Photodissociation Regions

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Dense ISM in Galaxies
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Operational definition: Neutral interstellar hydrogen gas where (6-13.6 eV) FUV radiation dominates the physical and chemical structure. Hence also called “photon-dominated regions” (PDRs).

Molecular photodissociation a key process.

Interstellar PDRs include:

The diffuse WNM and CNM clouds.

Translucent clouds: $A_v < 5 \quad n_H < 1000 \text{ cm}^{-3}$ weak interstellar FUV fields.

Dense molecular clouds: $A_v \text{ up to } \sim 10 \quad n_H > 1000 \text{ cm}^{-3}$ including intense FUV fields near OB stars

~90% of the Galactic molecular ISM may be “photon-dominated”.
Dense PDRs exposed to intense FUV fields in star-forming molecular clouds are particularly important as sources of luminous fine-structure and molecular line (cooling) radiation and far-IR thermal dust continuum emission.
Clumpy, time-dependent, PDRs

Molecular Hydrogen emission in the Ring Nebula.

1-0 S(1) 2.12 μm

Speck et al. 2003 PASP 115, 170

NIRIM camera @ WIYN 3.5m
Basic structure: 1-D steady-state model, escape probability method

Controlling parameters:
1) cloud density/pressure
2) FUV intensity
3) grain scattering properties
4) $\text{H}_2$ formation rate coefficient
5) geometry/clumpiness
6) gas phase abundances
7) magnetic field

$\text{H}_2$ self-shielding and dust attenuation vs. grain surface formation.

FUV 6-13.6 eV
Abinitio computations of the local FUV field, based on the Galactic birth-rate of OB associations.


**Key Results**

1) At any point, dust opacity limits contributing associations to within 500 pc.

7) Large angle scattering produces a diffuse field at the 10% level.

10) Time-dependent due to statistical fluctuations in the OB-association formation rates.

13) Median predicted value within 6% of the Draine field!
Heating Mechanisms:

Photoelectric heating beginning with Spitzer 1948 ApJ, 107, 6

FUV-pumping of $H_2$ in dense PDRs
Grain photoelectric heating efficiency:

- Heating dominated by smallest grains/PAHs.
- Half the heating from grains with \( a < 15 \text{ Å} \).
- The rest from grains with \( 15 \text{ Å} < a < 100 \text{ Å} \) for a \( dn = a^{-3.5} da \) (MRN) grain size distribution.

Different assumed electron-grain sticking coefficients.
CII 158 μm fine-structure line cooling:

- Expected theoretically e.g. Dalgarno & McCray 1972.

First far-IR (Lear jet) detections by Russell et al. 1980 in NGC 2024 and Orion.

Widely detected since with KAO, ISO...

Low-ionization fine-structure emission lines in star-forming molecular clouds

Accounting for CII 158 µm
  OI  63 µm
and other “low-ionization” fine-structure emission lines observed in star-forming molecular clouds.

Line strengths \( \sim 1\% \) of IR continuum.

FUV (6-13.6 eV) heating via photoelectric emission from dust grains

mean photon energy \( = 10 \text{ eV} \)
typical grain work function \( = 6 \text{ eV} \) (for neutral grains).
photoelectric yield \( = 0.1 \)

Thus,
heating efficiency \( = (4/10) \times 0.1 = 0.04 \) (smaller for positively charged grains.)
Fine-Structure Line Emission:

$\mu \text{m CII} 158\mu \text{m}$

$\mu \text{m} / [\text{CII} 158\mu \text{m} \text{ OI} 63\mu \text{m}]$


$\mu \text{m} / [\text{CII} 158\mu \text{m} \text{ OI} 63\mu \text{m}]$

[OI] 63\mu m can become optically thick.
Gas-Phase Chemistry:

\[ \text{PDR} \]

\[ \text{log density (cm}^{-3}\text{)} \]

\[ \text{H} \]

\[ \text{H}_2 \]

\[ \text{C}^+ \]

\[ \text{CO} \]

\[ \text{SO, SO}_2 \]

\[ \text{m.ions (core)} \]


Jansen et al. 1995
Gas-Phase Production of Hydroxyl and Water:

Ion-molecule chemistry in cold gas:

Neutral-neutral chemistry in warm gas regime of ion-molecule chemistry

Neufeld & Kaufmann 1995

![Graph showing the abundance of O, O_2, and H_2O relative to H_2 as a function of temperature (K). The graph illustrates two regimes: the regime of neutral-neutral chemistry and the regime of ion-molecule chemistry.]
OH and H$_2$O in PDRs:

Removal by photodissociation.

OH/H$_2$O remains large in warm PDR gas.
OH driven chemistry in warm H/H$_2$ transition zone:

$T = 300 - 1000$ K

Prediction:

CO$^+$/HCO$^+$ large in PDR
CO$^+$/HCO$^+$ small in dark core
For example, \( \text{CO}^+/\text{HCO}^- \)

NGC 7023  (reflection nebula)  
Fuente et al. 2003, AA, 899, 913

\[ G_0 = 2.4 \times 10^3 \]
\[ n = 10^4 \, \text{cm}^{-3} \]
Neutral Atomic Carbon:

\[ \text{C} + / \text{C}/\text{CO} \rightarrow \text{S} + \text{C} + \text{C}^+ + \text{S}^+ + \text{C} \]
[Cl] 609 µm fine-structure line emission in ρOph:

L1688 in ρOph
Mt Fuji submm-telescope 1.2m

Extended Cl may be due:

1) Scattered FUV in a clumpy medium.

