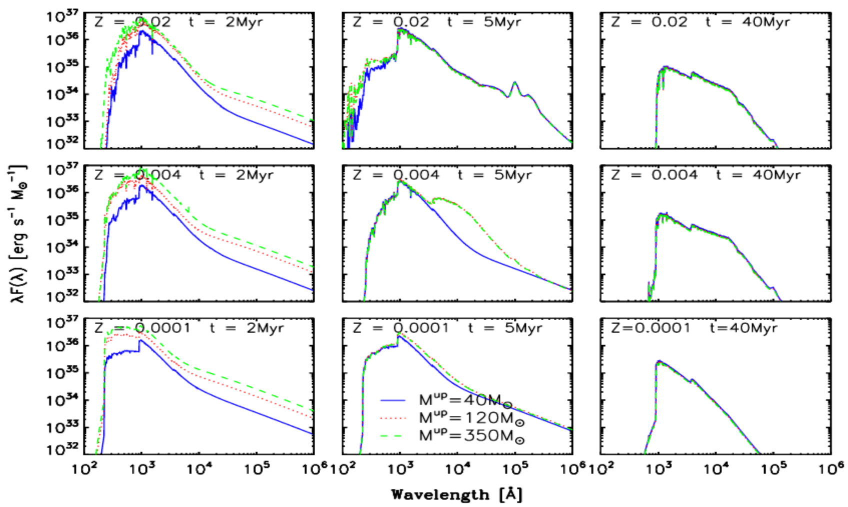


FIG. 6.— DECam *ugri* color-magnitude diagrams of ω Cen cluster members. Isochrones for the same age, $t = 12$ Gyr, and different metallicities are over-plotted (see labeled values). The respective zero age horizontal branch (ZAHB) tracks are also shown. Error bars are marked.

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



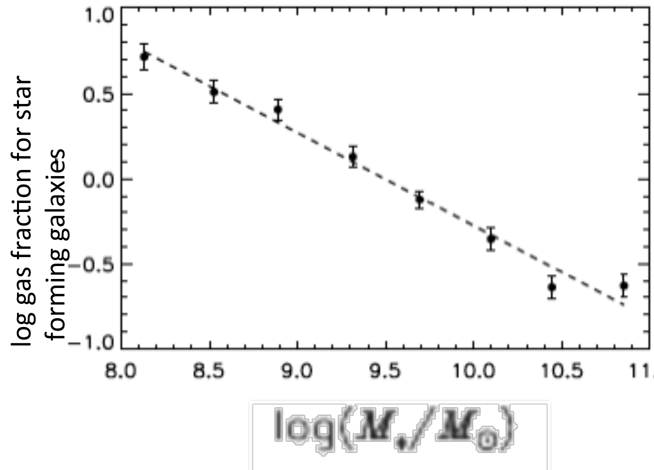
Gas- Big Picture

- 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

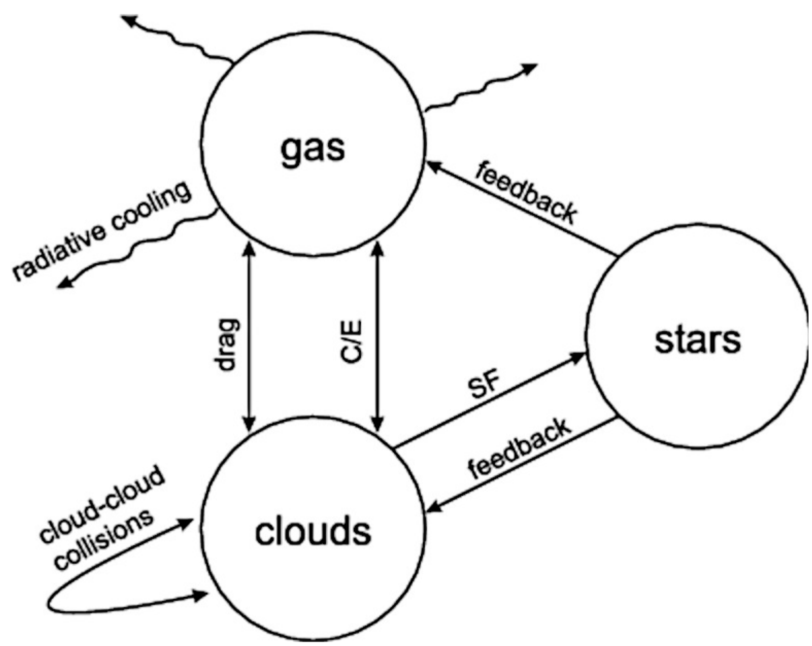


Peeples and Shankar 2011

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

Gas

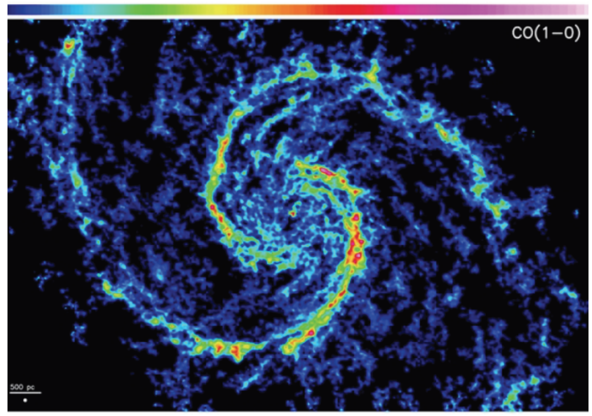
- interplay between the stars and gas
  - stars form out of the gas
  - enriched gas being ejected back into the interstellar medium from evolved stars.



