The Physics of PDRs

The Physics of PDRs

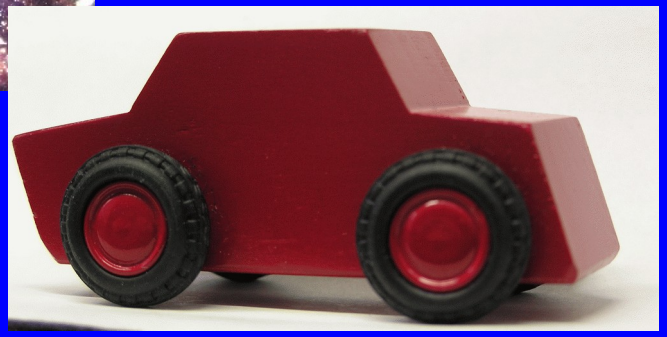
SO FAR!

Dark Gas paper 2
[CII] paper 4
G_0 paper 1

Chemistry paper 2
STO paper 1
GUSTO paper 1

The Physics of PDRs

STARS

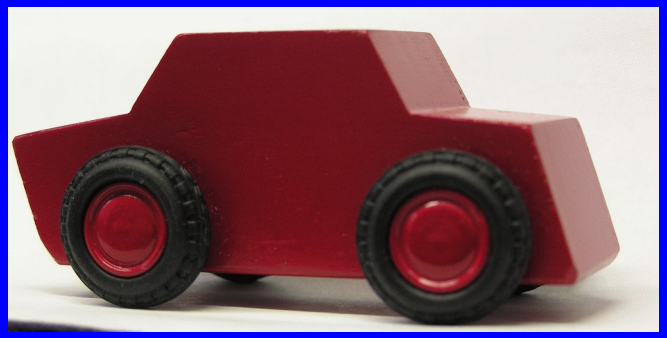


CARS

and PDRs

The Physics of PDRs

Introduction to PDRs: - What are they?
Where are they found?



CARS

and PDRs

The Physics of PDRs

Introduction to PDRs: - What are they?
Where are they found?

Structure and Chemistry, Heating Processes, Cooling Processes and Dominant Cooling Lines, Variation with density and radiation field

and PDRs

The Physics of PDRs

Introduction to PDRs: - What are they?
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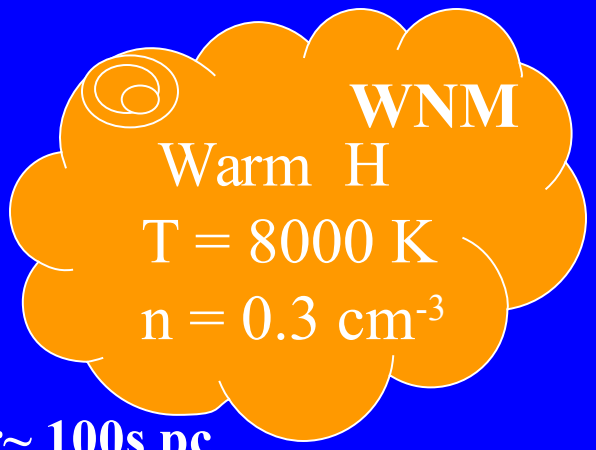
Questions and Problems in Modeling

PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry



r~ 100s pc

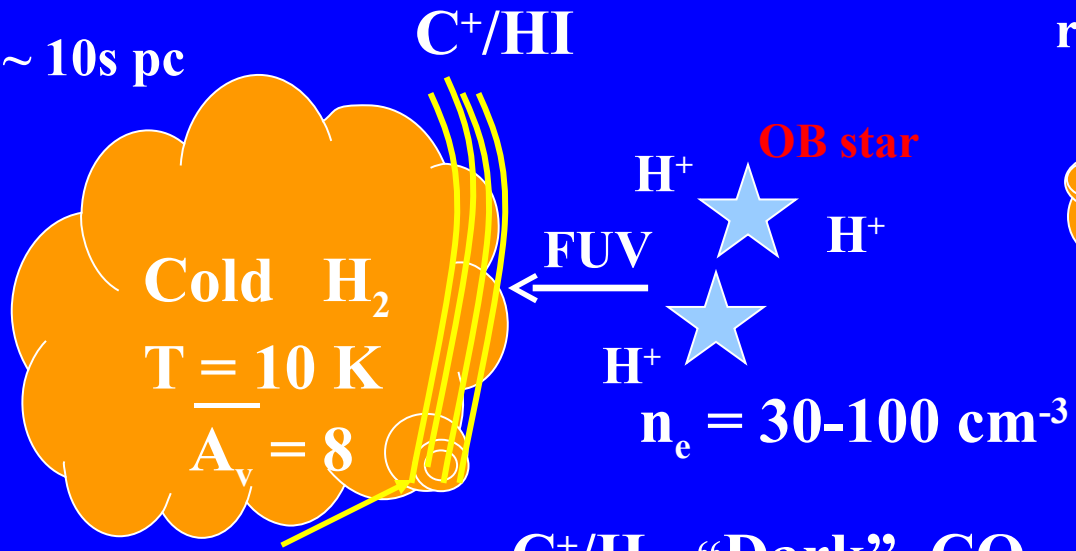
FUV: 6 eV – 13.6 eV

G_0 = 1 Interstellar field

G_0: Habing χ:Draine ~1.7 G_0

$G_0 = 10^5$ Orion trapezium

r ~ 10s pc

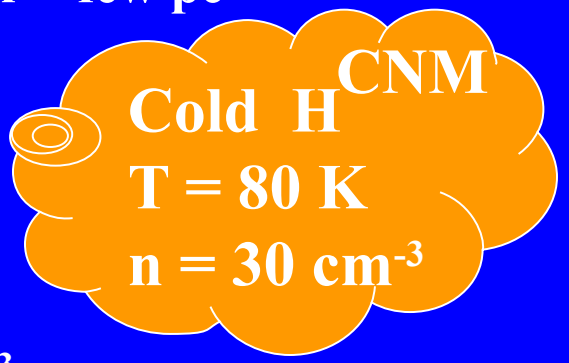


Classic PDR

n_e = 30-100 cm^{-3}

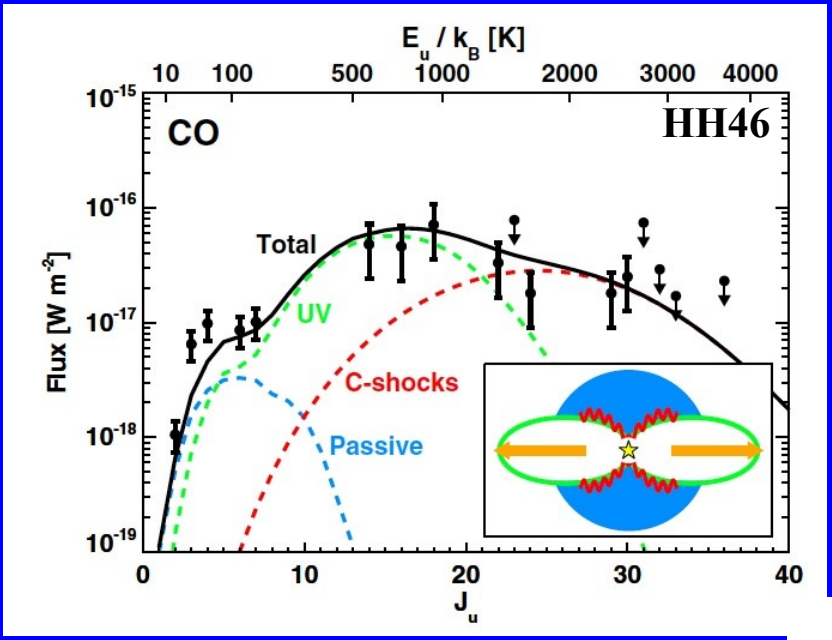
C^+/H_2 "Dark" CO

r ~ few pc



Diffuse ISM Talks for example: Gerin, Pineda, Goldsmith, Godard

Classic PDR Talks and Posters for example: Stock, Habart, Chevance, Fuente, Guzman

