The Physics of the Interstellar Medium

The material presented in this course is drawn from a variety of sources, including:

- class notes from Cornell University (1993-1996) Giovanelli, Haynes, Herter, Goldsmith, Cordes
- class notes from Caltech (2002) N. Scoville, A. Sargent
- class notes from the University of Texas, Austin (1991) H. Dinerstein
- class notes from Swarthmore College (1999, 2003) J. Gaustad, E. Jensen
The Galactic Ecosystem

The Interstellar Environment of Our Galaxy

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The Galactic Ecosystem

**Interstellar gas & dust** (and cosmic rays and magnetic fields) 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

1) probe of *s (e.g. OB* ⇒ UV ⇒ HII), also AGN (e.g., dust torii, broad lines)
2) probe of galactic structure, dynamics, evolution (metallicity $Z$) 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 (e.g., Hollenbach & Tielens 1999, Ferriere 2001). *Perhaps the most significant role 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 ⇒ next *s with higher $Z$

**The ISM is composed of dust, neutral+ionized+molecular gas; B fields** neutrinos & cosmic rays?
Q: How do we know there is an ISM?

**History of ISM**: dust 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
      \[ \theta \sim \frac{D}{d}, \text{flux} = \frac{L}{4\pi d^2} \]
      \[ \Rightarrow \text{flux} \sim \quad \text{if } L \text{ and } D \sim \text{constant} \]
      i)
      ii)
      iii)  
   
d) reddening; Whitford (1940) **Why the sky is blue.**

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

0.5-1% 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**

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

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

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

2) gas
   a) Herschel and Struve to some extent (previous page)
   b) narrow absorption lines in OB spectra and no Doppler shift
      in some spectral lines of binaries (e.g. Hartmann 1904)
      narrow ⇒ "cold" (T<1000 K)
   c) emission lines (Stromgren 1940)
   d) multiple absorption lines; # of absorbers ∝ d (Adams 1949)
   e) radio lines:
      21 cm HI predicted by van de Hulst 1945; observed 1950s
      and 1960s by Ewen & Purcell and Oort & Muller
      OH emission: IS masers (Townes 1963)
      molecular lines:
      CH, CH⁺, CN discovered by Swings & Rosenfeld,
      McKellar, Adams 1937-1941
      OH absorption at 18 cm (Barrett, Meeks, & Weinreb 1963)
      CO J=1-0 emission at 115 GHz (2.6 mm) Wilson, Jefferts,
      & Penzias
      UV lines
      H₂ in rocket experiment (Carruthers 1970)
   f) continuum: free-free, synchrotron
A S T R  5 4 7 0       P h y s i c s  o f  t h e  I n t e r s t e l l a r  M e d i u m

# 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 (Ferriere 2001)

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

$$\frac{M_{\text{dust}}}{M_{\text{gas}}} \sim 10^{-2} \quad \frac{N_{\text{dust}}}{N_{\text{gas}}} \sim 10^{-12}$$

Carina Nebula
3) Cosmic 'rays' \( E_{CR} \sim 1 \text{ eV/cm}^3 \)

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 CR data)
\[
P_{CR} \sim 1.3 \times 10^{-12} \text{ dyne cm}^{-2} \quad (1 \text{ dyne} = 10^{-5} \text{ Newtons})
\]

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

Radial distribution (from gamma ray intensity maps)
\[
L_{CR} \sim 19 \text{ kpc}
\]

Vertical distribution (from measured CR elemental composition)
\[
H_{CR} \sim 3 \text{ kpc}
\]

Spatial distribution
from measured synchrotron emission
4) Magnetic fields  \( B \sim 3 \mu \text{G} \) at \( n \sim 1 \text{ cm}^{-3} \)

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 degrees)

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)

\( B_{\text{regular}} \sim 1.5 \mu \text{G} \)
\( B_{\text{random}} \sim 5 \mu \text{G} \)

\[ \Rightarrow P_M \sim 1.0 \times 10^{-12} \text{ dyne cm}^{-2} \]