Peeples and Shankar 2011

GAS-ISM

- 'Cold' gas: dominates in **Spirals**-*many phases*
  - neutral hydrogen (HI)
  - 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
  - hot ism



CO Image of M51

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

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

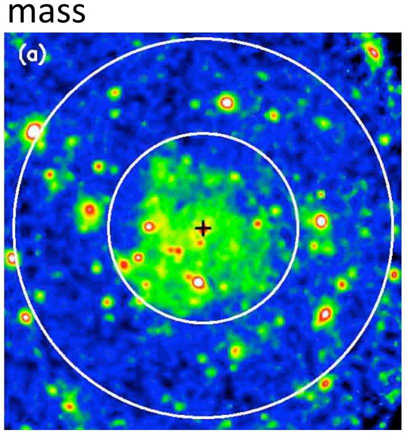
GAS-ISM

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

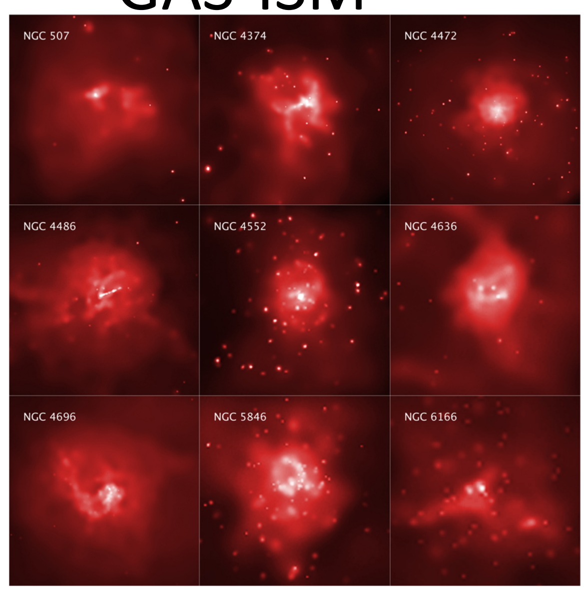
- seen via x-ray emission

In spirals

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



X-ray image of M101



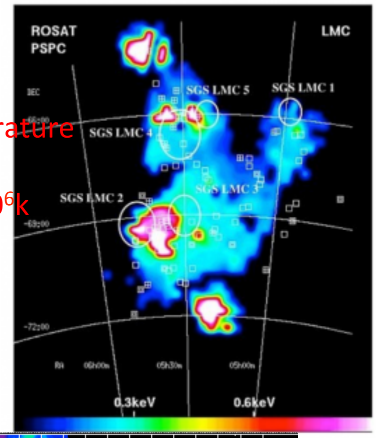
x-ray images of elliptical galaxies emphasizing structure

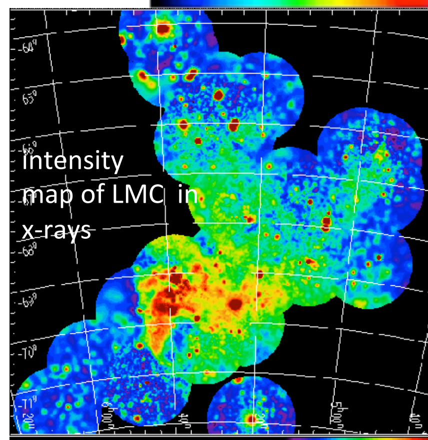
x-ray image of M101- 'dots' are x-ray binaries and SNR

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
0.6keV=7x10^6k





Importance of the ISM

- **Despite its relatively 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,

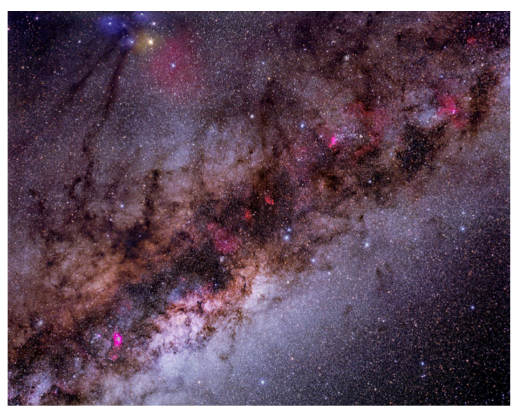
•can all be derived from observations of emission/ absorption lines
•lines are bright and can be seen (relatively) easily at cosmological distances.

Table 1.3: Energy densities in the ISM [Draine 2011 Table 1.5]

Type	Energy density ($eV\,cm^{-3}$)
Thermal energy	0.4
Turbulent kinetic energy	0.2
Cosmic microwave background	0.2606
Far-infrared from dust	0.3
Optical/near-IR from stars	0.6
Magnetic energy	0.9
Cosmic rays	1.4

How Does One Detect the ISM?

