ASTR 5470 Physics of the Interstellar Medium

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The interstellar environment of our galaxy

Katia M. Ferrière*

Observatoire Midi-Pyrénées, 31400 Toulouse, France

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This article reviews the current knowledge and understanding of the interstellar medium of our galaxy. The author first presents each of the three basic constituents—ordinary matter, cosmic rays, and magnetic fields—of the interstellar medium, with emphasis on their physical and chemical properties as inferred from a broad range of observations. The interaction of these interstellar constituents, both with each other and with stars, is then discussed in the framework of the general galactic ecosystem.

CONTENTS

I. INTRODUCTION

The stars of our galaxy—traditionally referred to as "the Galaxy" with a capital G to distinguish it from the countless other galaxies—are embedded in an extremely tenuous medium, the so-called "interstellar medium" (ISM), which contains ordinary matter, relativistic charged particles known as cosmic rays, and magnetic fields. These three basic constituents have comparable pressures and are intimately bound together by electromagnetic forces. Cosmic rays and magnetic fields influence both the dynamics of the ordinary matter and its spatial distribution at all scales, providing, in particular, an efficient support against the gravitational force. Conversely, the weight of the ordinary matter confines magnetic fields and, hence, cosmic rays to the Galaxy, while its turbulent motions can be held responsible for the amplification of magnetic fields and for the acceleration of cosmic rays.

The ISM encloses but a small fraction of the total mass of the Galaxy. Moreover, it does not shine in the sky as visibly and brightly as stars do. Yet it plays a vital role in many of the physical and chemical processes taking place in the Galactic ecosystem.

The most important aspect of Galactic ecology is probably the cycle of matter from the ISM to stars and back to the ISM. In the first step of this cycle, new stars form out of a reservoir of interstellar material. This material, far from being uniformly spread throughout interstellar space, displays dramatic density and temperature contrasts, such that only the densest, coldest molecular regions can offer an environment favorable to star formation. In these privileged sites, pockets of interstellar gas, losing part of their magnetic support, tend to become gravitationally unstable and collapse into new stars.

Once locked in the interior of stars, the Galactic matter goes through a succession of thermonuclear reactions, which enrich it in heavy elements. A fraction of this matter eventually returns to the ISM, be it in a continuous manner via powerful stellar winds or in an instantaneous manner via supernova explosions (violent stellar outbursts resulting from a thermonuclear instability or from the sudden gravitational collapse of the core of some stars at the end of their lifetimes). In both cases, the injection of stellar mass into the ISM is accompanied by a strong release of energy, which, in addition to generating turbulent motions, contributes to maintaining the highly heterogeneous structure of the ISM and may, under certain circumstances, give birth to new molecular regions prone to star formation. This last step closes the loop of the partly self-induced ISM-star cycle.

Thus the interstellar medium is not merely a passive substrate within which stars evolve; it constitutes their direct partner in the Galactic ecosystem, continually exchanging matter and energy with them and controlling many of their properties. It is the spatial distribution of the interstellar material together with its thermal and chemical characteristics that determines where new stars form as well as their mass and luminosity spectra. These, in turn, govern the overall structure, the optical appearance, and the large-scale dynamics of the Galaxy. Hence understanding the present-day properties of our Galaxy and being able to predict its long-term evolution require a good knowledge of the dynamics, energetics, and chemistry of the ISM.

*Electronic address: ferriere@ast.obs-mip.fr

The ISM is composed of dust and ______+_______+_______ gas
Tielens also refers to ‘energy sources’ like ___________, _____, ________, ________, ________

Interstellar gas & dust

critical to both stellar (*) and Galactic astronomy
10-15% of the total mass of the Galactic disk; ½ of this in 1-2% of volume

where?

1) probe of *s (e.g., OB* ⇒ UV ⇒ HII) and AGN (e.g., dust tori, broad lines)
2) probe of galactic structure, dynamics, evolution, metallicity NGC 300, NGC 628, NGC 4038/39
3) source of renewal for *s
4) ISM is reactive and dissipative on short timescales

Much of the activity in the ISM is due to star formation (SF)

Though by mass the constituents of the interstellar medium comprise a small portion of a galaxy, the physical and chemical processes that occur within the interstellar medium shape the structure, appearance, and large-scale dynamics of most galaxies (Hollenbach & Tielens 1999; Ferriere 2001). *Perhaps the most significant scenario played out in the interstellar medium is the cycle of material from stars to the interstellar medium and back again.*

OB*
1) luminous ⇒ dominates optical appearance of galaxies NGC 6946
2) energetic ⇒ heat (photo-ejected e^-) & kinetic energy (snowplows) to ISM
3) replenish ISM ⇒ ensuing *s have higher metallicity

History of ISM: How do we know there is an ISM? Dust was known first

1) **dust** a) Herschel (~1800): holes in the distribution of stars

b) star counts; Struve (1847) claimed ISM absorbs 1 mag/kpc

Barnard photography supported Struve (1900)

c) cluster properties; Trumpler (1930) found that smaller angular-sized clusters are fainter than expected. For *d*=distance and *D*=diameter,

$\theta \sim$ & $f(d) = L/4\pi d^2$ $\Rightarrow$ $f(\theta) \propto$ if L and $D \sim$ constant

possible interpretations of observed curve:

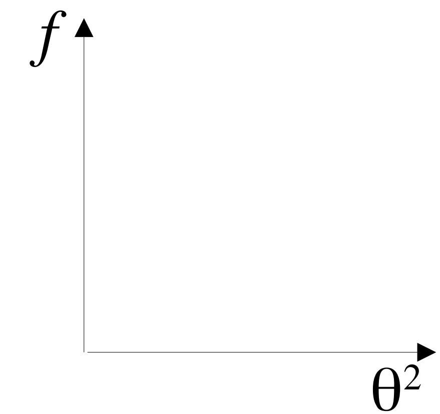
i)

ii)

iii)

iv)

Predict theoretical expectation and observed curves



d) reddening; Whitford (1940) Why the sky is blue.

Q: What's easier to measure: reddening or extinction?

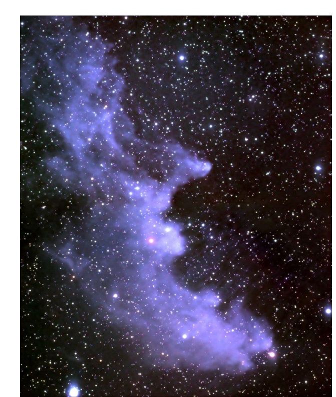
~0.2% of ISM mass is dust (size of cigarette smoke: 0.5-300 nm)

But plays a very important role in astronomy

Extinction, reddening, polarization, reflection nebulae, H_2 formation

Dust comes in many flavors: ices, graphites, silicates, metals, ...

Made of C, Fe, Si, Mg,O mixed with or coated with water



History of ISM: gas was known second, after dust

2) **gas** a) Herschel and Struve to some extent (previous page)

sketch! b) narrow absorption lines in OB spectra and no Doppler shift in some spectral lines of binaries (Hartmann 1904) narrow ⇒ ?

sketch! c) emission lines (Stromgren 1940)

sketch! d) multiple absorption lines; # of absorbers $\propto d$ (Adams 1949)

e) radio lines:

21 cm HI predicted in 1945 (van de Hulst); observed 1950s and 1960s (Ewen & Purcell and Oort & Muller)

OH emission: interstellar masers (Townes 1963) Nobel laureate

molecular lines:

CH, CH^+, CN discovered 1937-1941 (Swings & Rosenfeld, McKellar, Adams)

OH absorption at 18 cm (Barrett, Meeks, & Weinreb 1963)

CO J=1→0 emission at 115 GHz (2.6 mm) (Wilson, Jefferts, & Penzias) Nobel laureate Nobel laureate

UV lines

H_2 in rocket experiment (Carruthers 1970)

f) continuum: free-free, synchrotron

	#	mass	
H	91%	70.5%	
He	9%	28.0%	
metals	0.1%	1.5%	(C,N,O,Mg,Si,Fe,...)

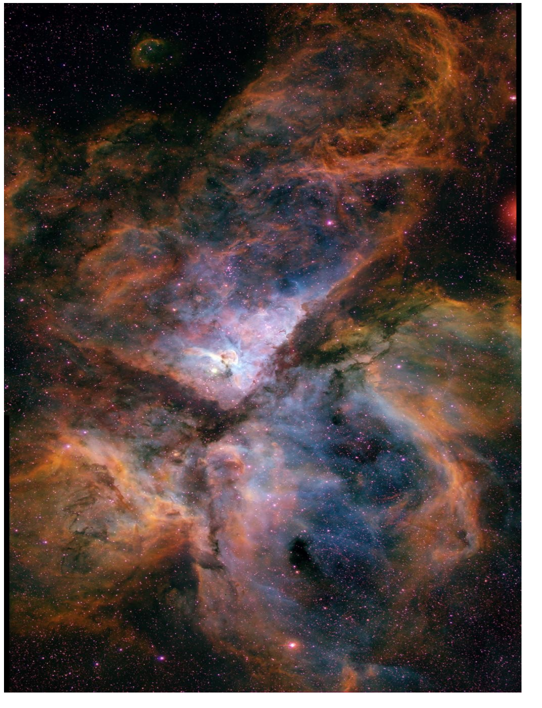
matches that in Sun, other disk stars, meteorites, ... sometimes the metals are "depleted" (locked up in dust grains)

Depletion higher for dense, low T regions and refractory elements (i.e., Mg,Si,Fe and not C,N,O) (Ferriere 2001)
why? why?

mass density ranges from 1.5×10^{-26} g cm^{-3} in the hot medium to 2×10^{-20}-2×10^{-18} g cm^{-3} in the densest molecular regions; average is 2.7×10^{-24} g cm^{-3}, about 20 orders of magnitude less dense than Earth's atmosphere (Ferriere 2001)

$M_{dust}/M_{gas} \sim 10^{-2}$ $N_{dust}/N_{gas} \sim 10^{-12}$

Average dust-dust separation: 150 m; 1 Earth volume of ISM = 1pair of dice


Carina Nebula

misnomer

3) **Cosmic 'rays'** $E_{CR} \sim 1$ eV/cm^3

Hess (1919) balloon experiment showed they exist outside Earth's atmosphere (hence the 'cosmic'), but interstellar cosmic rays weren't identified until the Galactic radio emission was connected to them in 1965 (Ginzburg & Syrovatskii)

typically traveling at close to c, but span a wide range of speeds

Near the Sun (from *Voyager* 1 cosmic ray data)

$P_{CR} \sim 1.0 \times 10^{-12}$ dyne cm^{-2} (1 dyne = 10^{-5} Newtons)

weak ones via the Sun; energetic ones come from the ISM

how?

