GMC Microphysics

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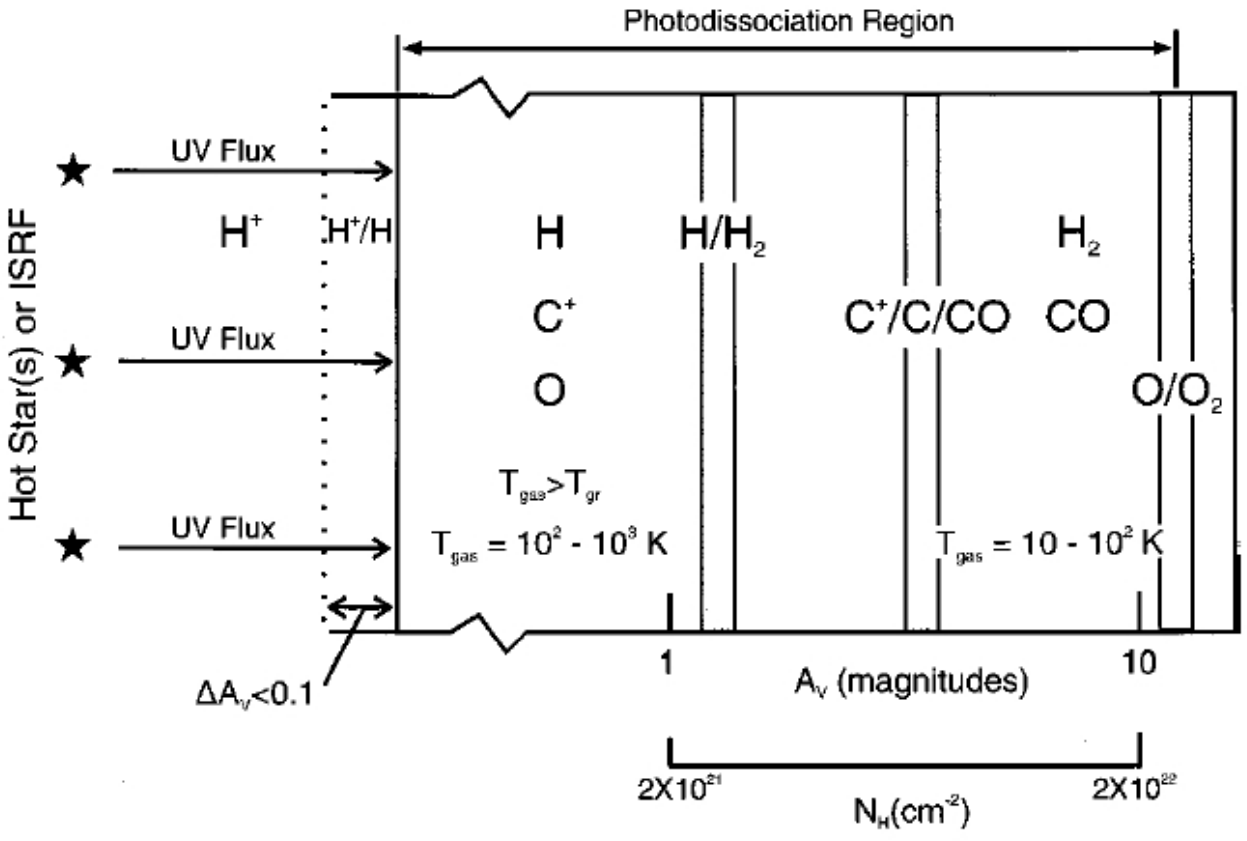
Outline

Overview

- A photodissociation region (PDR) is the interface between an HII Region and a molecular cloud
- It is marked by a photodissociation surface– a region where the hydrogen in half atomic and half molecular
- Nearly all of the atomic gas and most of the molecular gas in a galaxy can be found in a PDR

