Interstellar Clouds
- The physical state of interstellar matter depends on its composition and the local temperature, pressure, and density.
- The stability of the state depends on the relative rates of energy gain and loss.

Typical diffuse cloud
$T_K = 50-100 \text{ K}$  
$n_H = 10^{-2} \text{ cm}^{-3}$  
mostly HI; $n_e = 10^{-4} n_H$; $M \sim 400$ solar masses; $R = 5 \text{ pc}$

- Total thermal energy: $U \sim 3MkT/2m_H \sim 10^{46} \text{ ergs}$
- Gravitational binding energy: $E_G = 3M^2G/5R \sim 2 \times 10^{45} \text{ ergs}$

- NOT GRAVITATIONALLY BOUND $\implies$ clouds form because gas is THERMALLY UNSTABLE

Thermal stability $\Leftrightarrow$ Rate of heat transfer of gas $\Leftrightarrow$ pressure equilibrium

1st law of thermodynamics ($\Delta E = Q - W$): $\rho d\epsilon/dt = n d(3/2kT)/dt = nTds/dt - P/n$  
$dn/dt = nTds/dt - kTdn/dt$

where $\rho = \mu m_H n$, $\mu =$ mean molecular weight, $s =$ entropy, $\epsilon =$ internal energy per mass

For a monatomic gas whose pressure is held constant

$\Gamma - \Lambda = 3nk/2 \ dT/dt = nTds/dt$

where $\Gamma$ - heating rate  
$\Lambda$ - cooling rate  
$\Gamma, \Lambda$ complicated functions of $T, \rho, Z$

ASTR 5470  Physics of the Interstellar Medium
Gas Cooling & Heating

**Cooling processes**: A heated, partly-ionized gas cools through the conversion of kinetic energy into luminosity by collision processes.

The efficiency of cooling is a sensitive function of composition

⇒ the gas must be optically thin to emitted photons

**Cases**

i) completely ionized gas

⇒cooling due to bremsstrahlung

ii) partly ionized gas of cosmic abundance at high $T$

⇒cooling due to electron impact excitation of fine structure levels of neutral and ionized components

iii) as $T$ decreases, the fractional ionization decreases

⇒cooling by fine structure emission by neutral hydrogen impacts

<table>
<thead>
<tr>
<th>Element</th>
<th>A.W.</th>
<th>$n_x/n_H$</th>
<th>$n_x/n_H \times$ AW</th>
<th>$\chi$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>12</td>
<td>4 $10^{-4}$</td>
<td>0.0048</td>
<td>11.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>14</td>
<td>10$^{-4}$</td>
<td>0.0014</td>
<td>14.5</td>
</tr>
<tr>
<td>Oxygen</td>
<td>16</td>
<td>8 $10^{-4}$</td>
<td>0.0128</td>
<td>13.6</td>
</tr>
<tr>
<td>Mg</td>
<td>24</td>
<td>3 $10^{-5}$</td>
<td>0.0007</td>
<td>7.8</td>
</tr>
<tr>
<td>Silicon</td>
<td>28</td>
<td>3 $10^{-5}$</td>
<td>0.0008</td>
<td>8.1</td>
</tr>
<tr>
<td>Sulfur</td>
<td>32</td>
<td>1.6 $10^{-5}$</td>
<td>0.0005</td>
<td>10.4</td>
</tr>
<tr>
<td>Iron</td>
<td>56</td>
<td>2.5 $10^{-5}$</td>
<td>0.0014</td>
<td>7.9</td>
</tr>
<tr>
<td>Neon</td>
<td>20</td>
<td>26 $10^{5}$</td>
<td>0.0005</td>
<td>21.6</td>
</tr>
</tbody>
</table>

$\chi < 13.6$ eV  ⇒ partly ionized in HI regions

$\chi > 13.6$ eV  ⇒ ionized in HII regions
Gas Cooling & Heating

In a typical HII region the cooling occurs almost entirely from e⁻ excitation of ionized atoms of elements C,N,O,Ne since these have excited levels a few eV above the ground state; these levels are collisionally-populated at $T \sim 10^4$ K.

Collisional cross-sections are $10^5$ times the radiative cross-sections.

⇒ If not for the low abundance of these elements, there would be only cool HII regions!

In contrast, H at the $n=2$ level quickly becomes ionized, be it via $h\nu$ or e⁻. And atomic H at $n=1$ has weak fine structure radiation.