Radial distribution (spatial distribution measured from synchrotron emission)

$L_{CR} \sim 12$ kpc (Tielens Section 1.3.3)

Vertical distribution (from measured cosmic ray elemental composition)

$H_{CR} <\sim 2\text{-}3$ kpc (Tielens Section 1.3.3)

4) **Magnetic fields** $B \sim 3\ \mu G$ at $n \sim 1\ cm^{-3}$

First solid piece of evidence for B was polarization of starlight: dust grains aligned by B (Davis & Greenstein 1951)

From measured polarization of starlight (near the Sun; 'solar neighborhood')

B is "horizontal" and nearly azimuthal (deviation angle=7.2°)

From Faraday rotation measurements (near the Sun) (FR is the rotation of linearly polarized light due to a directional B field within an ionized region; see pp. 201-203 Dopita & Sutherland)

$B_{regular} \sim 1.5\ \mu G$

$B_{random} \sim 5\ \mu G$

$\Rightarrow P_B \sim 1.0 \times 10^{-12}$ dyne cm^{-2}

$l_{Breg} <\sim 4$ kpc

$h_{Breg} \sim 1.4$ kpc

Q: How can the cosmic ray distribution be measured at distances larger than the B scale length?

From measured synchrotron emission

synchrotron emissivity $\varepsilon_\nu \propto n_e B^{1.8}$

Assume $n_e \propto P_{CR}$ and $P_B \propto P_{CR}$ (recall that $P_B = B^2/8\pi$)

$\Rightarrow \varepsilon_\nu \propto P_{CR}^{1.9} \propto P_B^{1.9}$

$\Rightarrow P_{CR} \propto P_B \propto \varepsilon_\nu^{1/1.9}$

4) **Magnetic fields**

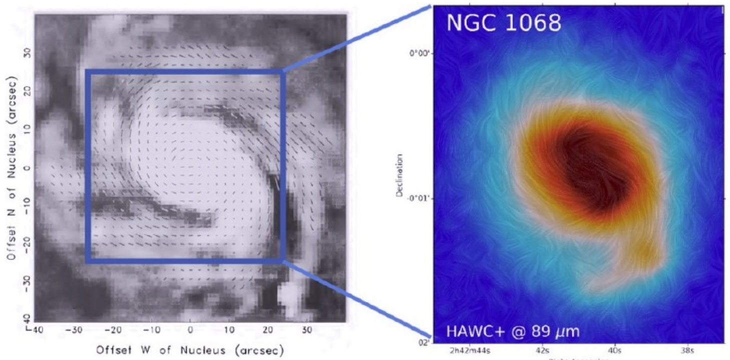


Figure 3.4-1. *The kpc-scale magnetic field of the spiral galaxy NGC 1068.* Left: *Visible image with magnetic field direction inferred from optical polarization (Scarrott et al. 1991). While the field in the outer galaxy follows the spiral arms, the central kpc devolves into a circular pattern due to dust scattering, with no information about the magnetic field.* Right: *SOFIA image of the FIR surface brightness (color scale) and magnetic field overlaid as streamlines using the line integral convolution method. Whereas the optical image is contaminated by scattered light, the SOFIA data show the magnetic field follows the spiral pattern all the way into the center of the galaxy.*

Taken from a 2018 SOFIA review

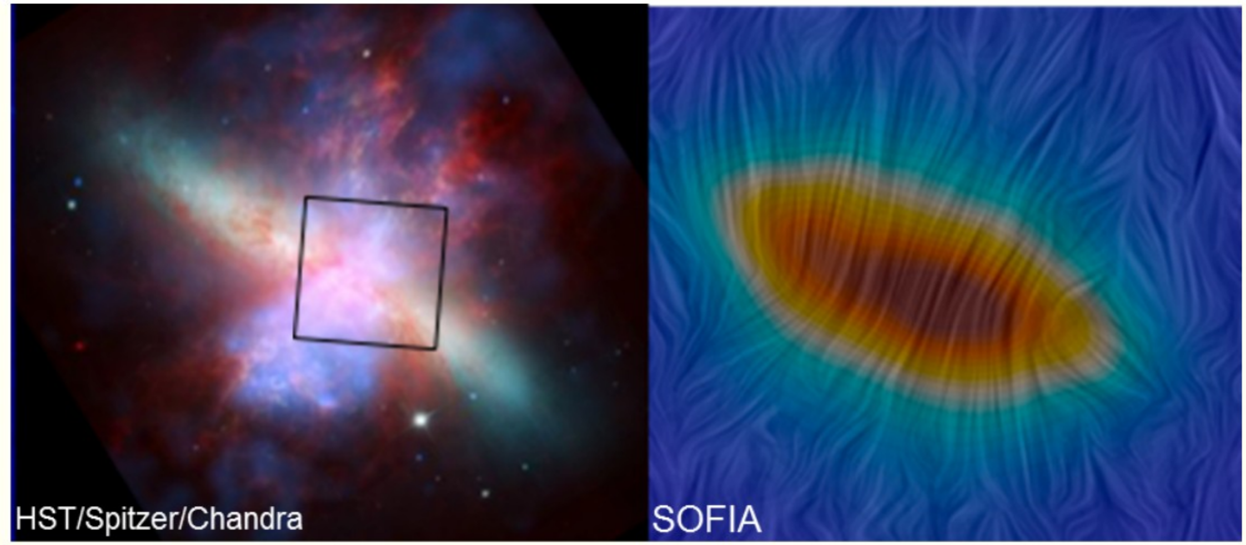


Figure 1-4. *SOFIA Maps the Magnetic Field in M82 Superwind*. The right panel is a SOFIA image covering the area of the black square on the left panel. In a typical galaxy, the magnetic field is usually parallel to its midplane. SOFIA polarimetry observations paint a very different picture for M82: the magnetic field lines are perpendicular to the galactic midplane. The orientation of these lines is evidence of a luminous central starburst violently ejecting matter

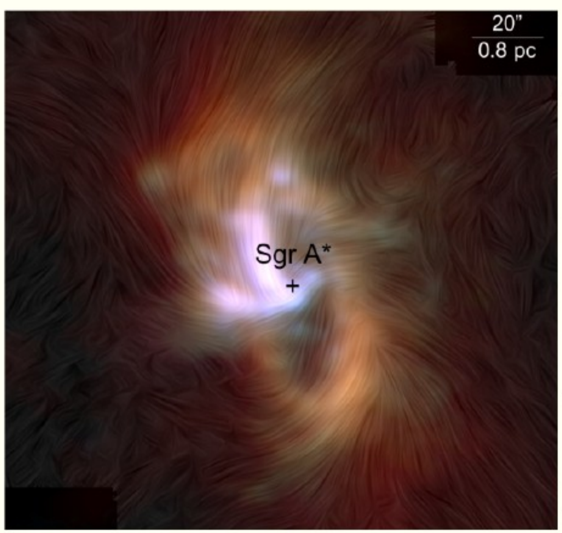


Figure 1-1. *SOFIA Reveals the Magnetic Field Morphology in our Galaxy's Circumnuclear Ring*. Only SOFIA can currently measure magnetic field directions in dusty regions by making polarization maps at FIR wavelengths. For the first time, SOFIA has measured the magnetic field directions in the central 2 pc of the Galaxy at ~10" (=0.4 pc) resolution. The color image shows 19.7, 24.2, 31.5, 37.1, and 53 μm continuum emission from dust (displayed as blue to red from shorter to longer wavelengths) and the streamlines of the inferred magnetic field direction from FIR polarization. The magnetic field is aligned with the warm east-west and north-south (blue-white) arcs, resulting in remarkably perpendicular magnetic-field vectors where the bars intersect on the sky. At larger radii the magnetic field approximately aligns with the 2 pc circumnuclear ring (red-brown). *SOFIA*

ISM Gas Phases

For the Solar Neighborhood

Phase	T(K)	n(cm^{-3})	Volume	lengthscale	$M_\odot$ pc^{-2}
Molecular "H_2"	10-20	10^2-10^6	<1%	1-100 pc	~2.5
Cold atomic "HI"	50-100	20-50	2-4%	pc-kpc	~3.5
Warm atomic "intercloud"	6-10•10^3	0.2-0.5	25%	pc-kpc	~3.5
Warm ionized "diffuse"	8•10^3	0.1	25%	pc-kpc	~1.1
Warm ionized "HII"	8•10^3	1-10^5	1%	pc-kpc	~1.4
Hot ionized "intercloud coronal"	~10^6	few 10^{-3}	~50%	pc-kpc	~0.3

ISM Gas Phases

Molecular Giant molecular clouds contain an appreciable fraction of the Galactic ISM, although they occupy a tiny fraction of interstellar space. *Best terrestrial 'vacuums' are of similar density!* *N*~234 interstellar and circumstellar molecules thus far (astrochymist.org).

Half of Milky Way H is molecular, e.g., H_2CO formaldehyde, CH_3CH_2OH ethyl alcohol, CH_3CH_2OH ethyl cyanide, H_20. Consists mostly of H_2, but CO more easily detected; complexes are a few 10^2 cm^{-3} & 10^4-10^7 $M_\odot$, whereas clouds are a few 10^3 cm^{-3} & 10^3 $M_\odot$

Cold atomic Distributed in relatively dense clouds; 21 cm & atomic absorption

Small-group problem:
What is the typical speed of 10 K hydrogen atoms?