\( l_{B_{\text{Breg}}} < ~ 4 \text{ kpc} \)
\( h_{B_{\text{Breg}}} \sim 1.4 \text{ kpc} \)

From measured synchrotron emission

synchrotron emissivity \( \varepsilon_v \propto n_e B^{1.8} \)

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

\[ \Rightarrow \varepsilon_v \propto P_{\text{CR}}^{1.9} \propto P_B^{1.9} \]

\[ \Rightarrow P_{\text{CR}} \propto P_B \propto \varepsilon_v^{1/1.9} \]

Q: Note the different scale lengths between cosmic rays and the Galactic magnetic field. How can the cosmic ray distribution be measured at distances larger than the \( B \) scale length?
## ISM Gas Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>$T$(K)</th>
<th>$n$ (cm$^{-3}$)</th>
<th>Vol %</th>
<th>lengthscale</th>
<th>$M_{\text{solar}}$ pc$^{-2}$</th>
<th>$10^9 M_{\text{solar}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular &quot;H$_2$&quot;</td>
<td>10-20</td>
<td>$10^2$-$10^6$</td>
<td>&lt;1%</td>
<td>1-100 pc</td>
<td>~2.5</td>
<td>1.3-2.5</td>
</tr>
<tr>
<td>Cold atomic &quot;HI&quot;</td>
<td>50-100</td>
<td>20-50</td>
<td>2-4%</td>
<td>pc-kpc</td>
<td>~3.5</td>
<td>&gt;~6.0</td>
</tr>
<tr>
<td>Warm atomic &quot;intercloud&quot;</td>
<td>6-10x$10^3$</td>
<td>0.2-0.5</td>
<td>25%</td>
<td>pc-kpc</td>
<td>~3.5</td>
<td></td>
</tr>
<tr>
<td>Warm ionized &quot;diffuse&quot;</td>
<td>8x$10^3$</td>
<td>0.1</td>
<td>25%</td>
<td>pc-kpc</td>
<td>~1.1</td>
<td></td>
</tr>
<tr>
<td>Warm ionized &quot;HII&quot;</td>
<td>8x$10^3$</td>
<td>0.2-0.5</td>
<td>10%</td>
<td>pc-kpc</td>
<td>~1.4</td>
<td>&gt;~1.6</td>
</tr>
<tr>
<td>Hot ionized &quot;intercloud coronal&quot;</td>
<td>$\sim 10^6$</td>
<td>few $10^{-3}$</td>
<td>70-90%</td>
<td>pc-kpc</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At the solar circle
Molecular Giant molecular clouds contain an appreciable fraction of the Galactic ISM, although they occupy a tiny fraction of IS space. Best terrestrial 'vacuums' are of similar density! $N \sim 200$ interstellar molecules thus far. Half of Milky Way H is molecular. e.g., H$_2$CO formaldehyde, CH$_3$CH$_2$OH ethyl alcohol, CH$_3$CH$_2$OH ethyl cyanide, H$_2$O
Consists mostly of H$_2$, but CO more easily detected; complexes' few $10^2$ cm$^{-3}$ & $10^4$-$10^7$ solar masses, whereas clouds' few $10^3$ cm$^{-3}$ & $10^3$ M$_{\odot}$

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

Board problem:
What is typical speed of 10 K hydrogen atoms?
Alcohol haze at galactic heart

A huge cloud of alcohol is out there somewhere

By BBC News Online science editor Dr David Whitehouse

The detection of yet more alcohol in a giant molecular cloud near the centre of our galaxy could give clues to the origin of complex organic molecules in space.

Astronomers have long been seeking evidence of this particular alcohol to help explain how these life-promoting substances got started.

"The discovery of vinyl alcohol is significant," said Barry Turner, one of the staff scientists at the US National Radio Astronomy Observatory who made the discovery.

"It gives us an important tool for understanding the formation of complex organic compounds in interstellar space," he said. "It may also help us better understand how life might arise elsewhere in the cosmos."

