How to Calculate Your Own Star

- Today on astro-ph
- arXiv:1509.06775 [pdf, ps, other] grayStar3 - gray no more: More physical realism and a more intuitive interface - all still in a WWW browser C. Ian Short
- The goal of the openStar project is to turn any WWW browser, running on any platform, into a virtual star equipped with parameter knobs and instrumented with output displays that any user can experiment with using any device for which a browser is available. .... The code integrates scientific modeling in JavaScript with output visualization HTML. The user interface is adaptable so as to be appropriate for a large range of audiences from the high-school to the introductory graduate level. The modeling is physically based and all outputs are determined entirely and directly by the results of in situ modeling, giving the code significant generality and credibility for pedagogical applications.
- gS3 also models and displays the circumstellar habitable zone (CHZ) and allows the user to adjust the greenhouse effect and albedo of the planet. In its default mode the code is guaranteed to return a result within a few second of wall-clock time on any device. The more advanced user has the option of turning on more realistic physics modules that address more advanced topics in stellar astrophysics.
- gS3 is a public domain, open source project and the code is available from www.ap.smu.ca/~ishort/grayStar3/ and is on GitHub. gS3 effectively serves as a public library of generic JavaScript+HTML plotting routines that may be recycled by the community.

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

Gas- Big Picture

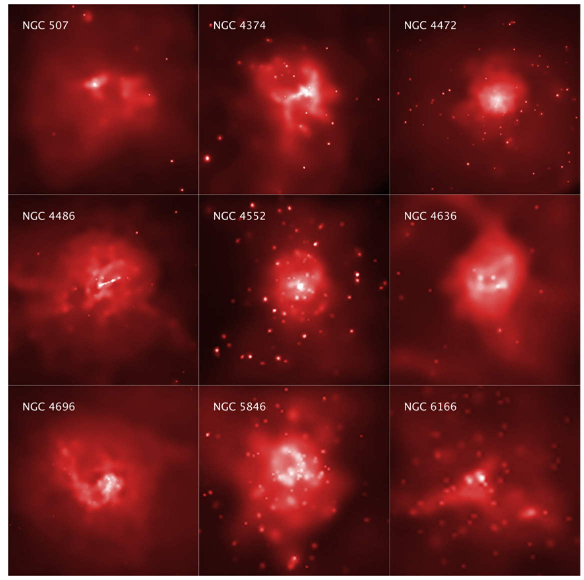
- Dark matter halos grow by merging and accretion (e.g. Galaxies can grow by accretion of gas, by merging with gas rich galaxies and by merging with gas poor galaxies)
- Gas falls into these halos, cools and forms stars.
- How does this occur- the physics of gas accretion,
  - How and when did galaxies accrete their gas and what do they do with it (e.g. form ISM, stars, expel the gas, feed the supermassive black hole ....)

Paper to Read

- Please read http://arxiv.org/abs/0906.0605 Dotter et al in Proceedings of IAU Symposium 258: The Ages of Stars
- How well can we measure the ages of stars

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

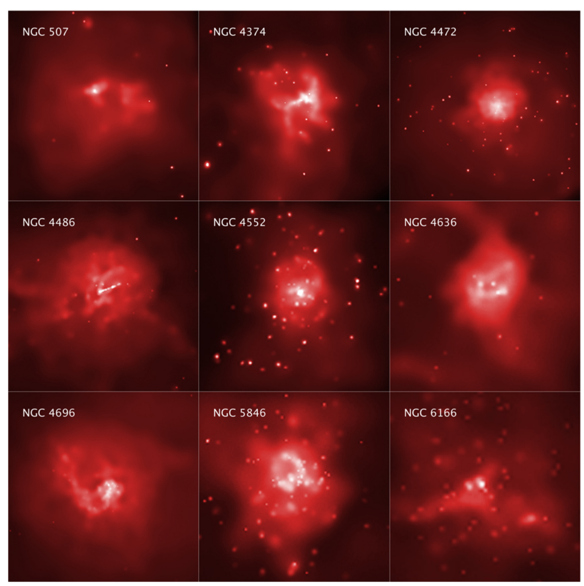


x-ray images of elliptical galaxies emphasing structure

GAS-ISM

- Milky-Way-like galaxies cold gas mass~10% of the stars
- For lower mass galaxies the baryonic fraction in gas is larger; at $M_{\mathbf{star}}<10^{9.5}M_{\odot}$ gas dominates the baryonic content
- Hot gas ($T\sim10^{6\text{-}7}$ k) <u>dominant</u> ISM in **elliptical** galaxies