SYFYWIRE

Contributed by

Elizabeth Rayne
@quothravenr...

Jul 27, 2017

BOOZE IS OVERFLOWING IN INTERSTELLAR SPACE

The Mos Eisley Cantina in *Star Wars* may not have been so far off with its intergalactic cocktails, because **space is bubbling over with alcohol**.

Ethanol molecules floating in gases within the interstellar medium (spaces between stars) essentially make space one immense brewery. As the universe cooled and expanded after the Big Bang, protons came into being as nuclear reactions occurred in the fiery and extremely dense cores of stars. These would be the nuclei of every atom that ever existed, including carbon, hydrogen, and oxygen, which are ubiquitous in star formation and throughout the universe. The chemical symbol for ethanol is $\mathbf{C_2H_6O}$—meaning, with such an overflow of those elements, booze is always on tap.

The atmosphere of these astral distilleries is hardly as exciting as your favorite bar. While we tend to get mesmerized by the parts of nebulae washed in mystical reds and blues and greens, the UV radiation produced by emerging stars in those colorful clouds will obliterate most molecules. It is in the shadowy areas of the interstellar medium where the magic happens. Think of them as the sketchy dives of the universe. Gas in these spaces is as widespread as it is dense, and at -436 degrees Fahrenheit, much colder than a beer that's been chilling in ice.

This beer contains no interstellar booze, but it was brewed from yeast that's been to space and back.

ISM Gas Phases

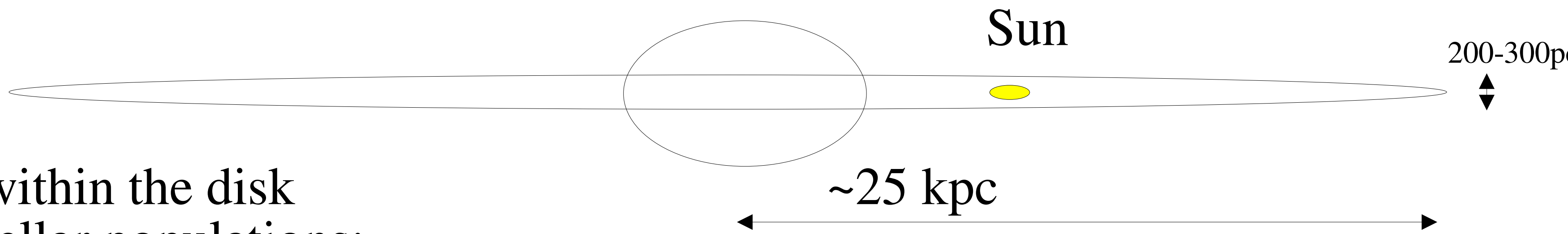
Warm atomic Envelopes the cooler interstellar clouds

Warm ionized Exemplified by the material of ordinary HII regions that surround groups of hot stars. Hα, radio continuum

Hot ionized Gas that has been heated by blast waves from SNe and hot stellar corona emission. Evidence from OVI absorption (which has an 'ionization potential' of 138 eV) and X-rays.

Middle four phases (on Slide 10) in ~pressure equilibrium. Molecular clouds are typically gravitationally bound, and the last phase is expanding into other phases.

ISM Gas Phases



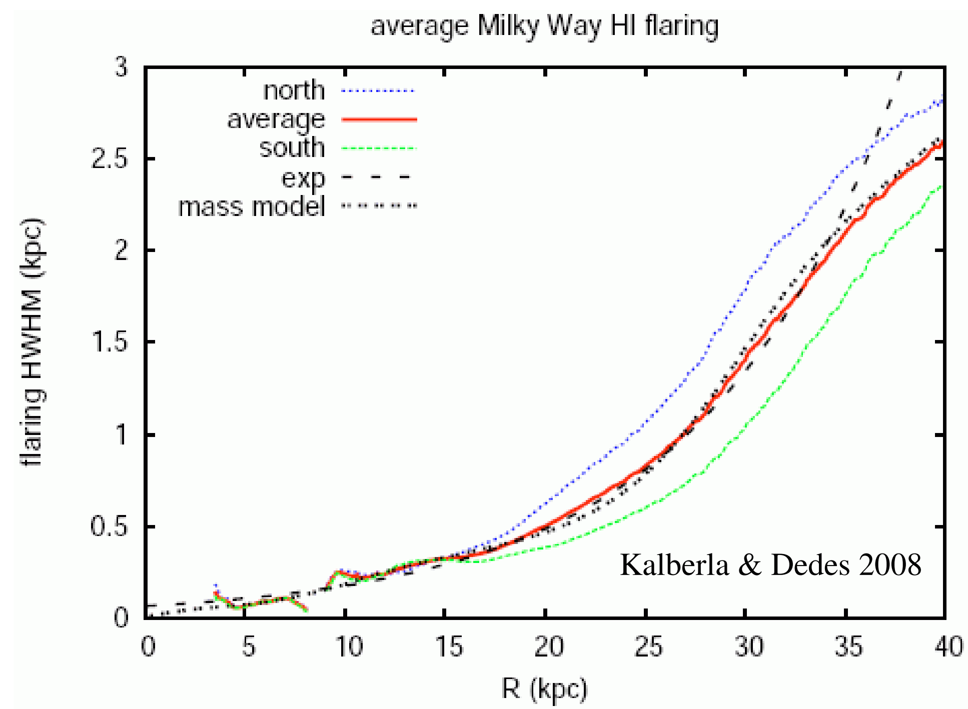
ISM within the disk

Stellar populations:

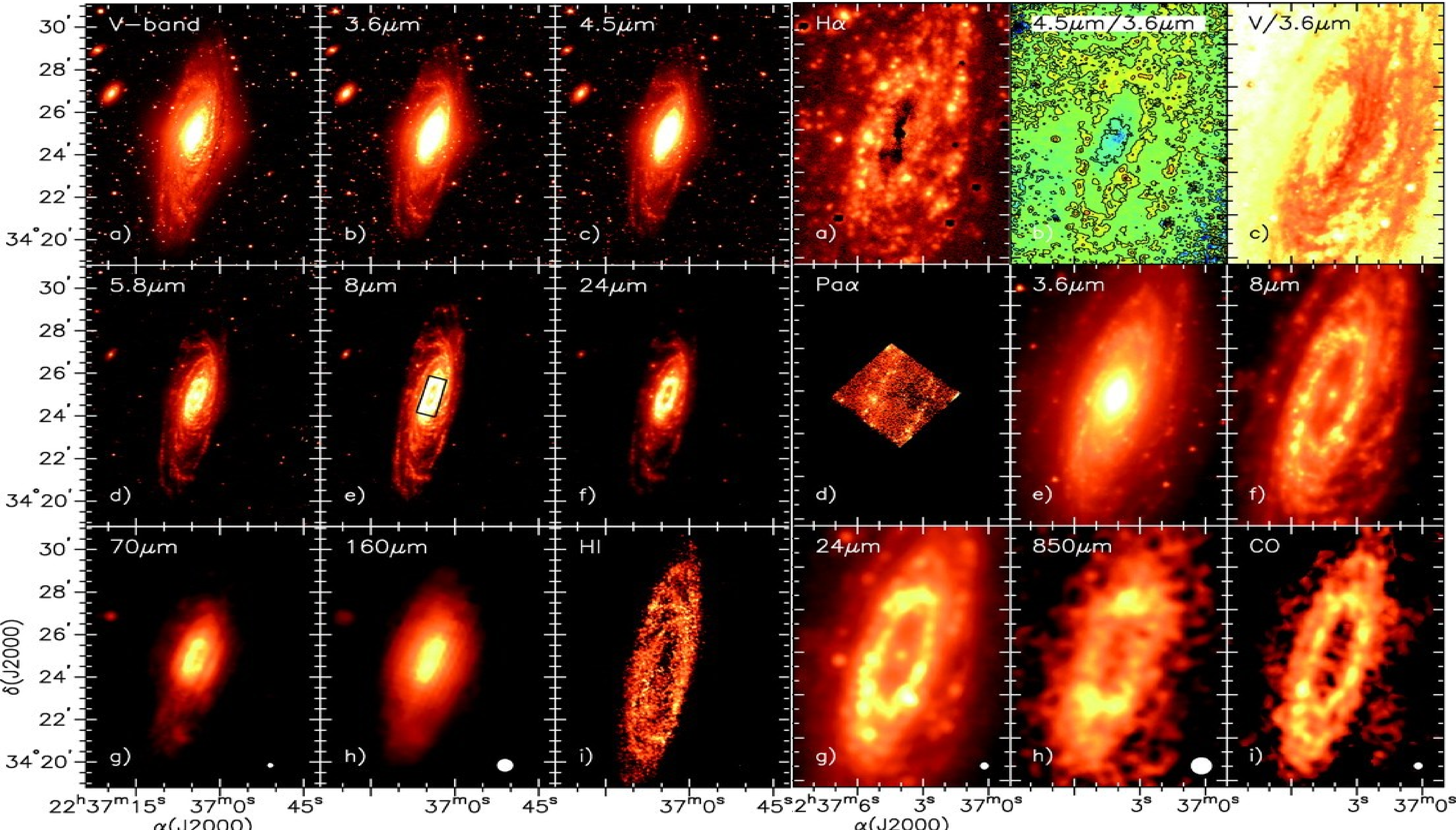
I (young): $Z \sim Z_\odot$
in disk
gas + 2nd generation *s