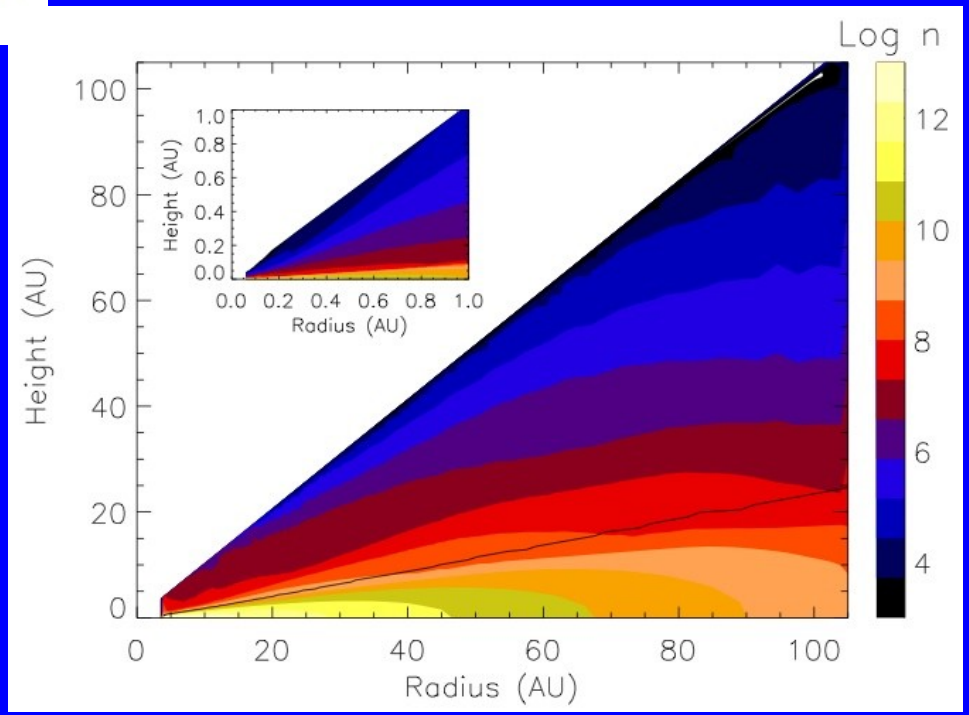


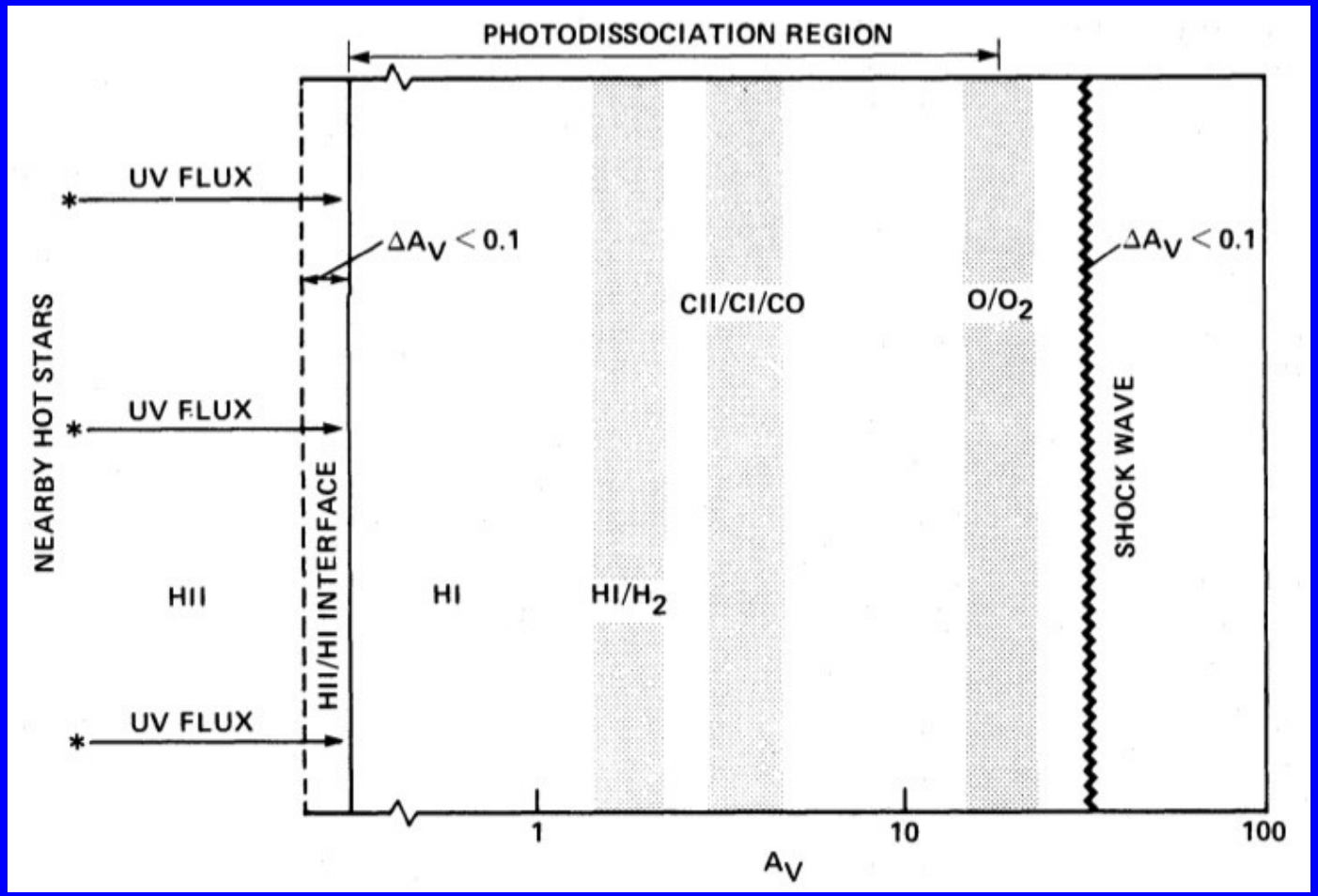
Protostellar Outflows

van Kempen et al. 2010
Visser et al. 2012
Karska et al. 2014

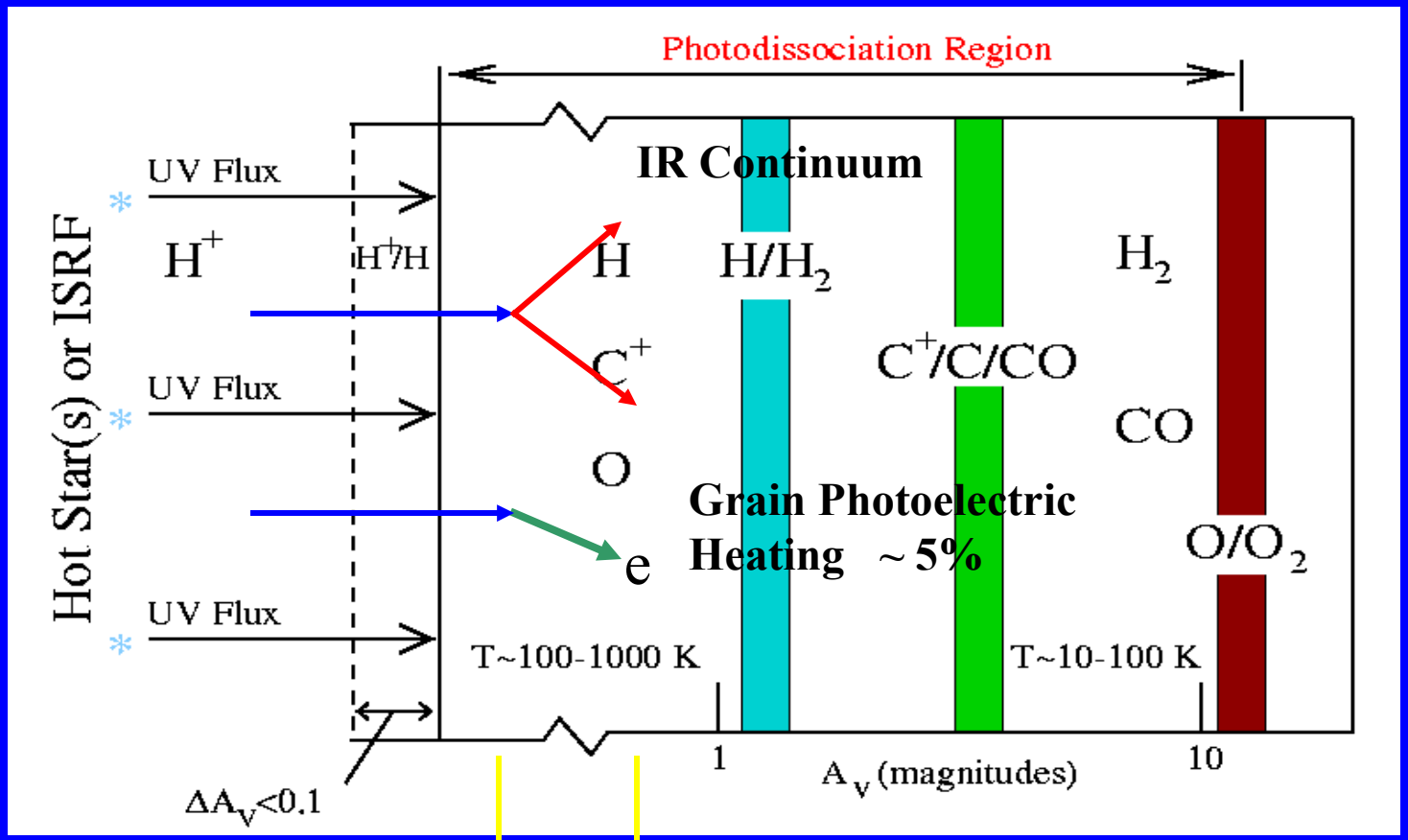
Protostellar Disks

Gorti, Hollenbach et al. 2011
Kamp et al. 2013
Bruderer et al. 2012
Adams, Hollenbach et al. 2004
PDR disk heating, chemistry, & structure



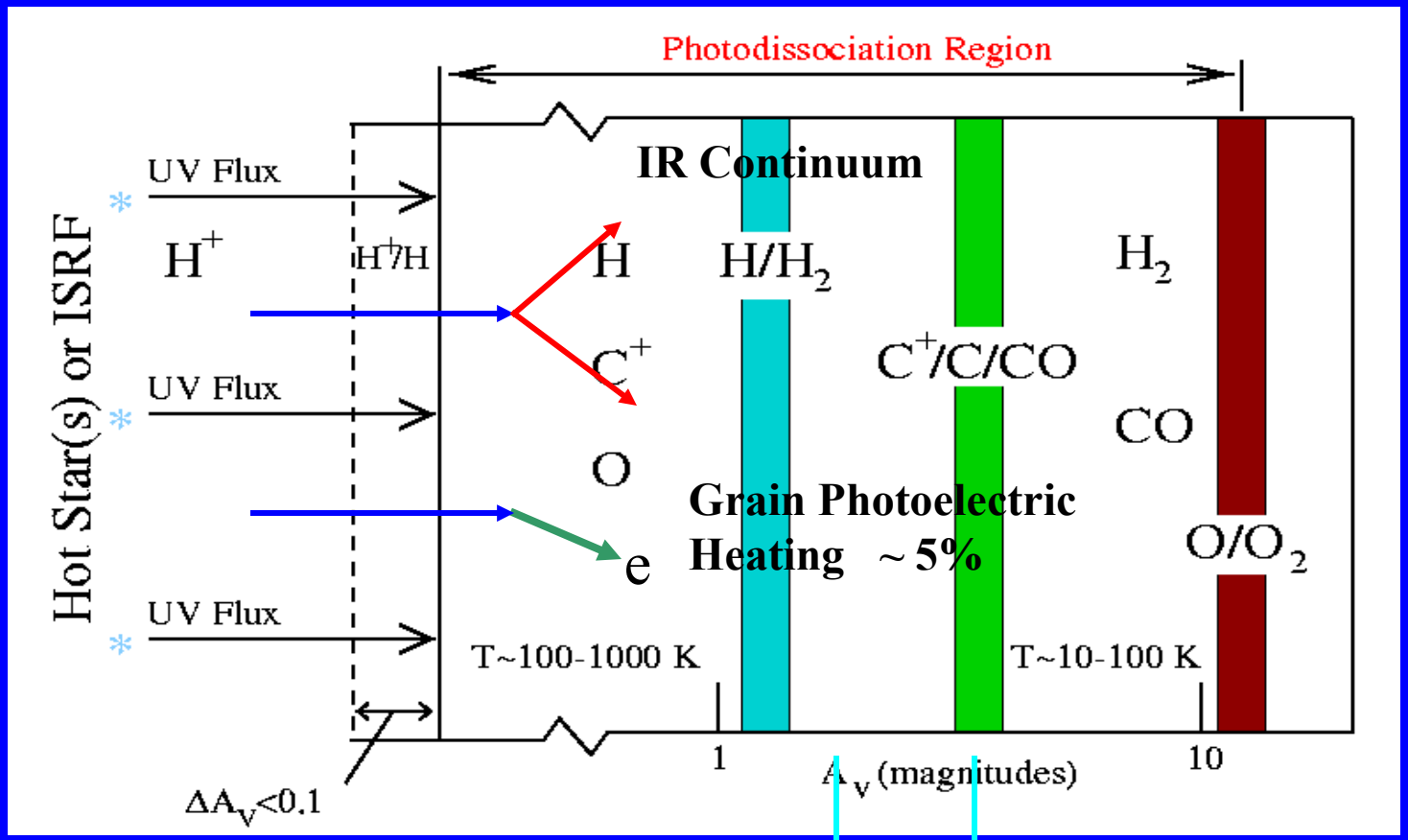


Tielens & Hollenbach 1985



Diagnostics:

C^+ 158 μm	Herschel, SOFIA
O 63 μm, 145 μm	Herschel, SOFIA
Si^+ 35 μm, Fe^+ 26 μm	Spitzer
Dust Continuum	Herschel, SOFIA
PAH 3.3, 6.2, 7.7, 8.6	Spitzer
11.3 μm	Spitzer



Diagnostics: C^+ 158 μm, OI 63 μm — Herschel
C 609 μm, 370 μm — Herschel

H_2 0-0 S(2) 12.3 μm — HEAT, Spitzer, SOFIA

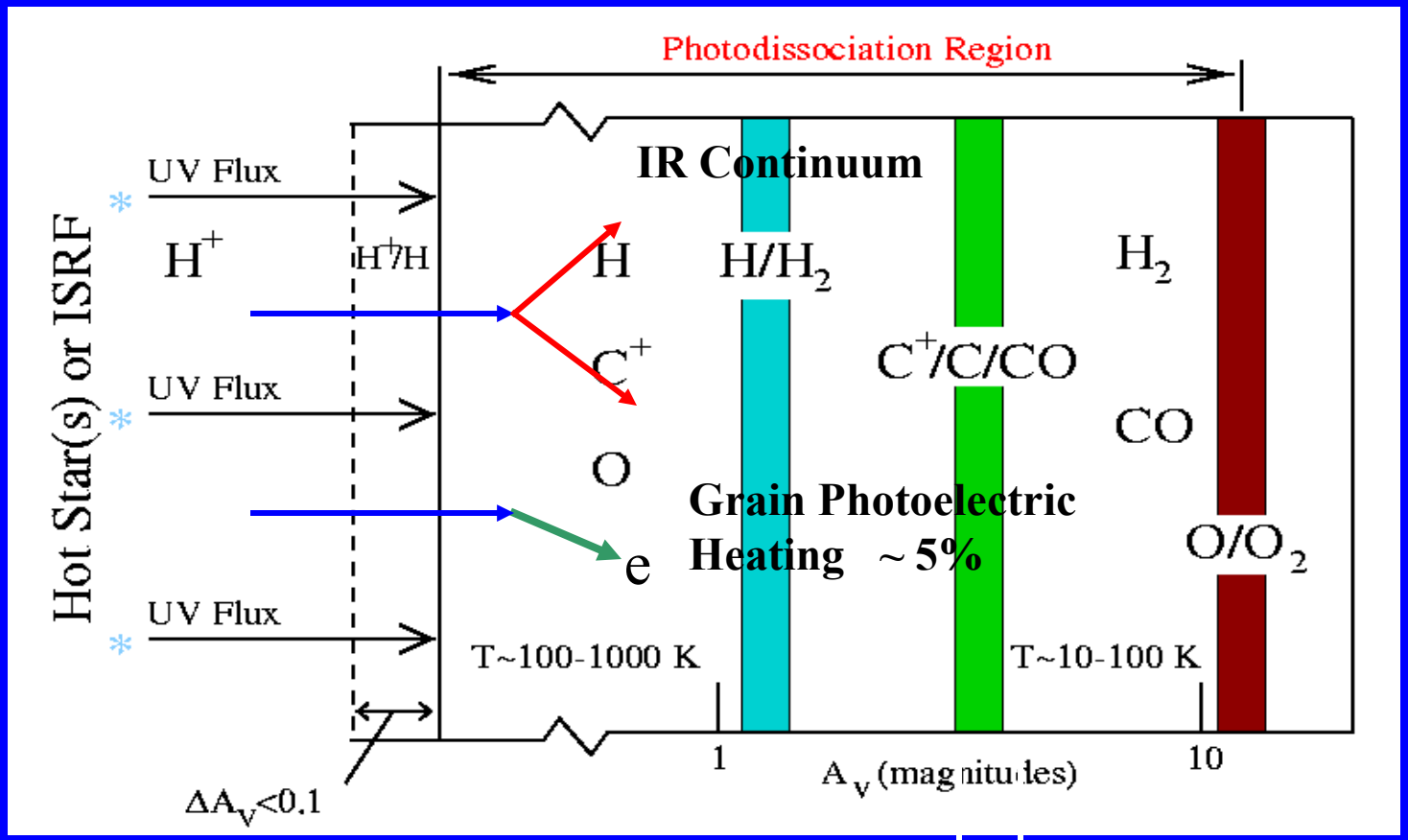
H_2O, H_2O^+, OH^+ — Herschel

H_2: Hollenbach & Salpeter 1971

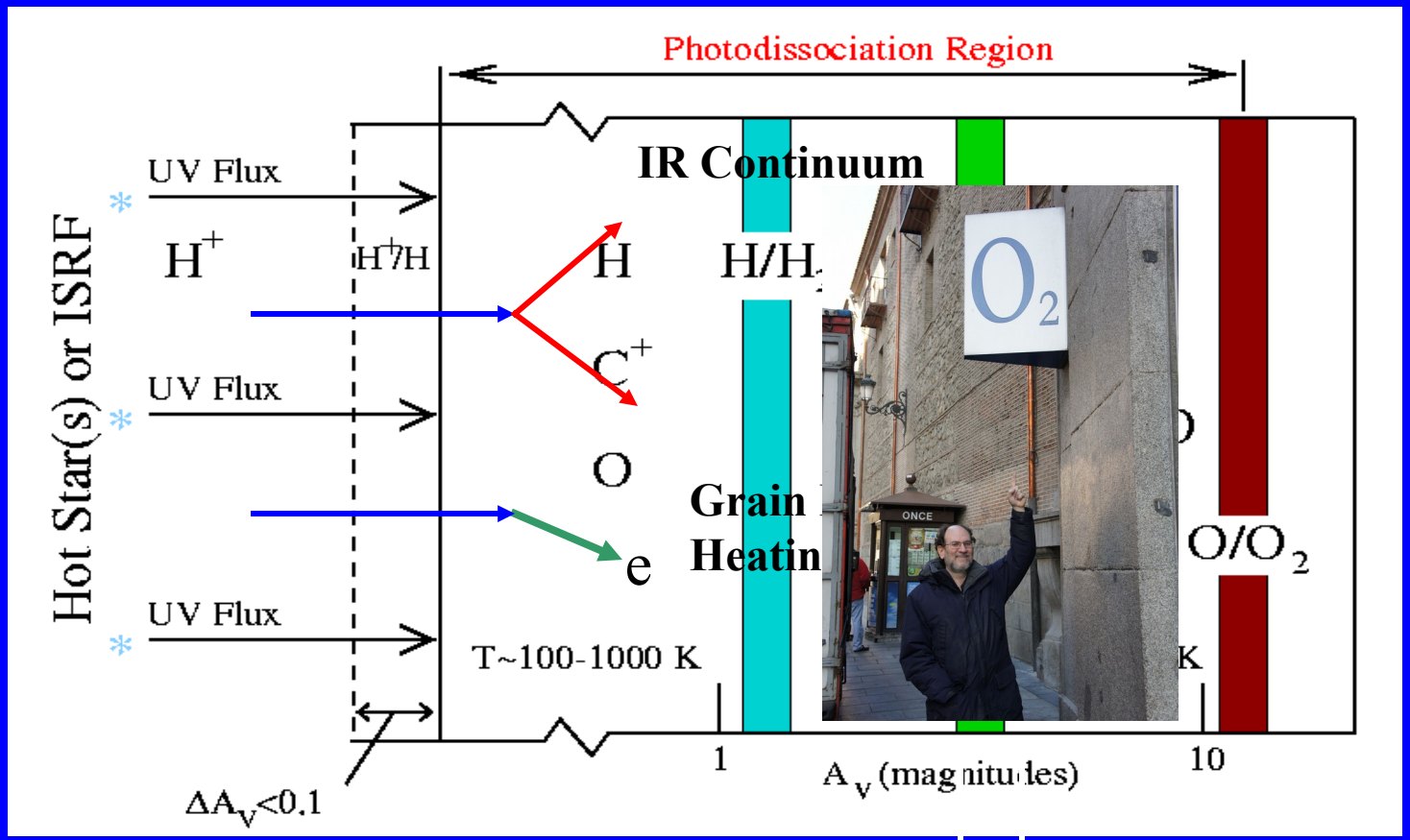
H_2, C^+: Wolfire, Tielens, Holllenbach, & Kaufman 2008

