Lecture 18 - Photon Dominated Regions

1. What is a PDR?
2. Physical and Chemical Concepts
3. Molecules in Diffuse Clouds
4. Galactic and Extragalactic PDRs

References

Tielens, Ch. 9
Hollenbach & Tielens, ARAA 35 197 1997
Hollenbach & Tielens, RMP 71 173 1999
Snow & Savage, ARAA 44 367 2005

What is a PDR?

PDR = Photon Dominated Region*

- The photon flux or density is large enough to affect the physical properties of the gas, I.e., temperature, ionization, chemistry and, above all, spectral diagnostics.
- The physical properties change with distance as the photons are absorbed going into the region.
- The photons ranges from FUV (< 2000 Å) to X-ray (< 100 Å).
- The range of photon density is large, extending from interstellar FUV to the EUV & X-rays near a cluster of O,B stars or an AGN.

  - **Tielens & Hollenbach use "Photo Dissociation Region", but PDRs involve the change from ions to atoms to molecules.**
  - **PDRs are a generalization of photoionization-recombination balance for diffuse interstellar clouds**

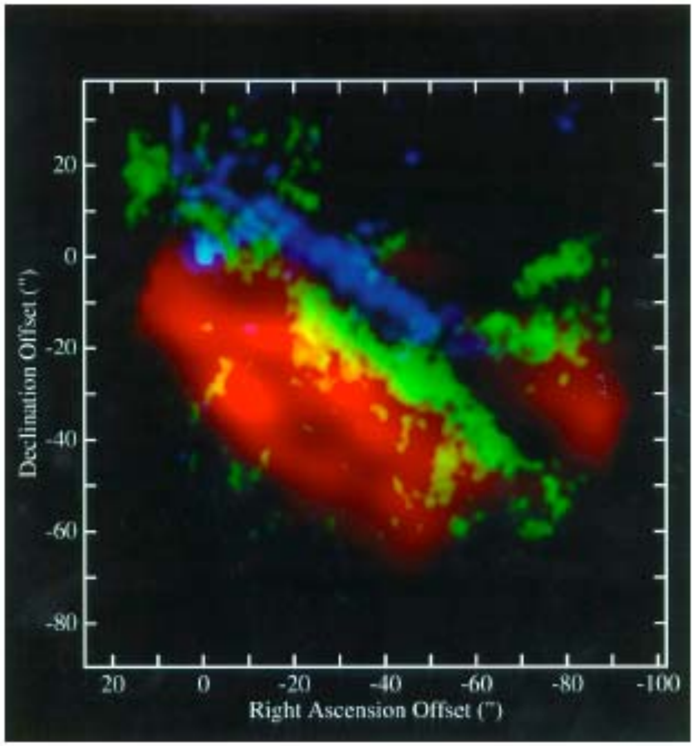
PDRs in the Milky Way and Beyond

PDRs occur in primarily neutral gas where FUV photons play a significant role in determining the physical and chemical properties. Examples are:

- Neighborhood of HII regions
- Diffuse and translucent clouds
- Outer regions of molecular clouds
- The pervasive WNM
- Reflection nebulae
- Red giant winds, especially the AGB phase
- The neutral envelopes of planetary nebulae
- Protoplanetary disk atmospheres
- The ISM of starburst galaxies
- Clouds around AGN

The Orion Bar PDR

10”

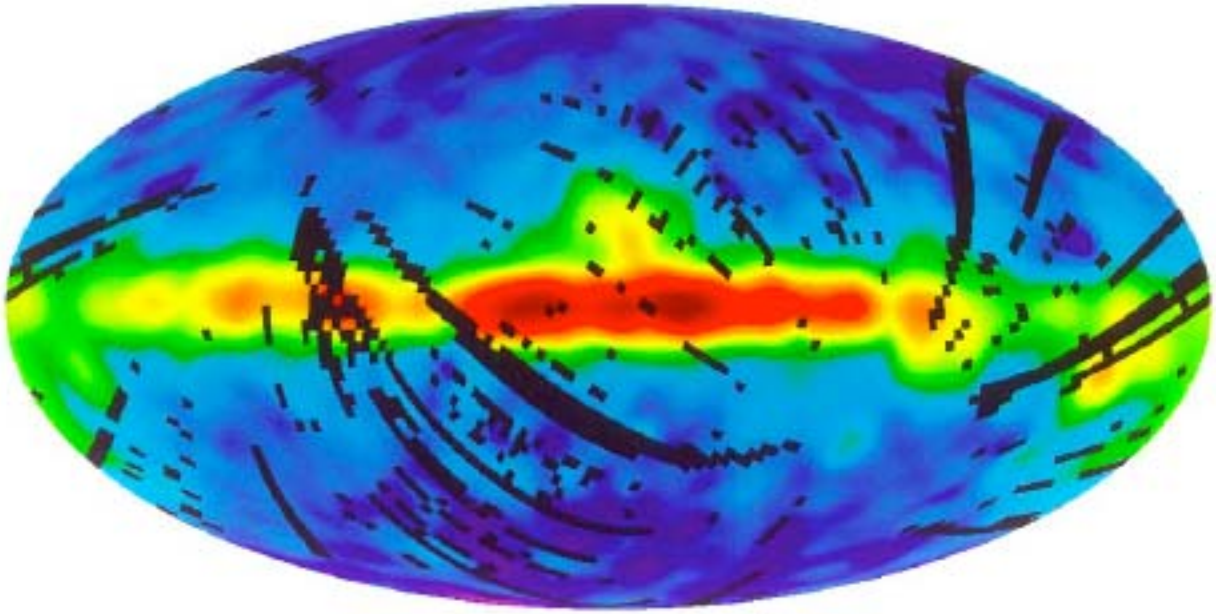


Orion bar below the ionization front (θ^1 C Ori is off to NW)

- Blue - PAH 3.3 μm
- Yellow - H_2 1-0 S(1)
- Red - CO J=1-0

Orion Nebula with bar and ionization front. The exciting star θ^1 C Ori is at the center of the trapezium cluster