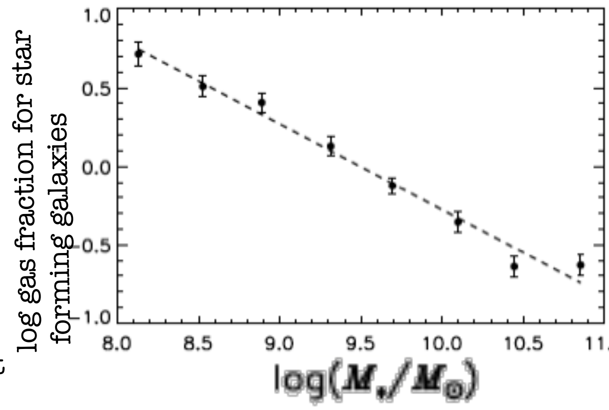
In spirals hot gas fills the volume but low total mass



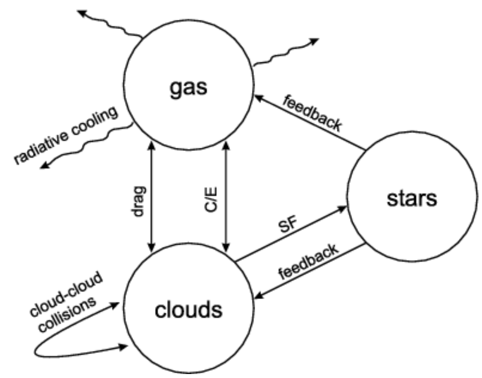
x-ray images of elliptical galaxies emphasing structure

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
  - temperature
  - velocities
  - ionization mechanism

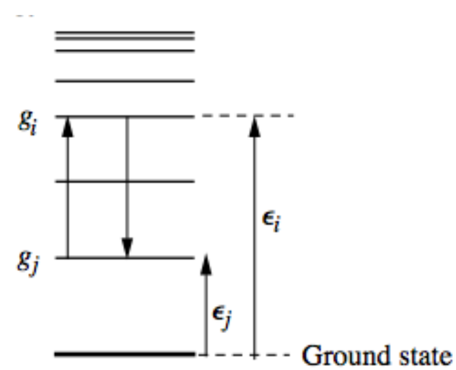


Peeples and Shankar 2011



A Bit of Physics

- 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 induced deexcitation. Transition in the upward direction is by photoexcitation or collisional excitation



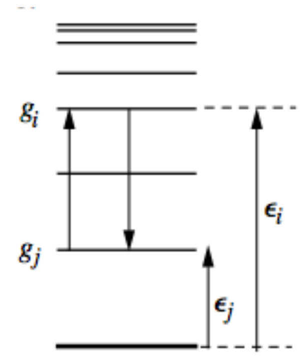
For lots of details see MBW appendix B

A Bit of Physics

- The rates of ionization and recombination are important (see eqs 2.21,2..22 in S+G); e.g. $X^+ + e^- \longrightarrow X + \gamma$
- the rate at which ions recombine thus clearly depends on the ion density, X^+ and the electron density and the recombination coefficient, α, which depends on the ion, (e.g. the number of electrons it has and its atomic number)
- Thus recombination rate of electrons for a given ion X^++ is

  $dn_e/dt = n_{x+} n_e \alpha(T_e)$;
- the recombination time is the #of electrons/ the rate :$n_e/dn_e/dt$

  a few thousand years in a HII region - α the recombination rate depends on QM and Boltzmann's law