Galactic heart

Vinyl alcohol, actually a non-inebriating complex organic molecule, is an important part of many chemical reactions on Earth, and the last of the three stable members of the C2H4O group of molecules to be discovered in interstellar space.
**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 (I.P. 138 eV) and X-rays.

Middle three phases in ~pressure equilibrium.  Molecular clouds are gravitationally bound, and the last phase is expanding into other phases.
ISM Gas Phases

ISM within the disk
Stellar populations:
I (young): $Z \sim Z_{\text{solar}}$
  in disk
gas + 2$^{\text{nd}}$ generation *s

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

H$I$ and H$_2$ distributions very different
The Galactic Ecosystem

NGC 7331 - Regan et al. 2004

cold atomic

cold dust
The Galactic Ecosystem

Column density

Interstellar Pressures

Space-averaged density at $R_\odot$

What do these plots indicate?
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) HII regions
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
SN
large-scale magnetic fields
emission and reflection nebulae
Radiative Processes

1) **Spectral lines**
   a) Recombination lines (emission)

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

   - Pf\(\alpha\) 7.46\(\mu\)m
   - Br\(\alpha\) 4.05
   - Pa\(\alpha\) 1.88
   - Ba\(\alpha\) 0.66
   - Ly\(\alpha\) 0.12

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

   \[ \Delta E = h \nu = 13.6 \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \text{eV} \]

   \[ \lambda = \frac{c}{\nu} \]

   From Bohr model:

   - Lyman Series (Ultraviolet)
   - Balmer Series (Visible)
   - Paschen Series (Infrared)

   - 656.3 nm (red)
   - 486.1 nm (bluegreen)
   - 434.1 nm (violet)
   - 410.2 nm (violet)

   - Electric transitions:
     6
     5
     4
     3
     2
     1
Radiative Processes

1) **Spectral lines**
   
   b) hyperfine structure: spin-nucleus interaction
   an example is the 21 cm H\textsc{i} line
   \[ A = 3 \times 10^{-15} \text{ s}^{-1} \]
   \[ 1/A \sim 10^7 \text{ yr}!! \]

   ![Diagram of hyperfine structure](image)

   c) forbidden and fine-structure transitions: spin-orbit interaction
   within same configuration (electric quadrupole & magnetic dipole)
   e.g. [\text{O\textsc{iii}}] 5007 Å
   [\text{S\textsc{ii}}] 6731/6716 Å
   [\text{Si\textsc{ii}}] 34.8 \text{ μm}
Let \( \psi_a \) = 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:**
  - \( I = m_1 m_2 R^2/(m_1 + m_2) \)
  - \( J = I \omega \)
  - \( E_{\text{rot}} = I \omega^2/2 \)

- **Add quantum mechanics:**
  - \( J = \{ J(J+1) \}^{1/2} \hbar/2\pi \) quantized
  - \( \nu = \Delta E/\hbar \), with \( \Delta J = 1 \) most likely

- **Then:**
  - \( E_{\text{rot}} = J \cdot J/2I = \hbar^2 J(J+1)/8\pi^2 I \)
  - \( \nu = \hbar (J+1)/4\pi^2 I \) \{ state \( J+1 \Rightarrow \) state \( J \) \}
Rotational transitions of Carbon Monoxide

- **CO molecule:** $A=6 \times 10^{-8}$ s$^{-1}$
  - $m_1 = 12$ amu $= 2.0 \times 10^{-26}$ kg
  - $m_2 = 16$ amu $= 2.7 \times 10^{-26}$ kg
  - $R = 1.1$ Å $= 1.1 \times 10^{-10}$ m

- **Plug in:**
  - $I = m_1 m_2 R^2/(m_1+m_2) = 1.4 \times 10^{-46}$ kg m$^2$
  - $\nu = \hbar(J+1)/4\pi^2 I = 121$ GHz ($J+1$)

- **Actually:**
  - $\nu = 115.271$ 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)
      
e.g. CaI  H&K  4227 Å
      NaI  D$_1$D$_2$  5890,5896 Å
      * absorption usually from a non-excited state. Why?