COBE FIRAS MAP of the CII 158 μm Line

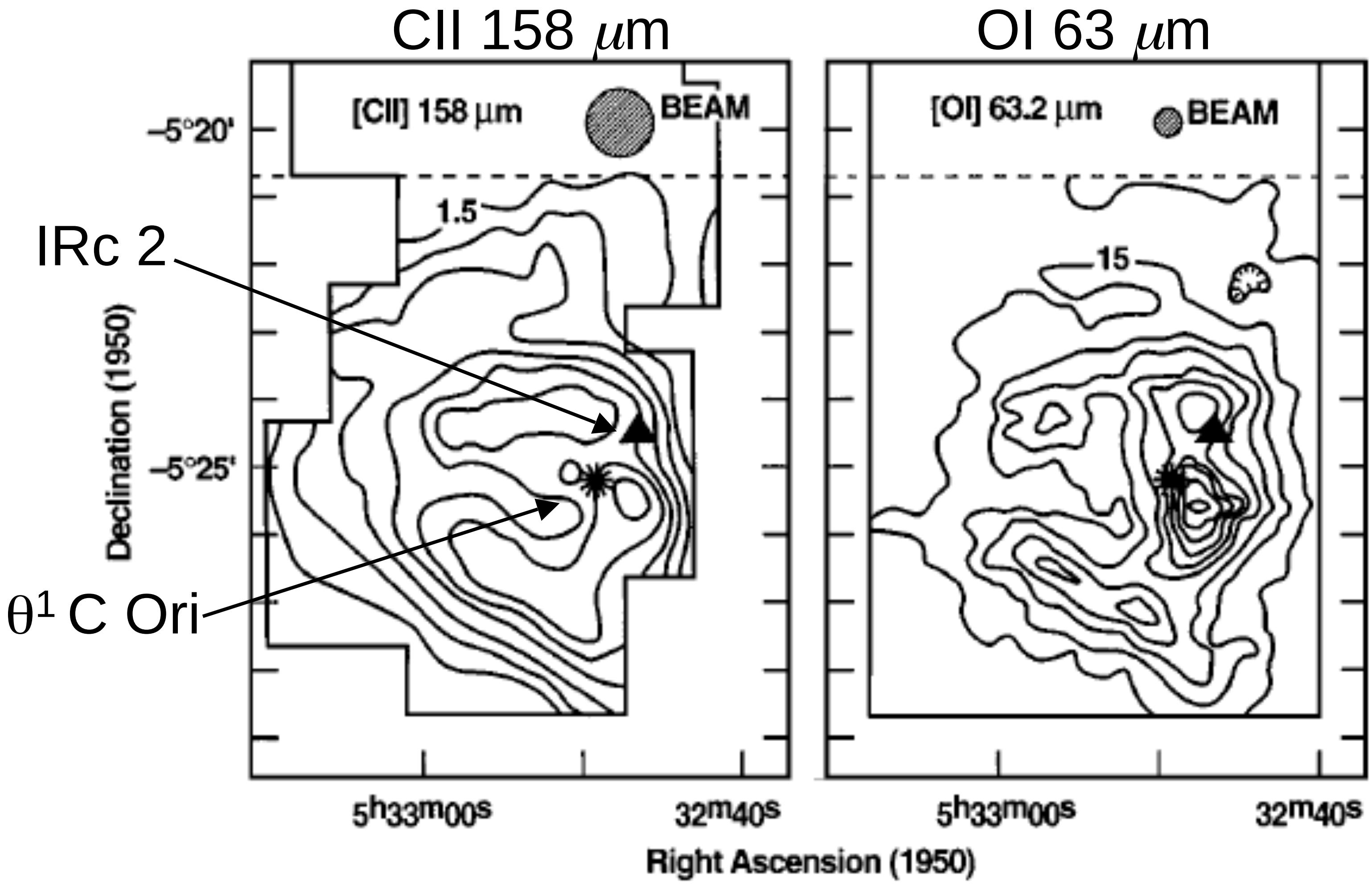


Bennett ApJ 434 587 1994

The dominant features in this map of the Milky Way are PDRs associated with the 3-kpc molecular ring and with star-forming regions in the thin disk, e.g., in Cygnus, Ophiuchus, Carina, Vela, and Orion.
This 158 μm line is a characteristic signature of PDRs.

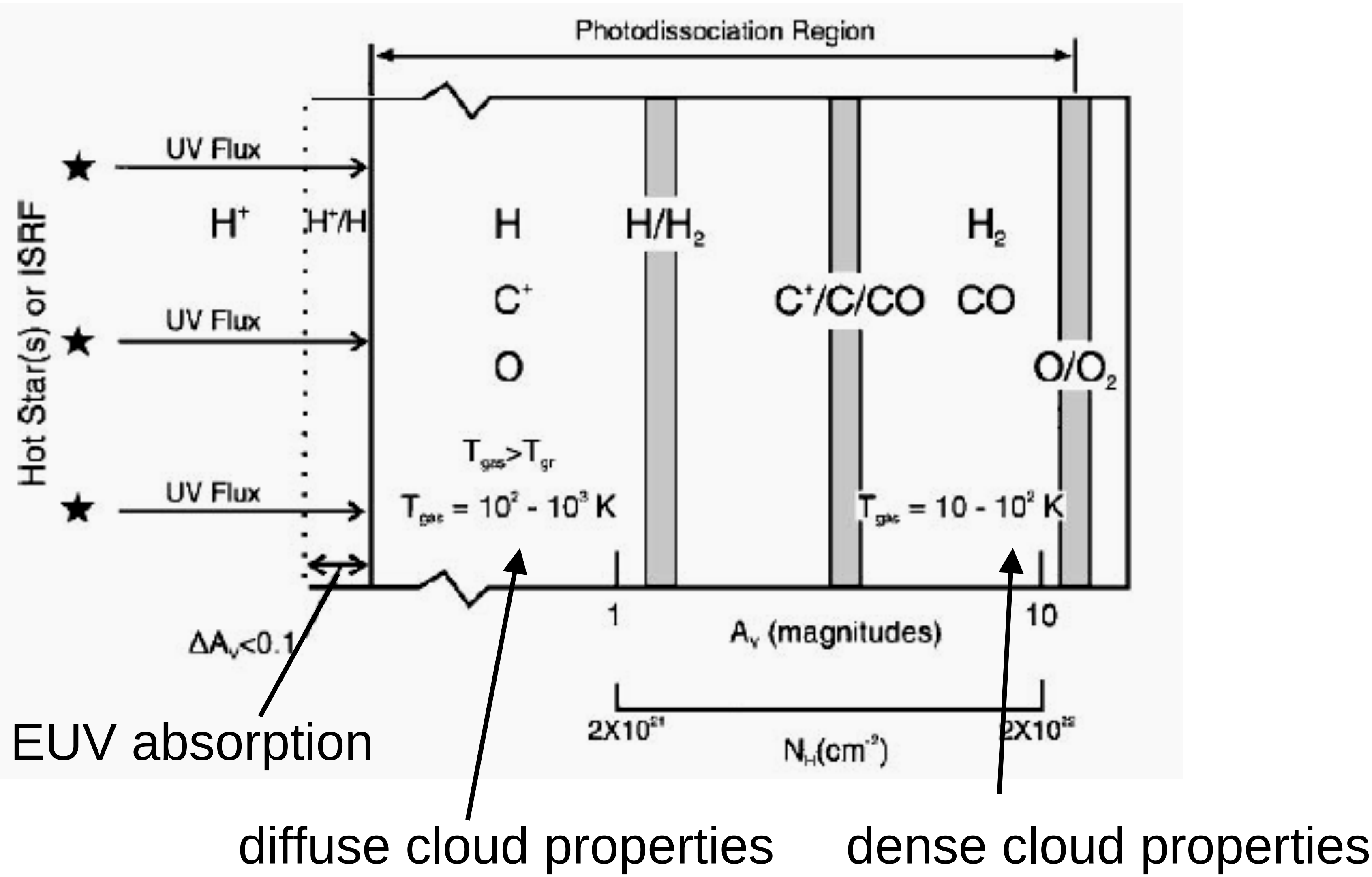
Fine Structure Line Emission from Orion A

Hermann et al. ApJ 481343 1997



The OI emission exhibits shock signatures within 1' of IRc 2.