II (old): $Z \sim Z_\odot/(10\text{-}100)$
spherical
first generation *s

HI and H_2 distributions very different



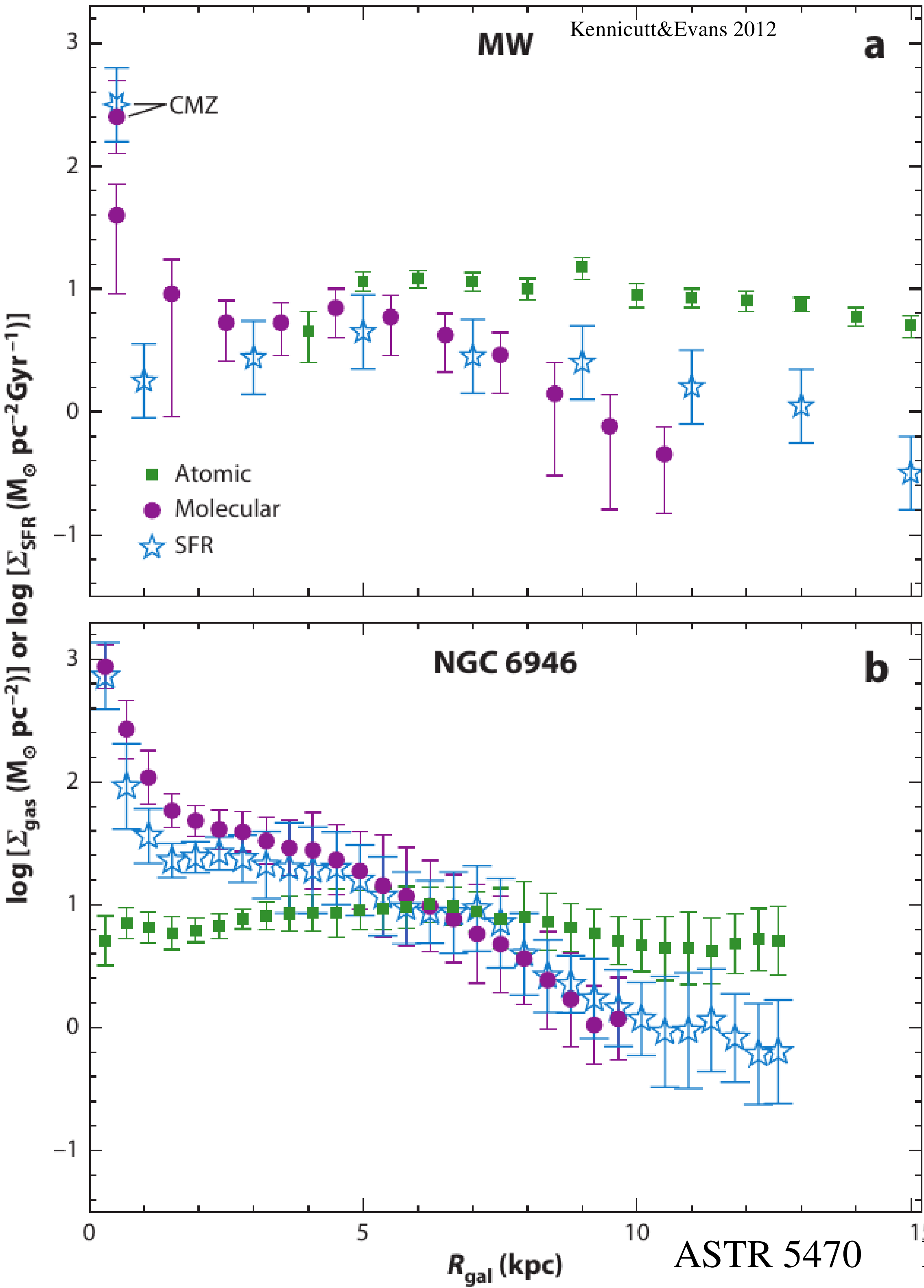
NGC 7331 - Regan et al. 2004

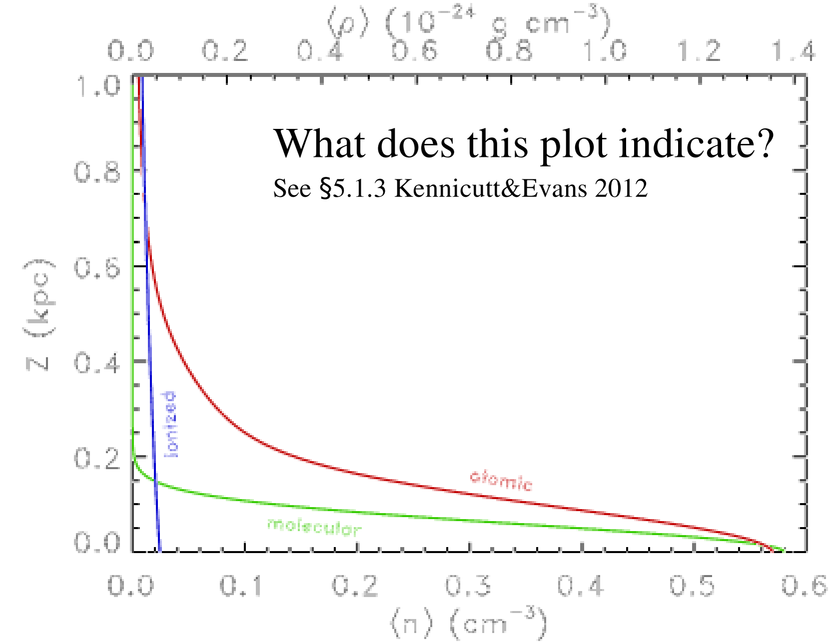


cold dust

cold atomic

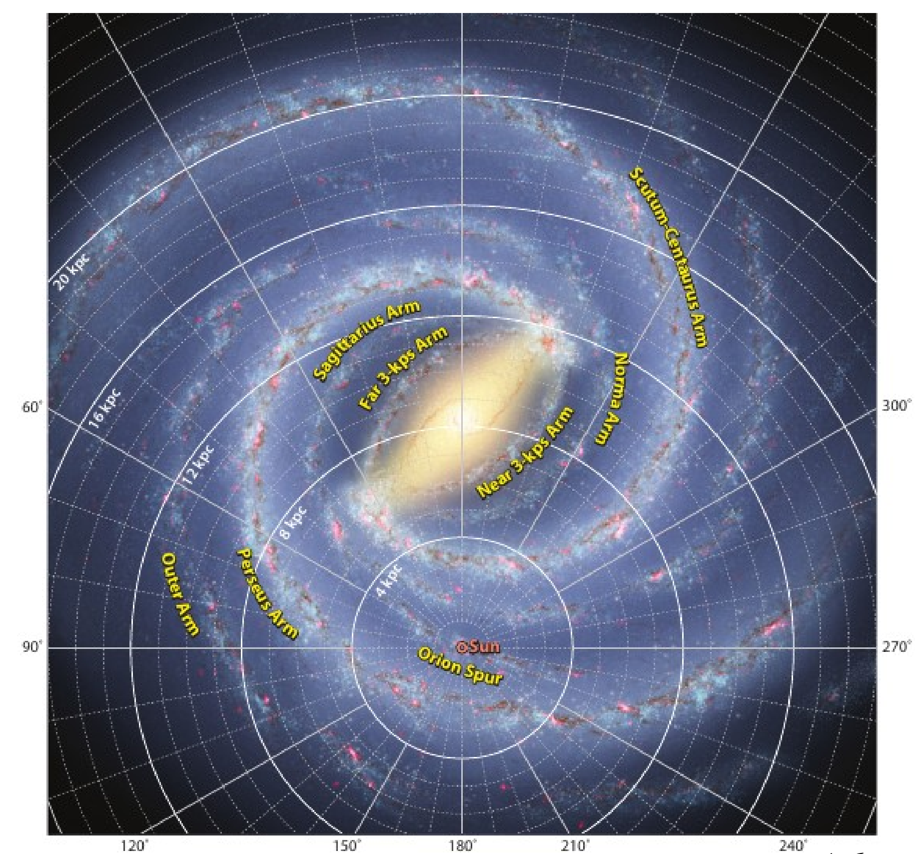
molecular





What does this plot indicate?

See §5.1.3 Kennicutt&Evans 2012



Physical Processes

essentially all radiative processes
synchrotron, Bremsstrahlung ('free-free'),
    forbidden radiation
radio recombination lines
X-rays from hot thermal plasma
ionization processes
line absorption, line emission
inverse Compton scattering
hyperfine structure emission
molecular rotation transitions

Phenomena:

Hot gas, cold gas
CO & hydrogen molecular clouds
diffuse neutral Hydrogen (HI)
ionized Hydrogen regions (HII)
protoplanetary disks
star formation
    triggered by shocks (SN, OB clusters, spiral wave pattern, galaxy collisions)
    protostars, dusty T Tauri's, nebular-like Herbig-Haro objects,
    bipolar flows, sub-parsec Bok Globule clouds
SNe
large-scale magnetic fields
emission and reflection nebulae

