Neutral Gas: Line Emission

Lecture 2

Gordon Stacey

Topics

- The Galactic ISM
- [CII] regions
- PDR models
- Orion example
The Interstellar Medium

- Vertical distributions of major ISM components in the Solar Neighborhood in terms of $H/cm^3$
  - Molecular: $0.58 \exp[-(z/81 \text{ pc})^2]$ 15 K 300 cm$^3$
  - Cold HI: $0.57-0.70\exp[-(z/127 \text{ pc})^2]$ 93 K 30 cm$^3$
  - Warm Hla: $0.57-0.18\exp[-(z/318 \text{ pc})^2]$ 5000 K 0.68 cm$^3$
  - Warm Hlb: $0.57-0.12\exp[-(|z|/403 \text{ pc})]$ 8000 K 0.36 cm$^3$
  - HII Regions: $0.015 \exp[-(|z|/70 \text{ pc})]$ 7500 K 30 cm$^3$
  - Diffuse HII: $0.025 \exp[-(|z|/1000 \text{ pc})]$ 9000 K 0.3 cm$^3$
  - Hot HII: $0.007 \exp[-(|z|/4000 \text{ pc})]$ > $10^5$ K 0.01 cm$^3$

- Notice that there is rough pressure equilibrium between the various components: $nT \sim 3000$

Cox, D.P. ARAA 43, 2005, 337

The Interstellar Medium

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass Fraction</th>
<th>Volume Filling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular</td>
<td>49%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Cold HI</td>
<td>33.6%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Warm Hla</td>
<td>8.6%</td>
<td>19%</td>
</tr>
<tr>
<td>Warm Hlb</td>
<td>5.8%</td>
<td>17%</td>
</tr>
<tr>
<td>HII Regions</td>
<td>1.3%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Diffuse HII</td>
<td>2.1%</td>
<td>8.3%</td>
</tr>
</tbody>
</table>

- Most of the ISM is neutral in form especially near the Galactic plane;
- However, the volume filling factors of the neutral ISM (and dense HII regions) are quite small

- The total filling factor is ~ 46% -- the rest of interstellar space is filled with less dense media -- especially the coronal gas with filling factors of 25 to 50%
The Interstellar Medium

- The cold ISM dominates at low scale heights
- > 200 pc from the plane, most of the gas is in the warm diffuse components
  - Total ISM is black, the warm diffuse component is red
- Why? The dense components are less influenced by forces that fluff up the more diffuse ISM

The scale heights of the various components are determined by the interplay between Galactic gravity (stars), the pressure required to support the overlying weight, their intrinsic thermal (nT) pressure, and non-thermal pressure support (e.g. magnetic, cosmic ray, and dynamical)

- The fraction of support that is thermal is only 10% at the mid-plane, decreasing outwards
- Most of the support comes from the non-thermal pressure sources:
  - magnetic fields (4.8 μG fields required, similar to estimates)
  - cosmic ray flux (0.24 cm\(^{-3}\))
  - Dynamical (6 km/sec vertical gas flows)
A Bit of History: C⁺ Regions

- Carbon is the 4th most abundant element: C/H $\sim 3 \times 10^{-4}$
- Among the 6 most abundant elements, only carbon has an I.P. less than that of H so that C⁺ is found in "neutral" clouds
- Therefore, to study C⁺ regions is to study photodissociation regions – at least the leading edge!

<table>
<thead>
<tr>
<th>Element</th>
<th>Ionization Potential</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>13.60 eV</td>
<td>9.35E-1</td>
</tr>
<tr>
<td>He</td>
<td>24.59 eV</td>
<td>6.5E-2</td>
</tr>
<tr>
<td>O</td>
<td>13.62 eV</td>
<td>6.32 \times 10^{-4}</td>
</tr>
<tr>
<td>C</td>
<td>11.26 eV</td>
<td>3.47\times10^{-4}</td>
</tr>
<tr>
<td>N</td>
<td>14.53 eV</td>
<td>1.10\times10^{-4}</td>
</tr>
<tr>
<td>Ne</td>
<td>21.56 eV</td>
<td>1.01\times10^{-4}</td>
</tr>
</tbody>
</table>

How important are C⁺ Regions?