Schematic of PDR Transitions



The Essential Parameter for a PDR

- The variable used to plot the transition regions is the column density N_{H} or the equivalent thickness in visual magnitudes ($A_V = N_{\mathrm{H}}/1.8 \times 10^{21}$ cm^{-2} for diffuse clouds).
- N_{H} and A_V are appropriate because because the changes in physical conditions are induced by the absorption of the dissociating and Ionizing radiation by the gas, especially the dust component.
- The location of a transition depends on the column density and not directly on the volumetric density n_{H}.
- The underlying PDR transitions also depend on the strength of the external radiation field and on its attenuation.
- The most basic physical variable is the ***ionization parameter.***

Recalling The Ionization Parameter

In Lecture 3, we calculated the Ionization parameter just inside a Strömgren sphere,

$$U_{St} = \frac{n_{\pi}}{n_{\mathrm{H}}} = \frac{S}{4\pi R_{St}{}^{2} c n}$$

where S is the number of ionizing photons and $U_{st} = 3.49\mathrm{x}10^{-3}(n_2 S_{49})^{1/3}$

The corresponding ionization parameter for the diffuse ISM can be estimated from the mean interstellar FUV radiation field in the solar neighborhood from 912-1103 Å, which is responsible for ionizing atomic carbon, the main donor of electrons in diffuse neutral gas.

$$n_{\mathrm{FUV}} = 6.5x10^{-4} \text{ FUV photons cm}^{-3}$$

$$F_{\mathrm{FUV}} = n_{\mathrm{FUV}} c = 2x10^{7} \text{ FUV photons cm}^{-2} \text{ s}^{-1}$$

using Habing's value of F_{FUV} (Draine's is 1.75 larger) , and find

$$\boxed{U_{\mathrm{FUV}} = \frac{n_{\mathrm{FUV}}}{n_{\mathrm{H}}} = \frac{6.5\mathrm{x}10^{-6}}{n_2} \quad \text{(Habing Field)}}$$

The Ionization Parameter for PDRs

For the Habing radiation field, $U_{St}/U_{FUV} \sim 500$. The FUV radiation field for a PDR near a star-forming region can easily be 3 or more dex larger than for the local ISM.This is usually expressed in terms of the flux ratio G_0 to the Habing field, where G is a common notation for the FUV flux.

The physical basis for the ionization parameter is that radiation effects are proportional to n_{FUV}/n_H.Consider the balance between photo-ionization and recombination for an atom such carbon:

$$\varsigma_{\mathrm{FUV}}(\mathrm{C})\; n(\mathrm{C}) = F_{\mathrm{FUV}}\; \sigma_{\mathrm{phion}}(\mathrm{C})\; n(\mathrm{C}) = \alpha(\mathrm{C}^+)\; n_{\mathrm{e}}\; n(\mathrm{C}^+)$$

Dividing by n_H^2,

$$\frac{x(\mathrm{C}^+)}{x(\mathrm{C})} = \frac{F_{\mathrm{FUV}}\; \sigma_{\mathrm{phion}}}{n_{\mathrm{H}}\alpha(\mathrm{C}^+)\; x_{\mathrm{e}}}$$

The abundance ratio of C^+ to C is determined by F_{FUV}/n_H, not just by F_{FUV}. In many PDRs, the electrons come mainly from C^+ and

$$x(\mathrm{C}^+) \cong x_{\mathrm{e}} \cong \sqrt{\frac{F_{\mathrm{FUV}}\; \sigma_{\mathrm{phion}}}{n_{\mathrm{H}}\alpha(\mathrm{C}^+)}}$$

Another Ionization Parameter

A more physically motivated ionization parameter than the photon-particle density ratio is

$$R_{\mathrm{ionpara}} = \frac{F_{\mathrm{FUV}}}{n_{\mathrm{H}}} \sigma_{\mathrm{phion}} \ = \ \text{photoionization rate / particle density}$$

with dimensions cm^3s^{-1}. For diffuse matter with $n_H = 100$ cm^{-3}, the following values pertain. For the PDR, we have assumed that the $\sigma_{\mathrm{phion}} = 10^{-17}$ cm^{-2}.

PDR	$R_{\mathrm{ionpara}} = 2\mathrm{x}10^{-12} G_0$	cm^3s^{-1}
Single HII region	$R_{\mathrm{ionpara}} = 10^{-9}$	cm^3s^{-1}
Cosmic rays	$R_{\mathrm{ionpara}} = 5\mathrm{x}10^{-19}$	cm^3s^{-1}

In practice G_0 ranges from unity to 10^6.

3. Molecules in Diffuse Clouds

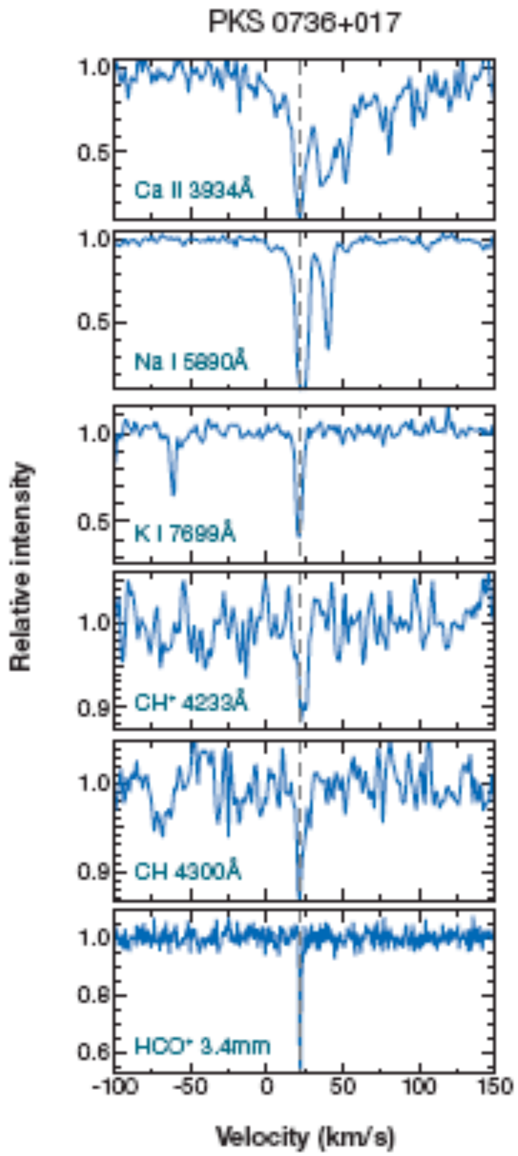
- Incomplete list of molecules detected in diffuse clouds (Snow & McCall 2006).
- Primary source for UV & optical detections is a bright Star like ς Oph (O9Ve, V = 2.8, A_V = 1.06)
- Of the 30 listed by Snow & McCall, > 40% have been detected at mm wavelengths toward extragalactic sources e.g., by Liszt & Lucas.
- Diffuse clouds are especially useful because they provide the most reliable information on physical conditions, albeit for a special part of the ISM