H_2: Burton, Hollenbach, & Tielens 1990, 1992

OH^+, H_2O^+, and H_3O^+: Hollenbach et al. 2012



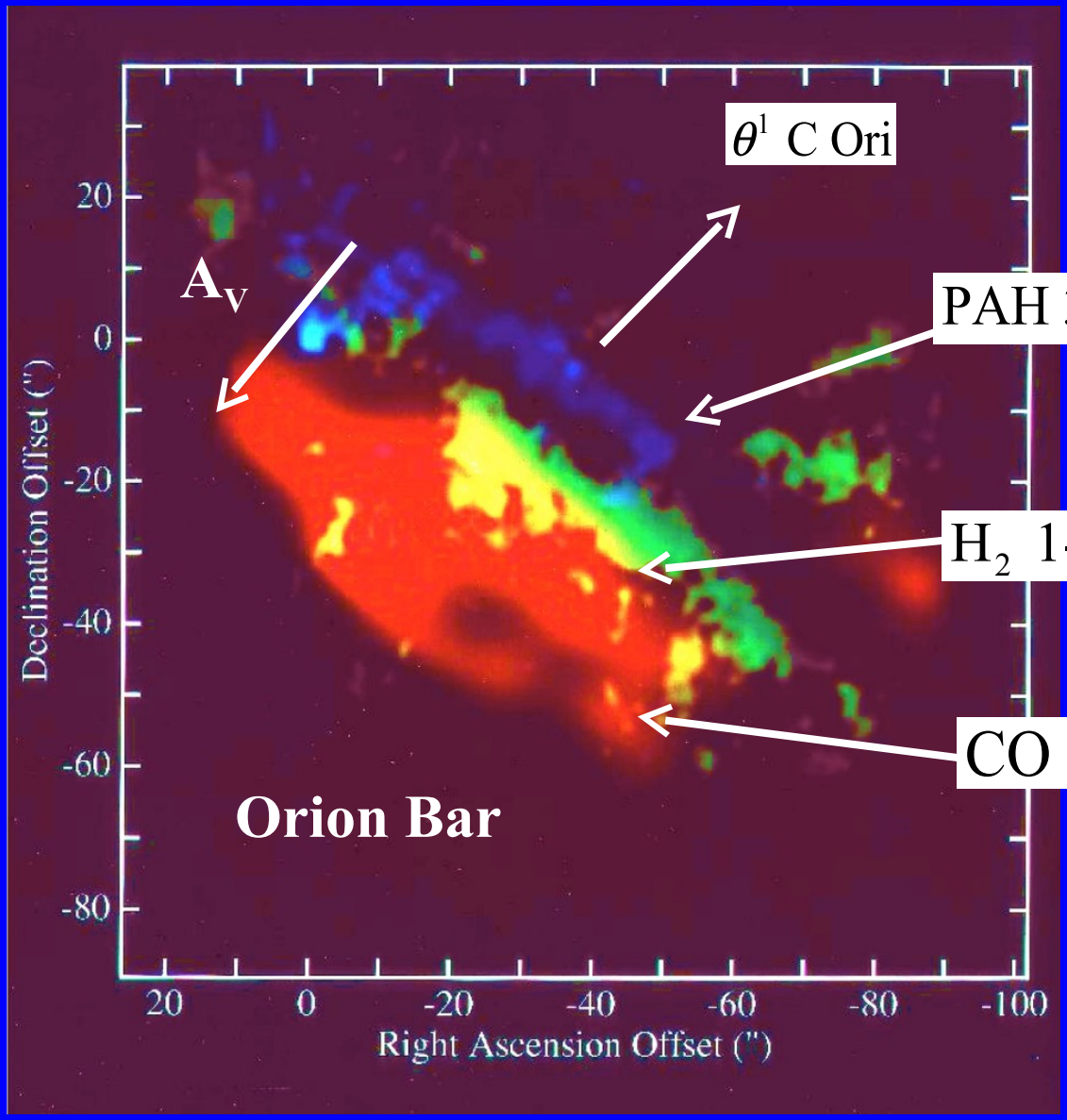
Diagnostics: High –J CO Herschel
ALMA



Diagnostics: High –J CO Herschel
ALMA

O_2 : Hollenbach et al. 2009
Melnick et al. 2012

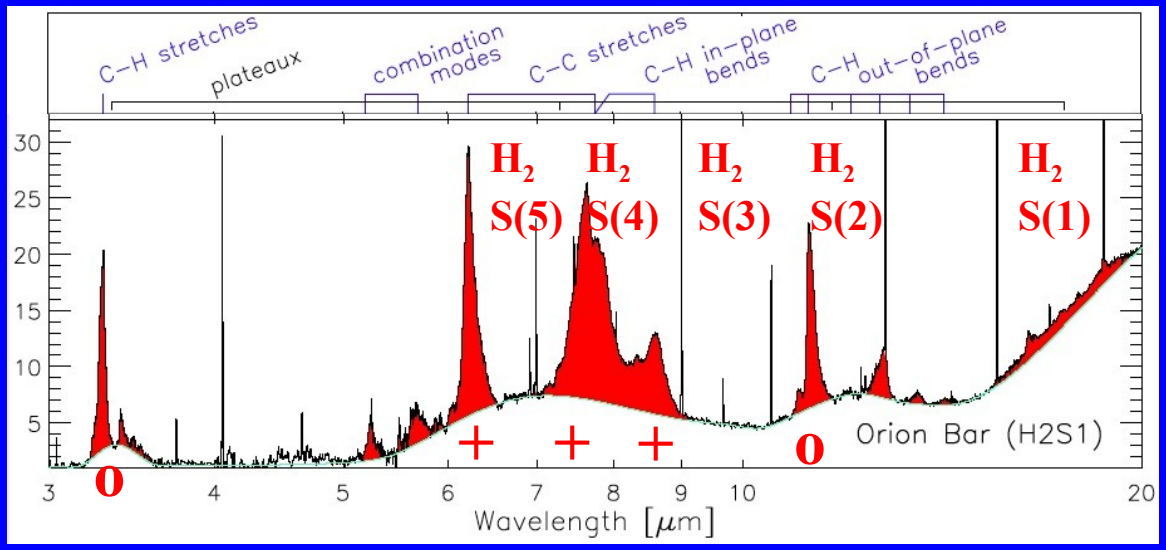
Freeze-out: Hollenbach et al. 2009



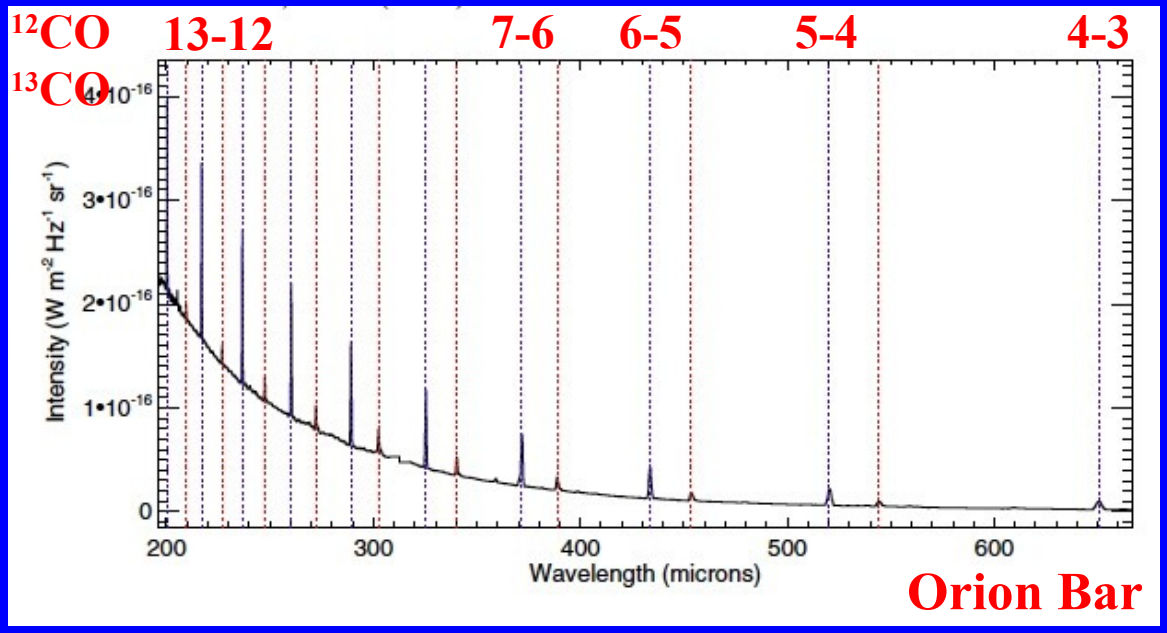
Orion Bar Talks:
Andree-Labsch
Kaplan

Tielens, Meixner, et al. 1993

Peeters, E. 2011 3.3, 6.2, 7.7, 8.6, 11.3, 12.7 μm



Habart et al. 2010



PAHs:

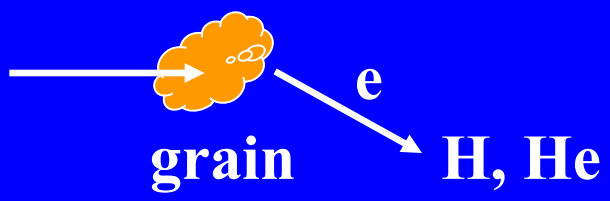
Puget & Leger 1989
Allamandola et al. 1989
Joblin et al. 1996
Verstraete et al. 2001
Peeters et al. 2004
Cami et al. 2010

H_2:

Dinerstein et al. 1988
Sternberg & Dalgarno 1989
Burton, Hollenbach et al. 1992
Goldsmith et al. 2010
Habart et al. 2011
Sheffer, et al. 2011

CO:

Harris et el. 1987
Jaffe et al. 1989
Schneider et al. 2003
Pon et al. 2015



Electron K.E. is a function of the grain charge.