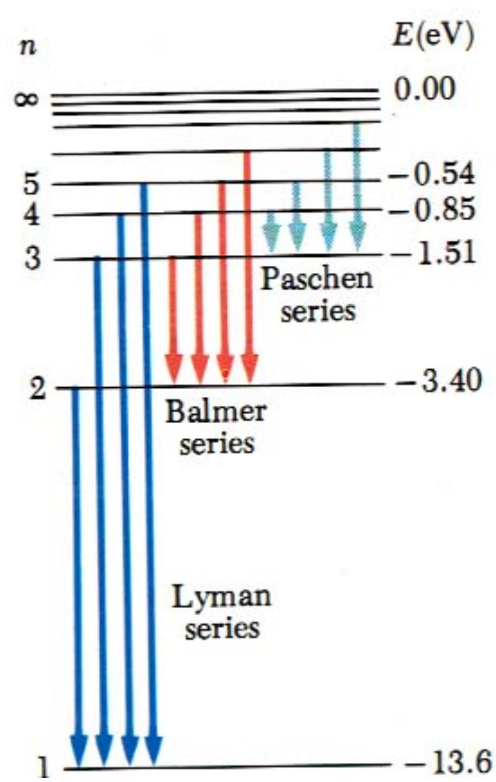


In steady state # of ionizations= # of recombinations

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

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)- effects of radiative transfer in stellar atmospheres of hot stars is VERY important

- These photons ionize and heat the gas
- The gas responds by emitting lines characteristic of the chemical composition, temperature, ionization state, density etc ...

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

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.
- 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
- 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).

Line Emission from Hydrogen (MBW 476-478)

- Need detailed balance the flux $\mathcal{F}$ (number of photons per unit time) has to be balanced 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

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

c_s=sqrt($k_B T/\mu$)

where k_B is Boltzmann's constant and μ is the mean molecular weight of the gas

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

Reason: an increase in temperature due to compression will be followed by radiative cooling to the original equilibrium temperature.

Alfvén speed: The speed at which magnetic fluctuations propagate.

v_A = B /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, t is 0.3, 1, and 3 km/s at 10 K, 100 K, and 1000 K- most of the velocites measured are supersonic (e.g. gas is tubulent)

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

  v_A= 2 km/sec

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 $\tau \sim \ell/v$; $\ell \sim n\sigma$; 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})

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 x 10^4 yr /sqrt{n_H /10^6}

https://en.wikipedia.org/wiki/Jeans_instability; $n_H$is the particle density

ρ is the mass density

Simple Derivation of Jeans Collapse

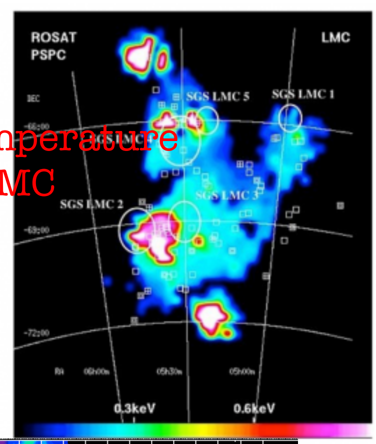
- Kinetic energy in cloud is $KE=(3/2kT)N$; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U=-3/5GM^2/R$ (uniform density sphere- derivation later in class)
- Using the viral theorm (lots more later)

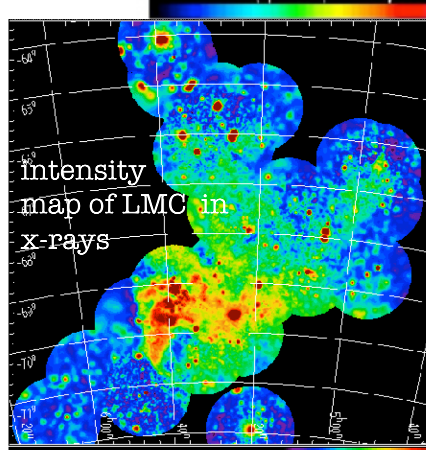
  system is in equilibrium if $3NkT=(3/5)GM^2/R$
- So to collapse the internal energy <binding energy
- Assume all the mass is in hydrogen with a mass m per particle
- then to collapse $M>(5kT/Gm)^{3/2}(3/4\pi\rho)^{1/2}$ where ρ is the density (e.g. $(M/[4/3p\pi r^3])$)
- M is called the Jeans mass
- The material to read is Spitzer 1978- Physical Processes in the ISM pg 286-287 (see web page for text)

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





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 (board)
- 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