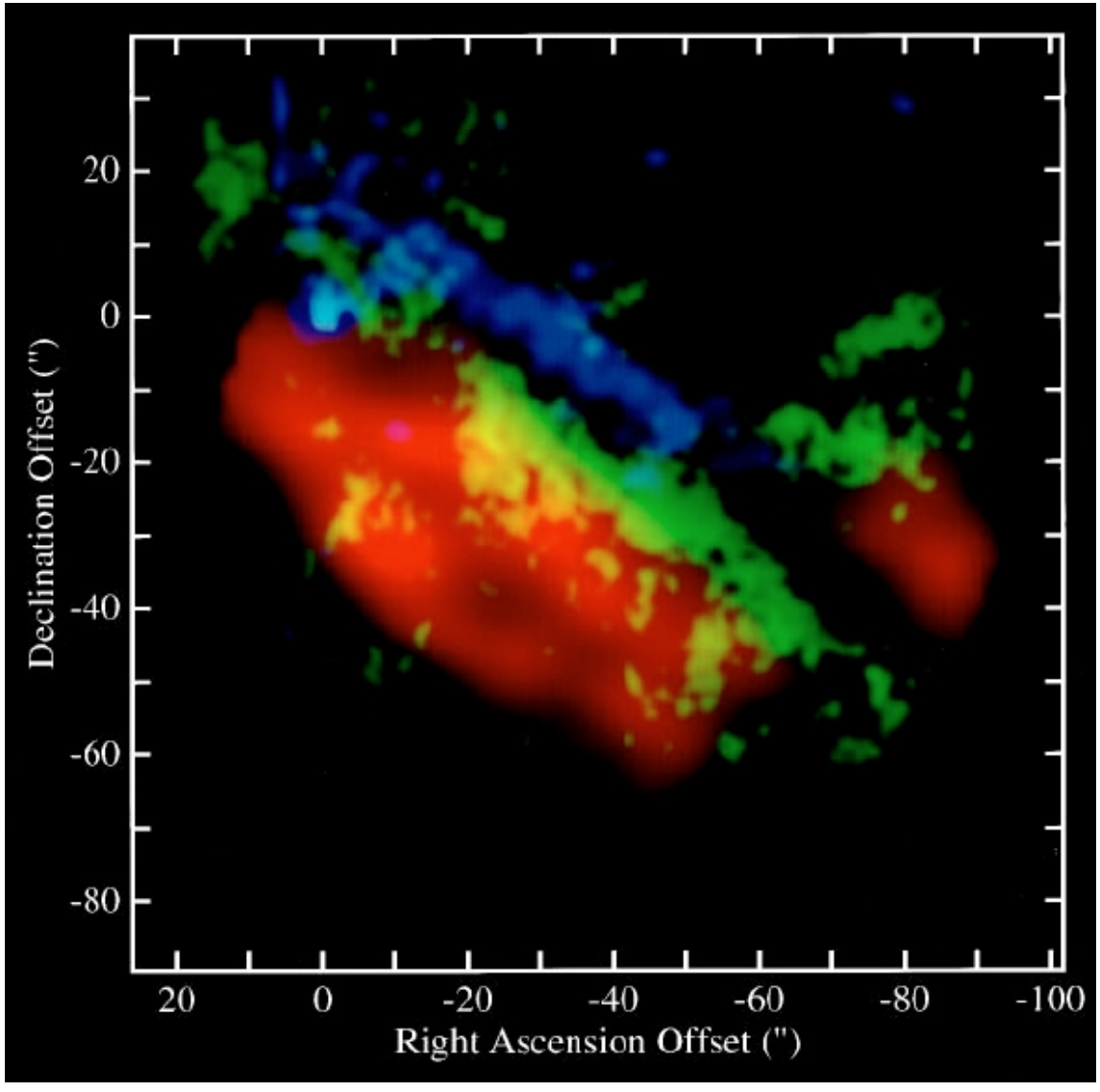
Structure



Tielens and Hollenbach 1999

- We will discuss each of the zones in a PDR in detail

Observation



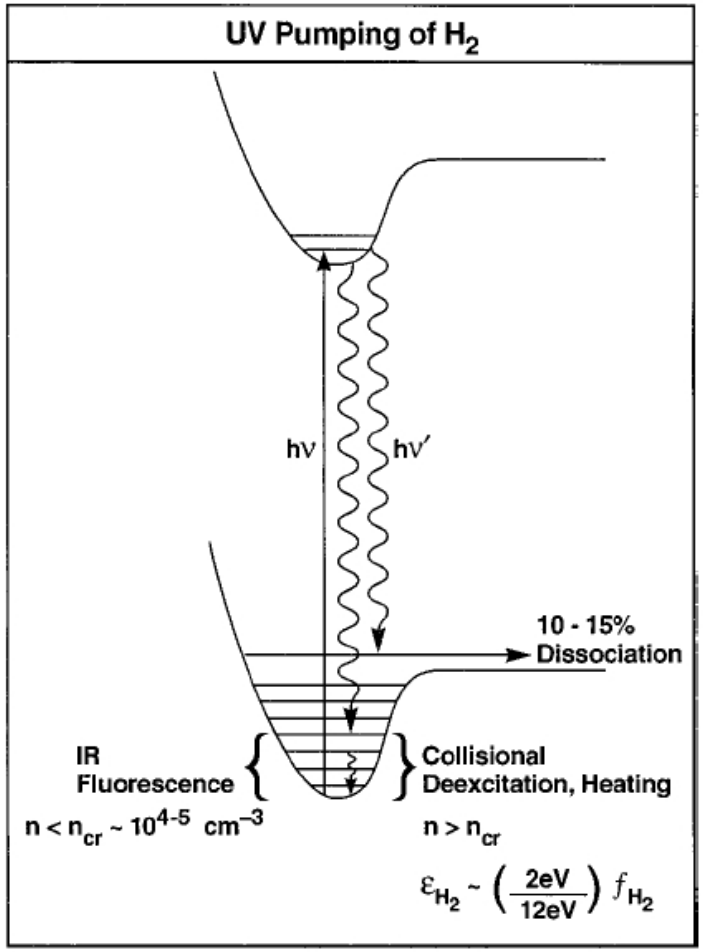
Tielens et al 1993

H_2 Formation and Dissociation

- H_2 is by far the most common molecule in PDRs (factor 10^4 more abundant than CO)
- Most H_2 forms on the surfaces of dust grains

H_2 Formation and Dissociation

- Upon absorption of a FUV photon, H_2 has a $\sim 10 - 15\%$ chance of dissociating
- Otherwise, H_2 will remain in a vibrationally excited state. Collisional de-excitation from this state can heat the gas



Tielens and Hollenbach 1999

Self-Shielding

- Because the H_2 density is so high, FUV lines can become optically thick
- This creates a sharp transition between HI and H_2
- The location of this transition is set both by self-shielding (high density / low radiation regime) and by dust opacity (low density / high radiation regime)

CO Formation and Dissociation

- C^+ and C are balanced by photoionization and radiative recombination
- CO formed through burning neutral radicals like CH and CH_2
- Alternatively:

$$\begin{aligned} C^+ + OH &\rightarrow CO^+ + H \\ CO^+ + H_2 &\rightarrow HCO^+ + H \\ HCO^+ + e &\rightarrow CO + H \end{aligned}$$

- CO is slow to form because its reactants have relatively low abundance
- CO is not significantly shelf-shielded due to low abundance
- Thus, CO exists primarily deep within a cloud, and the transition to CO is set by dust extinction

Dust

- Silicate and carbonaceous grains provide the dominant source of opacity
- Dust receives $10^2 - 10^3$ more heating than the gas, but maintains lower temperature by effective cooling
- Greatly affect heating/cooling balance via IR radiation
- Also important for catalyzing H_2 formation

PAHs

- Polycyclic aromatic hydrocarbons (PAHs) are large carbon molecules that give rise to distinctive IR features
- Typical size: 50 C atoms, giving a PAH abundance relative to H of $\sim 10^{-7}$
- Important for photoelectric heating

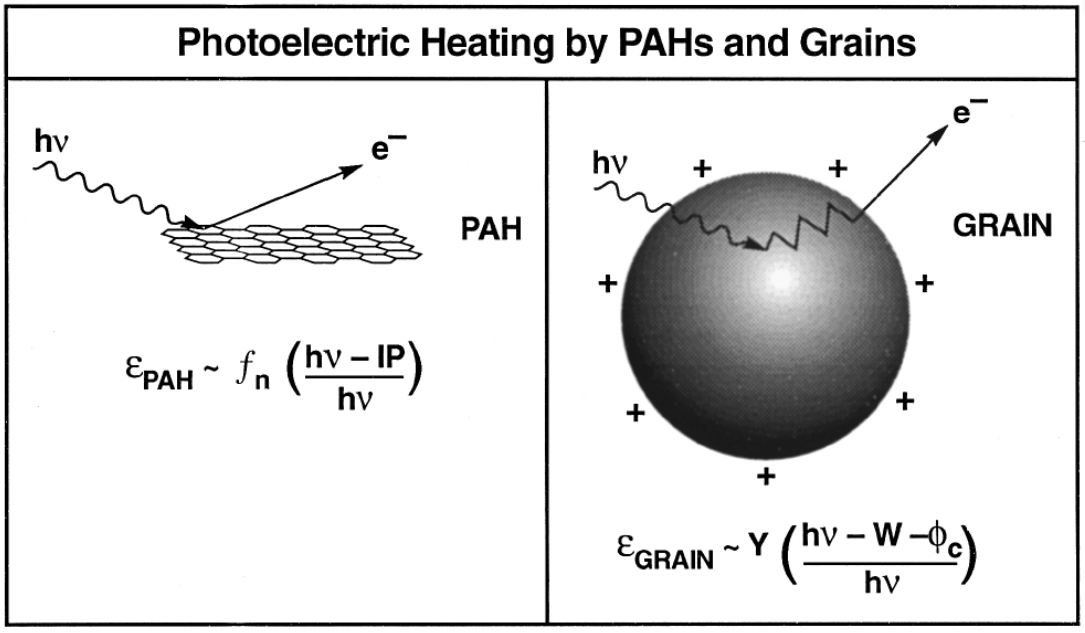
Heating and Cooling

- Heating
  - Photoelectric Heating
  - Collisional De-excitation
  - Cosmic Ray Heating
- Cooling
  - Atomic Line Emission
  - Molecular Line Emission
  - Collisional Excitation
  - Grain Cooling