Concept Question:
Does the cooling rate increase with $T$ for HII regions? (see Spitzer 1978 Fig. 6.1)
**Interstellar Cooling Function**

\[ \Lambda(x,t) = \sum n(x_i)/n_H \{ xL_{e-} (x_i/T) + (1-x)L_H (x_i/T) \} \]

where \( x = n_{e-}/n_H \) fractional ionization

\( L_{e-} \) cooling efficiency by e\(-\) impact excitation

\( L_H \) cooling efficiency by neutral hydrogen impact excitation

**Thermal Equilibrium** \( \Gamma = \Lambda \) at \( T_{eq} \)

Consider the rate of change in temperature when \( T \neq T_{eq} \)

\[ \frac{dT}{dt} = -\frac{(T-T_{eq})/t_{relax}}{t_{relax}} \]

\( t_{relax} \) relaxation time

**Equation of state** for ideal gas \( P = nkT \)

\[ \Gamma - \Lambda = 3/2nk dT/dt = -3/2 \frac{P}{T} \left( \frac{T-T_{eq}}{t_{relax}} \right) \]

solve for relaxation time

\[ t_{relax} = -3/2 \frac{P}{T} \left( \frac{T-T_{eq}}{\Gamma - \Lambda} \right) \]

\( t_{relax} > 0 \): if \( T \neq T_{eq} \), the gas will tend to return to \( T_{eq} \) (thermal)

\( t_{relax} < 0 \): if \( T \neq T_{eq} \), the difference \( T-T_{eq} \) will continue to grow (thermal)

**Define** \( Q \equiv \Gamma - \Lambda = \text{function of density & temperature} \)

expand \( Q \) around \( T = T_{eq} \); since \( P \) is held constant:

\[ Q(T) \approx Q(T_{eq}) + \frac{\partial Q}{\partial T_{eq}} (T-T_{eq}) \]
\[
Q(T) \approx Q(T_{eq}) + \frac{\partial Q}{\partial T_{eq}} (T - T_{eq})
\]
but \(Q(T_{eq}) = 0\), so \(t_{relax} = -3/2 \frac{P}{T} (\frac{\partial Q}{\partial T_{eq}})^{-1}\)

the sign of \(t_{relax}\) depends on the change in \(Q\) with temperature at constant pressure

condition for instability \((\frac{\partial Q}{\partial T})_p = \frac{\partial Q}{\partial T} + (\frac{\partial Q}{\partial \rho})(\frac{\partial \rho}{\partial T})_p > 0\)
given \(Q=\Gamma - \Lambda\), one can determine whether gas is stable or not

Some important cooling transitions in cool interstellar clouds (T~100 K)

<table>
<thead>
<tr>
<th>Transition</th>
<th>Colliding Partners</th>
<th>(\Delta E/k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^+) ((^2P_{\frac{1}{2}} \rightarrow ^2P_{\frac{3}{2}}))</td>
<td>H,e(^-),H(_2)</td>
<td>92 K</td>
</tr>
<tr>
<td>Si(^+) ((^2P_{\frac{1}{2}} \rightarrow ^2P_{\frac{3}{2}}))</td>
<td>e(^-)</td>
<td>413 K</td>
</tr>
<tr>
<td>O ((^3P_2 \rightarrow ^2P_{1,0}))</td>
<td>H,e(^-)</td>
<td>228 K, 326 K</td>
</tr>
</tbody>
</table>

Main Cooling Mechanisms at Different Temperatures for Neutral and Partially Ionized Gas

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Main Coolant</th>
<th>Approx. Cooling Rate (J m(^{-3}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>CO</td>
<td>(10^{-45}n^2)</td>
</tr>
<tr>
<td>100</td>
<td>(H_2,C^+)</td>
<td>(10^{-40}n^2)</td>
</tr>
<tr>
<td>1,000</td>
<td>Metastable ions</td>
<td>(10^{-38}n^2)</td>
</tr>
<tr>
<td>10,000</td>
<td>(H,H^+,p^+,e^-)</td>
<td>(10^{-35}n^2)</td>
</tr>
</tbody>
</table>
Gas Cooling & Heating

**Heating Processes:** conversion of energy originally stored in some background radiation field (including cosmic rays) into kinetic energy, which then is carried away by particles, especially electrons, thermalized in elastic collisions

Primary interaction \[ A + \{ \text{hv or p}^+ \} \rightarrow A^+ + e^- + \{ \text{nothing or altered p}^+ \} \]