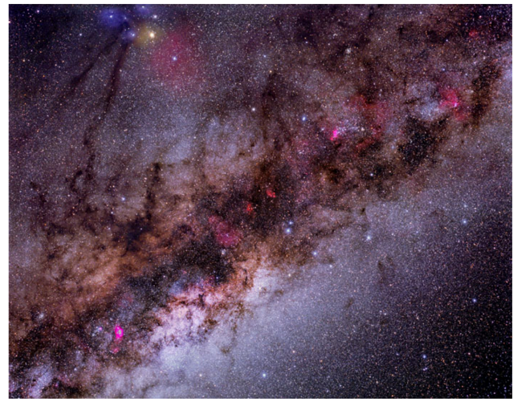
- Emission
  - lines
    - wide range representing many temperatures and species (radio thru x-ray)
  - continuum
    - bremmstrahlung
    - thermal from from dust
- Absorption in spectra of stars
  - lines (sharp compared to stellar atmospheres)
  - reddening/extinction



http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Intro.pdf

How Does One Detect the ISM?

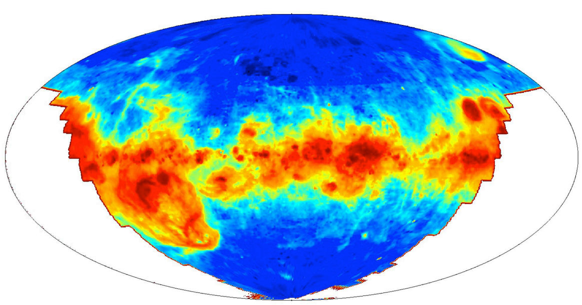
- Diffuse nebulae have spectra dominated by either bright optical/IR emission lines (William Huggins in the 1860s & James Keeler in the 1890s)
- or a reflected stellar absorption-line spectrum ("reflection nebulae"). Slipher's spectrum of the Pleiades reflection nebulosity in the early 20th century showed it to be reflected starlight.
- Diffuse x-ray emission, not due to point sources, with 'thermal spectrum

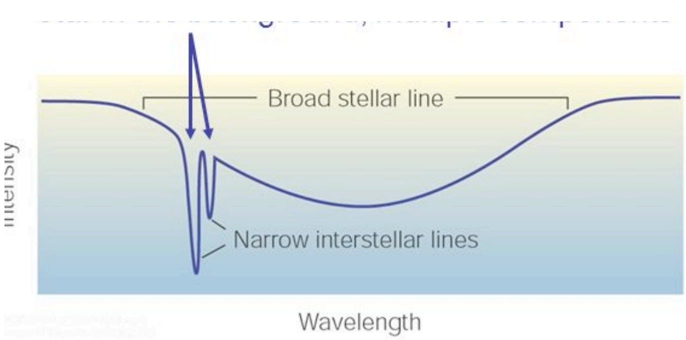


See http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Intro.pdf for an extensive historical discussion and the basic physics

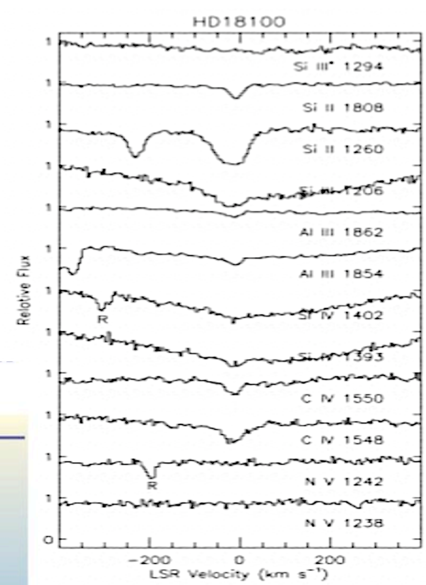
Observing the ISM

- Emission due to Hα





High Ionization UV absorption lines in spectra of a bright star



Physics of Emission from Gas-MWB sec 10.3.7, 14.2.4

- 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 (electrons do no have MB distribution, system not in equilibrium)

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

Please read Heiles and Troland 2002ApJ 586,1067 which discussed in much more depth the ISM revealed by HI observations

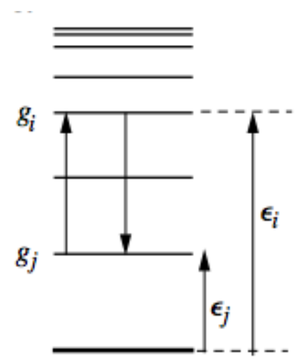
Please connect this to the physics of galaxies, the geometry of the ISM and the ecology of the ISM

OR
The Interstellar Environment of our Galaxy
Katia M. Ferri`ere astro-ph/0106359.pdf
Ch V- How Everything Fits together
Please s