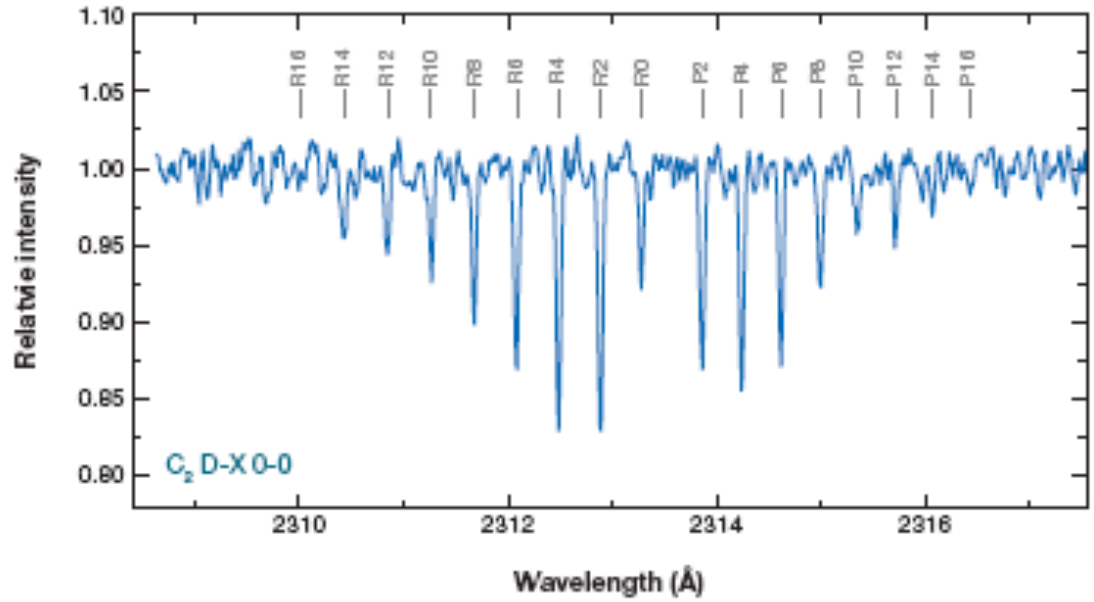
Table 2 Molecules detected in diffuse molecular clouds

Weight	Species	Method	Target	$N(X)/N_H$	Reference
2	H_2	UV	ζ Oph	0.56	1
3	HD	UV	ζ Oph	4.5 (−7)	2
3	H_3^+	IR	ζ Per	5.1 (−8)	3
13	CH	Optical	ζ Oph	1.5 (−9)	4
13	CH^+	Optical	ζ Oph	2.4 (−8)	5
14	$^{13}CH^+$	Optical	ζ Oph	3.5 (−10)	6
15	NH	Optical	ζ Oph	6.2 (−10)	7
17	OH	UV	ζ Oph	3.3 (−8)	8
24	C_2	Optical	ζ Oph	1.3 (−8)	9
25	C_2H	mm abs.	BL Lac	1.8 (−8)	10
26	CN	Optical	ζ Oph	1.9 (−9)	11
27	HCN	mm abs.	BL Lac	2.6 (−9)	12
27	HNC	mm abs.	BL Lac	4.4 (−10)	12
28	N_2	UV	HD 124314	3.1 (−8)	13
28	CO	UV	X Per	6.4 (−6)	14
29	HCO^+	mm abs.	BL Lac	1.5 (−9)	15
29	HOC^+	mm abs.	BL Lac	2.2 (−11)	15
29	^{13}CO	UV	X Per	8.9 (−8)	16
29	$C^{17}O$	UV	X Per	7.4 (−10):	16
30	$C^{18}O$	UV	X Per	2.1 (−9):	16
30	H_2CO	mm abs.	BL Lac	3.7 (−9)	17
36	C_3	Optical	ζ Oph	1.1 (−9)	18
36	HCl	UV	ζ Oph	1.9 (−10)	19
38	C_3H_2	mm abs.	BL Lac	6.4 (−10)	10
44	CS	mm abs.	BL Lac	1.6 (−9)	20
64	SO_2	mm abs.	BL Lac	≤8.2 (−10)	20