Importance of the ISM

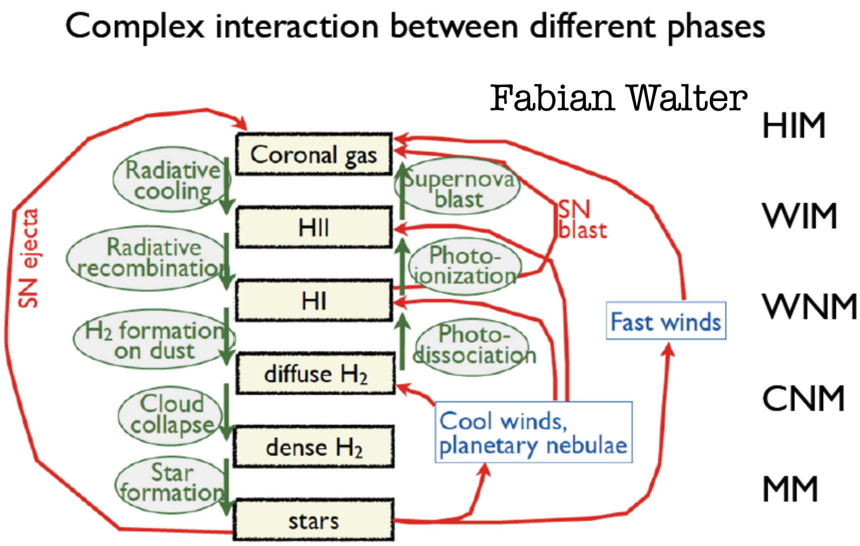
- Despite its low mass, the ISM is very important
- crucial role in the star-gas cycle in spirals and irregulars,
  - it facilitates ongoing (& current) star formation
  - it is a repository for elements created in SNR and stars and therefore is a key to measure chemical evolution
- Because it can cool,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

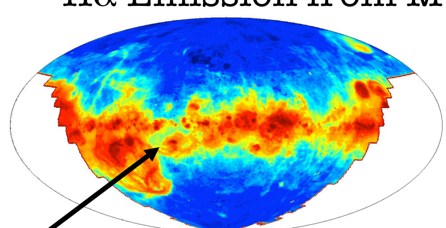


At low redshift ISM in spirals not affected much by AGN

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

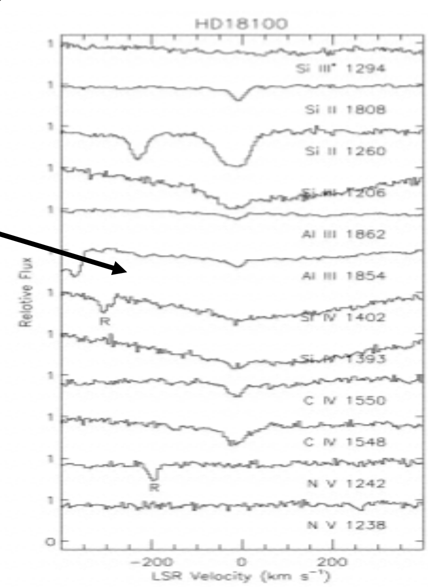
How Does One Observe the ISM (sec 5.2 in S&G)