A Bit of Physics- see MBW B1.3

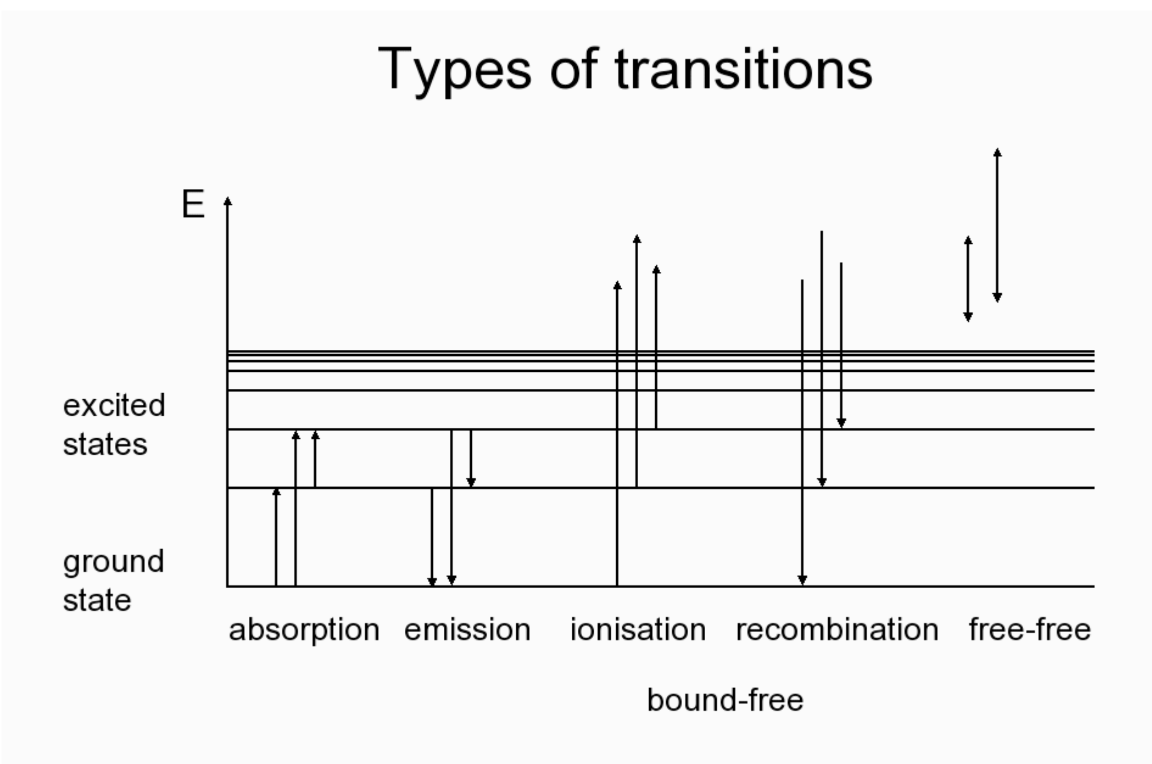
Radiative Processes

- The rates of ionization and recombination are important (see eqs 2.21,2..22 in S+G); e.g. $X^+ + e$ $X + \gamma$ or $\longrightarrow$
  $X^0 + \gamma \rightarrow X^- + e$
- 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



- http://www.astro.uu.se/~ulrike/Spectroscopy/PPT/Arten_von_Uebergaengen.GIF

Radiative Processes(sec B1.3 MBW)

- Bound–bound processes: These are the processes by which an electron makes a transition from one bound level to another bound level in an atom (or ion).
  - Such transitions can be made either by collisions with electrons (collisional excitation and de-excitation) or by interactions with photons (photon excitation, spontaneous and stimulated decay).
- Bound–free processes: These processes involve the removal of an electron from a bound orbit,
  - when an atom (or ion) collides with an electron (collisional ionization) or
  - when it absorbs a photon (photoionization).

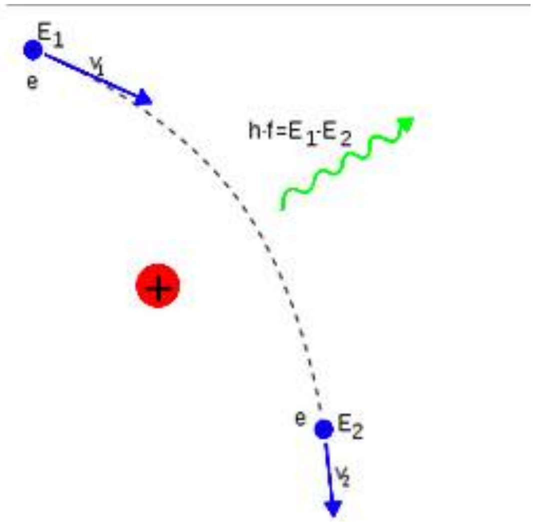
  The reverse process is recombination, by which a free electron recombines with an ion.
- Free–free processes: These processes involve electrons only in unbound (free) states.
  - a free electron is accelerated or decelerated, it emits photons through **bremsstrahlung.**
  - A free electron can also absorb a photon through free–free absorption.

Continuum

- Gas emits continuum radiation primarily via thermal Bremmstrahlung
- 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}

integral emissivity



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 spontaneous deexcitation.

Transition in the upward direction is by photoexcitation

For lots of details see MBW appendix B

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 and abundance of given element (corrected for ionization balance
- **Thermal radiation processes** J.S. Kaastra, F.B.S. Paerels, F. Durret, S. Schindler, P. RichterSpace Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008 astro-ph/0801.1011 for the background physics

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 emited 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)

If the decay is 'slow' the line being emitted is called 'forbidden'

If the decay is rapid the line is 'permitted'

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 $(T_e/10^4)^{-3/4} (100 \text{ cm}^{-3}/n_e)$