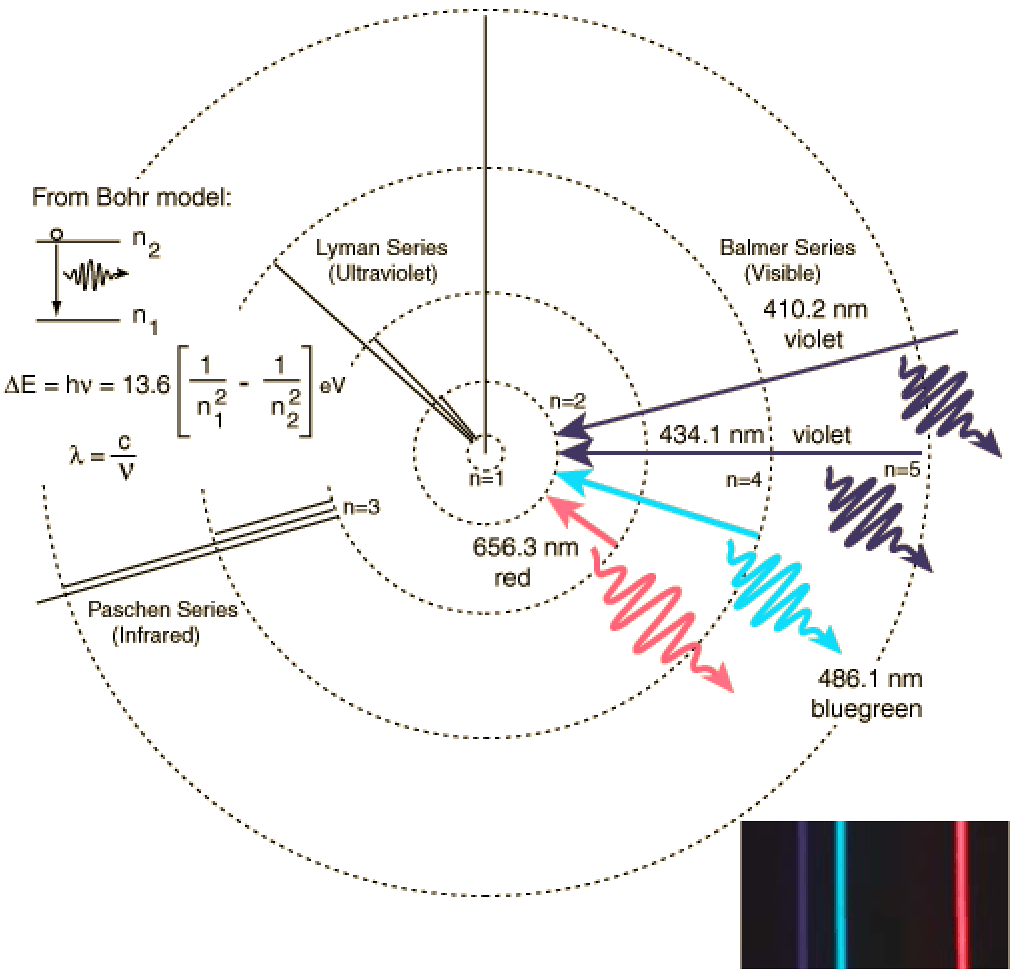
Radiative Processes

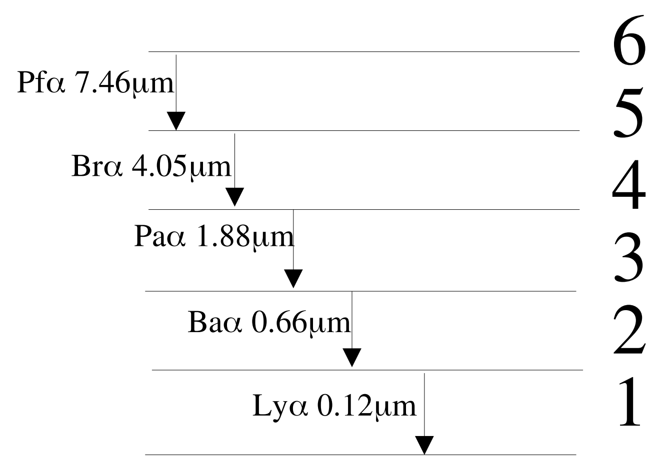
1) Spectral lines

a) Recombination lines (emission)

$$e^- + p^+ \rightarrow \text{H I} + \gamma$$

http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html





Radiative Processes

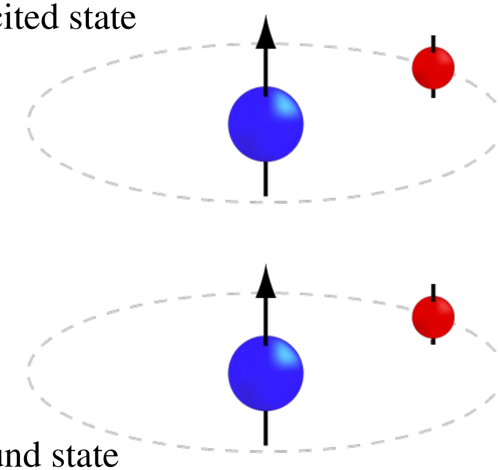
1) Spectral lines

b) hyperfine structure: spin-nucleus interaction

an example is the 21 cm HI line

$A = 3 \times 10^{-15}\ s^{-1}$

$1/A \sim 10^7$ yr!!



c) forbidden and fine-structure transitions: spin-orbit interaction

within same configuration (electric quadrupole & magnetic dipole)

e.g. [OIII] 5007Å

[SII] 6731/6716Å

[SiII] 34.8μm

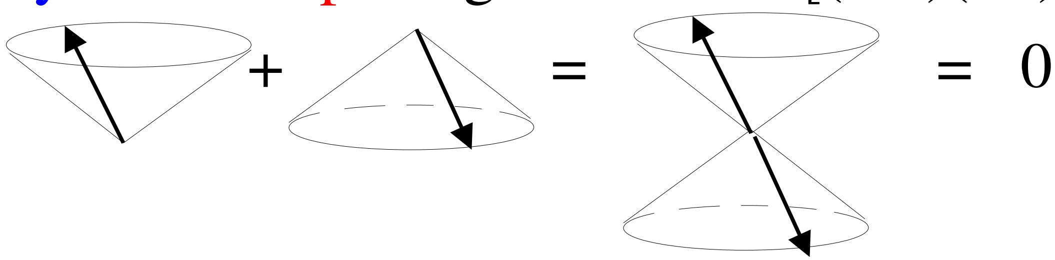
Let ψ_a = eigenfunction state for particle a

AntiSymmetric space eigenfunction: $[\psi_a(1)\psi_b(2)-\psi_b(1)\psi_a(2)]/\sqrt{2}$

Symmetric space eigenfunction: $[\psi_a(1)\psi_b(2)+\psi_b(1)\psi_a(2)]/\sqrt{2}$

The e^- and p are fermions, which means they have half-integral spin:

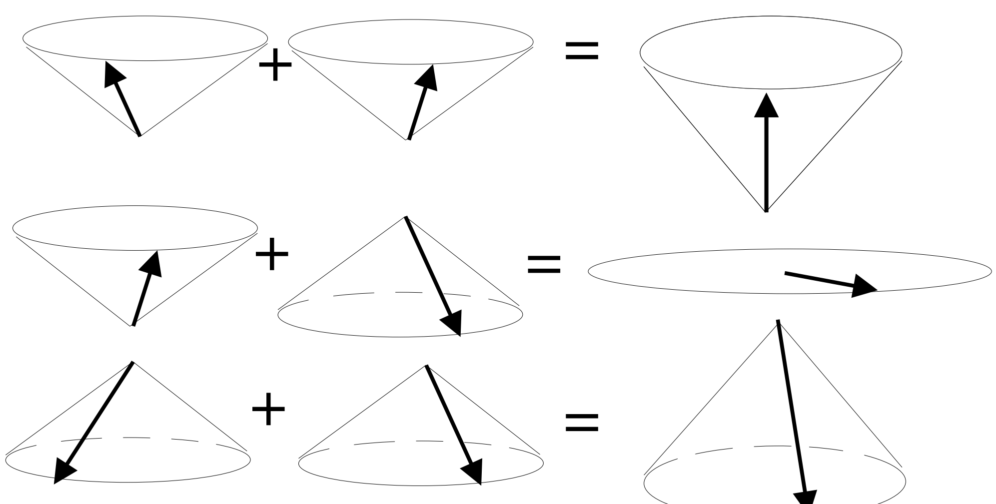
AntiSymmetric spin eigenfunction: $[(+\frac{1}{2})(-\frac{1}{2})-(-\frac{1}{2})(+\frac{1}{2})]/\sqrt{2}$ (singlet)



Symmetric spin eigenfunction: $[(+\frac{1}{2})(+\frac{1}{2})+(+\frac{1}{2})(+\frac{1}{2})]/\sqrt{2}$ (triplet)

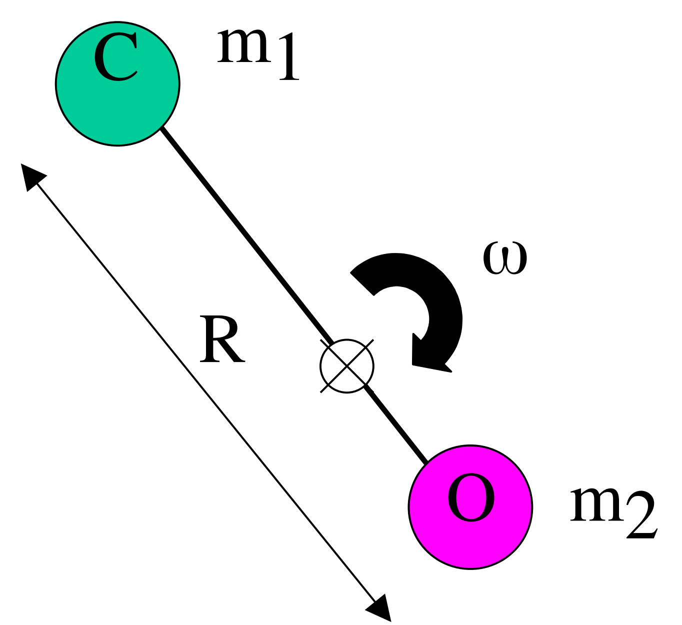
Symmetric spin eigenfunction: $[(-\frac{1}{2})(-\frac{1}{2}) + (-\frac{1}{2})(-\frac{1}{2})]/\sqrt{2}$ (triplet)

Symmetric spin eigenfunction: $[(+\frac{1}{2})(-\frac{1}{2})+ (-\frac{1}{2})(+\frac{1}{2})]/\sqrt{2}$ (triplet)