Photoelectric Heating

- UV photons can liberate electrons from PAHs
- An ejected photoelectron can then heat the gas
- Photoelectric heating is dominated by the smallest grains
- $0.1 - 1\%$ of the UV intensity goes into photoelectrons ejected by PAHs

Photoelectric Heating Schematic



Tielens and Hollenbach 1999

- Limiting factor for high-efficiency small grains is that some may have an ionization potential > 13.6 eV
- Efficiency drops as PAHs become more charged

Collisional De-excitation

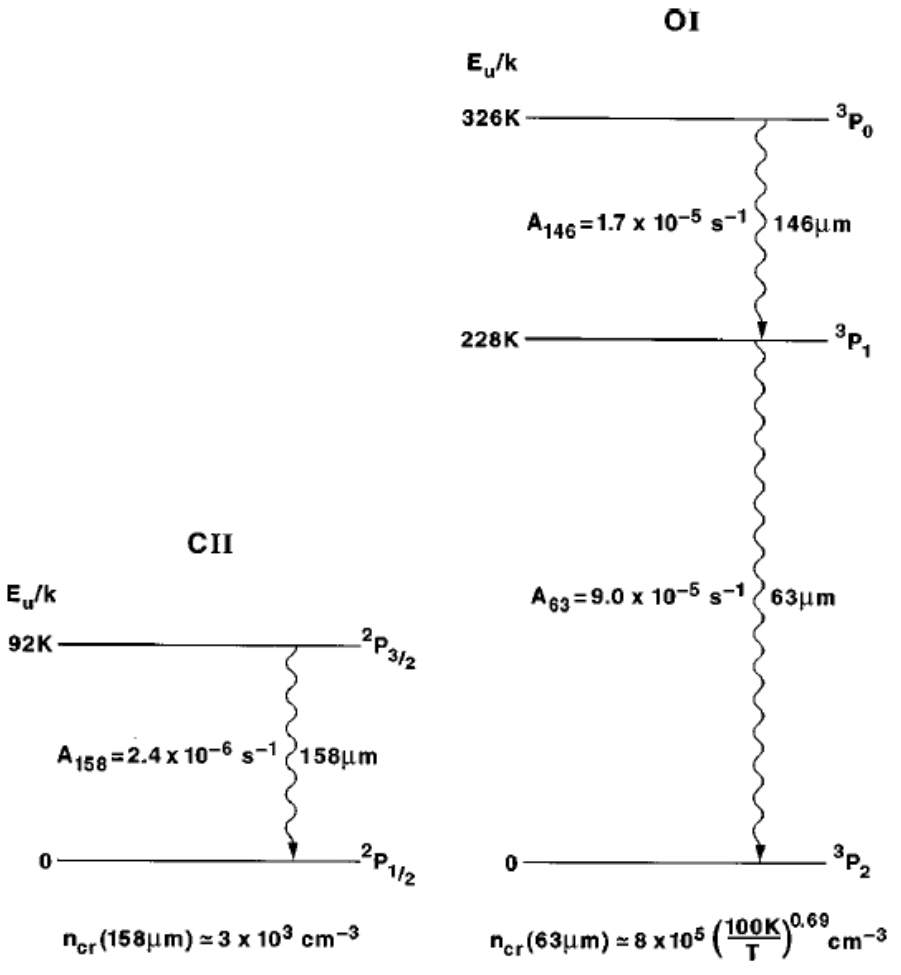
- Recall that H_2 molecules may absorb a photon, then decay radiatively to a vibrationally excited state
- At high densities, these molecules may be de-excited via collisions with atomic H, thereby heating the gas
- A vibrationally excited H_2 molecule has ~ 2 eV of vibrational energy

Cosmic Ray Heating

- At high densities, cosmic ray ionization of molecules becomes important
- Standard H_2 cosmic ray ionization rate of 3×10^{-17} molecules per second
- Important for ionizing in regions where UV does not penetrate

Atomic Line Emission

- Infrared fine structure lines, notably [CII] 158 μm and [OI] 63 μm, 146 μm
- The [CII] fine structure line often dominated cooling in the ISM of a galaxy