2) **Continuum**
   
a) BB Planck (e.g. *s and dust)
   b) Bremstrahlung (free-free) $h\nu \sim kT$
      
      e$^-$  p$^+$
   c) synchrotron (magneto-Bremstrahlung)
      
      ions spiraling around interstellar magnetic field lines $\rightarrow$ synchrotron radiation
   d) dust
Radiative Processes

Sun

\( M = 1.99 \times 10^{30} \text{ kg} \)
\( R = 6.96 \times 10^8 \text{ m} \)
\( T_{\text{eff}} = 5780 \text{ K} \)
\( L = 3.85 \times 10^{26} \text{ W} \)

Q: Is the effective temperature accurate?

Other *s: \( 0.1-100 \, M_{\text{solar}} \)
\( 900-60000 \, \text{K} \) (→ spectral classes)
\( 10^{-3}-10^6 \, L_{\text{solar}} \)

Hertzsprung-Russell diagram and evolutionary times
Radiative Processes

Galaxies (stars and gas): Elliptical, Spiral, Starburst, Irregular
Milky Way \( \sim 1.4 \times 10^{11} \) solar masses; \( R \sim 25 \) kpc

very different physics in ISM vs *s (non-equilibrium vs equilibrium)

\( l = \text{mean free path} = \)

- in ISM, atomic \( \sigma \sim 10^{-16} \), \( n \sim 1 \) \( \Rightarrow \) \( l = 10^{16} \) cm
- in * , \( n \sim 10^{20} \) \( \Rightarrow \) \( l = 10^{-4} \) cm

\( \tau = \text{timescale for collision} = \)

in *, m.f.p. \( l_v \) is small « lengthscale of \( \rho, P, T \) \( \Rightarrow \) radiation in thermal equilibrium with gas, hence L.T.E.

Planck radiation field \( I_v = B_v = 2h v^3/c^2 \left( e^{hv/kT_R} - 1 \right) \)

Maxwellian velocity distribution \( f(v) = 4\pi v^2 (m/2\pi kT_K)^{3/2} e^{-mv^2/2kT_K} \)

Both radiation and gas characterized by same \( T \) i.e., \( T_R = T_K \)

in *, \( F_v \neq 0 \) (they radiate; some photons escape), hence not TE, just LTE
Radiative Processes

in ISM, $n$ much lower, thus $l_v \gg$ lengthscale of clouds $d$ (radiation easily escapes) $\Rightarrow$ radiation not Planck in shape or energy density
dilution factor $w \sim (r_*/d)^2 \sim 10^{-15}$
therefore expect $T_e \ll T_*$, but not so!!
Non-equilibrium $\Rightarrow$ different $T_K, T_{Rad}, T_{e-}, T_{x-ray}, T_{diffuse}, T_{CMB}$

ISM evolves

ISM sources and sinks
sink: star formation $-3$ solar masses/year
sources: **High Velocity Clouds** $< 1.4$
AGB & planetary nebulae $0.3-1$
OB* winds $0.08-0.5$
SNe $0.03$
Novae $0.003$
Sum of the sources $0.4-1.5$
Radiative Processes

Mass of Milky Way's ISM $\sim 6 \times 10^9$ solar masses
⇒ timescale for converting all the ISM mass to stars:

Galaxy's energy: $L_B = 1-2 \times 10^{10} L_{\text{solar}}$
$L_{\text{IR}} = \text{same}$
$SNe = 10^{51}$ ergs/50 yr $= 6 \times 10^{41}$ ergs/s $= 1.7 \times 10^8 L_{\text{solar}}$
$\text{OB}^* \text{ winds} = 10^{50}/50 \text{ yr} \sim 1.7 \times 10^7 L_{\text{solar}}$
ISM ionization $\sim 2 \times 10^8 L_{\text{solar}}$
Radiative Terminology