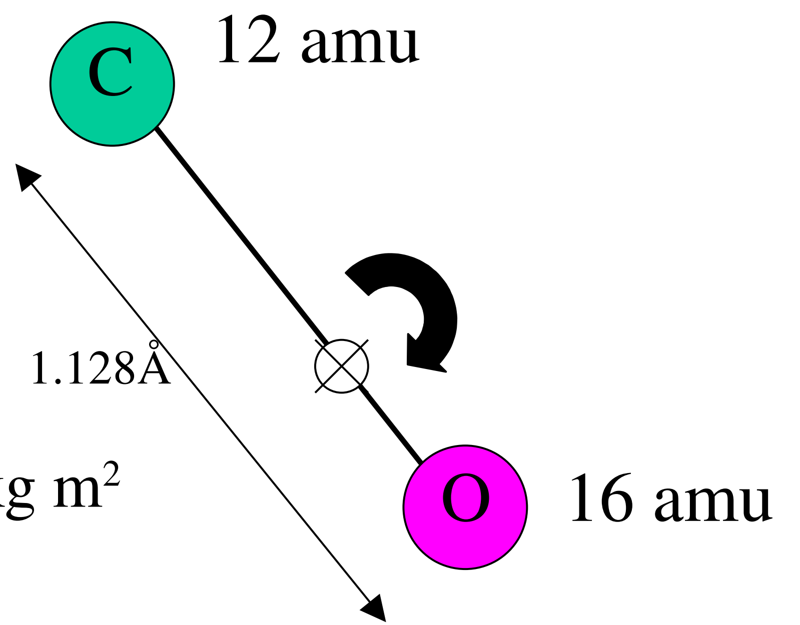
d) Rotational transitions

- Start with classical mechanics:
  - $I = m_1 m_2 R^2/(m_1+m_2)$
  - $J = I\omega$
  - $E_{rot} = I\omega^2/2$
- Add quantum mechanics:
  - $J = \{J(J+1)\}^{½}\, h/[2\pi]$ <u>quantized</u>
  - $\nu = \Delta E/h$, with $\Delta J = 1$ most likely
- Then:
  - $E_{rot} = J \cdot J/[2I] = h^2 J(J+1)/[8\pi^2 I]$
  - $\nu = h(J+1)/[4\pi^2 I]$ {state J+1 Þ state J}



Example: rotational transitions of carbon monoxide

- CO molecule:
  - m_1 = 12 amu = 1.994424×10^{-26} kg
  - m_2 = 16 amu = 2.656696×10^{-26} kg
  - D = 1.128 Å = 1.128×10^{-10} m
- Plug in:
  - $I = m_1 m_2 D^2/(m_1+m_2) = 1.449506\times10^{-46}$ kg m^2
  - $\nu = h(J+1)/[4\pi^2 I] = 115.791$ GHz $(J+1)$
- Actually:
  - ν = 115.271 GHz, 230.538 GHz, 345.796 GHz, …



Q: Why isn't the more abundant H_2 used to trace molecular clouds?

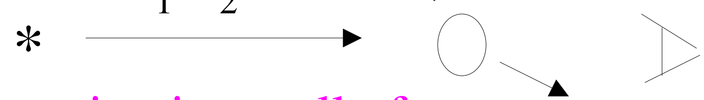
Radiative Processes

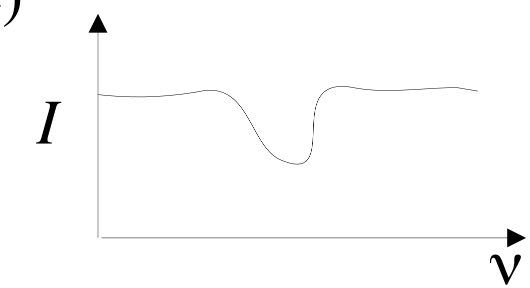
1) Spectral lines

e) Absorption lines (need background continuum source)

CaI H&K 4227 Å

NaI $D_1 D_2$ 5890,5896 Å





Absorption is usually from a non-excited state. Why?

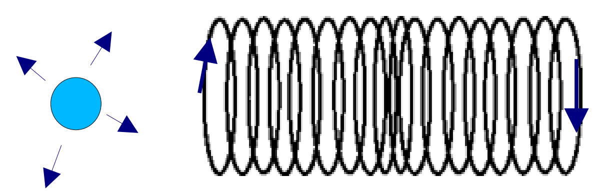
2) Continuum

a) Blackbody (Planck) (e.g., *s and dust)

b) Bremstrahlung ("free-free") $h\nu \sim kT$

e^- p^+

c) synchrotron (magneto-Bremsstrahlung)



ions spiraling around interstellar magnetic field lines→synchtron radiation

d) dust

Radiative Terminology

Term	Description	Units	Equation
m	Apparent magnitude	mag	$-2.5\log(L/4\pi d^2)+\text{constant}$
M	Absolute magnitude	mag	$-2.5\log L+\text{constant}$
$m-M$	Distance modulus	mag	$5\log(d/10\text{pc})$
L	Luminosity	W	
f	Flux	W/m^2	$L/4\pi d^2$, $k10^{-0.4m}$
I_ν	Specific intensity	$W/m^2/Hz/sr$	
L_ν	Luminosity density	W/Hz	
f_ν	Flux density	$W/m^2/Hz$	$\int d\Omega I_\nu \cos\theta$
f_λ	Flux density	$W/m^2/m$	$\int d\Omega I_\lambda \cos\theta$
f	Flux	W/m^2	$\approx f_\nu \Delta\nu$
B-V	Color; logarithmic flux ratio	mag	
$B_\nu(T)$	Blackbody; Planck spectrum	$W/m^2/Hz/sr$	$2h\nu^3/c^2/(e^{h\nu/kT}-1)$
$B_\lambda(T)$	Blackbody; Planck spectrum	$W/m^2/m/sr$	$2hc^2/\lambda^5/(e^{h\nu/kT}-1)$

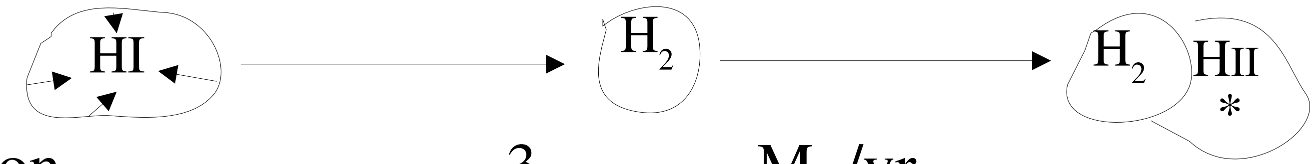
Note:

- $f=\nu f_\nu=\lambda f_\lambda$ $\qquad d\nu=c/\lambda^2 d\lambda$
- Bolometric flux is flux from all wavelengths
  - → in practice it's *never* measured
- Wien's law for thermal radiation: $\lambda_{max}T\simeq 0.29$ cm K
- Stefan-Boltzman law for thermal radiation: $F=\sigma T^4$
- The subscript ν or λ implies a *monochromatic* quantity

The Galactic Ecosystem

ISM evolves

ISM sources and sinks



sink:	star formation	-3	$M_\odot$/yr
sources:	**H**igh **V**elocity **C**louds	<1.4	$M_\odot$/yr
	AGB & planetary nebulae	0.3-1	$M_\odot$/yr
	OB* winds	0.08-0.5	$M_\odot$/yr
	SNe	0.03	$M_\odot$/yr
	Novae	0.003	$M_\odot$/yr
Sum of the sources		0.4-1.5	$M_\odot$/yr

Mass of Milky Way's ISM ~ 6×10^9 solar masses

⇒timescale for converting all the ISM mass to stars:

Path lengths in ISM vs stars

l=mean free path= in ISM, atomic $\sigma \sim 10^{-16}$cm^2, $n \sim 1$cm^{-3} ⇒ $l = 10^{16}$cm

in stars, $n \sim 10^{20}$cm^{-3} ⇒ $l = 10^{-4}$cm

τ=timescale for collision=

Application: The 10 micron Background Problem

Infrared astronomy can be difficult since the objects of astronomical interest can be emitting photons with the same wavelengths typical of the atmosphere's thermal emission!

At room temperature, we can compute the number of photoelectrons generated per second per resolution element:

$$N_e = \varepsilon_\lambda B_\lambda(T) \Delta\lambda \; A\Omega \; \eta\tau \; / h\nu$$

Assume

ε_λ=emissivity of background=0.3	η=quantum efficiency of detector=0.2
τ=transmission=0.1	$\Delta\lambda$=bandwidth=1μm
A=telescope area	λ=10μm
T=290 K	Ω=solid angle of FOV ($\frac{1}{4}\pi\theta_D^2$)

$$B_\lambda(T) = 2hc^2/\lambda^5/(e^{h\nu/kT}-1) = 8.4 \text{ W/m}^2/\mu\text{m/sr}$$

For diffraction-limited performance,

$$A\Omega = \tfrac{1}{4}\pi D^2 (\qquad)^2 = 9.2\ 10^{-13}\ \lambda^2(\mu\text{m})\ [\text{m}^2\ \text{sr}]$$

Analogy: daytime observing in B band is 10^8 e^-/s/pixel

$\Rightarrow N_e \cong 2.3\ 10^8$ e^-/sec/resolution element

Keck Observatory: 3-25μm Boeing Si:As 128x128 array with a $1.1\text{x}10^7$ e^-/pixel full-well capacity. ⇒ read out rate must be ____! Otherwise, saturate in 50 ms!