- What is the size of a C⁺ region relative to an H⁺ region?
- From Monday, the Strömgren radius is related to the ionizing flux and the gas density by:
  \[ N_{\text{Lyc}} = \frac{4}{3} \pi r_s^3 n_H^2 \alpha_B \]
  \[ \Rightarrow r_s = \left( \frac{3 N_{\text{Lyc}}}{4 \pi \cdot n_H^2 \alpha_B} \right)^{1/3} \]
  \[ r_{\text{HII}} = \left( \frac{3 N_{\text{Lyc,H}}}{4 \pi \cdot n_H^2 \alpha_{B,H}} \right)^{1/3} \]
  \[ r_{\text{CII}} = \left( \frac{3 N_{\text{Lyc,C}}}{4 \pi \cdot n_C^2 \alpha_{B,C}} \right)^{1/3} \]
- A similar relationship should exist for carbon ionizing photons:
How important are C\(^+\) Regions?

- Taking the ratio of the two:
  \[
  \frac{r_{\text{CII}}}{r_{\text{HII}}} = \left( \frac{N_{\text{LyC},C} \cdot \alpha_{\text{B,H}} \cdot n_H^2}{N_{\text{LyC},H} \cdot \alpha_{\text{B,C}} \cdot n_C^2} \right)^{1/3}
  \]

- Roughly then:
  \[
  \frac{r_{\text{CII}}}{r_{\text{HII}}} \sim \left( \frac{n_H}{n_C} \right)^{2/3}
  \]

- Since \(n_H/n_C \sim 3.7 \times 10^{-4}\), we have:
  \[
  \frac{r_{\text{CII}}}{r_{\text{HII}}} \sim 200!
  \]

- We might expect C\(^+\) regions to be \textbf{MUCH} larger than H\(^+\) regions!

But, the penetration of carbon ionizing photons is determined by extinction of those photons by dust absorption, not the photo-ionization – radiative recombination equilibrium of the C\(^+\) ion.

Therefore, the depth of a C\(^+\) region is given by:

\[
d_{\text{PDR}} \sim \text{a few } \tau_{\text{UV}} (11.3 \text{ eV} < h\nu < 13.6 \text{ eV})
\]

\[
\Leftrightarrow N_H \sim 6 \times 10^{21}\text{cm}^2
\]

For the Orion HII region, with neutral gas densities in the PDR \(\sim 2 \times 10^5\) cm\(^{-3}\), this corresponds to a physical size, \(d \sim N_H/n_H = 3 \times 10^{16}\) cm, or about 0.01 pc.

The Orion HII region has a diameter \(\sim 0.3\) pc (but the gas density is 100 times lower, so \(N_H(\text{PDR}) \sim 3 N_H(\text{HII})\))
What Should We Expect?

- Lines from easily excited elements in the appropriate ionization states (ionization potentials less than 13.6 eV)
- The levels must be within a few hundred K of ground (P configuration fine-structure), and the element must be abundant
  - C$^+$ 11.26 eV  $^2P$  $3.47 \times 10^{-4}$
  - O 13.62 eV  $^3P$  $6.32 \times 10^{-4}$
  - Si$^+$ 8.15 eV  $^2P$  $3.1 \times 10^{-5}$
- Lines from easily excited molecules that survive 13.6 eV (rare) or “self-shield”, e.g. CO, H$_2$

First Observations

- C$^+$ regions were first investigated in:
  - Optical lines of C$^0$ and O$^0$ at the interfaces between HII regions and neutral clouds (e.g. Hippelein and Munch)
  - Radio recombination lines (e.g. Palmer et al. 1967, Pankonin, Thomasson, and Barsuhn, 1977)
    - Find: $n_e \sim$ few cm$^{-3}$ so that $n_H \sim 10^3$ to $10^4$ cm$^{-3}$
    - Associated with molecular material outside of HII regions
  - The $^2P_{3/2} \rightarrow ^2P_{1/2}$ [CII] fine structure line at 158 µm was predicted to be the predominant coolant for atomic clouds (Dalgarno and McCray, 1972)
  - First detected in Orion from NASA’s Lear Jet Observatory (Russell et al. 1979)
First Results and Conclusions

- Found:
  - Very bright $I_{[\text{CII}]} \sim 3 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ or $\sim 0.3$ to $3 \times L_{\text{FIR}}$
  - Very widespread: $R_{[\text{CII}]} \sim 12$ pc for M17
  - In the light of contemporary theoretical predictions, they interpreted the emission as arising from an enveloping cloud of HI, however:
    $$n_{\text{HI}} \sim 2 \times 10^3 \text{ cm}^{-3} \text{ – not at all like the traditional HI clouds!}$$
- Perhaps it was associated with the molecular gas? (Russell et al. 1981)
- We now believe this is true for most of the [CII] emission on galactic scales

Photodissociation Regions

- Whenever far-UV photons impinge on a neutral gas cloud, molecules can be dissociated and elements ionized if their potentials are less than 13.6 eV, forming a "photodissociation region", or PDR
- Far-UV photons heat the gas and dust leading to intense emission in the dust continuum, polycyclic aromatic hydrocarbon (PAH) emission features and in several far-IR fine structure lines (e.g. [CII] 158 $\mu$m, [OI] 63 and 146 $\mu$m), the H$_2$ ro-vibrational transitions, and (deeper into the cloud) CO rotational lines and the fine structure lines of [CI] at 370 and 609 $\mu$m
- PDRs emission can dominate line and continuum emission from Galaxies, and are an important component of the ISM mass
- All neutral hydrogen gas, and much of the molecular ISM is in PDRs (also known as photon dominated regions)
Photodissociation Regions

Molecular cloud collapses, forming stars.