Snow & McCall 2006

Novel Observations of Diffuse Clouds

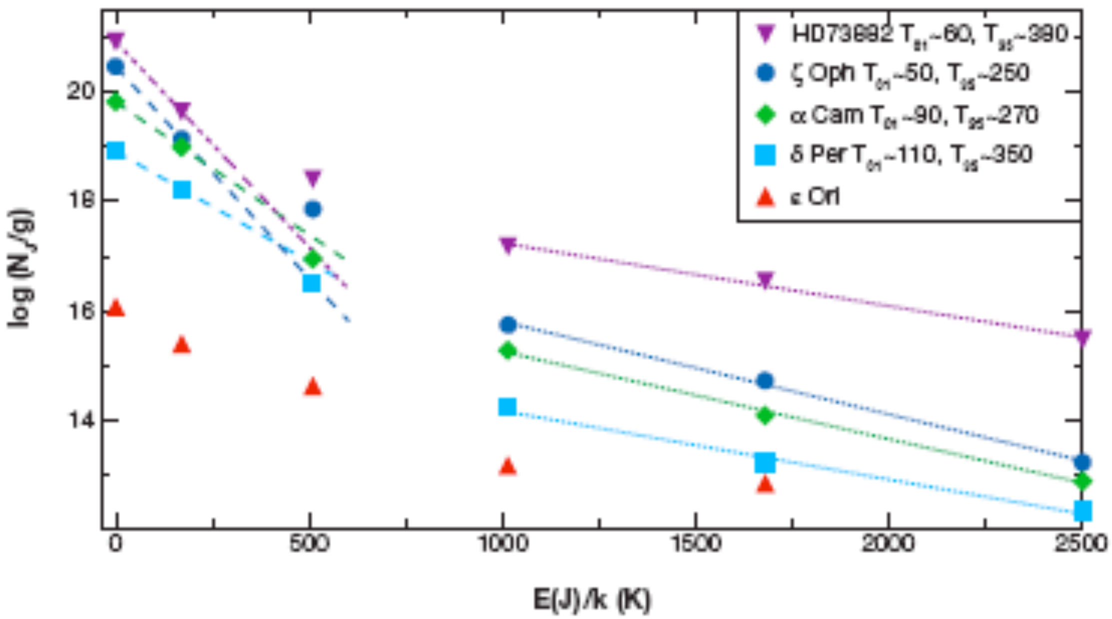




Rotational bands of C_2 provide rotational temperatures (van Dishoeck & Black, 1982) in rough agreement with those from H_2.

Species seen in absorption by a diffuse cloud along the l.o.s towards an extragalactic source, including HCO^+ at mm wavelengths.

Non-Uniform Properties of Diffuse Clouds



• **Two rotational temperatures** are usually required to fit measured H_2 rotational populations. T_{01} is always smaller than T_{35}; T_{01} is associated with the kinetic temperature and T_{35} with radiative excitation. A typical kinetic temperature of a diffuse cloud is ~ 80 K

• Detailed models of diffuse clouds also require **inhomogeneous densities**, e.g., Black & van Dishoeck (ApJS 34 405 1977; ς Oph) and Le Petit et al. (A&A 417 963 2004; ς Per), also discussed in Lec16 in connection with the interpretation of the H_3^+ observations.

Interpreting Diffuse Cloud Observations

- Observations of diffuse clouds are usually interpreted with steady-state slab models with variable density.
- They use the heating and chemical-ionization processes discussed in Lec07.
- Some essential features are;
  - Irradiation by FUV photons with $G_0 \approx 1$
  - Photoelectric heating (small grains and PAHs)
  - Cooling by fine-structure line radiation
  - Electron fraction ~ 10^{-4} (C^+)
  - H_2 formation on grains

- The status of diffuse cloud modeling is reviewed by Snow & McCall (2006).
- Especially noteworthy is the recent work by the Paris Meudon group (Roueff, Pineau des Foret, Flower, et al, (e.g., A&A 417 963 2004).
- Factor of few agreement is considered good.

Problems Interpreting Diffuse Clouds

1. CH+ was one of the first interstellar molecules discovered.

-- Older chemical models failed because the first step in the ion-molecule paradigm is endothermic,

$$\mathbf{C^+ + H_2 \text{ --> } CH^+ + H - 4600\ K,}$$

(and is suppressed at the low temperatures of diffuse clouds).

-- Radiative association,

$$\mathbf{C^+ + H \text{ --> } CH^+ + \mathit{h}\nu}$$

was rejected because it is too weak (k ~ 10^{-16} cm^3 s^{-1})

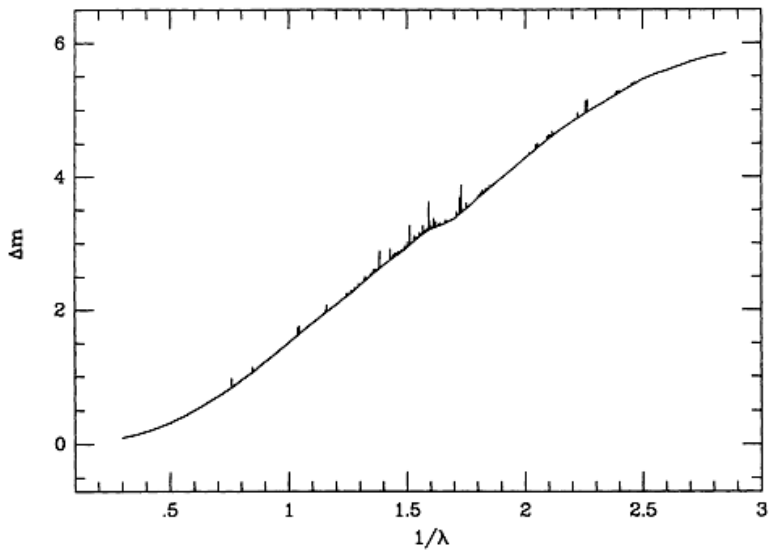
-- Shocks are promising, but they have the potential to affect over other species (Le Petit et al. A&A 417 963 2004; Shaw et al. ApJ 675 405 2008).

2. H_3^+ - Implied high cosmic ray ionization rate may be less of a problem than previously thought (c.f. Lec16), but see Shaw et al. 2008)

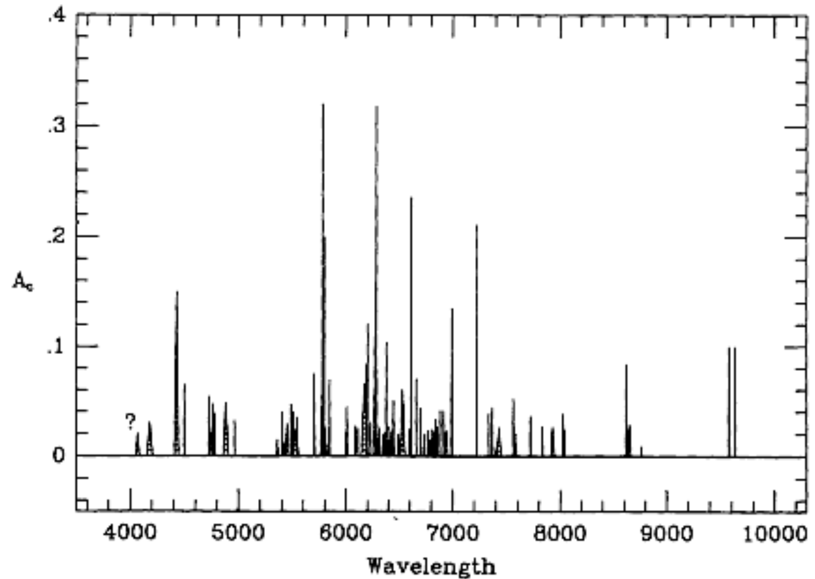
3. Larger molecules seen at mm wavelengths - omitted in recent modeling