n_e is the number density

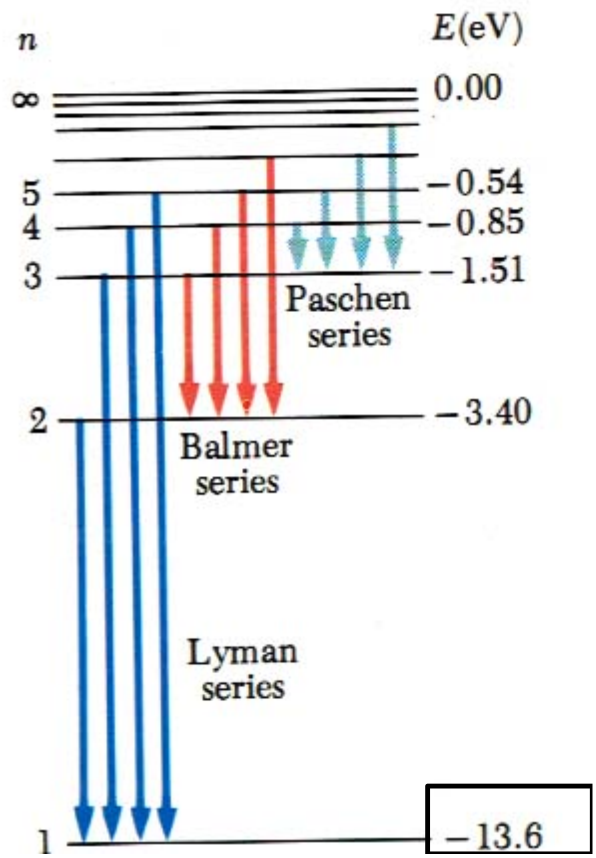
the recombination time is the #of electrons/ the rate

$n_e/dn_e/dt$ ~ 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 Lines (Again)

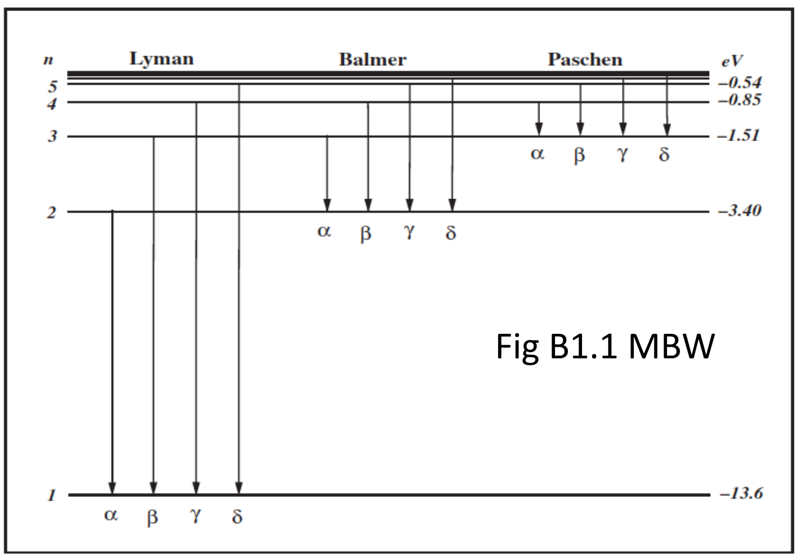
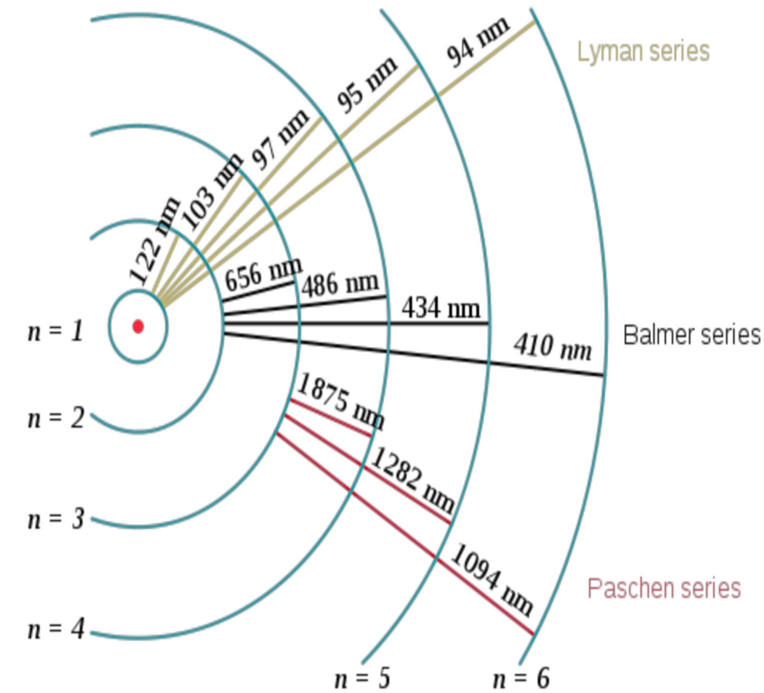


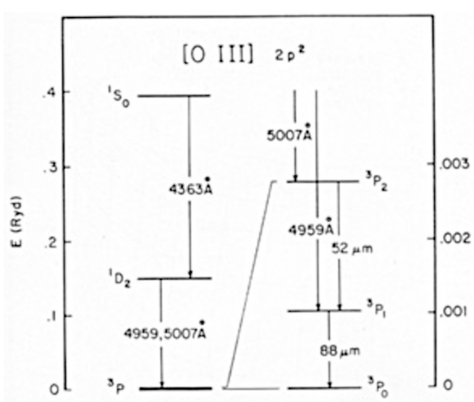
Fig B1.1 MBW

Hydrogen Line Wavelengths

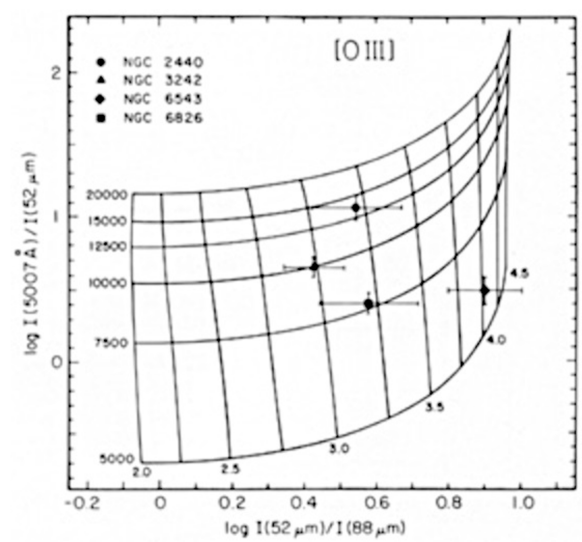
- Lyman lines are in the UV
- Balmer lines in the optical
- Paschen in the IR