<table>
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<tr>
<th>Term</th>
<th>Description</th>
<th>Units</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Apparent magnitude</td>
<td>mag</td>
<td>$-2.5\log(L/4\pi d^2)+\text{constant}$</td>
</tr>
<tr>
<td>M</td>
<td>Absolute magnitude</td>
<td>mag</td>
<td>$-2.5\log L+\text{constant}$</td>
</tr>
<tr>
<td>m-M</td>
<td>Distance modulus</td>
<td>mag</td>
<td>$5\log(d/10\text{pc})$</td>
</tr>
<tr>
<td>L</td>
<td>Luminosity</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>Flux</td>
<td>W/m²</td>
<td>$L/4\pi d^2$, $k10^{-0.4m}$</td>
</tr>
<tr>
<td>$l_\nu$</td>
<td>Specific intensity</td>
<td>W/m²/Hz</td>
<td></td>
</tr>
<tr>
<td>$L_\nu$</td>
<td>Luminosity density</td>
<td>W/Hz</td>
<td></td>
</tr>
<tr>
<td>$f_\nu$</td>
<td>Flux density</td>
<td>W/m²/Hz</td>
<td>$\int d\Omega l\nu \cos \theta$</td>
</tr>
<tr>
<td>$f_\lambda$</td>
<td>Flux density</td>
<td>W/m²/m</td>
<td>$\int d\Omega l_\lambda \cos \theta$</td>
</tr>
<tr>
<td>f</td>
<td>Flux</td>
<td>W/m²</td>
<td>$\approx f_\nu \Delta \nu$</td>
</tr>
<tr>
<td>B-V</td>
<td>Color; logarithmic flux ratio</td>
<td>mag</td>
<td></td>
</tr>
<tr>
<td>$B_\nu(T)$</td>
<td>Blackbody; Planck spectrum</td>
<td>W/m²/Hz</td>
<td>$2h\nu^3/c^2/(e^{hv/kT}-1)$</td>
</tr>
<tr>
<td>$B_\lambda(T)$</td>
<td>Blackbody; Planck spectrum</td>
<td>W/m²/m</td>
<td>$2hc^2/\lambda^5/(e^{hv/kT}-1)$</td>
</tr>
</tbody>
</table>

Note:
- $f=\nu f_\nu=\lambda f_\lambda$  \hspace{1cm}  $d\nu=(c/\lambda^2)d\lambda$
- Bolometric flux is flux from all wavelengths \hspace{1cm} in practice it's never measured
- Wien's law for thermal radiation: $\lambda_{\text{max}} T \approx 0.29$ cm K
- Stefan-Boltzmann law for thermal radiation: $F=\sigma T^4$
- The subscript $\nu$ or $\lambda$ implies a monochromatic quantity

Q: Which of these units is evil?
Radiative Transport Terminology

$I_v = \text{specific intensity} \quad [\text{Power/area/frequency/steradian}] \quad \text{"surface brightness"}$

$\Rightarrow$ energy from a given direction

$= h \nu c \frac{dn_v}{d\Omega} \quad \text{number density of photons per unit frequency interval} \quad (\text{number/cm}^3/\text{Hz})$

$F_v = \text{flux density} \quad [\text{Power/area/frequency}] \text{ or } [\text{Power/area/wavelength}]$

$F_v = \int d\Omega I_v \cos \theta$

azimuthal symmetry $\Rightarrow -\int d(\cos \theta) 2\pi I_v \cos \theta$

$d\Omega = 2\pi \sin \theta d\theta$

$dA \Rightarrow \text{projected area is } dA \cos \theta$

if $I_v$ is constant, $F_v =$
Radiative Transport Terminology

Observed flux from a star of radius \( R \) and distance \( d \):

\[
F_v = \int \! d\Omega I_v \cos \theta' \quad (\cos \theta' \approx 1)
\]

\[
d\Omega = \frac{dA_{\text{proj}}}{d^2} = 2\pi r dr/d^2 = 2\pi R \sin \theta \frac{d(R \sin \theta)}{d^2}
\]

\[\Rightarrow f_v = \frac{F_v R^2}{d^2}\]

if the star emits like a blackbody \( I_v = B_v(T) \)

\[\Rightarrow f_v = \pi B_v(T) \frac{R^2}{d^2}\]