Ionized Hydrogen (HII) regions surrounding newly formed stars.

Photodissociation regions form where ever far-UV photons impinge on neutral clouds.

Pillars in M16

HST Image
Structure of the PDR

- Neutral gas is illuminated by hot stars or the ISRF
- There is a thin HII/HI interface that absorbs the Lyman continuum photons
- Detailed structure depends on G/n:
  - $G \approx 1.6 \times 10^{-3} \text{erg cm}^{-2} \text{s}^{-1}$
  - $n \approx 0.5$ (WNM); 30 (CNM); $10^3$-$10^7$ (GMCs)
- Typically, HI layer extends to $A_V \approx 1$-$2$, or $N_{\text{HI}} \approx 2$-$4 \times 10^{21}$ cm$^{-2}$ from the ionization front

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)

Structure of the PDR

- Far-UV pumped H$_2$ emission peaks at the HI/H$_2$ interface
- C$^+$ layer extends to $A_V \approx 2$-$4$
- O is atomic to $A_V \approx 5$-$10$ – this defines the extent of the PDR
- Neutral C exists at the C$^+$/CO interface
- The H, C$^+$, O layers are established through the balance of far-UV photon-dissociation of molecules and photoionization of C
- Atomic clouds (CNM) or the WNM typically have $A_V < 2$ so that they are nearly entirely atomic.
The H/H$_2$ Transition

- The H/H$_2$ transition is established by the equilibrium of the photodissociation rate for H$_2$, $R_{\text{diss}}$, and the rate of formation of H$_2$, $R_f$
- The rate of formation is given by: $R_f = \gamma H_2 n \cdot n_H$
  Where the rate coefficient is: $\gamma H_2 = 1 - 3 \times 10^{-17} \text{ cm}^3 \text{s}^{-1}$
  And $n = n_H + n_{H_2}$
  
  Jura, 1975; Andersson and Wannier, 1993

- The photodissociation rate is strongly influenced by H$_2$ self-shielding
- H$_2$ absorbs far-UV 912 to 1100 Å photons to Lyman and Werner electronic bands
- The electronically excited states rapidly decay
- 10 to 15% of decays go to the vibrational continuum of the ground state leading to dissociation

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)
The H/H$_2$ Transition

- If $N(\text{H}_2) > 10^{14}$, the far-UV absorption lines become optically thick, and H$_2$ begins to "self-shield"
- The photodissociation rate then depends on the local H$_2$ abundance and level population distributions
- A simple approximation for self shielding (Drain and Bertoldi, 1996) approximates the photodissociation rate of H$_2$ per unit volume is by:

$$R_{\text{diss}} = f_{\text{shield}}(N_{\text{H}_2}) \cdot e^{-\tau_{1000}} I_{\text{diss}}(0)n_{\text{H}_2}$$

Where the unshielded dissociation rate is:

$$I_{\text{diss}}(0) = 4 \times 10^{-11} G_0 \text{s}^{-1}$$

The optical depth of the dust at 1000 Å is: $\tau_{1000}$

And $f_{\text{shield}}$ is the self-shielding factor given by:

$$f_{\text{shield}} = 1, \quad N_{\text{H}_2} \leq 10^{14} \text{ cm}^{-2},$$

or

$$f_{\text{shield}} = \left( \frac{N_{\text{H}_2}}{N_0} \right)^{-0.75}, \quad N_0 = 10^{14} \text{ cm}^{-2} \leq N_{\text{H}_2} \leq 10^{21} \text{ cm}^{-2}$$

In the region where dust opacity is small ($N < 10^{20.7} \text{ cm}^{-2}$), we can equate the formation rate to the dissociation rate to derive an expression for the H$_2$ abundance: $X_{\text{H}_2} = n_{\text{H}_2} / n$ and column density: $N_{\text{H}_2}$
The H/H$_2$ Transition

$$N_{H_2} = A^4 \left( \frac{N}{N_0} \right)^4 N_0,$$

$$x_{H_2} = 4 \cdot A^4 \left( \frac{N}{N_0} \right)^3$$

where: $$A = \gamma_{H_2} \cdot n / \left[ 4 J_{\text{diss}} (0) \right]$$

- Notice that: $A \propto n / G_0$, a ratio that controls PDR structure
- The column density at which gas is half molecular, and half atomic is obtained by setting $x_{H_2} = 1/4$: The HI/H$_2$ front is located at: $N_{DF} = A^{-4/3} N_0$