Radiation Transport

Consider the propagation of radiation of frequency ν along the line-of-sight toward an observer, in the region of an interstellar cloud.

j_ν	=	emission coefficient of the gas	[energy/time/volume/frequency/sr]
$d\Omega$	=	solid angle toward observer	[sr]
$j_\nu d\Omega$	=	gas emission in $d\Omega$	[energy/time/volume/frequency]
I_ν	=	intensity of radiation	[energy/time/area/frequency/sr]
$I_\nu d\Omega$	=	intensity in $d\Omega$	[energy/time/area/frequency]
κ_ν	=	absorption coefficient per unit length	[cm^{-1}]

Between s and $s+ds$, intensity increases by $j_\nu d\Omega ds$. Conversely, undergoes attenuation $\propto I_\nu$: $\kappa_\nu I_\nu d\Omega ds$

$$\Rightarrow dI_\nu d\Omega \equiv j_\nu d\Omega ds - \kappa_\nu I_\nu d\Omega ds \quad \Rightarrow \quad dI_\nu/ds = -\kappa_\nu I_\nu + j_\nu$$

For pure absorption $j_\nu=0$ and an incident intensity $I_{\nu,0}$ at $s=0$,

$I_\nu(s^*)=I_{\nu,0}\exp(-\int ds\ \kappa_\nu(s))$ [from 0 to s^*] $\equiv$ $I_{\nu,0}\exp(-\tau_\nu)$ 'optical depth'

$\tau_\nu \ll 1$ optically thin

$\tau_\nu \gg 1$ optically thick

Radiation Transport (adapted from Chapter 2 of Dyson & Williams)

Applying an integrating factor $\exp(\tau_\nu)$ to the differential equation on the previous page, and integrating,

$$I_\nu = I_{\nu,0}\exp(-\tau_\nu) + \int d\tau'_\nu \; j_\nu/\kappa_\nu \exp(-(\tau_\nu - \tau'_\nu)) \qquad \text{[from 0 to } \tau_\nu\text{]}$$

If the system is in thermodynamic equilibrium, then Kirchoff's Law gives

$$j_\nu = \kappa_\nu \, B_\nu(T)$$

and

$$I_\nu = I_{\nu,0}\exp(-\tau_\nu) + B_\nu(T)(1-\exp(-\tau_\nu))$$

Radio astronomers think in terms of "brightness temperatures", and at radio wavelengths, $h\nu/kT \ll 1$, so

$$B_\nu(T) \approx$$

and

$$T_b \approx T_{b,0}\exp(-\tau_\nu) + T\,(1-\exp(-\tau_\nu))$$

In the limit of low optical depth $\tau_\nu \ll 1$: $T_b =$

In the limit of high optical depth $\tau_\nu \gg 1$: $T_b =$

21 cm line transfer

1. if $\tau \gg 1 \Rightarrow \quad T_b = T_s$ $\qquad T_s$ = 'spin' or 'excitation temperature' for 21 cm line

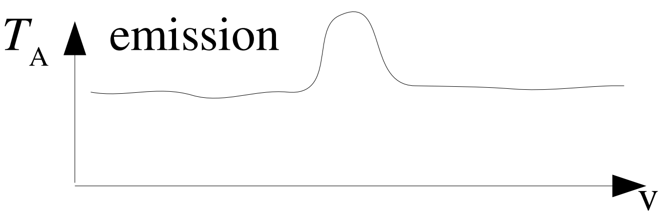
2. if $\tau \ll 1$ and $T_{b,0} = 0 \quad \Rightarrow \quad T_b \sim T_s \tau = T_s \int \kappa_\nu ds$ $\qquad$ [from 0 to s^*]

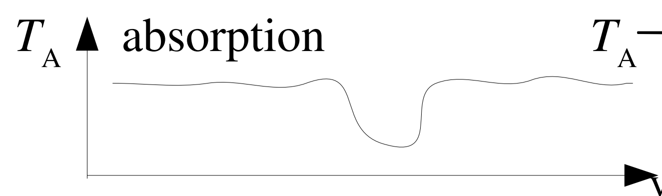
   and $N_H^{tot}(\tau \ll 1) = 1.83 \times 10^{18} \int dv T_b(v)$ $\qquad$ v in km/s; T_b in K; N_H in cm^{-2}

   remembering that $n_H = n_0 + n_1 = n_0(1 + g_1/g_0 \exp(-T_{10}/T_s))$ $\qquad T_{10} \sim h\nu_{10}/k = 0.0681$ K

   $$\sim n_0(1 + 3(1 - T_{10}/T_s))$$
   $$\sim 4n_0$$

Spectral lines: what can we learn?



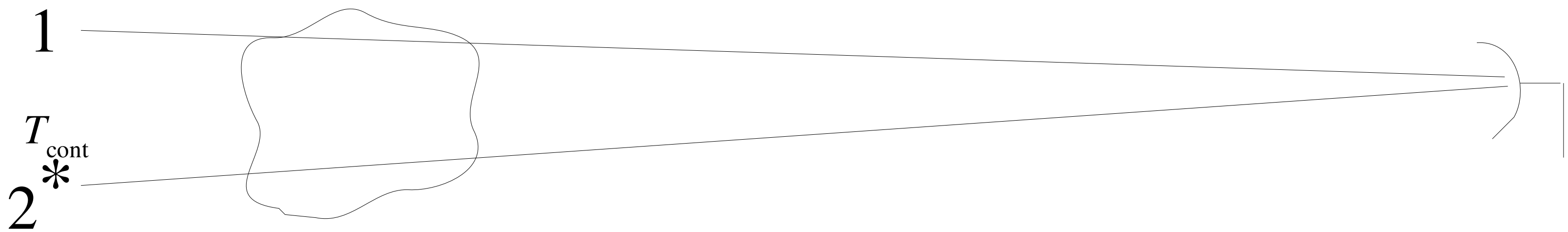


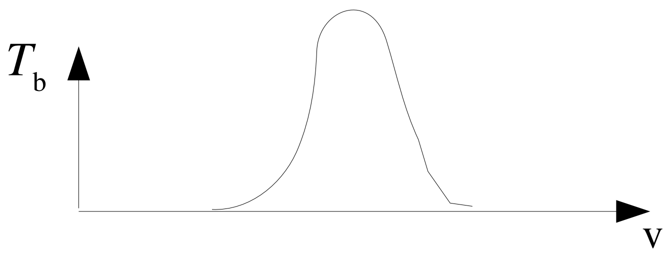
$T_A \rightarrow T_b$ given geometry, telescope

Relative line strengths
- different species
- different isotopes
- different states
- temperatures
- densities

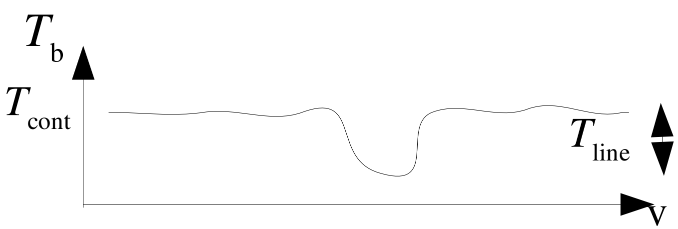
Velocity
- kinematics
  - galactic rotation / distance
  - internal-to-cloud or internal-to-complex
- line width
  - natural broadening
  - thermal broadening
  - pressure broadening
  - beam broadening (line of sight)

Absorption and Emission in the same cloud





1. $T_b(v) = T_s(1 - e^{-\tau})$



2. $T_b(v) = T_{cont} e^{-\tau} + T_s(1 - e^{-\tau})$

$$T_{line} = T_{cont} - T_b(v) = T_{cont} - (T_{cont} e^{-\tau} + T_s(1 - e^{-\tau}))$$

HI emission and absorption

Radhakrishnan et al. 1972 ApJ Supp, 24, 115
Dickey et al. 1983 ApJ Supp, 53, 591
Colgan et al. 1988 ApJ, 328, 275
Dickey & Lockman 1990 ARAA, 28, 215