Flux \( f \) (\( \approx f_v \Delta \nu \)): flux of radiation through unit surface

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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 \( \varepsilon_\lambda = \) emissivity of background = 0.3 \( \eta = \) quantum efficiency of detector = 0.2

\( \tau = \) transmission = 0.1

\( A = \) telescope area

\( T = 290 \) K

\( \lambda = 10 \)\( \mu m \)

\( \Delta \lambda = \) bandwidth = 1\( \mu m \)

\( \Omega = \) solid angle of FOV \((\pi/4 \theta_D^2)\)

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

For diffraction-limited performance,

\[ A\Omega = \pi/4 D^2 (\theta_D^2)^2 = 9.2 \times 10^{-13} \lambda^2(\mu m) \text{[m}^2 \text{sr]} \]

\[ \Rightarrow N_e \cong 2.3 \times 10^8 e^-/\text{sec/resolution element} \]

At Keck, the 3-25\( \mu m \) detector is a Boeing Si:As 128x128 array with a 1.1 \( 10^7 \) e^-/pixel full-well capacity. \( \Rightarrow \) read out rate must be \( \ldots \)! Otherwise, you will saturate in 50 ms!

Analogy: daytime observing in B band is \( 10^8 \) e^-/s/pixel
Radiation Transport

Let's consider the propagation of radiation of frequency $\nu$ along the l.o.s. towards the observer, in the region of an interstellar cloud.

\[
I_{\nu,0} \quad \text{0} \quad ds \quad s^* \quad I_{\nu} \quad \rightarrow \quad S
\]

\[
j_{\nu} = \text{emission coefficient of the gas} \quad \text{[energy/time/volume/frequency/sr]}
\]
\[
d\Omega = \text{solid angle towards observer} \quad \text{[sr]}
\]
\[
j_{\nu}d\Omega = \text{gas emission in } d\Omega \quad \text{[energy/time/volume/frequency]}
\]
\[
I_{\nu} = \text{intensity of radiation} \quad \text{[energy/time/area/frequency/sr]}
\]
\[
I_{\nu}d\Omega = \text{intensity in } d\Omega \quad \text{[energy/time/area/frequency]}
\]

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

$\kappa_{\nu}$: absorption coefficient per unit length (cm$^{-1}$)

\[
\Rightarrow dI_{\nu}d\Omega = j_{\nu}d\Omega ds - \kappa_{\nu} I_{\nu} d\Omega ds \quad \Rightarrow \quad dI_{\nu}/ds = -\kappa_{\nu} I_{\nu} + j_{\nu}
\]

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

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

$\tau_{\nu} \ll 1$ \quad optically thin

$\tau_{\nu} > 1$ \quad optically thick

The Galactic Ecosystem

ASTR 5470 Physics of the Interstellar Medium
Radiation Transport (adapted from Chapter 2 of Dyson & Williams)

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

$$I_v = I_{v,0}\exp(-\tau_v) + \int \tau_v j_v / \kappa_v \exp(-\tau_{v-}\tau_v)]$$  [from 0 to $\tau_v$]

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

$$j_v = \kappa_v B_v(T)$$

and

$$I_v = I_{v,0}\exp(-\tau_v) + B_v(T)(1-\exp(-\tau_v))$$

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

$$B_v(T) \approx 2\nu^2kT_b/c^2$$

and

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

In the limit of low optical depth $\tau_v \ll 1$: $T_b = \ldots$

In the limit of high optical depth $\tau_v \gg 1$: $T_b = \ldots$
21 cm line transfer

1. if \( \tau \gg 1 \) \( \Rightarrow \ T_b = T_s \)
   \( T_s \) = 'spin' or 'excitation temperature' for 21 cm line