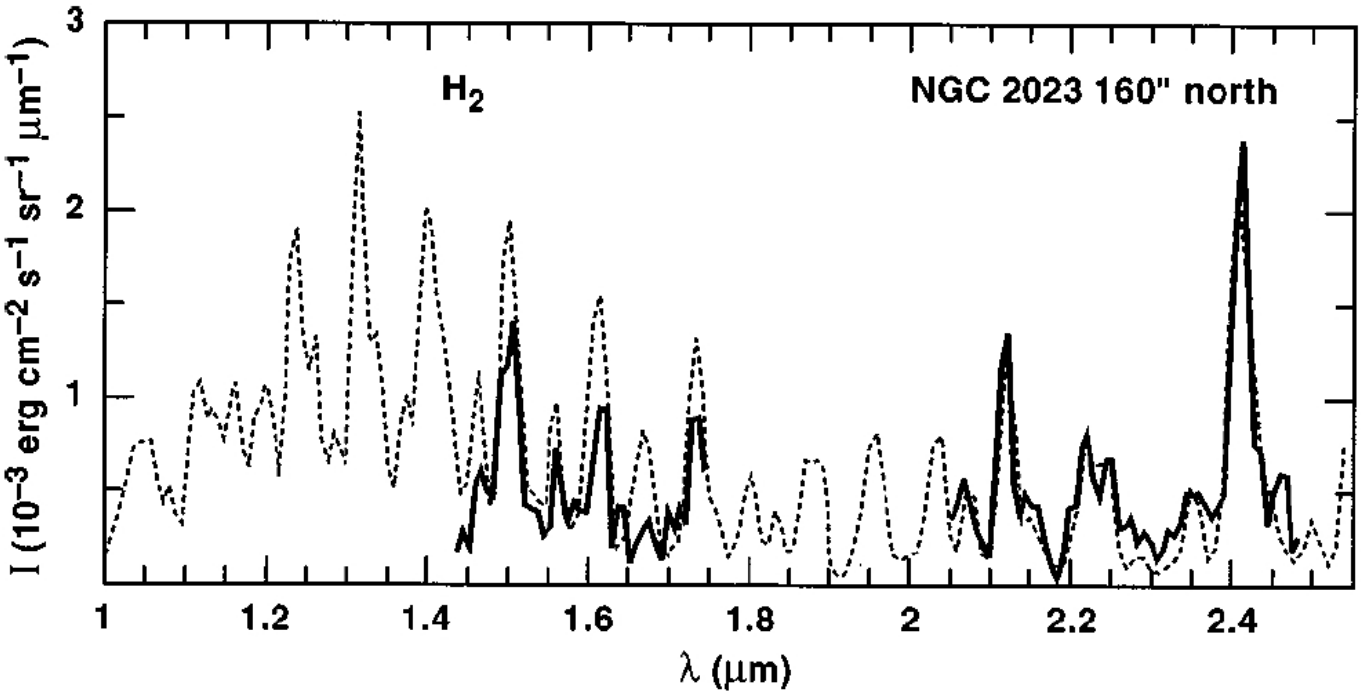
Tielens and Hollenbach 1999

Atomic Line Emission

- [CII] and [OI] lines are good for determining density and temperature since their range of critical densities ($3 \times 10^3 - 3 \times 10^5 \mathrm{cm}^{-3}$) and excitation temperatures ($100 - 300$K) span the range of conditions found in PDRs
- Ratio of the cooling rate to FIR dust emission yields the photoelectric heating efficiency