Heating occurs if K.E. carried away by the liberated electron exceeds the mean K.E. of the gas

i) **Processes that continuously operate in space and time**
   1. starlight at \( \lambda < 911 \, \text{Å} \)
   2. low energy cosmic rays (1-10 MeV)
   3. soft x-rays (~100-300 eV)
   4. cloud collisions
   5. hydromagnetic waves
   6. dissipation of turbulent energy of the ISM

ii) **Processes that continuously operate in time, but localized in space**
   1. heating and ionization due to photons with \( \lambda < 911 \, \text{Å} \) in the vicinity of O,B *s
   2. same, near UV *s (on way from red giant to white dwarf)
   3. EUV photons from helium recombinations
   4. photoelectric emission from grains
   5. collisional de-excitation of vibrational levels of \( \text{H}_2 \)
   6. radiative dissociation of \( \text{H}_2 \)

iii) **Processes that are time-dependent and localized in space**
    e.g., supernovae (McKee and Ostriker model)

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What's so special about 911?
Models of the ISM:

1. Heating mechanisms

2. Thermal equilibrium \( \Gamma = \Lambda \)

3. Ionization balance ionizations = recombinations

\[ \Rightarrow \frac{n_e}{n_H} = x(T) \quad \text{fractional ionization} \]

\[ \Rightarrow \frac{\xi}{n_H(T)} \quad \text{primary hydrogen ionization rate per atom} \]

If the gas is thermally stable, then \( \frac{dT}{dt} = 0 \)

and \( \Gamma - \Lambda = 3nk/2 \frac{dT}{dt} = 0 \)

Equilibrium temperature \( \Lambda(\rho, T_{eq}) = \Gamma(\rho, T_{eq}) \)

where \( \rho \approx m_H n_H \) for HI clouds \( (n_H \gg n_e) \)

Example application: Milky Way coronal gas \( (10^6 \text{ K}) \):

Spitzer 1956 (ApJ 124, 20) \( \Rightarrow \) suggested possibility of Galactic corona

high \( T \ (>10^6 \text{ K}) \) gas radiates inefficiently (no ion quantum states, therefore only free-free)

rate of radiation \( \varepsilon_{ff} = 2^5 \pi e^6 Z^2 n_e n_i 3h m_e c^3 (2\pi kT/3m_e)^{\frac{1}{2}} \Rightarrow \)

\( t_{\text{dissipate}} = \)

\( \Rightarrow \) once gas is very hot, stays hot for > 10\(^{10}\) yr

For \( T < 10^6 \text{ K} \), cooling occurs fairly quickly (<10\(^8\) yr) via collisionally-induced line transitions

\( \Rightarrow \) medium-hot gas must be continually heated to stay medium-hot

Two-phase model: clouds $n_c \sim 10 \, \text{cm}^{-3}$, $T_c \sim 10^2 \, \text{K}$

intercloud medium $n_h \sim 10^{-1} \, \text{cm}^{-3}$, $T_h \sim 10^4 \, \text{K}$

- original evidence that all the HI gas is not at $T \sim 125 \, \text{K}$
  1. HI self-absorption seen in emission profiles
  2. consistent difference seen in appearance between emission and absorption profiles
  3. difficult to understand how gravitationally unbound clouds could hold together

$\Rightarrow$ pressure confinement $P \sim (n_e + n_{\text{H}})kT$ $n_{\text{cold}} T_{\text{cold}} \sim n_{\text{hot}} T_{\text{hot}}$

- cosmic ray heating of hot ISM
- cooling due to collisional excitation of H, He at high $T$ and C$^+$ (among others) at lower $T$

balance heating by cosmic rays against cooling by H at high \(T\) and \(\text{C}^+\) at low \(T\)

(updated two phases: McKee 1995, Physics of ISM & IGM, ASP, 80, 292)

FGH 1969

find three phases in pressure equilibrium; two are thermally stable ('F' and 'H')
a third stable phase should exist above \(10^6\) K, with bremsstrahlung cooling (Spitzer 1956?)
~75% of the gas in cool phase 'H' (HI + \(\text{H}_2\),?)

heating \((\Gamma)\) from cosmic rays (2 MeV from SN ejecta)
assume \(\xi_H\) = H ionization rate = 4 \(10^{-16}\) sec\(^{-1}\) \(\text{H}^{-1}\)
get 8-20 eV per ionization
\[
\Gamma_{\text{CR}} = n_H \xi_H <E> = n_H \times 4 \times 10^{-16} \times 10\text{eV} = 6.4 \times 10^{-27} n_H
\]
In-depth analysis of one heating mechanism: the heating of neutral gas by photo-ejected electrons from small grains.