Charge: Photoionization = Recombination

Photoionization α UV photon field [G_0]

Recombination α $n_e/T^{1/2}$

Photoionization/Recombination α $G_0 T^{1/2}/n_e$

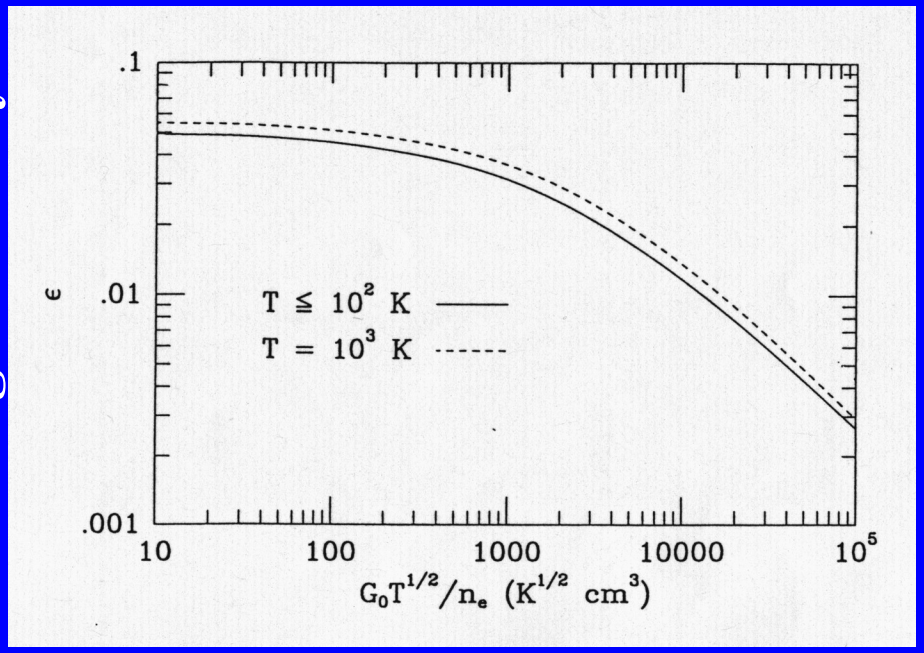
ε = Energy to Heating/Absorbed UV Photon Energy
= Heating Efficiency

ε is a function of $G_0 T^{1/2}/n_e$ (Photoionization/Recombination)

Bakes & Tielens (94) **ε for a = 0.25 μm -> 5 A**
Weingartner & Draine (01)

Neutral ⟶ Positive

Heating Efficiency



(Ionization/Recombination)

1/2 Heating from smallest grain sizes < 15 A

1) Yield increases as grain size decreases
2) Ionization/Recombination goes as (grain size)^2

$$n\Gamma = 1.3\text{x}10^{-24}\, n\varepsilon G_0 \ (\text{erg cm}^{-3}\ \text{s}^{-1})$$

POLYCYCLIC AROMATIC HYDROCARBONS AND THE UNIDENTIFIED INFRARED EMISSION BANDS: AUTO EXHAUST ALONG THE MILKY WAY!

L. J. ALLAMANDOLA[1] AND A. G. G. M. TIELENS
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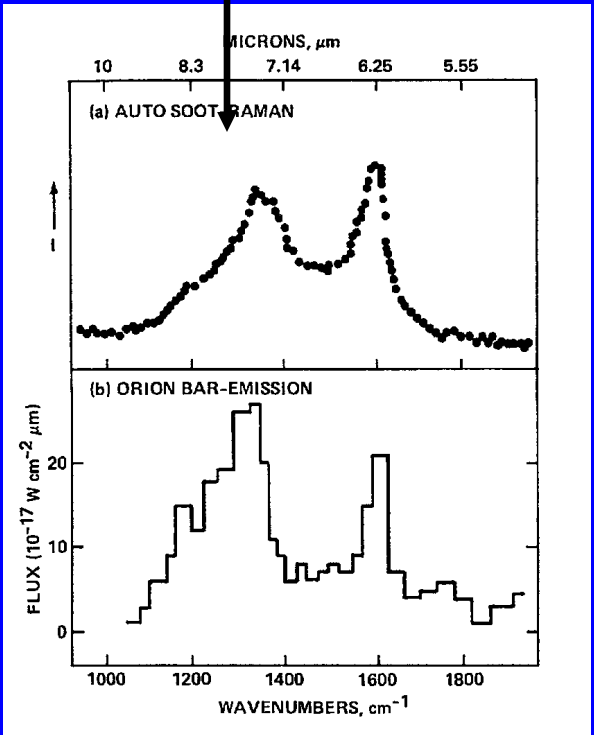
Received 1984 October 19; accepted 1984 November 27

1985 ApJ



"The close agreement…is strong circumstantial evidence that they arise from similar groups of species" (PAHs)

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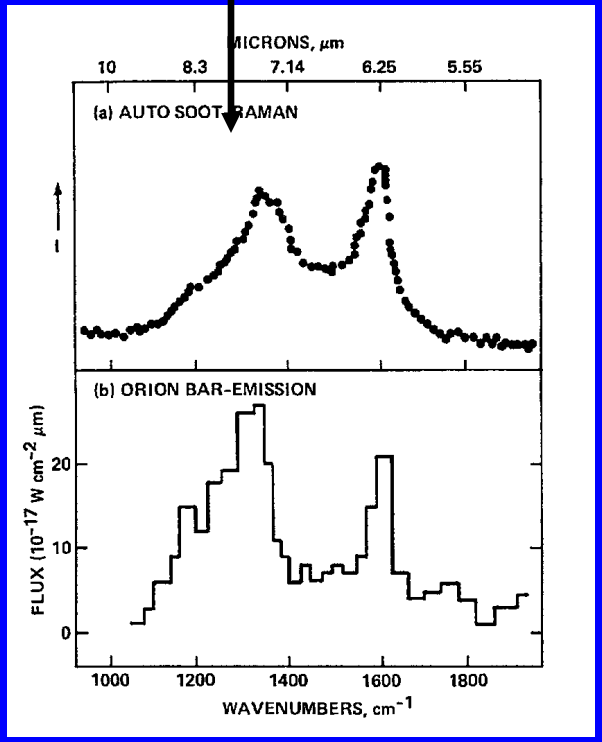


Grain Photoelectric Effect

Stellar Photons → Small Particles → PDRs

PAHs

Auto Exhaust

H_2

Formation: HI combines to H_2 on grain surfaces

Dissociation: Const $G_0\ \beta[N(H_2)]\ \exp(-2.5\ Av)$

$\tau_{LW} = N(H_2)/(1.2 \times 10^{14}\ cm^{-2})$

$\tau_{LW} > 1$ H_2 "Self-shielding"

$\beta[N(H_2)] = [N(H_2)/10^{14}]^{-0.75}$

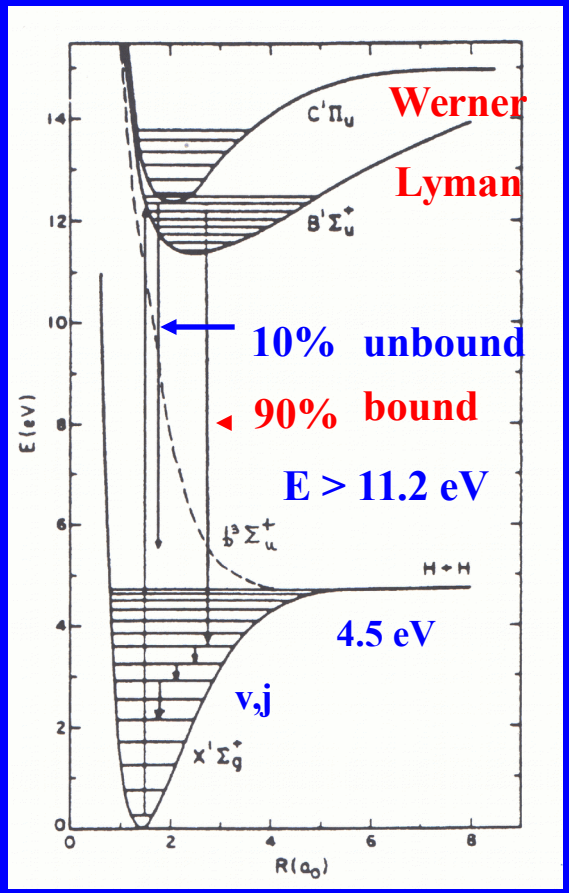
Draine & Bertoldi 1996

Column density where H_2 forms: $f(G_0/n)$

Sternberg & Dalgarno 1989
Sternberg 2012

Heating: Formation
Dissociation
De-excitation

Burton, Hollenbach, & Tielens 1990



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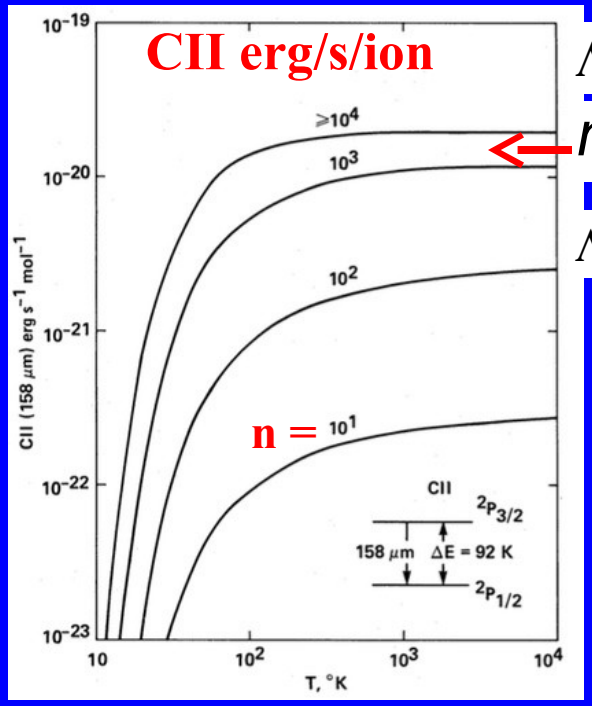


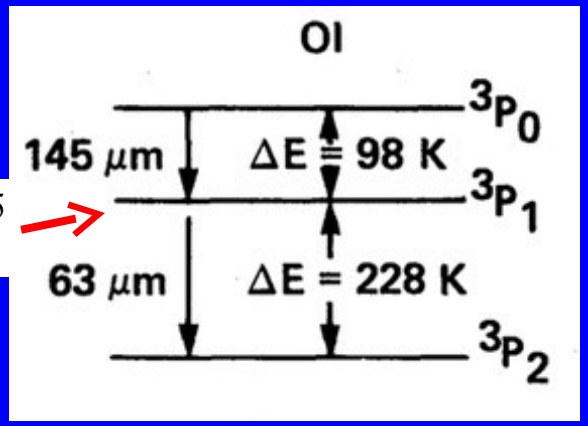
$\Lambda \mu n$ (erg s^{-1} cm^{-3})