Molecular Line Emission

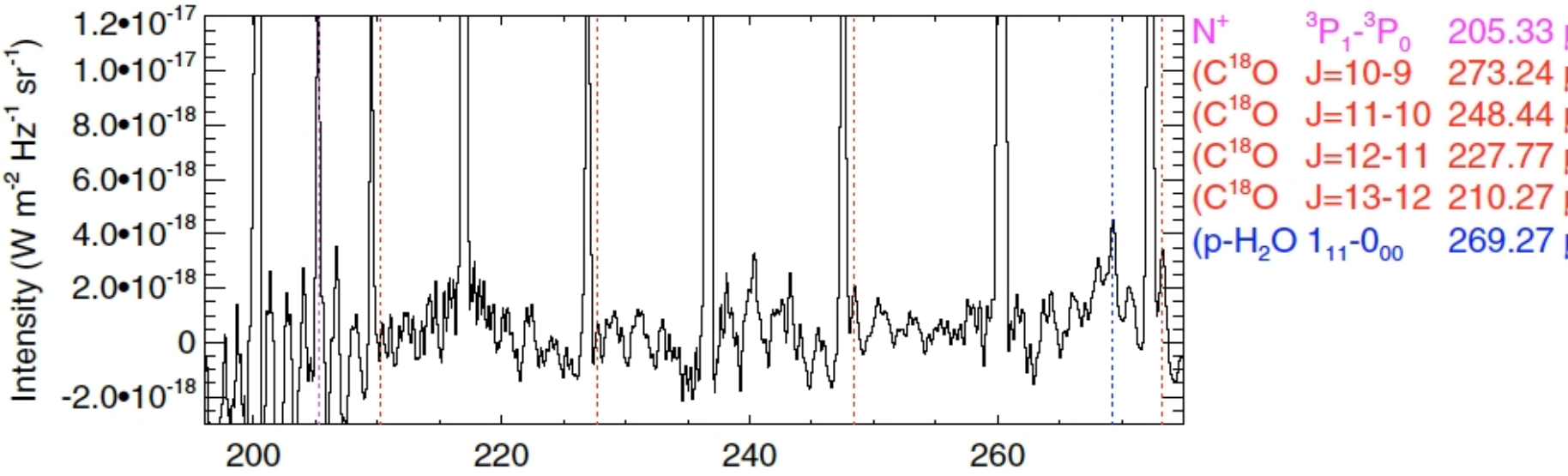
- Ro-vibrational emission from H_2



Tielens and Hollenbach 1999

- UV-pumped H_2 decays via electric quadrupole transitions, emitting in the red and NIR

Molecular Line Emission



Habart et al 2010

- The dipole moment of CO allows it to be an effective radiator

CO to H_2 Relation

- The strength in the CO 1-0 line has been observed to correlate well with the mass of H_2

$$X_{CO} \equiv N(\mathrm{H_2}) / \int T_A \mathrm{d}v$$

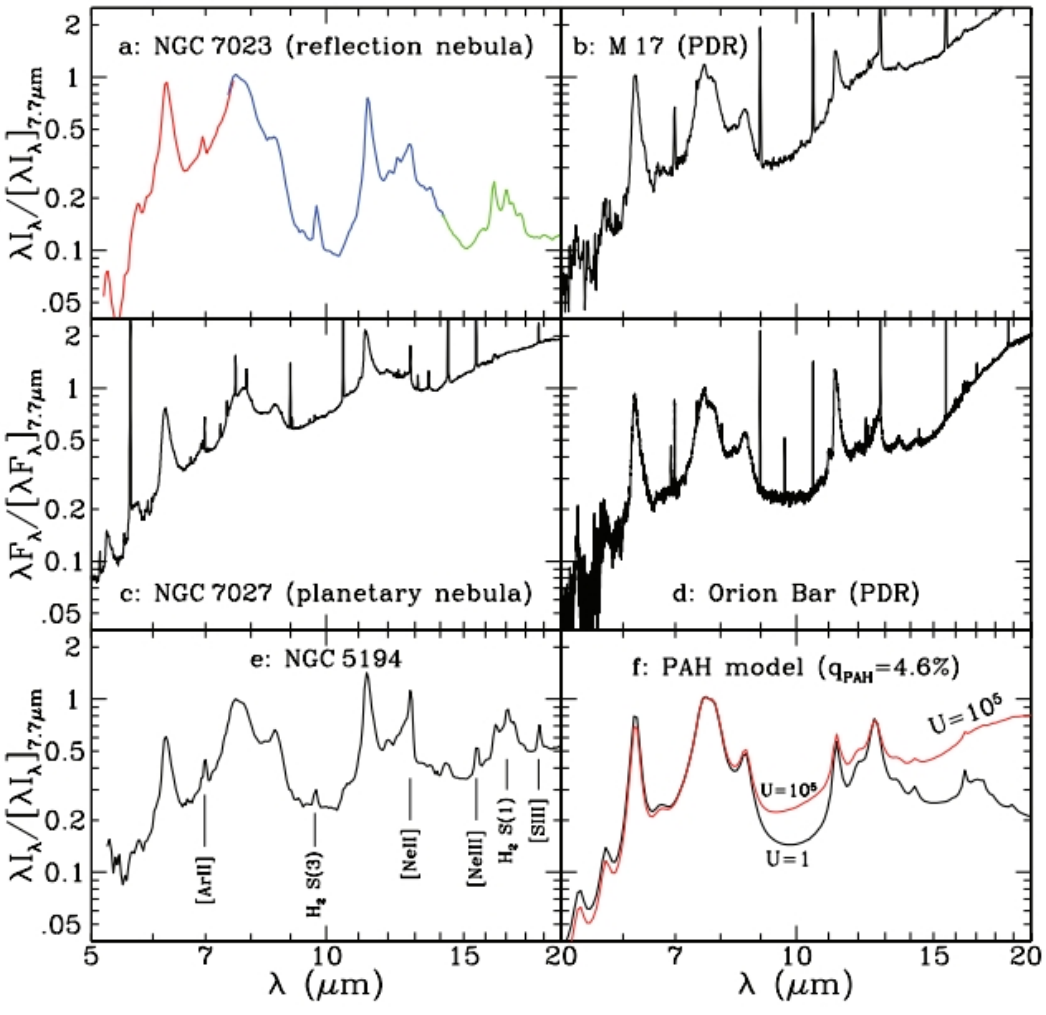
- In “dark molecular gas” (Wolfire 2010), the hydrogen is in molecular form but the CO is not
- $\sim$30% of the molecular cloud mass may be in such gas