Early references: Watson 1972; Jura 1976
Recent review: Hollenbach & Tielens 1999, Reviews of Modern Physics

Efficiency of grain heating ($\varepsilon_{\text{grain}}$) depends on probability $Y$ that electrons escape times the fraction of the photon energy carried away as kinetic energy by the electron.

The yield is a complex function of the grain size $a$, the collision lengthscale for low-energy electrons in solids $l_e$ (~10 Å), the far-ultraviolet absorption lengthscale inside a grain $l_a$ (~100 Å), and the photon energy $h\nu$. $Y \approx l_e/l_a$.

With typical FUV photon energy of 10eV and $W\approx$5eV, the maximum efficiency is only ______. Including positive charging, the efficiency will be much less.'
The heating of neutral gas by photo-ejected electrons from small grains.

It's much easier to eject electrons from very small grains and planar PAH molecules. For PAHs, the ionization potential is \( IP = W + \Phi_c = W + (Z + 0.5)e^2/C \), where the capacitance \( C \) for compact PAHs is ______. The limiting factor here is that \( IP \) can be greater than 13.6eV. Only a fraction \( f_n \) of PAHs can be ionized by FUV photons. So with photon energy of 10eV and \( IP \) of 7eV, and assuming that half of the incoming photon energy is converted to electronic excitations, the maximum efficiency is ______.

So about half of the photoelectric heating arises from grains with size less than 15Å, and the other half from grains between 15 and 100Å. Grains of size >100Å contribute negligibly to the heating.

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FIG. 14. The contribution to the photoelectric heating of interstellar gas by grains of different sizes (Bakes and Tielens, 1994). The results of these calculations are presented in such a way that equal areas under the curve correspond to equal contributions to the heating. Species with \( \approx 50 \) C atoms are the carriers of the IR emission features at 3.3, 6.2, 7.7, and 11.3 \( \mu \)m. The plateaus underneath these features and the 12 \( \mu \)m cirrus are carried by somewhat larger species (\( \approx 200 \) C atoms). The 25 and 60 \( \mu \)m cirrus correspond to species with \( 5 \times 10^4 \) and \( 5 \times 10^5 \) C atoms, respectively.
The heating of neutral gas by photo-ejected electrons from small grains.

Theoretical models, buttressed by laboratory efforts, predict that the PAH emission features near 8μm are more ionized than the features at 11μm. Therefore, predict how the 8μm/11μm PAH ratio should vary as a function of the “hardness” of the radiation field (“harder” implies “bluer”, with relatively more energetic photons).
From my *Spitzer Space Telescope* proposal

The energized and liberated electrons ultimately bump into atoms in the *neutral* ISM. \([\text{CII}]158\mu\text{m}\) and \([\text{OI}]63\mu\text{m}\) dominate the resultant cooling of the *neutral* ISM. The reason it is these two particular transitions is governed by the balance of abundance and requisite excitation energy (see \(\Delta E/k\) column):

<table>
<thead>
<tr>
<th>Species</th>
<th>(\lambda) ((\mu\text{m}))</th>
<th>I.P.(_1) (eV)</th>
<th>I.P.(_2) (eV)</th>
<th>(\Delta E/k) (K)</th>
<th>Model Abundance (per 10(^6) H nuclei)</th>
<th>(\log \frac{I}{I_{[\text{CII}]}})</th>
<th>(\log \frac{I}{I_{[\text{CII}]}})</th>
<th>(\log \frac{I}{I_{[\text{CII}]}})</th>
<th>(\log \frac{I}{I_{[\text{CII}]}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{CII}])</td>
<td>157.7</td>
<td>11.3</td>
<td>24.4</td>
<td>91</td>
<td>(A_C = 140,150)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>([\text{OII}])</td>
<td>63.2</td>
<td>13.6</td>
<td>228</td>
<td>(A_O = 300,400)</td>
<td>-1.4,-2.8</td>
<td>-0.10,-0.93</td>
<td>0.70,0.15</td>
<td>1.3,1.0</td>
<td></td>
</tr>
<tr>
<td>([\text{FeII}])</td>
<td>35.3</td>
<td>7.9</td>
<td>16.2</td>
<td>407</td>
<td>(A_{\text{Fe}} = 1.7,1.0)</td>
<td>-10.5,-5.4</td>
<td>-5.3,-5.5</td>
<td>-5.6,-3.9</td>
<td>-2.3,-1.8</td>
</tr>
<tr>
<td>([\text{SiII}])</td>
<td>34.8</td>
<td>8.2</td>
<td>16.4</td>
<td>413</td>
<td>(A_{\text{Si}} = 1.7,1.0)</td>
<td>-4.0,-4.5</td>
<td>-5.0,-3.2</td>
<td>-1.0,-2.0</td>
<td>-0.17,-0.70</td>
</tr>
<tr>
<td>([\text{H}_2\text{S(0)}])</td>
<td>28.2</td>
<td></td>
<td></td>
<td>510</td>
<td></td>
<td>-2.9,-2.9</td>
<td>-1.3,-2.5</td>
<td>-1.2,-2.0</td>
<td>-1.4,-1.4</td>
</tr>
<tr>
<td>([\text{FeII}])</td>
<td>26.0</td>
<td>7.9</td>
<td>16.2</td>
<td>554</td>
<td>(A_{\text{Fe}} = 1.7,1.0)</td>
<td>-6.5,-4.8</td>
<td>-3.7,-3.8</td>
<td>-2.5,-2.2</td>
<td>-1.4,-0.63</td>
</tr>
</tbody>
</table>