Things Can Get Complex



Energy level diagram for [O III]. (From Dinerstein, Lester, & Werner 1985)



Temperature and density diagnostics using 3 lines dues to [OIII]

"Two Types" of Ionized Gas

- Photoionized
  - in ISM O and B stars ionize gas and produce HII regions and Planetary Nebulae
    - gas properties determined by density and spectrum of stars
  - Photoionization by the stellar radiation field is balanced by recombination into *excited* states of H.
  - (Total # of ionizing photons/sec emitted)=Total # of recombination into excited levels of H per second
- Collisional Ionization
  - Gas is heated by some process and ionization balance is controlled by collisions (ISM in elliptical galaxies)

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 477-478 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)

Ionization Balance

- In <u>collisional Ionization equilibrium</u> the fraction of a given element in a given ionization state is solely a function of **temperature**

Oxygen Iron

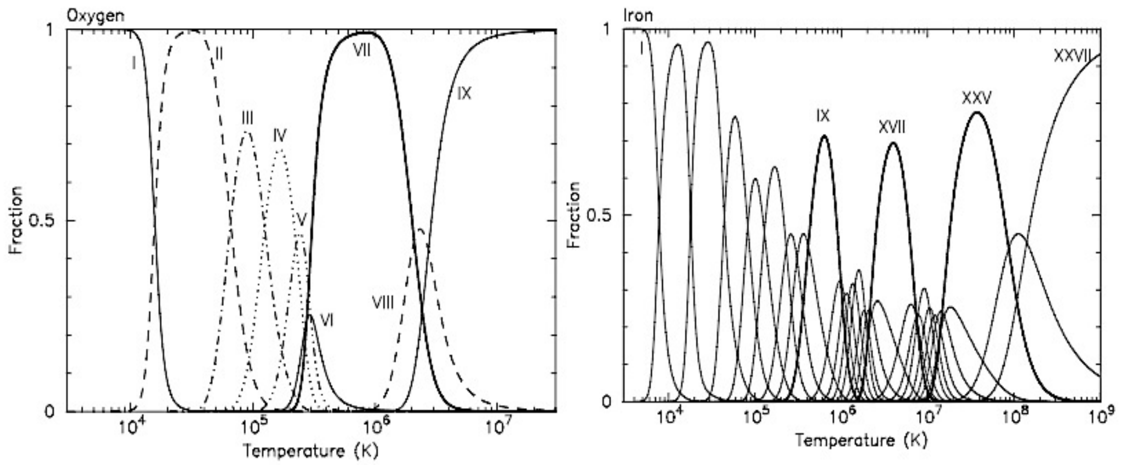
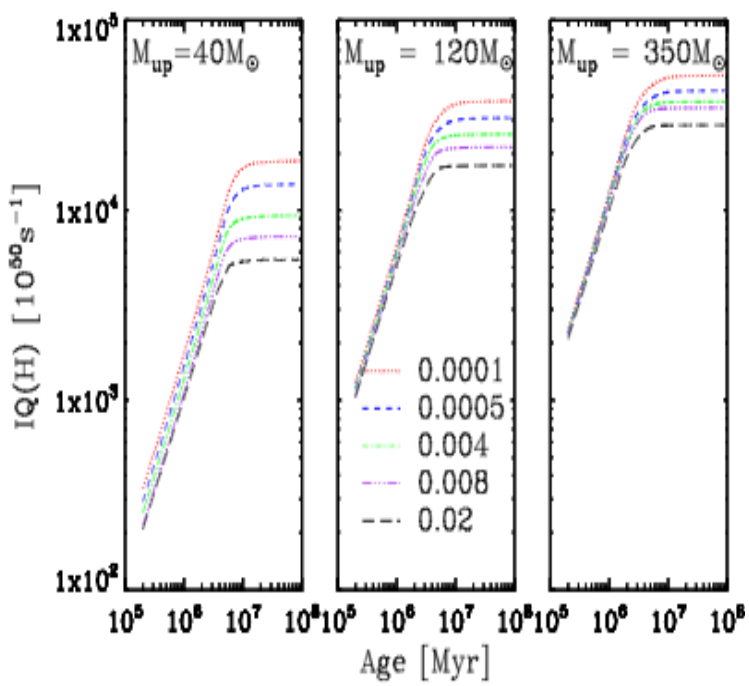


Fig. 7 Ion concentration of oxygen ions (left panel) and iron ions (right panel) as a function of temperature in a plasma in Collisional Ionisation Equilibrium (CIE). Ions with completely

How Number of Ionizing Photons Changes

- The number of ionizing photons IQ(H) 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

- 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)