4. Diffuse Interstellar Bands (DIBs)

Introduction to DIBS



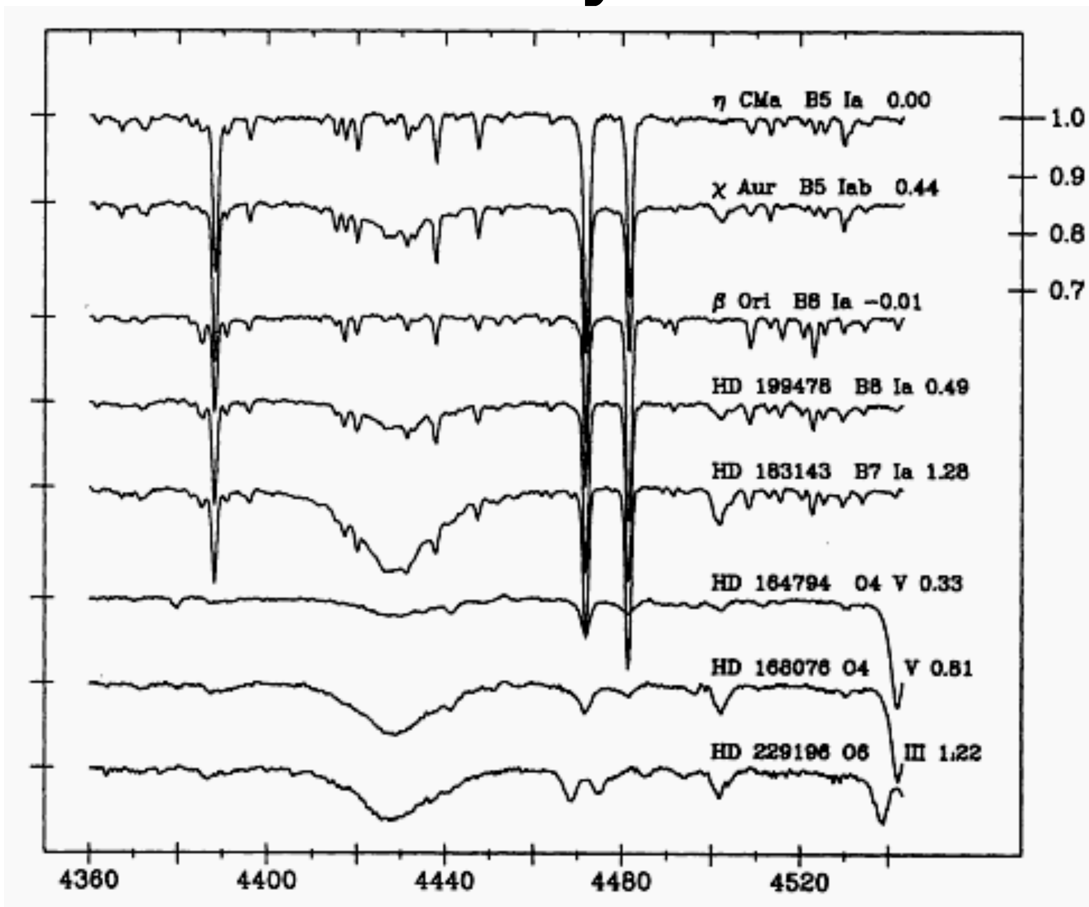
Extinction Curve for HD 183143



Same data replotted

- The fine structure in the extinction curve is a common feature seen in atomic diffuse interstellar clouds (mainly H).
- Bands suggests a molecular origin.
- Recommended review: GH Herbig, ARAA 33 19 1995
- **Reported in 1922. The origin of the DIBS is still unknown**.

Uniformity of DIBs



- Uniformity suggests free molecules rather than solid features.
- Popular candidates: small carbon chains, PAH-like aromatic compounds, and similar carbonaceous structures
- For near current status, see Snow & McCall (2006)

4. Galactic and Extragalactic PDRs

A general treatment of PDRs is nearly impossible because the applications are so broad, e.g., from slide 3:

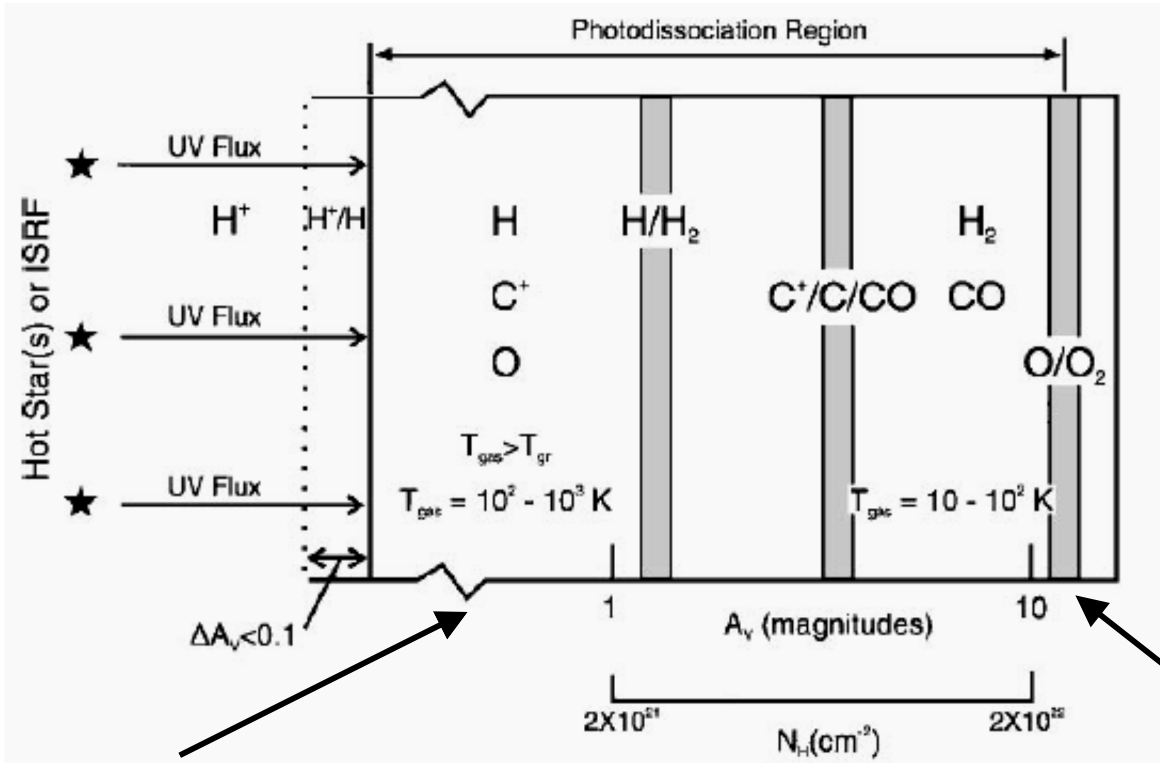
- Neighborhood of HII regions
- Diffuse and translucent clouds
- The pervasive WNM
- Outer regions of molecular clouds
- Reflection nebulae
- Red giant winds, especially the AGB phase
- Neutral envelopes pf planetary nebulae
- Protoplanetary disk atmospheres
- The ISM of starburst galaxies
- Clouds around AGN

The underlying physics can vary, although properties scale with the ionization parameter G_0/n_H.