Hα Emission from MW



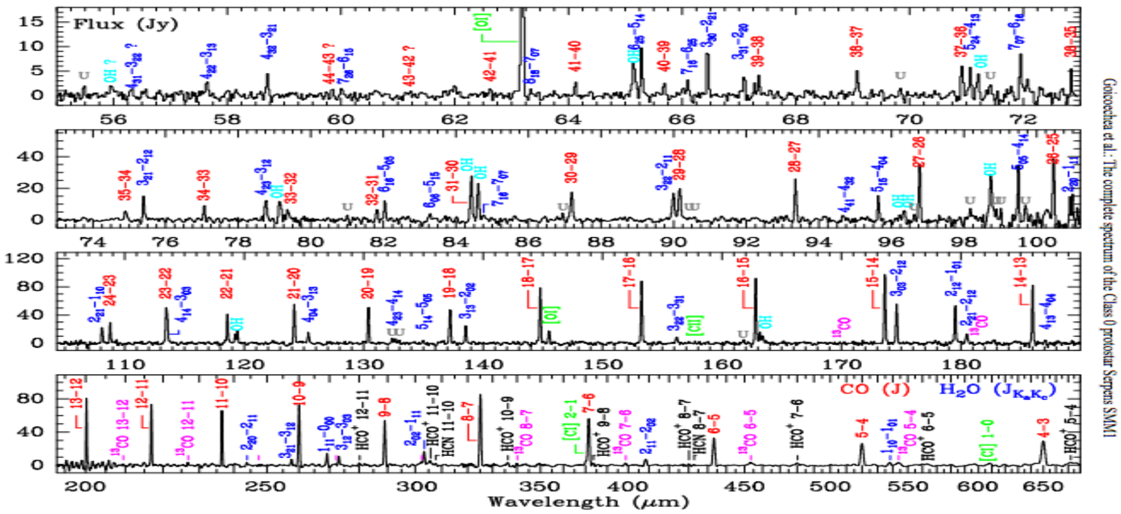
- Because of the wide range in temperatures and densities a wide variety of techniques are needed
- Radio:
  - free-free emission and 21cm for HI
  - high freq radio-far IR (CARMA, ALMA, Herschel) wide variety of molecular lines
- IR spectral lines [OI]63,145um and [CII]158 and [CI]370,609um
- Optical/UV
  - 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 $T\sim10^6$-10^7k gas (spirals and ellipticals) - gas is collisionally ionized

γ-ray
  - interaction of cosmic rays with gas



Far IR Lines

- 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



- this paper (Goicoechea et al 2015 ApJ 799 102) is very recent data from the Herschel observatory on Far IR lines from a star forming region but is too detailed for a discussion in the class.
-

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.

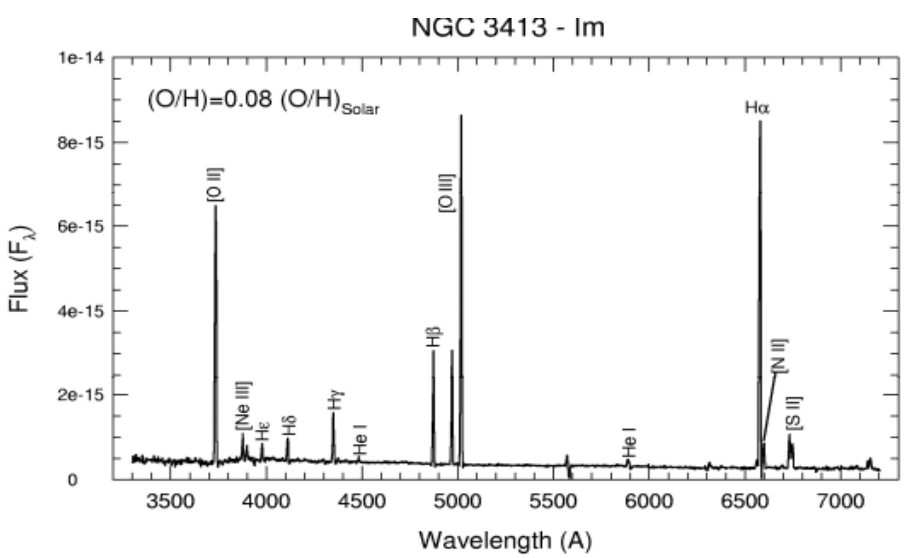
Fabian Walter

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 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 pressure of the gas . The magnetic fields therefore affects the dynamics of the ISM

- Book on the subject Bruce Draine ' Physics of the Interstellar and Intergalactic Medium' Princeton series on Astrophysics