Intensities \(I\) predicted by the models of Kaufman et al. (1999) and Draine & Bertoldi (2000) for:

A: \(\chi = 1\), the average interstellar UV radiation field and \(P/k = 10^4\) cm\(^{-3}\) K
B: \(\chi = 10^{2.0}\) times the average interstellar UV radiation field and \(P/k = 10^5\) cm\(^{-3}\) K
C: \(\chi = 10^{3.5}\) times the average interstellar UV radiation field and \(P/k = 10^6\) cm\(^{-3}\) K
D: \(\chi = 10^{5.0}\) times the average interstellar UV radiation field and \(P/k = 10^7\) cm\(^{-3}\) K
Gas Cooling & Heating

[CII]158µm is the most important coolant of the neutral ISM. It is the fourth most abundant element and has a lower ionization potential (11.26eV) than hydrogen, so that carbon will be in the form of C⁺ in the neutral surface layers of far-UV illuminated neutral gas clouds. The depth of these C⁺ zones is generally determined by dust extinction and often extends to $A_v < 4$ mag. The 158µm line is also easy to excite ($\Delta E/k \sim 91$ K or $\Delta E \sim 8$meV), so that C⁺ can cool warm ($30 \text{ K} < T < 10^4 \text{ K}$) neutral gas whereas the two most abundant atoms H and He cannot (Malhotra et al. 2001).

[CII]/FIR is about 0.2-0.7% in normal and star-forming galaxies. This jibes with theoretical predictions of 0.1-1.0%. The efficiency here is defined as the energy input to the gas divided by the total energy of the FUV photons absorbed by dust grains. Although the gas receives $10^2$-$10^3$ times less heating energy per unit volume than the dust, the gas attains higher equilibrium temperatures because ______________? (see also slide 17)

Photodissociation Regions: FUV-illuminated (6eV<13.6eV) neutral ISM \(\Rightarrow\) majority of mass of ISM

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**FIG. 3.** A schematic diagram of a photodissociation region. The PDR is illuminated from the left and extends from the predominantly atomic surface region to the point where O₂ is not appreciably photodissociated ($A_v \approx 10$). Hence the PDR includes gas whose hydrogen is mainly H₂ and whose carbon is mostly CO. Large columns of warm O, C, C⁺, and CO, and vibrationally excited H₂ are produced in the PDR.

**FIG. 4.** The Cosmic Background Explorer (COBE) observation of the far-infrared spectrum of our Milky Way Galaxy (Wright et al., 1991; figure from Genzel, 1991). With the exception of the [NII] emission and a controversial portion of the [CII] emission, the bulk of the emission is from PDRs. Note that there is no information from COBE on the line spectrum of the Milky Way at wavelengths less than the [OI] 145 µm line.
Gas Cooling & Heating

Since most of the heating in the neutral ISM is done by small grains, and very little by big grains, what happens to the ratio \([\text{CII}] / \text{FIR}\) as the intensity and 'hardness' of the ISRF increases?

*Hint:* \([\text{CII}]158\mu m\) represents gas cooling, FIR is starlight reprocessed by dust grains into the far-infrared, and the neutral ISM is predominantly heated by photo-ejection from very small grains/PAHs.

a) What happens to \(\text{FIR}\) as the ISRF increases? Make a plot. (easy)

b) What happens to photo-ejection heating from PAHs as the ISRF increases? Make a plot. (maybe not so easy)

c) Take the above two results to make a predicted curve of \([\text{CII}] / \text{FIR}\) vs ISRF.
a) FIR increases with the heating as gauged by dust temperature, as expected.