$n_{cr} = A_{ul} / \gamma_{ul}$

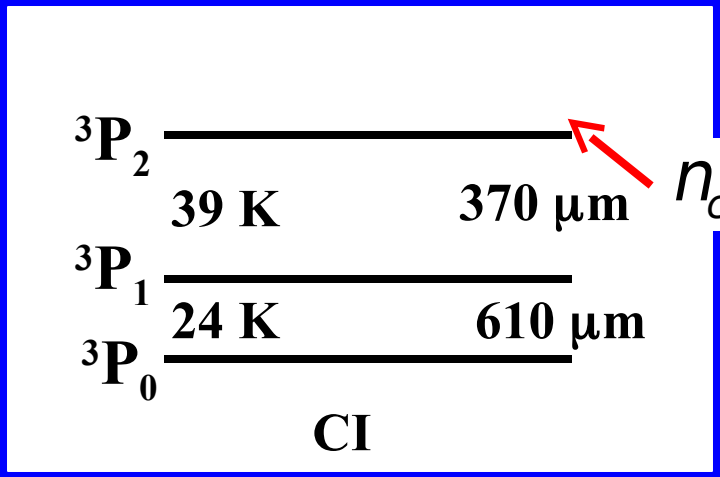
$\Lambda \mu n^2$ (erg s^{-1} cm^{-3})

See also Goldsmith et al. 2012

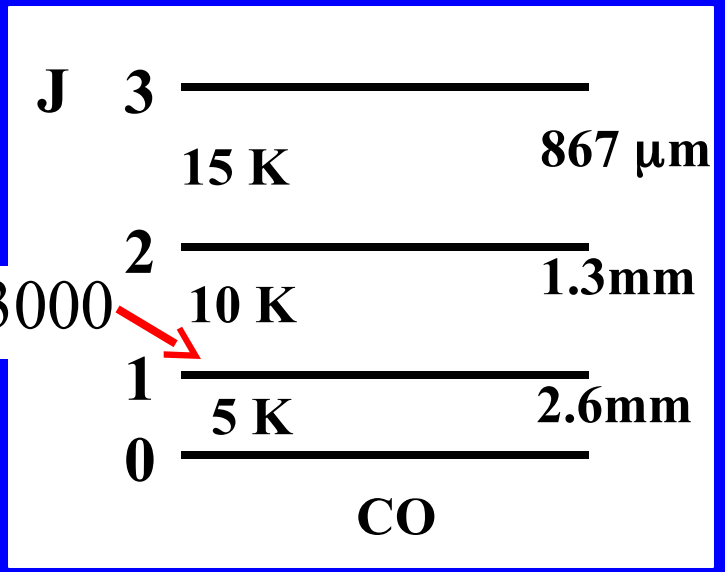
Tielens & Hollenbach 1985

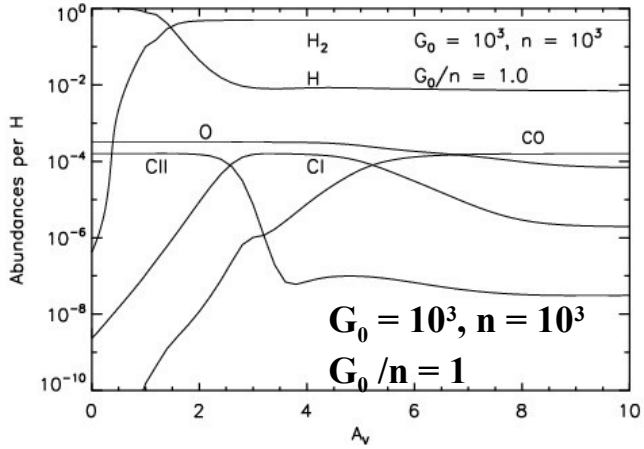


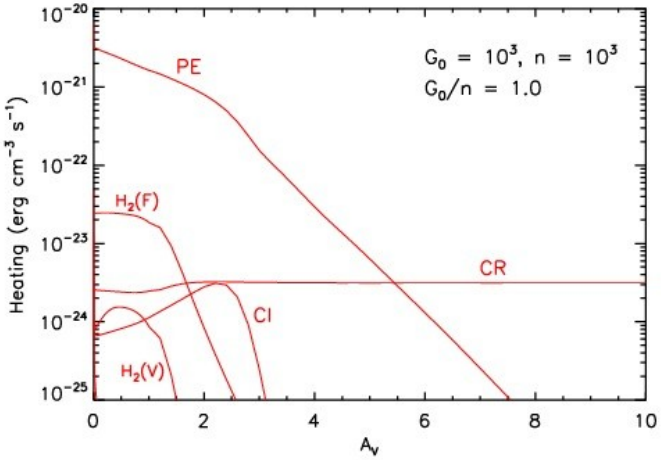
$n_{cr} \approx 5 \times 10^5$

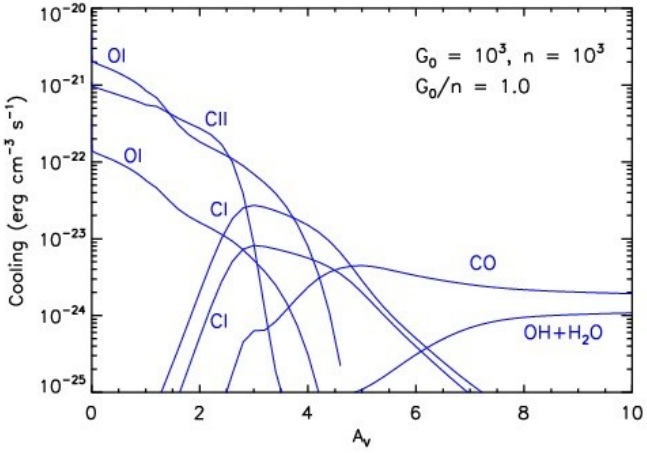


$n_{cr} \approx 3000$









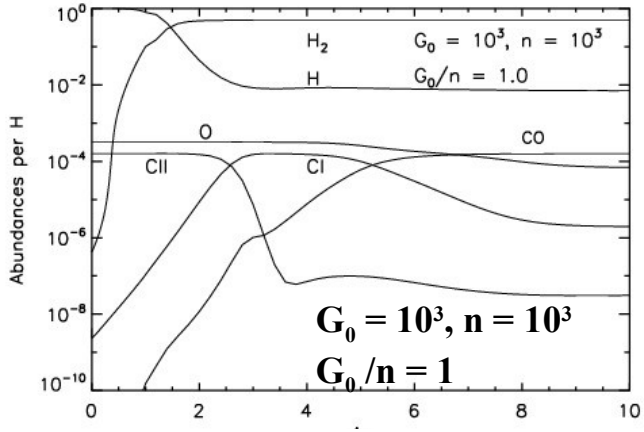
Tielens & Hollenbach 1985
Kaufman, Wolfire, & Hollenbach 2006
Hollenbach et al. 2009
Hollenbach et al. 2012

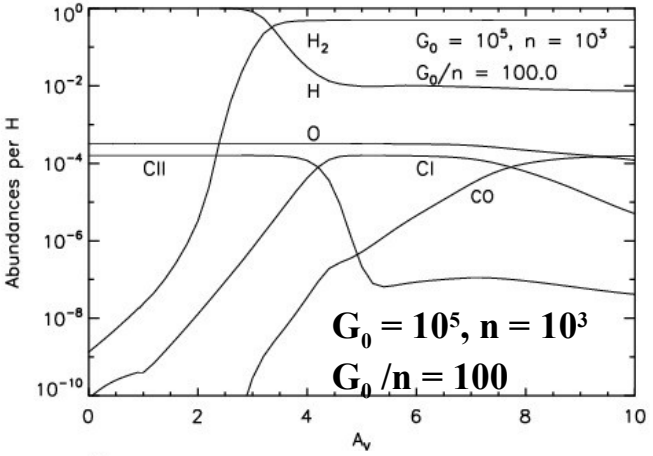
Meudon:
Le Petit et al. 2006

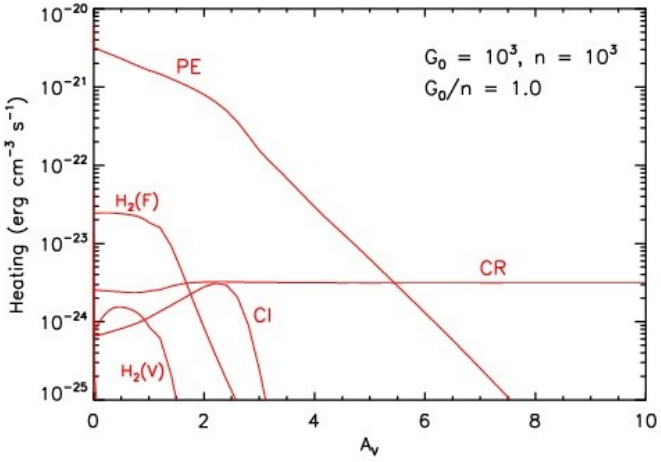
KOSMA-Tau:
Sterberg & Dalgarno 1995
Rollig et al. 2006

Leiden:
Meijerink et al. 2007

UCL:
Viti et al. 2014


H2
H
G0 = 10^3, n = 10^3
G0/n = 1.0
O
CO
CII
CI
Abundances per H
G0 = 10^3, n = 10^3
G0 /n = 1