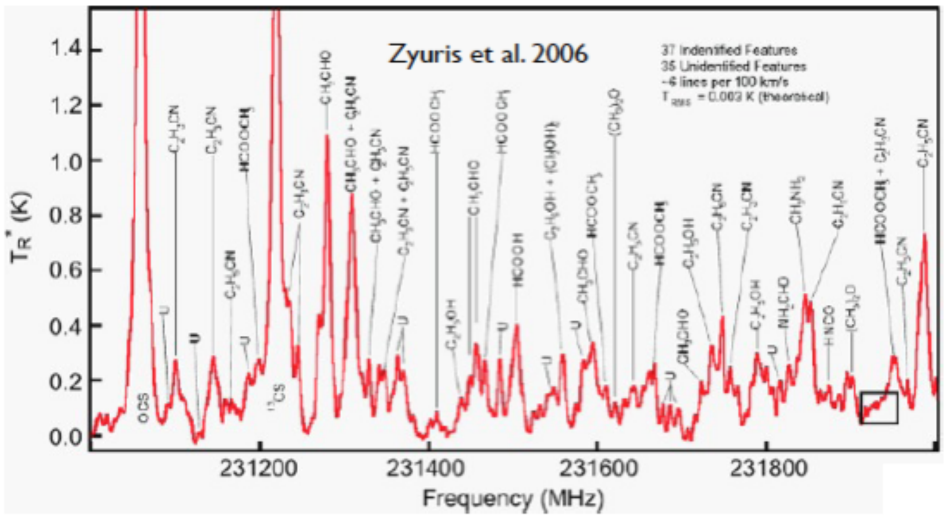
Optical spectrum of HII Region



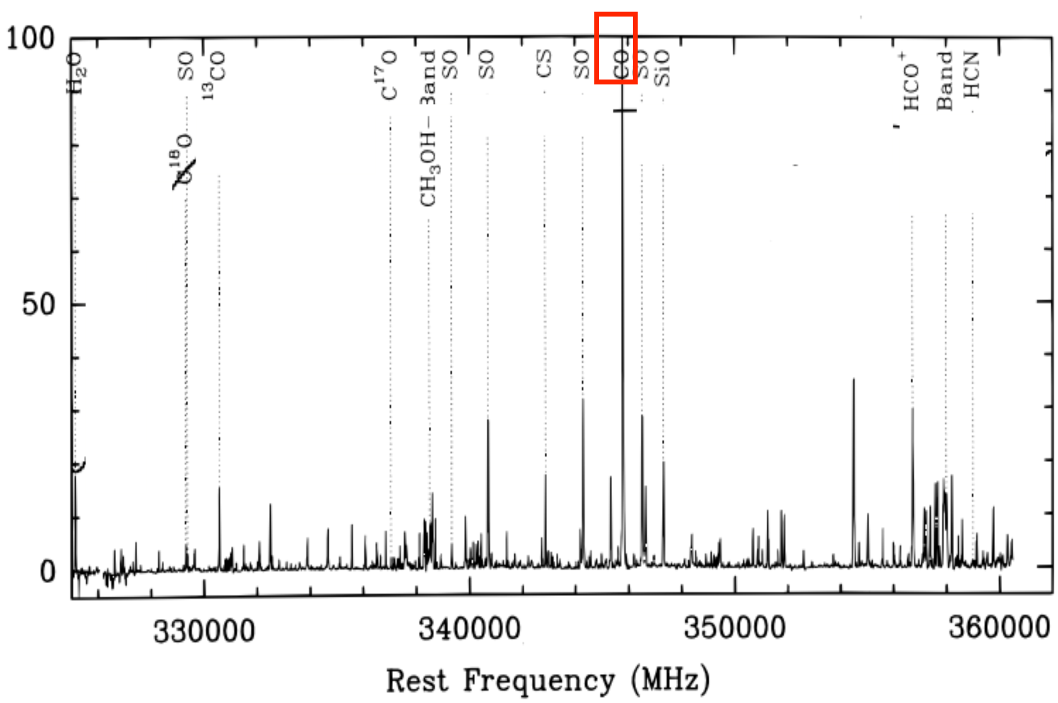
- Optical spectrum show lines due to [OII]. [OIII],Hα, [NII], etc