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)

The H/H$_2$ Transition

- The dust opacity comes into play at high columns, or large $G_0/n$:
  $$N_{DF} \geq 5 \times 10^{30} \text{cm}^{-3}, \text{or when}:$$
  $$G_0/n \geq 4 \times 10^{-2}$$
- If $G_0/n$ is small self-shielding alone determines the location of the HI/H$_2$ front:
  - diffuse clouds exposed to weak radiation fields
  - dense clumps embedded in PDRs that are exposed to much higher far-UV fields
- The result of self-shielding is that the H$_2$ column and abundance increase very rapidly with depth near the transition, so that the HI/H$_2$ transition is very sharp
The H/H$_2$ Transition

- PDRs associated with bright far-UV sources (e.g. Orion Nebula) typically have G$_0$/n $\sim$ 1 cm$^{-3}$, so that the location of the HI/H$_2$ transitions is determined by dust absorption.
- The transition typically occurs at A$_V$ $\sim$ 2 where the dust absorption reduces the photo-dissociation rate to a level that an appreciable column of H$_2$ builds up and H$_2$ self-shielding can take over.
- The HI/H$_2$ transition is then rapid again.
- For very dense (n $>$ 10$^6$ cm$^{-3}$) clouds exposed to high far-UV fields (G$_0$ $>$ 10$^4$), chemical destruction of H$_2$ through reactions with C$^+$ and O can change the location of the transition region (Bertoldi, 1998).

The C$^+/C$/CO Transition

- The transition from C$^+$ to CO occurs in PDRs – this is of great interest, since the CO rotational lines are used as a proxy for molecular gas content in galaxies.
- The formation of CO occurs through several chemical routes with reactants that have low abundances.
- Therefore the formation rate is slow so that even very weak far-UV fields can photo-dissociate CO producing C$^+$ and C deep within a cloud.
- CO photodissociation occurs through discrete absorption into pre-dissociating bound states so that like H$_2$, CO can be self-shielding.

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)
The C⁺/C/CO Transition

- For low values of $G_0/n$ CO self shielding leads to isotopic fractionation at the cloud edges where the rarer isotopes are preferentially dissociated.
- For strong fields, however, the C⁺/C/CO transition is primarily determined by dust extinction.
- Since CO is much less abundant than $H_2$ ($X_{CO} \sim 8 \times 10^{-5}$), CO rarely builds up enough column to self-shield in the $A_0 < 1$ layer.
- The C⁺/C/CO transition is therefore much less sharp than the H/H₂ transition.

The UIR bands

- The mid-IR spectra of HII regions and PDRs are dominated by the unidentified infrared (UIR) bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm.
- These features are characteristic of the ISM when it is exposed to far-UV photons.
- They also dominate the spectra of reflection nebula, starburst galaxies, the IR cirrus, and the diffuse ISM of starforming galaxies.
- The relative strengths of the bands vary from source to source: whatever the material, its physical composition is modified by ambient conditions, but it is not easily destroyed.

UIR spectrum of the “Red Rectangle” from Sloan et al. 1994 and Jesse Bregman
The UIR bands

- The UIR bands are similar to those of aromatic hydrocarbons
  - The 3.3, 8.6, and 11.3 μm features are identified with stretching, and in and out of plane bending modes of the C-H bond
  - The 6.2 and 7.7 μm features are identified with the C-C stretching modes
- There is general agreement that the UIR features are due to these type of modes
- Less certain, is the assignment of these features to polycyclic aromatic hydrocarbons (PAH) \textit{molecules}, rather than carbonaceous solids

The UIR bands as PAHs

- It can be shown that dust heated by the ISRF reaches radiative temperatures given by:
  \[ T \simeq 15(a / 3000 \text{ Å})^{0.2} \text{ K} \]
- The observed emission temperature of the UIR bands is ~ 650 K \( \Rightarrow \) the UIR bands are due to small species heated to high T with the absorption of a single far-UV photon for which:
  \[ T \simeq 1500(E_{\text{far-UV}} / N_{C})^{0.5} \text{ K} \]
  where \( E_{\text{far-UV}} \) is the energy of the photon, and \( N_{C} \) is the number of carbon atoms in the molecule
- Since \( E_{\text{far-UV}} \sim 10 \text{ eV} \), the observed temperature corresponds to about 50 carbon atoms
How important are PAHs?