H2
H
G0 = 10^5, n = 10^3
G0/n = 100.0
O
CII
CI
CO
Abundances per H
Av
G0 = 10^5, n = 10^3
G0 /n = 100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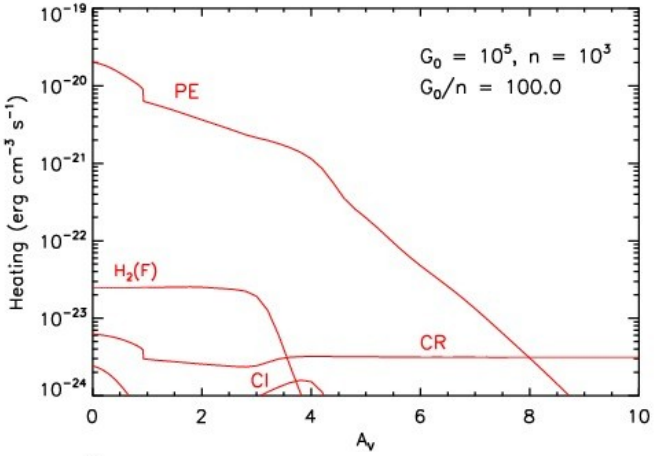
G0/n = 1.0
PE
H2(F)
CR
CI
H2(V)
Heating (erg cm^-3 s^-1)
Av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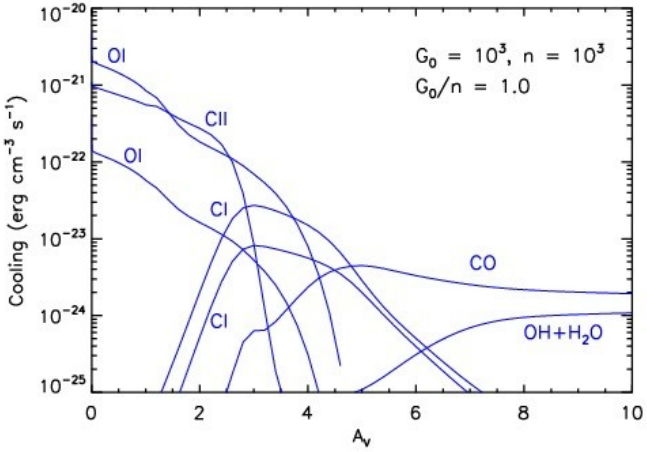
G0/n = 100.0
PE
H2(F)
CR
CI
Heating (erg cm^-3 s^-1)
Av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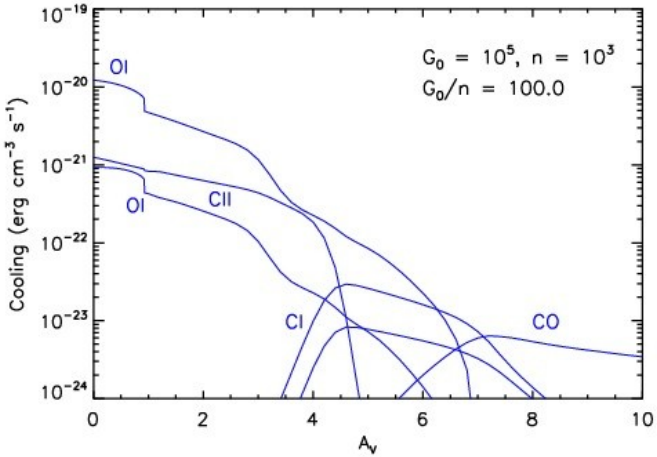
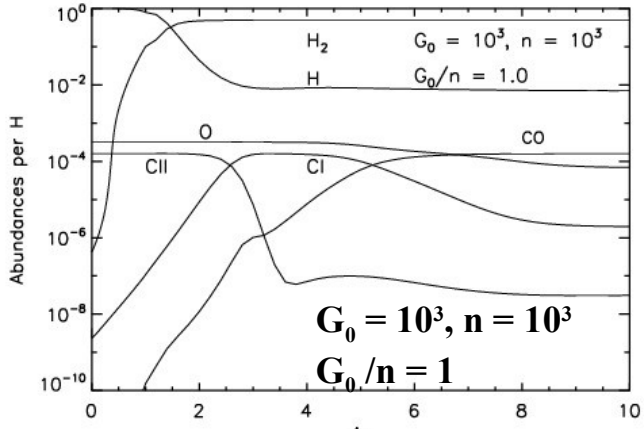
G0/n = 1.0
OI
CII
OI
CI
CO
CI
OH+H2O
Cooling (erg cm^-3 s^-1)
Av


G0 = 10^5, n = 10^3
G0/n = 100.0
OI
OI
CII
CI
CO
Cooling (erg cm^-3 s^-1)
Av


H2
H
G0 = 10^3, n = 10^3
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O
CO
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Abundances per H
G0 = 10^3, n = 10^3
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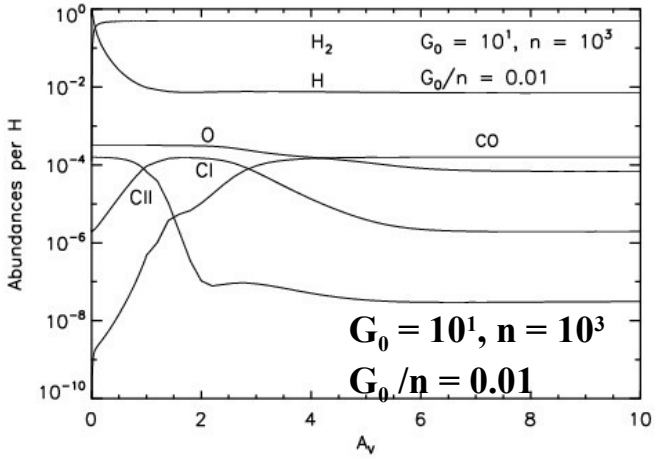
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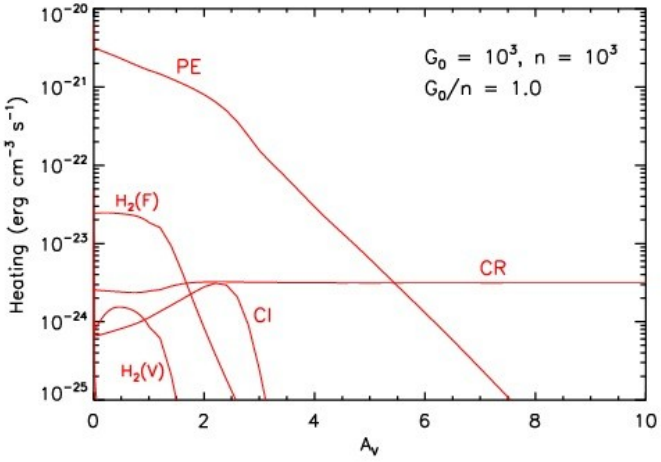
H
G0 = 10^1, n = 10^3
G0/n = 0.01
O
CO
CI
CII
Abundances per H
Av
G0 = 10^1, n = 10^3
G0 /n = 0.01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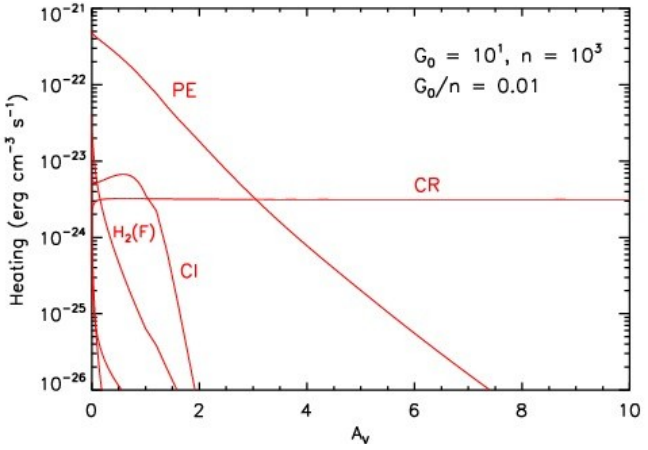
G0/n = 1.0
PE
H2(F)
CR
CI
H2(V)
Heating (erg cm^-3 s^-1)
Av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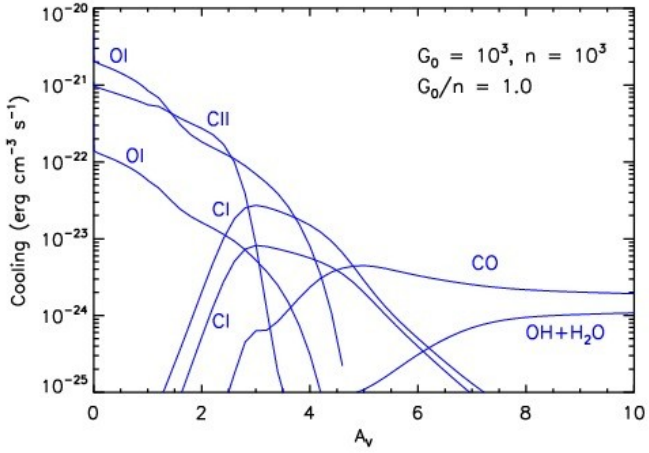
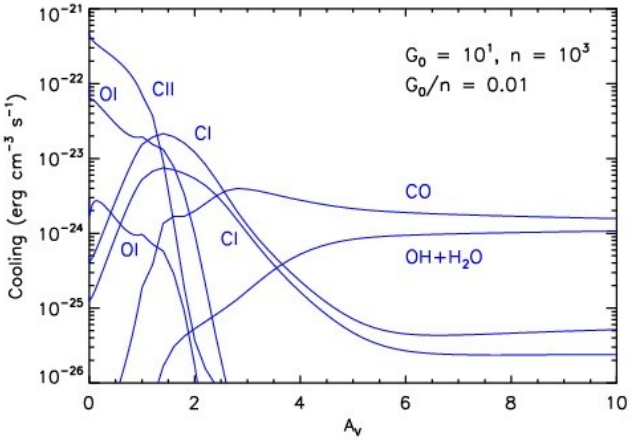
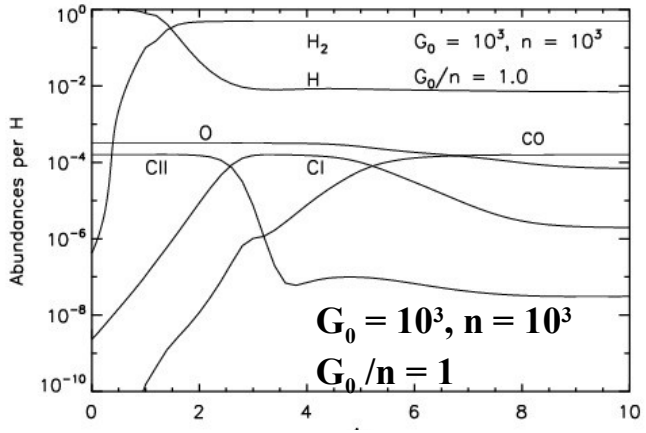
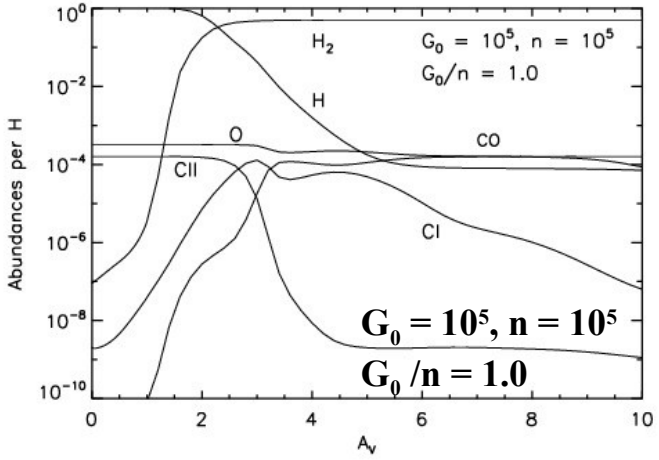
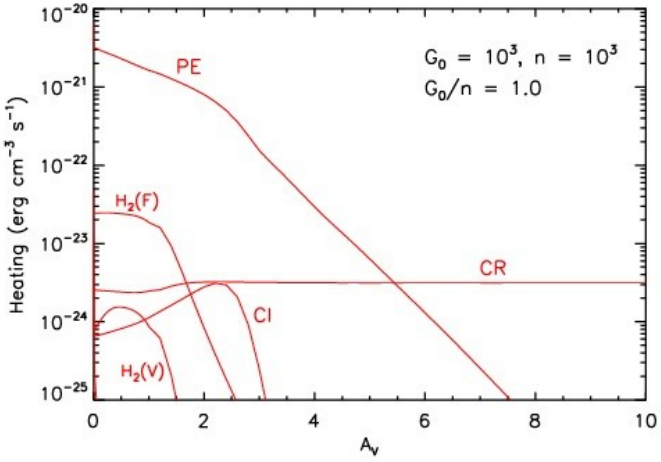
G0/n = 0.01
PE
CR
H2(F)
CI
Heating (erg cm^-3 s^-1)
Av