Collisional Excitation

- Collisional excitation of atoms, molecules, and ions by electrons, H, or H_2 followed by radiative decay cools the gas

Grain Cooling

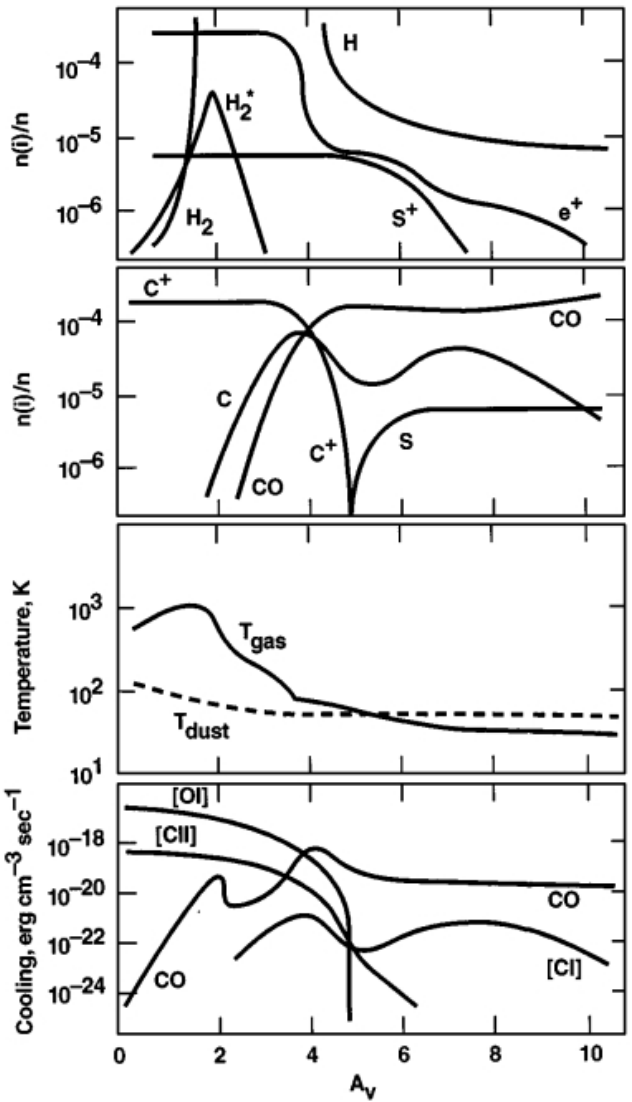
- Grains absorb UV radiation and re-radiate in the IR
- Collisions with grains, which are typically cooler than the gas, can also lead to net cooling