Molecular Lines

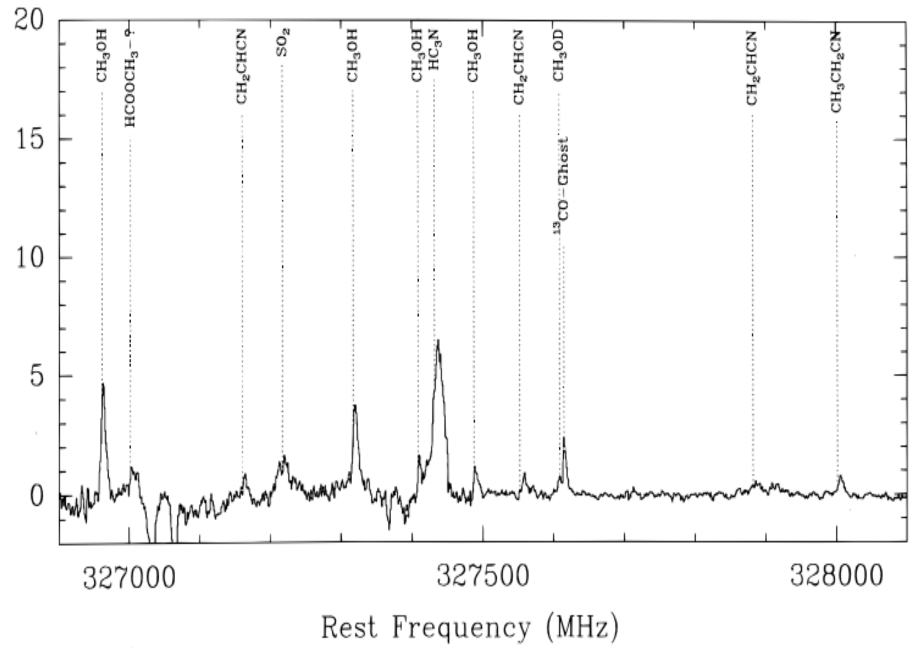
- Molecular clouds are very rich in spectral features from a wide variety of molecules- lots of information
- Some of the lines (CO) are so strong that they can be seen at high redshift



Millimeter Band Spectrum of Molecular Cloud



Millimeter Band Spectrum of Molecular Cloud



- zoom in on previous plot

How do Molecules Emit Radiation

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

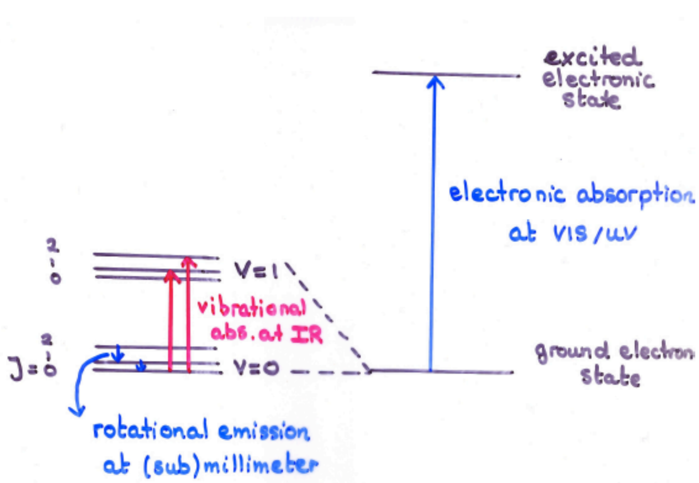
Infrared absorption: vibrational transitions

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

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



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;

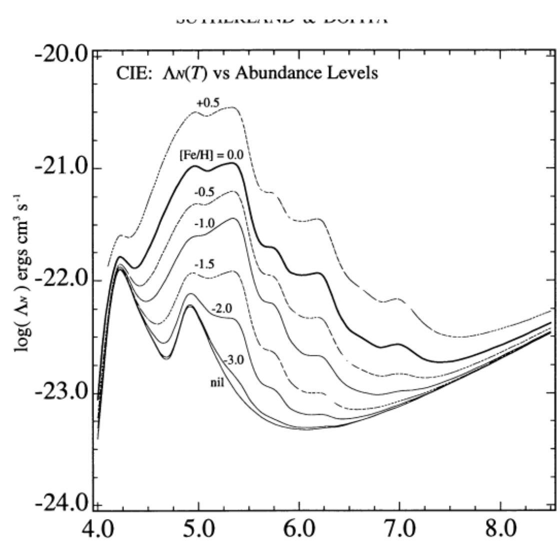
Gas Cooling

- 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**)

Reference on Cooling via molecular rotational lines and dust emission (Neufeld, Lepp and Melnick (1995, Ap.J.Supp., 100, 132)

Gas Cooling $L=n^2\Lambda(T)$ MWB sec 8.1.3, 8.4

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



log T

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