- Key reviews by Hollenbach & Tielens (1997, 1999).
- For up to date calculations, see the website of Mark Wolfire et al.

http://dustem.astro.umd.edu/pdrt/index.html

PDR Transitions



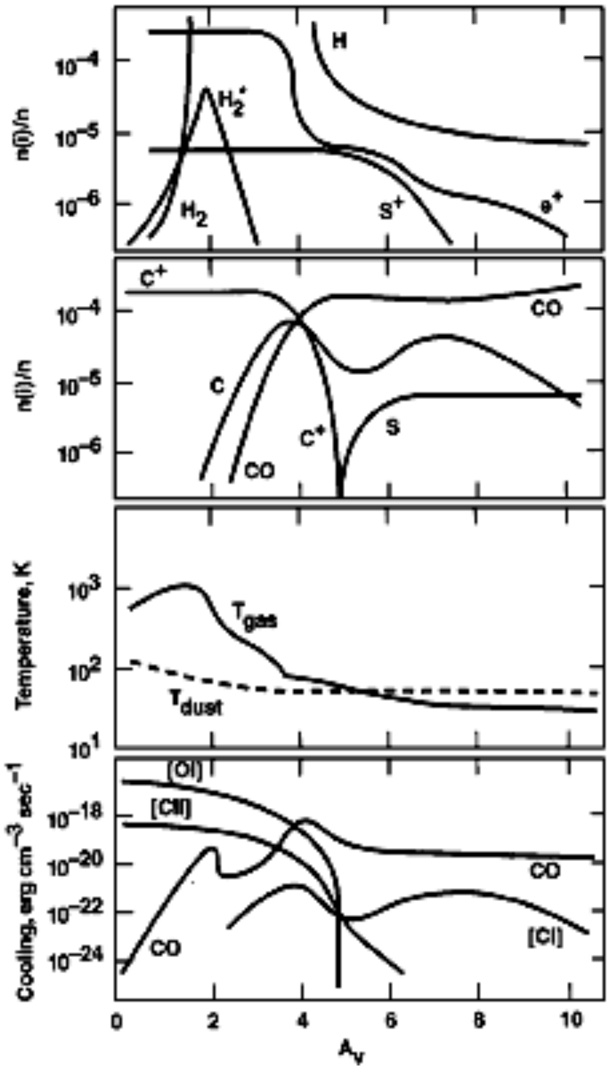
Thin cloud PDR $A_V \sim 1$

- H/H2 transition is almost complete
- C and C^+ are only partially converted into CO
- Other molecules at low-abundance

Thick cloud PDR $A_V > 1$

- H/H_2 and $C^+/C/CO$ transitions are complete
- $O/O_2/H_2O$ transition depends on temperature etc,

Example of the Orion Bar PDR



H species

C species

Temperature

Cooling

OI - 63 μm

CII - 158 μm

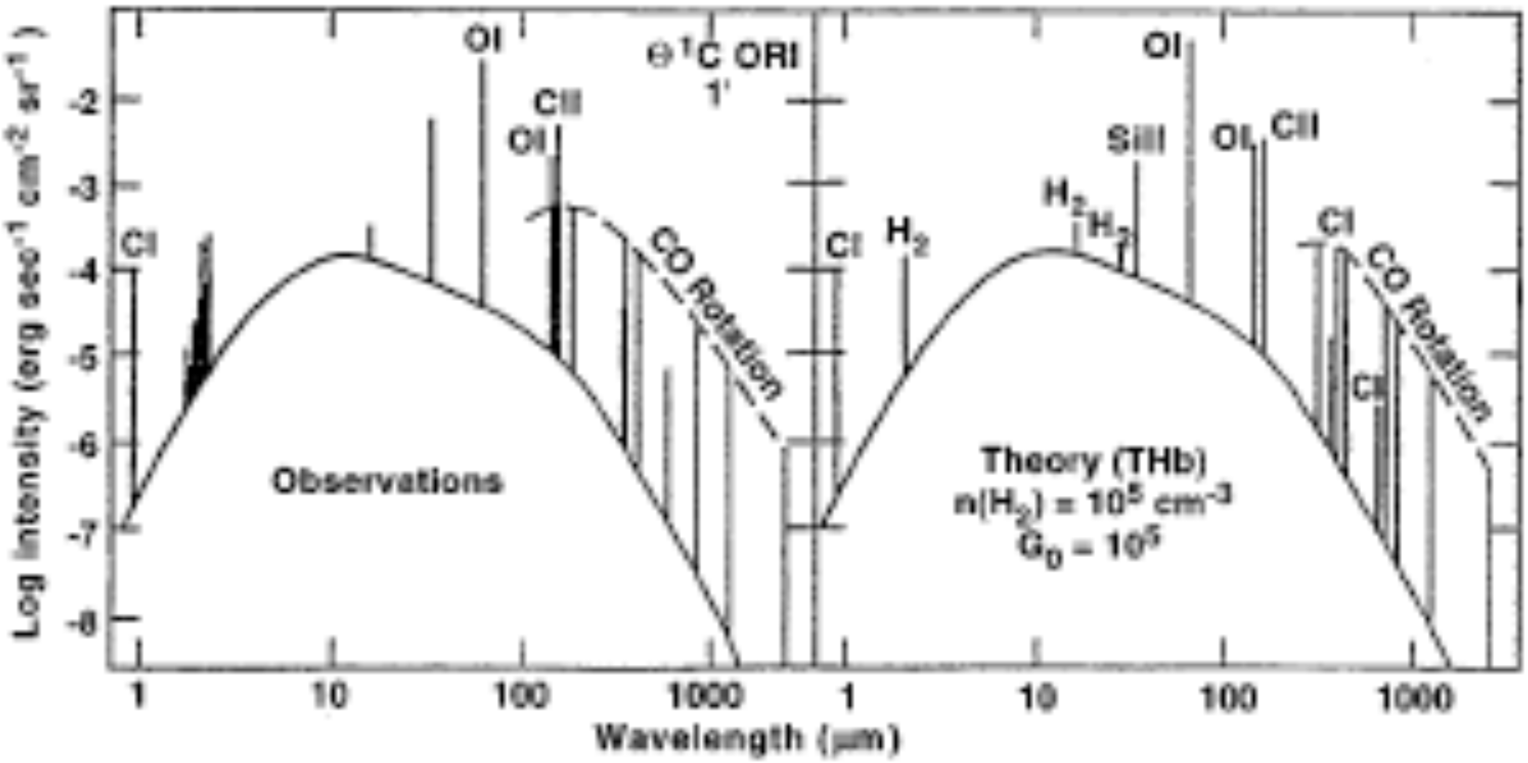
CI - 610 μm

The abscissa varies from A_V =0 -10 mag

- **The parameters are G_0 - 10^5, n_H = 2.3 x 10^5, so the ionization parameter is G_0/n_H = 0.4.**
- **The ionization parameter for diffuse clouds is in the range ~ 0.01-0.1**