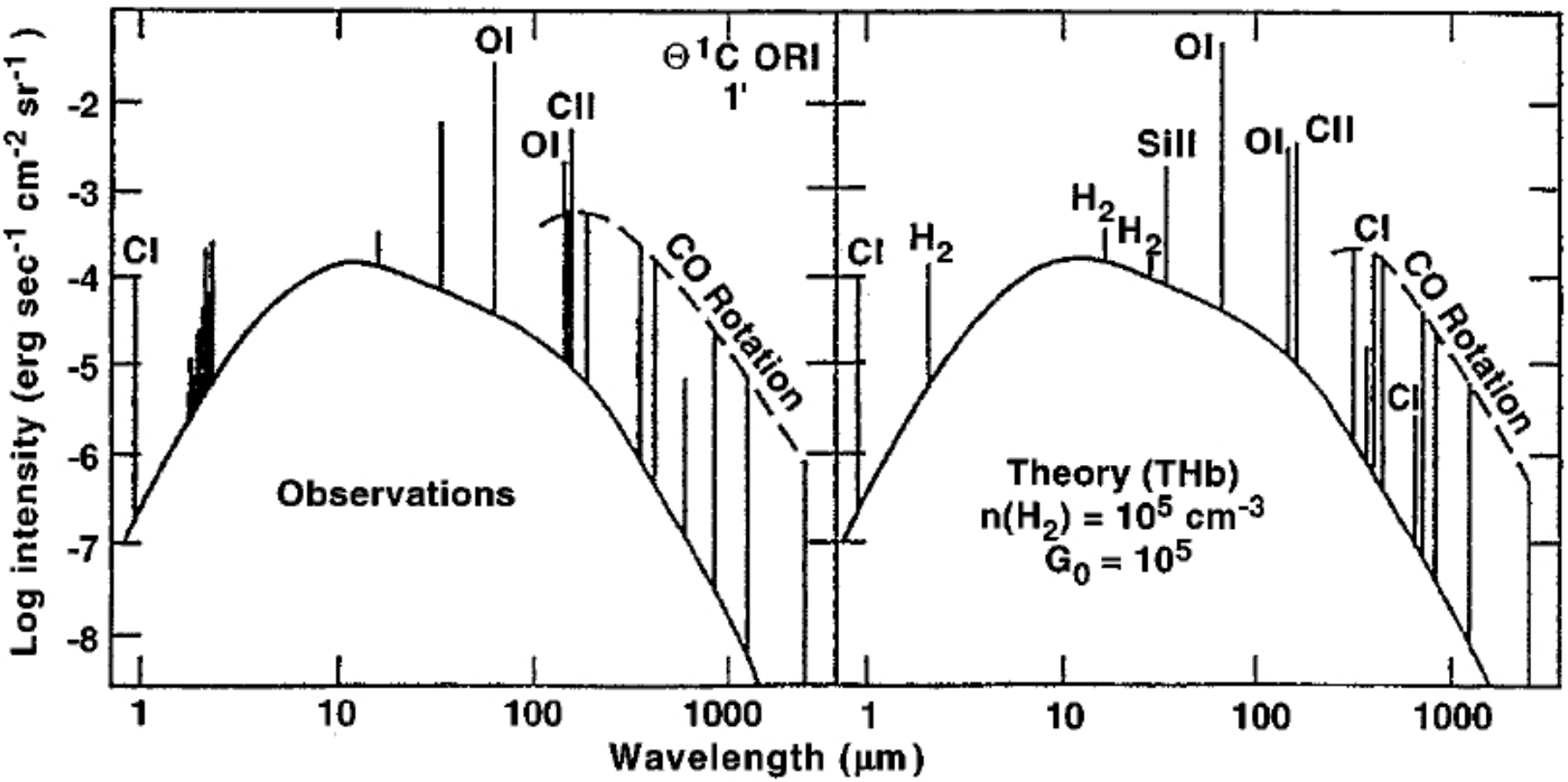
Draine and Li 2007

Summary

- We can now understand the detailed structure and spectrum of a PDR



Summary



Tielens and Hollenbach 1999

Simulations

Simulations

Simulations

- Simulations of PDRs can be difficult
  - Reaction rates can span many orders of magnitude– timestep needs to be quite small
  - Solving for abundance of N species implicitly goes as $O\left(N^3\right)$
  - 3D problem with turbulence, magnetic fields...
- Some common simplifications are made

Gas Clumpiness

- Molecular gas will be inherently clumpy, but can it be modeled as a constant-density medium?
- Levier et al 2012 compared clumpy vs constant density models of PDRs and found constant density models underpredicted chemical abundances by a factor of $2 - 4$
- Also found $35 - 40\%$ dark molecular gas

Simulations and XCO

- Glover and Clark 2012 studied a range of PDR simulations, from relatively simple to quite complex
- Varied primarily in complexity of chemical reactions / species considered
- Fairly robust agreement in value of X_{CO}, lending credence to universiality of the relation that is relatively insensitive to chemistry
- However, CO *distribution* varied considerably among models

Simulations and XCO

Table 2. Computational performance of the various approaches.

Method	Approximate runtime (CPU hours)	
	Run 1	Run 2
G10g	1190	1360
G10ng	880	1240
NL97	110	140
NL99	310	460
KC08e	100	130
KC08n	120	150

Glover and Clark 2012

Table 4. Comparison of the CO-to-H_2 conversion factor X_{CO}, at the end of the runs.

Method	X_{CO} $[10^{20}\,cm^{-2}\,(K\,km\,s^{-1})^{-1}]$	
	Run 1	Run 2
G10g	2.67	1.30
G10ng	2.01	1.23
NL97	0.57	0.90
NL99	1.47	1.17
KC08e	0.50	0.89
KC08n	0.49	0.87

Glover and Clark 2012

Summary

- PDRs are a site of rich interstellar chemistry that has dramatic effects on gas sturcture, temperature, etc
- Simulations of PDRs are difficult but have been successful in reproducing key observables