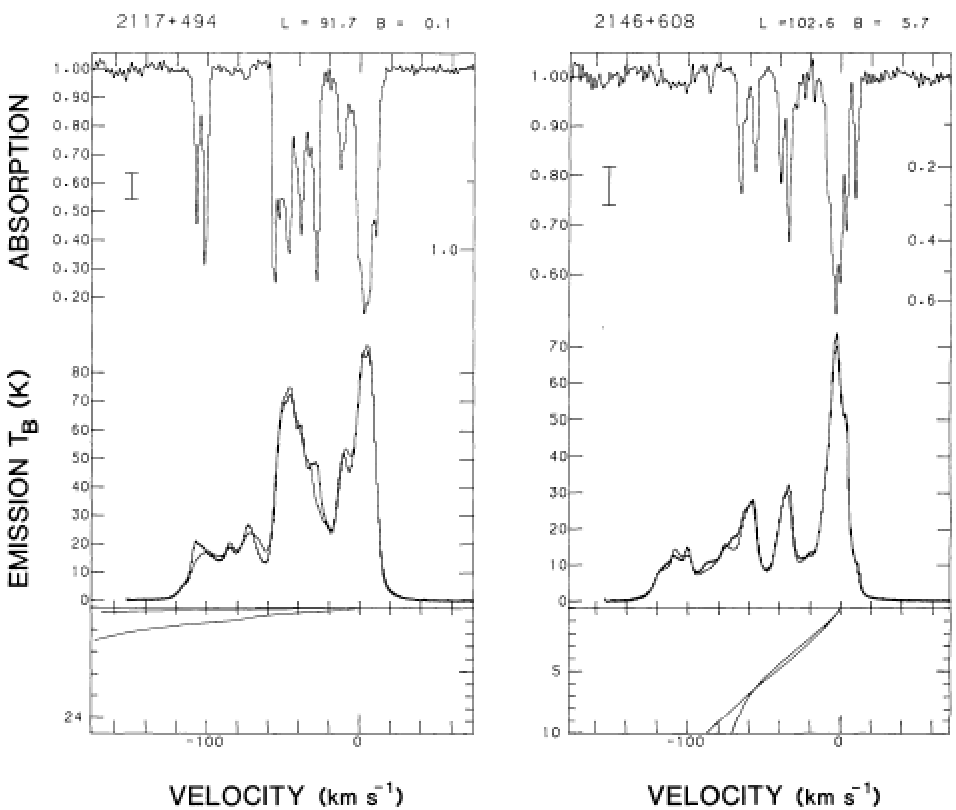


FIG. 12

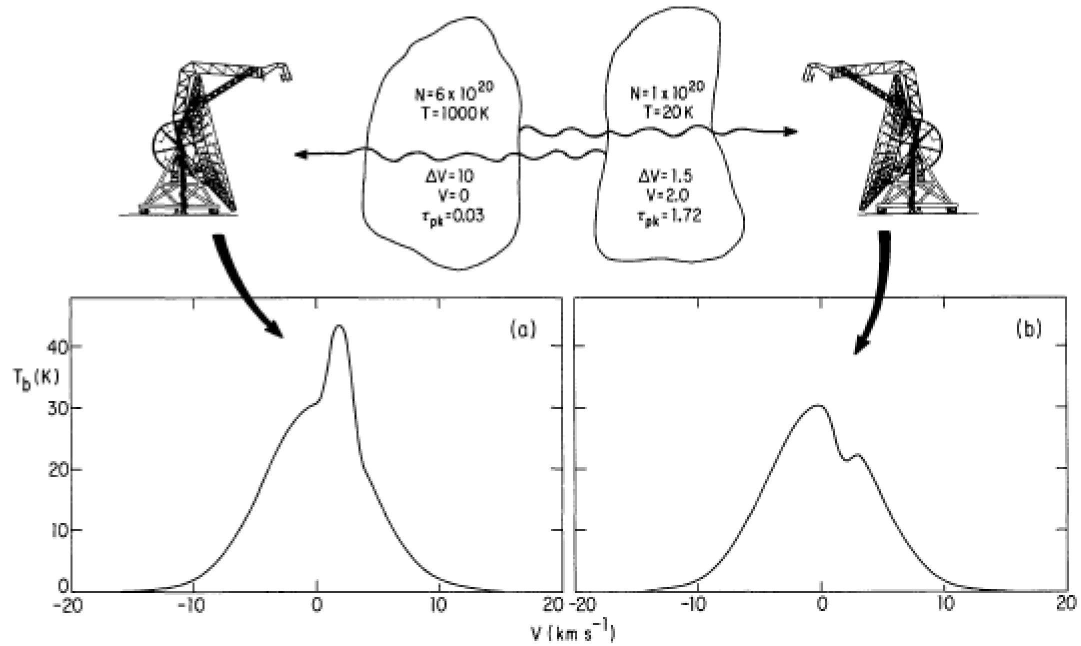
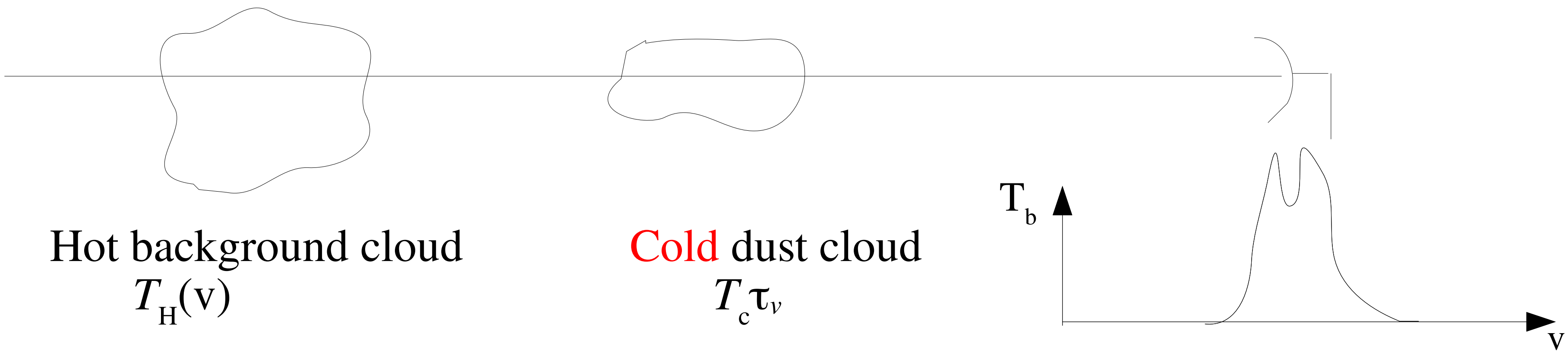


Figure 1 Schematic of the geometry of 21-cm self-absorption. The structure of an emission profile depends on the relative location of hot and cold clouds as viewed by the observer. Superpositions like this are very common at low and intermediate latitudes. The profile on the right (*b*) is self-absorbed.

HI self-absorption: suppose that the HI in a dust cloud is colder than that of the surrounding ISM

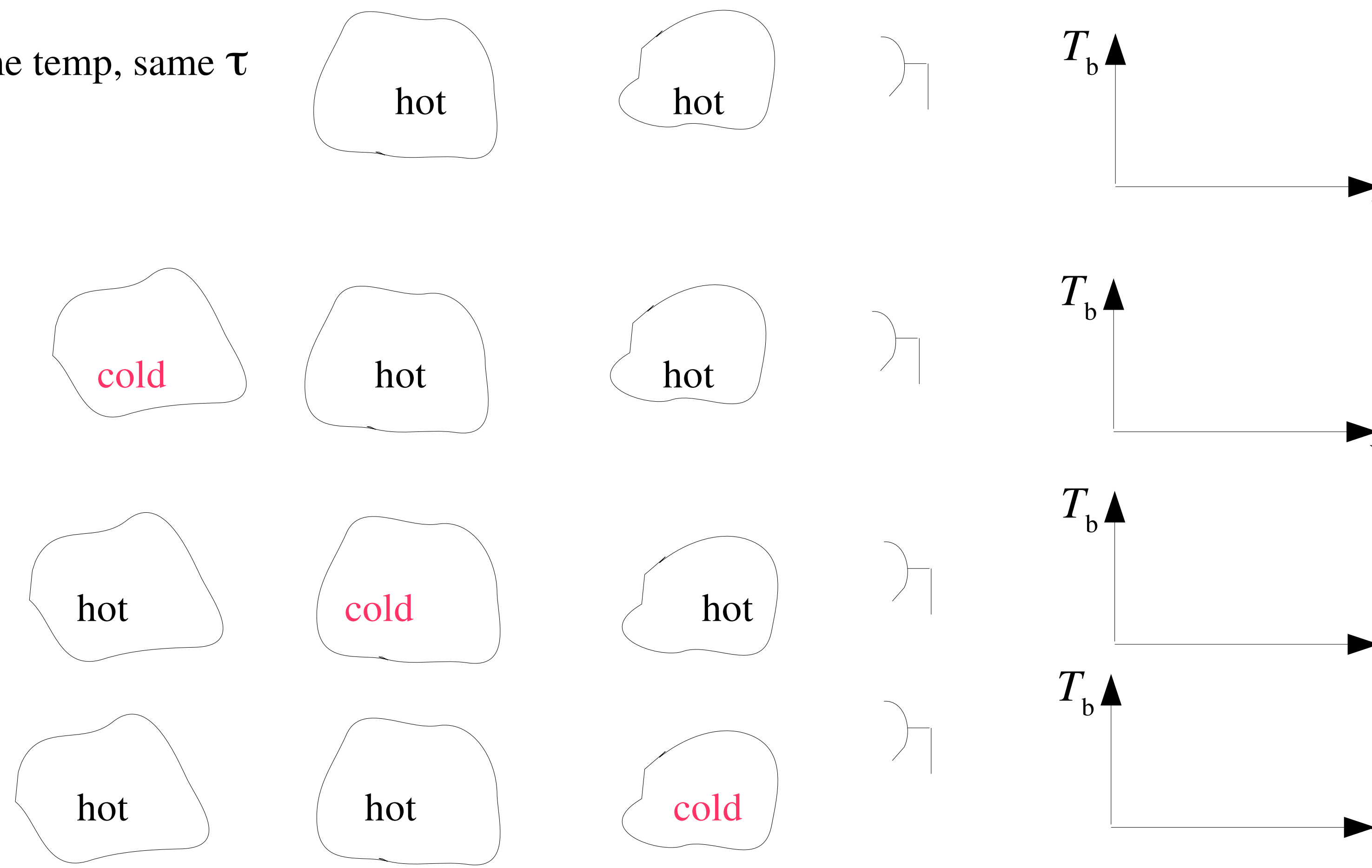


1. Two hot clouds, same temp, same τ
   - $T_1 = T_2 = 150$ K
   - $\tau_{tot} = 1$ (½+½)
   - ‹v›=0 km/s
   - Δv=5 km/s

2. Cold cloud behind
   - $T_c = 50$ K
   - $\tau_{tot} = 4$ (3+½+½)
   - ‹v›=+0.4 km/s
   - Δv=1 km/s

3.

4.



Natural Line Widths (Dyson & Williams §2.2.2)

Atomic emission has a natural line width. If the atomic emitter is regarded as an oscillator, it is damped by its interaction with the electric field of the emitted radiation. A fairly sharp spectrum of frequencies is emitted, following a Lorentzian profile,

$$I_\nu \propto \gamma/[(\nu-\nu_0))^2+(\gamma/4\pi)^2]$$

Doppler Broadening

Random velocities within a gas can significantly broaden line profiles, e.g.,

$$(\nu-\nu_0)/\nu_0 = v_z/c$$

ν_0 = emitted frequency
ν = observed frequency
v_z = atomic velocity in direction of travel of the photon

If the velocity distribution is Maxwellian, then the # of atoms with z-component velocities between v_z and v_z+dz is $dN_z \propto \exp(-Mv_z^2/2kT)\, dv_z$ where M is the mass of the atom.

There's also a spread in frequency with

$$I_\nu \propto \exp[-(\nu-\nu_0)^2/2\delta^2] \qquad \text{where } \delta^2 = \nu_0^2 kT/Mc^2$$

Collisional Broadening

Usually insignificant for standard ISM conditions. The frequency width due to collisions scales as τ_0^{-1}, where τ_0 is the mean interval between collisions and may be of order a thousand years, insignificant compared to even natural broadening for which Einstein coefficients may be $A \sim 10^8$ Hz.

Concept Question

Your evil twin lures the Andromeda galaxy into slamming into the Milky Way. After a 'long' time, you discover that things in Milky Way Prime look qualitatively similar to the way they did in the Milky Way. Since Andromeda was very similar to the Milky Way, of course the density of the new ISM is double the old value. In addition, each self-luminous object like the nucleus and stars/HII regions/clouds/etc have surprisingly exactly doubled their intrinsic brightness. (play along with me here...)

•You, the virtuous astronomer and Galactic hero, feel obliged to understand the impact of this new situation, and to recalibrate the starfinders aboard the redoubtable USS Physical Sciences. As viewed from your ship, and assuming τ_V=1,

- What is the effect on the (V-band) brightness of Galactic stars? Quantify.
- What is the effect on the (B-R) observed colors of stars? Quantify.
- What is the effect on the observed colors of reflection nebulae?
- What is the effect on the brightness of reflection nebulae?