- **Full conversion to H_2 occurs before that of CO because of its greater line self-shielding.**
- **At the depth where CO is fully converted, dust plays a key role in attenuating the FUV.**
- **Substantial vibrationally excited H_2 is produced**

Line Spectrum for the Orion PDR



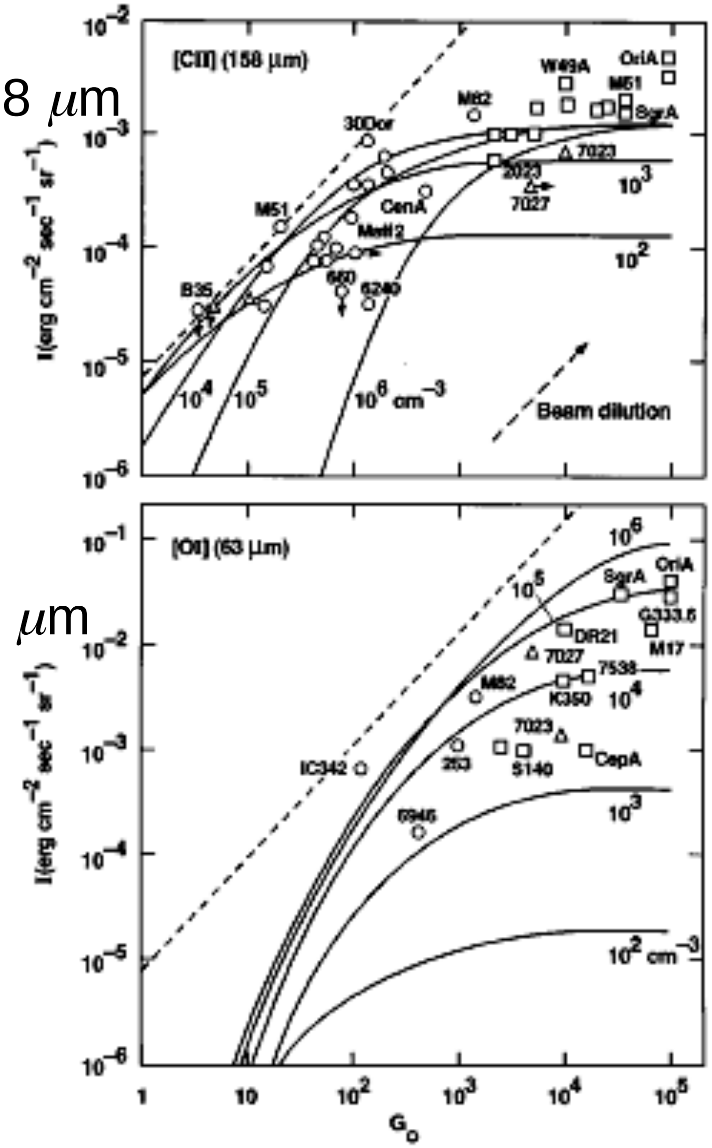
Hollenbach & Tielens 1997

Good agreement with observations except for high-*J* lines of CO (e.g., *J*=7-6, *J*=14-13), where the observed fluxes are 3 dex stronger than theory.

Fits of the Cooling Lines

CII 158 μm

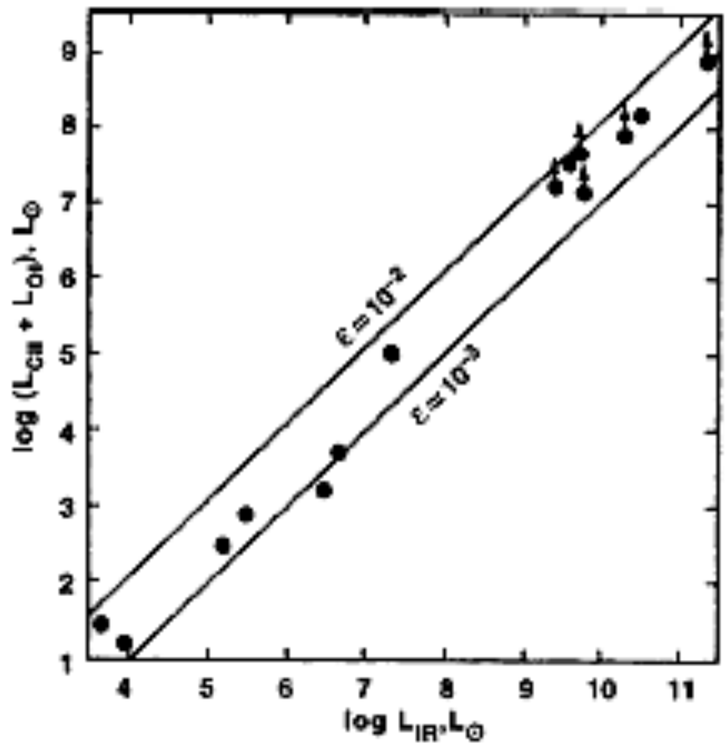
OI 63 μm



- The fitting parameters are G_0 and n_H .
- G_0 is along the abscissa
- The sold curves are n_H starting at 100 cm^{-3}
- The dashed curve corresponds to 3% efficiency for converting the FUV energy flux into line emission
- Most of the FUV is absorbed by dust particles and PAHs
- Cooling by OI 63 μm and CII 158 μm is supplemented by CO rotational lines and various forbidden lines
- For further details, see Tielens 9.9

Hollenbach, Takahashi & Tielens, ApJ 377 192 1991

Efficiency of PDR Line Radiation



- Luminosity of the CII and OI fine-structure lines plotted against the total continuum IR luminosity.
- Observations suggest an efficiency 0.001- 0.01.

X-ray Dominated Regions (XDRs)

• Where the X-ray flux is comparable or larger than the FUV flux, e.g., near AGN and YSOs, the character of the transition region changes (Maloney, Hollenbach & Tielens, ApJ 466 561 1996).

• One essential difference is that X-rays are absorbed by the photoelectric effect over a column density ~ 10^{22} cm^{-2} $(E_X/\mathrm{keV})^{2.7}$.

• CO and H_2 are destroyed mainly by secondary-electron collisional ionization. The transitions are smooth and C^+/C/CO occurs before H/H_2.