2. if \( \tau \ll 1 \) and \( T_{b,0} = 0 \) \( \Rightarrow \ T_b \sim \tau T_s = T_s \int_k \kappa \, ds \) [from 0 to \( s^* \)]
   and \( N_H^{\text{tot}}(\tau \ll 1) = 1.83 \times 10^{18} \int dv \ T_b(v) \quad v \) in km/s; \( T_b \) in K; \( N_H \) in cm\(^{-2}\)

   remembering that \( n_H = n_0 + n_1 = n_0 \left( 1 + \frac{g_1}{g_0} \exp \left( -\frac{T_{10}}{T_s} \right) \right) \)
   \( T_{10} \sim \hbar \nu_{10} / k = 0.0681 \) K
   \( \sim n_0 \left( 1 + 3(1 - \frac{T_{10}}{T_s}) \right) \)
   \( \sim 4n_0 \)

**Spectral lines: what can we learn?**

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

- Velocity kinematics
  - galactic rotation/distance
  - internal to cloud/complex

- Line width
  - natural broadening
  - thermal broadening
  - pressure broadening
  - beam broadening (line of sight)
Absorption and Emission in the same cloud

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

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

\[ T_{\text{line}} = T_{\text{cont}} - (T_{\text{cont}} e^{-\tau} + T_s (1 - e^{-\tau})) \]

at maximum absorption \( T_{\text{line}} = (T_{\text{cont}} - T_s)(1 - e^{-\tau_0}) \)
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HI emission and absorption
Dickey & Lockman 1990 ARAA, 28, 215

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 clouds, same temp, same $\tau$
   \[ T_1 = T_2 = 150 \text{ K} \]
   \[ \tau = 1 \ (\frac{1}{2} + \frac{1}{2}) \]
   \[ v = 0 \]
   \[ \Delta v = 5 \]

2. Cold cloud in back of 1.
   \[ T_c = 50 \text{ K} \]
   \[ \tau = 4 \ (\frac{1}{2} + \frac{1}{2} + 3) \]
   \[ v = +0.4 \text{ km/s} \]
   \[ \Delta v = 1 \text{ km/s} \]

3. Hot hot cold hot cold

4. Hot hot cold hot cold

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Natural Line Widths (see 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,

\[ I_\nu \propto \frac{1}{[(\nu-\nu_0)^2 + (\gamma/4\pi)^2]} \]

Doppler Broadening

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

\[ \frac{(\nu-\nu_0)}{\nu_0} = \frac{v_z}{c} \]

\( \nu_0 \) = emitted frequency
\( \nu \) = 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

\[ dN_z \propto \exp\left(-\frac{Mv_z^2}{2kT}\right) dv_z \]

where \( M \) is the atomic mass.

There's also a spread in frequency with

\[ I_\nu \propto \exp[-(\nu-\nu_0)^2/2\delta^2] \]

where \( \delta^2 = \nu_0^2kT/Mc^2 \)

Collisional Broadening

Usually insignificant for standard ISM conditions. The frequency width due to collisions scales as \( \tau_0^{-1} \), where \( \tau_0 \) 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,

- What is the effect on the brightness of Galactic stars? Quantify.
- What is the effect on the 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?
**Concept Question**

In class we've discussed H\textsubscript{2} molecules having no electric dipole moment, and thus being difficult to observe. One might think from that discussion that H\textsubscript{2} molecules suffer from a dearth of emission and absorption lines. On the contrary, H\textsubscript{2} lines exhibit a multitude of lines, with UV absorption lines and infrared emission lines particularly prominent in observational astronomy. Why does H\textsubscript{2} have so many available transitions? Another way to phrase the question: what is the physical mechanism(s) responsible for all these transitions?

**Follow-up question:**

Hey, if an H\textsubscript{2} molecule absorbs a photon, shouldn't there be another photon emitted? So why do even see an absorption line – wouldn't each absorption be followed by an equally-energetic emission?