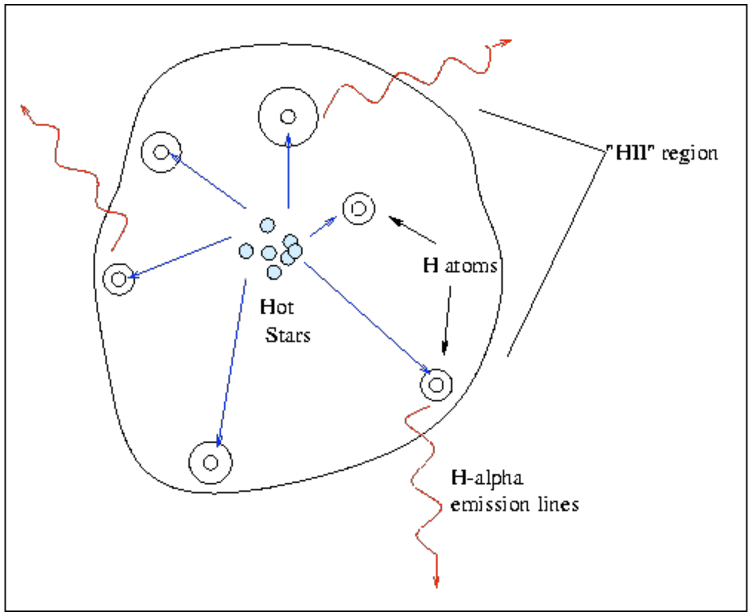
Physics of Emission from Gas (MWB B1.3)

- 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

HII Region



Line Emission from Hydrogen (MBW 476-478)

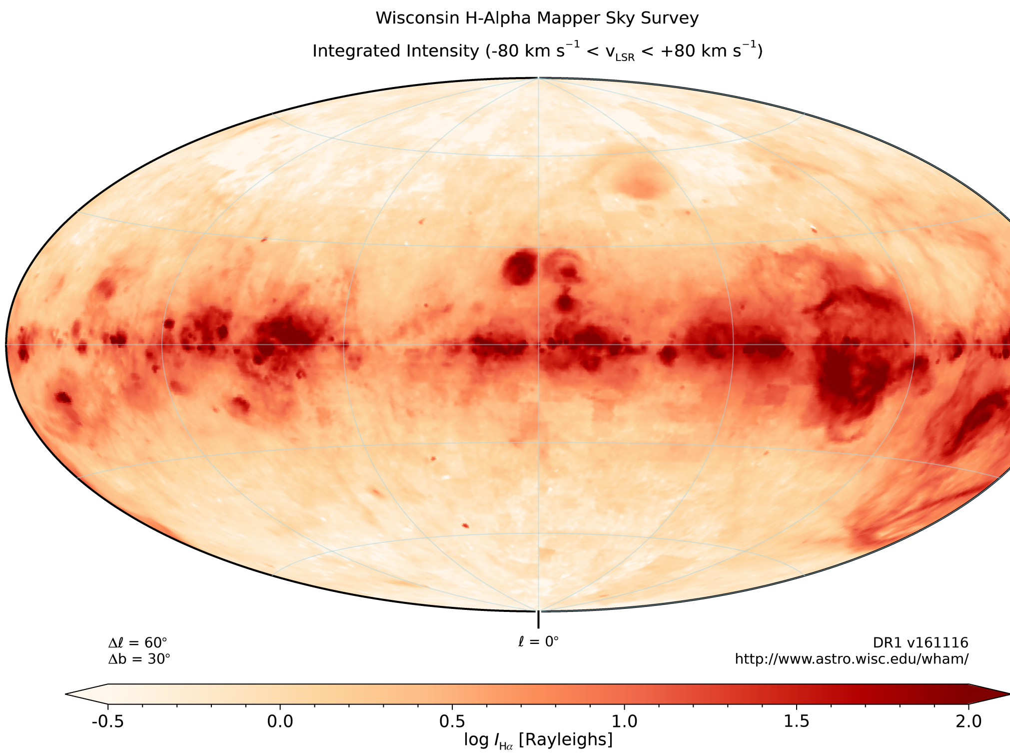
- Balance the flux $\mathcal{F}$ (number of photons per unit time) by the recombination rate.
- $\mathcal{F}=\alpha_B N_p N_e V$; α_B is the recombination coefficient, N_p is the proton density, N_e is the electron density, V is volume.

- 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 ; h= Plancks constant;V=colume

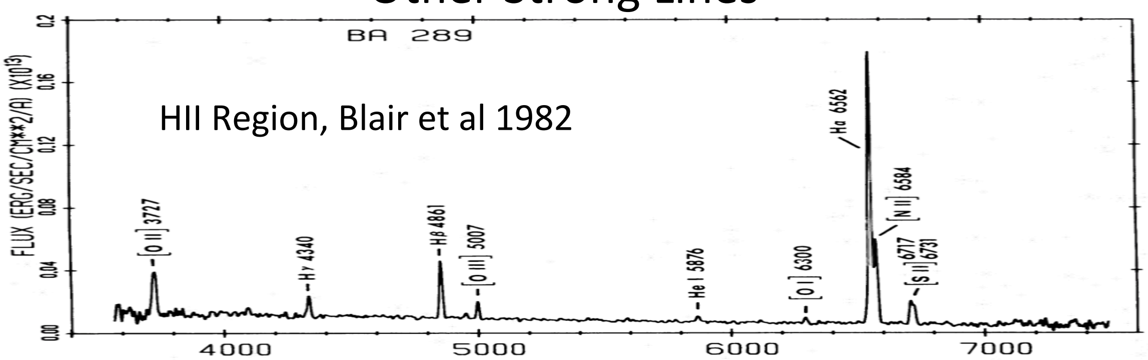
$\mathcal{F}=0.45hN_pN_eV\nu_{H\alpha}$ and $H\alpha/H\beta=3.8$