2) Possible time-dependent effects. Recombining C+ in shadowed PDR clumps where cooling-time is longer than C formation time.

Stoerzer, Stutzki & Sternberg 1997
Polycyclic Aromatic Hydrocarbons (PAHs)

NGC 7023 (reflection nebula)

Optical $\rightarrow$ “internal conversion” $\rightarrow$ IR

ISO spectrum of NGC7023

(D. Cesarsky et al. 1996)

$I_\nu$ (MJy sr$^{-1}$)

- $\lambda$ ($\mu$m)
  - 6.25: C skel
  - 7.62: in-plane C-H bend
  - 8.6: mono duo trio quartet
  - 11.3: out-of-plane C-H bend
  - 12.0: in-plane C-H bend
  - 12.7: out-of-plane C-H bend
  - 13.55: in-plane C-H bend

B. T. Draine 2003.04.25
PAHs in PDRs


+PAH ←→ PAH ←→ -PAH

dashed – without PAHs
solid – with PAHs (2 x 10^{-7})

mutual neutralization

\[ X^+ + \text{PAH}^- \rightarrow X + \text{PAH} \]

competes with or dominates radiative recombination

\[ X^+ + e \rightarrow X + \text{hv} \]

Lepp & Dalgarno 1988, Apj, 335, 769
Dense PDRs dominate:

\[ G_0 = 500 \]
\[ n_H = 10^5 \text{ cm}^{-3} \]

(CNM a small fraction.)
CII line deficit in Ultra-Luminous IR Galaxies (ULIRGs):

$L_{\text{IR}} > 10^{12} \, L_{\odot}$

Possible Explanations

3) $G_0 / n >> 1 \, \text{cm}^3$ in ULIRGs
   inefficient photoelectric gas heating.

8) Underabundance of OB stars (unlikely).

12) Absorption of UV photons in dusty HII regions. Requires high ionization-parameters ($U \propto \tau_{\text{dust}}$).

Is this consistent with nebular emission-line excitation? TBD

(basic assumption: FIR is reradiated FUV energy)
The interacting galaxies NGC 4038/4039

Infrared Space Observatory

Keck

Infrared Space Observatory
UV-pumped Molecular Hydrogen in the Antennae


Mid-IR Cluster

H$_2$ lines
FUV Pumping and Photodissociation of Molecular Hydrogen:

Effective Potential Energy

\[ v=0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

Internuclear Separation

Black & Dalgarno 1976
Black & van Dishoeck 1987
Sternberg 1988
Sternberg & Dalgarno 1989
Draine & Bertoldi 1996
Sternberg & Neufeld 1999

\( \lambda \) (microns)

\( \text{ergs} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{s}^{-1} \)
$H_2$ level populations in the mid-IR cluster: Indicating radiative excitation in PDRs.

- $v = 1$
- $v = 2$
- $v = 3$

$T_{\text{vib}} = 6000 \text{ K}$

- non-thermal
- $T > 300 \text{ K}$ gas!

o/p ratio for excited states $\approx 1.8$

A signature of warm $T > 300 \text{ K}$ gas!
Curve of growth for absorption lines

thin  --------------------  thick  --------------------  saturated

log column density in ground state

log number of photons absorbed

logarithmic scale:
- Linear
- Flat
- Square root

Doppler core

radiative damping wings
The FUV H$_2$ absorption lines are highly saturated.

Therefore,

\[
N^* \sim N^{1/2}_{\text{ground}}
\]

So

\[
\frac{N^*_o}{N^*_p} = \left(\frac{N_o}{N_p}\right)^{1/2}
\]

If \( \frac{N_o}{N_p} = 3 \), then

\[
\frac{N^*_o}{N^*_p} = \sqrt{3} \approx 1.7
\]
Magnetically Regulated Star-Formation:

Critical magnetic mass:

\[ M_\Phi = \frac{\Phi}{2\pi G^{1/2}} \]

Subcritical clouds:

\[ M < M_\Phi \]

Stable against gravitational collapse for any external pressure.

Collapse requires flux loss, e.g. via ambipolar diffusion (ion-neutral slip).

Supercritical clouds:

\[ M > M_\Phi \]

Gravitational collapse is possible if the bounding pressure is sufficiently high, or alternatively, if the mass exceeds the "Bonner-Ebert" (Jeans) mass.
Ionization Structure:

ambipolar diffusion time \( t_{AD} = 10^{14} \times e \) yr

Magnetic field "frozen in".

Cosmic-ray ionized core

Rapid magnetic flux loss
Photoionization Regulated Star-Formation:

Photoionization regulated star-formation:

Predicts:

1) Galactic star-formation rate of $4 \, M_\odot \, yr^{-1}$

2) Star-formation is restricted to regions of relatively high extinction, $A_V > 4$.

(consistent with observations)
A golden future!

Space Infrared Telescope Facility (SIRTF)

Stratospheric Observatory for Infrared Astronomy

Atacama Large Millimeter Array (ALMA)

Herschel Space Observatory (submillimeter)