\([\text{CII}] / \text{PAH}\) does not drop with heating \(\Rightarrow\) direct evidence for coupling between heating by photo-ejection from PAHs and \(\text{C}^+\) cooling!

c) \([\text{CII}] / \text{FIR}\) drops with heating. The cooling by \(\text{C}^+\) is not one-to-one with big dust grain emission.
Dust grains are heated by the interstellar radiation field. The large (i.e. normal) dust grains are in thermal equilibrium. Why then is the interstellar gas at such a higher temperature than the dust? Doesn't that seem strange? -- the gas is bathed in the same interstellar radiation field as the dust.

Deep inside molecular clouds where little to no spectral line radiation escapes, the cooling is dominated by dust grain radiation. However, in order to cool, dust grains must be first heated. They are heated by ______________. They then re-radiate in the infrared, and thus provide the primary form of protostellar cooling that permits these clouds to contract to form stars.

The rate at which grains can cool the gas is only as fast as the molecules can transfer the energy to the grains. The rate of heat transfer is

\[ \frac{dQ_{gr}}{dt} = n_{H_2} \pi a^2 (3kT_{H_2}/m_{H_2})^{1/2} (T_{H_2} - T_{gr}) \alpha (c_v T_{H_2}/N_{Avogadro}) \]

\( \alpha \) is an efficiency factor for energy transfer via impacts by molecules

\( c_v T_{H_2}/N_{Avogadro} \) is the energy the molecule could transfer \( (c_v \text{ heat capacity/mole}) \)

The number density of grains is

\[ n_{gr} = n_{H_2} X_{gr} m_{H_2}/\rho_{gr} (4\pi a^3/3) \]

\( X_{gr} \) is grain fraction by mass
Gas Cooling & Heating

The product of these two equations gives the amount of gas cooling (grain heating):

\[ L_{\text{gr}} = \frac{dQ_{\text{gr}}}{dt} = 10^{-22} \left( \frac{n_{\text{H}_2}}{10^4 \text{ cm}^{-3}} \right)^2 \left( \frac{X_{\text{gr}}}{10^{-3}} \right) (\alpha/0.333) (2 \text{ g cm}^{-3}/\rho_{\text{gr}}) (10^{-5} \text{ cm}/a) (c_v/N_A/1.5) (T_{\text{H}_2}/50 \text{ K})^{1.5} ((T_{\text{H}_2} - T_{\text{gr}})/30 \text{ K}) \text{ erg/cm}^3/\text{s} \]

This is how quickly the gas can transfer its heat energy to the grains. Compare this to the rate at which grains can shed this energy – the grain radiative cooling with efficiency \( Q_{\text{em}} \) is

\[ L_{\text{rad}} = 4\pi a^2 n_{\text{gr}} \sigma T_{\text{gr}}^4 Q_{\text{em}} = 4.4 \times 10^{-21} \left( \frac{n_{\text{H}_2}}{10^4 \text{ cm}^{-3}} \right) \left( \frac{X_{\text{gr}}}{10^{-3}} \right) (Q_{\text{em}}/10^{-4}) (2 \text{ g cm}^{-3}/\rho_{\text{gr}}) (10^{-5} \text{ cm}/a) (T_{\text{gr}}/20 \text{ K})^4 \text{ erg/cm}^3/\text{s} \]

The numbers I've used are typical for a molecular cloud. In other words, the radiative cooling is sufficient to keep molecular clouds cool. As the clouds collapse, the density rises and thus \( L_{\text{gr}} \) rises more quickly than \( L_{\text{rad}} \). Why? As the grains become hotter they begin emitting at shorter wavelengths where their efficiency \( Q_{\text{em}} \propto T_{\text{gr}} \propto a/\lambda \). Thus \( L_{\text{rad}} \) rises in proportion to \( T_{\text{gr}}^5 \).
Gas Cooling & Heating

**Question:** The most important cooling lines of the atomic interstellar medium are all infrared transitions. e.g., [CII]158um, [OI]63um, [CI]370um, [OI]145um, [CI]609um, [FeII]26um, [SiII]35um .... Why?

Name two reasons why X-ray heating for the local ISM is substantially less than the photo-electric heating rate due to FUV photons.

For a pure hydrogen gas, what is the approximate ratio of X-ray absorption cross-sections for 0.1 keV X-rays and 1.0 keV X-rays?