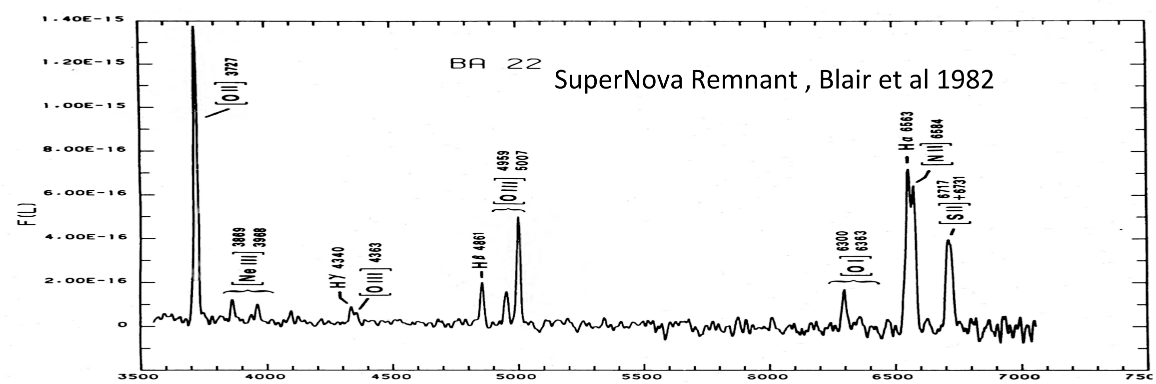
- **Thus, by measuring the luminosity of a *HII region* in a recombination line, one can in principle infer the rate which, in turn, can be used to infer the number of OB stars that generate the ionizing photons**

Hα Emission in the MW



Other Strong Lines





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

- Alfvén speed: The speed at which magnetic fluctuations propagate.

$v_A = B/\mathrm{sqrt}\{4\pi\rho\}$ Alfvén waves are transverse waves along the direction of the magnetic field.

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)

Alfven speed- for typical ISM values B=1μG, # density $n \sim 1\mathrm{cm}^{-3}$

$v_A = 2$ km/sec

- Given typical ISM conditions
  - $c_s \sim v_A$ in dense gas
  - $c_s < v_A$ in diffuse gas

A Bit of Physics- Scales

- 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) = ($1cm^{-3}$, 10^4)the collision time is 45 years

Jeans Length and Mass

- Jeans Length (smallest size that collapses)

$\lambda_J \sim sqrt(kT/G\rho m)$

- Jeans Mass : (smallest mass that collapses)
- $M_j \sim \rho L^3 \sim T^{3/2} \rho^{-1/2}$

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 x 10^4 yr /sqrt{n_H /10^6} if gas is hydrogen
- *Jeans length* $\lambda_J = c_s\,\mathrm{Sqrt}(\pi/G\rho)$ *S&G 2.24*

n_H is the particle density

ρ is the mass density

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

- Much of what we know—about the chemical evolution history of the universe depends upon the interpretation of the strong emission lines originating from HII regions.
- These emission lines enable us to investigate the metallicity evolution of the universe as a whole
- Measure the mass–metallicity relationship of disk galaxies
- Understand how chemical abundance gradients are formed and maintained
- They encode information about the history of star formation, mass infall, and radial mixing driven by viscous processes in galactic disks.

(adapted from Dopita et al 2013)

Simple Derivation of Jeans Collapse S&G 8.5.1

If the mass of a cold cloud, M_{cl}, exceeds the Jeans mass, *MJ*, it is subject to collapse under its own gravity

- 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

http://scienceworld.wolfram.com/physics/JeansLength.html

Simplest Derivation of Jeans Collapse

If the mass of a cold cloud, M_{cl}, exceeds the Jeans mass, *MJ*, it is subject to collapse under its own gravity

- Consider N atoms of mass min a box of size L and temperature T
- Thermal energy in cloud is E_{Th}~kTN; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U \sim GM^2/L$
- Ratio is $E_{th/}U \sim GM^2/LNkT \sim G(\rho L^3)m/LkT=L/L_J$ if $L_j \sim \mathrm{sqrt}(kT/G\rho m)$
- So to collapse the internal energy <binding energy
- Gravity wins when $U>E_{th}$ $L>L_{j;}$ Pressure wins for $L < L_J$

Large cool dense regions collapse.

Jeans Mass MBW Sec 4.1.3 pg 167

- Jeans length λ_J= distance a sound wave can travel in a gravitational free fall time- $t_{ff} \sim (G\rho)^{-1/2}$.
- For c_s= sound speed $\lambda_J = c_s \mathrm{sqrt}(\pi/G\rho)$

  $c_s = (5kT/3m)^{1/2}$ where m is the mass of the particle

$= \mathrm{sqrt}(5kT/4m\pi G\rho)$

Full up perturbation stability analysis https://ay201b.wordpress.com/2011/04/12/course-notes/#the_jeans_mass

Molecular Gas at High Redshift

- Observations of CO at z=4.69 when the universe was 2.1 Gyrs old
- ALMA can observe CO lines from luminous star forming galaxies at high redshift