- The UIR bands contain about 5% of the total IR flux from PDRs \(\Rightarrow\) PAHs absorb about 5% of the incident far-UV flux
- The remainder is absorbed by larger dust grains, which equilibrate at lower T, and radiate in the far-IR
- Assuming a far-UV absorption cross section of \(10^{-17}\text{cm}^{-2}/\text{C atom}\), and taking standard dust parameters:
  \[ A_{\text{far-UV}} / A_V = 1.8 \]
  \[ N_H / A_V = 1.9 \times 10^{21}\text{cm}^{-2}\text{mag}^{-1} \]
- One can show about 1% of the carbon is tied up in PAHs
- With a typical size of 50 C atoms, the abundance of PAHs with respect to H is then \(\sim 10^{-7}\)

Very Small Grains

- Underlying the UIR features, one often finds a broad emission plateau
- The strength of the plateau relative to the UIR bands varies spatially \(\Rightarrow\) plateau emission arises from a separate dust component
- The likely candidate is clusters of PAHs totally some 400 to \(10^5\) C atoms
- These grains are much smaller (\(\sim 1\) to 10 nm) than typical grains in the ISM (\(\sim 0.1\ \mu\text{m}\)), hence they are often termed “very small grains”
Heating of PDRs

- There are two primary heating mechanisms for photodissociation regions
  - Photoelectric heating
  - Heating through collisional de-excitation of vibrationally excited H₂

Photoelectric Heating

- Photoelectric heating is dominated by the smallest grains so that PAHs and very small grains are quite important
- The physics of P.E. heating is:
  - Far-UV photons absorbed by the grain create energetic (~ several eV) electrons
  - e⁻ diffuse through grain and on reaching the grain surface they can escape if K.E. > the work function of the grain, W, and any Coulomb potential, $\phi_c$
  - Any excess K.E. is then injected into the gas phase

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)
Photoelectric Heating

- The efficiency of the P.E. effect, $\varepsilon_{\text{grain}}$, is the ratio of the gas heating rate to the grain far-UV absorption rate.
- It is given by the yield, $Y$ (the probability that an $e^-$ escapes) times the fraction of the photon energy that is carried away by the electron:

$$\varepsilon_{\text{grain}} \approx Y \left( \frac{h \nu - W - \phi_c}{h \nu} \right)$$

- The yield, $Y$ is a complex function:
  - Grain size, $a$,
  - Collision length scale for low energy electrons in solids ($l_e \sim 10$ Å)
  - Photon energy $h \nu$
- For large grains, photons with energy well above threshold are absorbed $\sim 100$ Å inside the grain, so that they therefore rarely escape:

$$Y \sim \frac{l_e}{l_a} \approx 0.1$$

- With typical far-UV energies of 10 eV, and a work function of 5 eV, the efficiency is just 5%
- In general, it is far less due to grain charging
Photoelectric Heating

- Semi-empirical models were developed along these lines to fit the model parameters to the observed Copernicus cooling rates (measured columns of C⁺ in the excited state along l.o.s to nearby stars, Pottasch et al. 1979)
- Such models (de Jong, 1977, Draine 1978) were then used to constrain grain properties and formed the basis of early PDR models (e.g. Tielens and Hollenbach 1985)

- More recent include the PE heating contributions of VSGs and PAHs
- For these small grains, diffusion of the electron plays no role
- Therefore, the yield for planar PAHs is typically much higher than classical sized grains
- A limit is that the I.P. of a charged PAH may be > 13.6 eV – in which case far-UV photons absorbed due not release an e⁻, so there is no heating

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)
Photoelectric Heating

- For example, the second I.P. of C\textsubscript{16}H\textsubscript{10} is 16.6 eV!
- The heating efficiency is therefore reduced by the fraction of the PAHs that can be photo-ionized by 13.6 eV photons, \( f_n \)

\[
\varepsilon_{PAH} \approx f_n \left( \frac{h\nu - IP}{h\nu} \right)
\]

- Therefore, with an I.P. of 7 eV, a 10 eV photon yields a maximum efficiency of about 15%, if \( f_n \sim 0.5 \)

Grain Size and P.E. Heating

- Bakes and Tielens (1994) calculated the photoelectric heating efficiency as a function of grain size. They plot the total heating as a function of grain size from large grains down to molecular PAHs
  - 1/2 heating arises from a < 15 Å (1500 C atoms) grains
  - 1/2 comes from 15 < a < 100 Å grains
  - Larger grains do not contribute much!