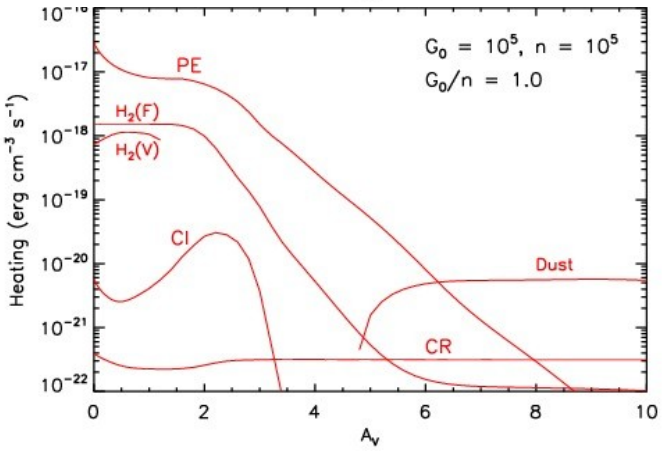

G0 = 10^3, n = 10^3
G0/n = 1.0
OI
CII
OI
CI
CO
CI
OH+H2O
Cooling (erg cm^-3 s^-1)
Av

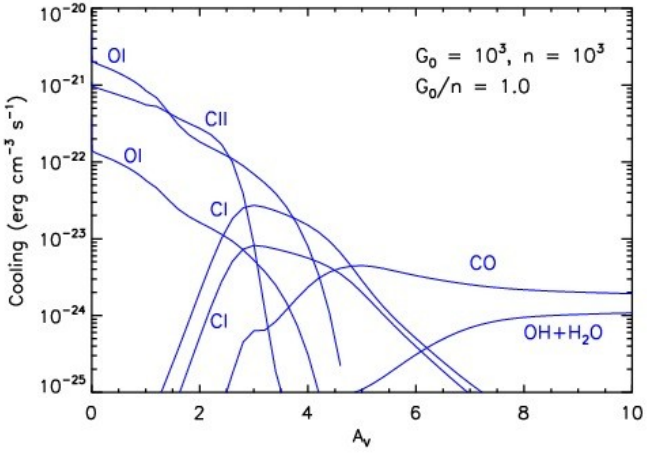

G0 = 10^1, n = 10^3
G0/n = 0.01
OI
CII
CI
CO
OI
CI
OH+H2O
Cooling (erg cm^-3 s^-1)
Av

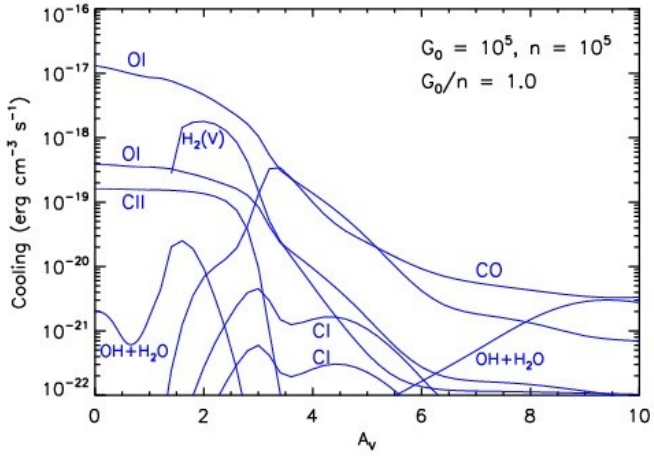

H2
H
G0 = 10^3, n = 10^3
G0/n = 1.0
O
CO
CII
CI
Abundances per H
G0 = 10^3, n = 10^3
G0 /n = 1


H2
G0 = 10^5, n = 10^5
G0/n = 1.0
H
O
CO
CII
CI
Abundances per H
Av
G0 = 10^5, n = 10^5
G0 /n = 1.0


G0 = 10^3, n = 10^3
G0/n = 1.0
PE
H2(F)
CR
CI
H2(V)
Heating (erg cm^-3 s^-1)
Av


G0 = 10^5, n = 10^5
G0/n = 1.0
PE
H2(F)
H2(V)
CI
Dust
CR
Heating (erg cm^-3 s^-1)
Av

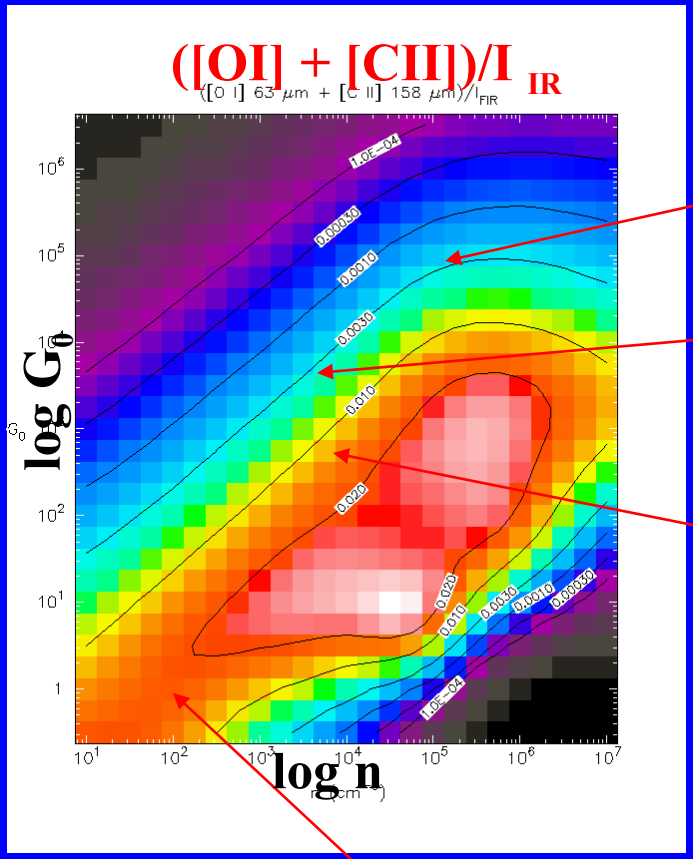

G0 = 10^3, n = 10^3
G0/n = 1.0
OI
CII
OI
CI
CI
CO
OH+H2O
Cooling (erg cm^-3 s^-1)
Av


G0 = 10^5, n = 10^5
G0/n = 1.0
OI
H2(V)
OI
CII
CO
CI
CI
OH+H2O
OH+H2O
Cooling (erg cm^-3 s^-1)
Av

PDR Emission

Heating Efficiency

$([OI] + [CII])/I_{IR}$



Orion PDR

G_0/n = constant

$\varepsilon = f(G_0/n)$

Classic PDRs

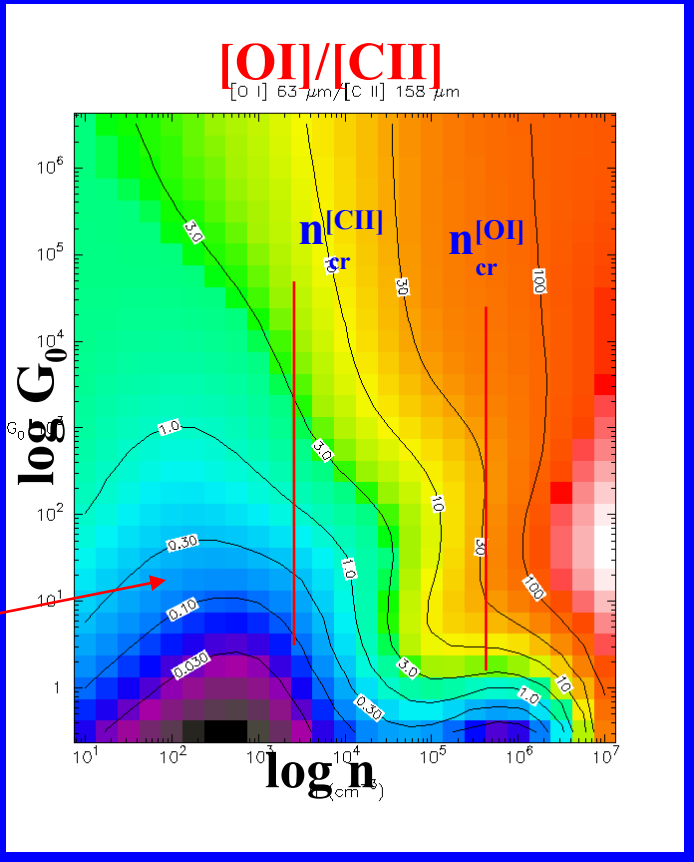
$\varepsilon < 0.03$

$\varepsilon \sim 0.03$

Diffuse Gas

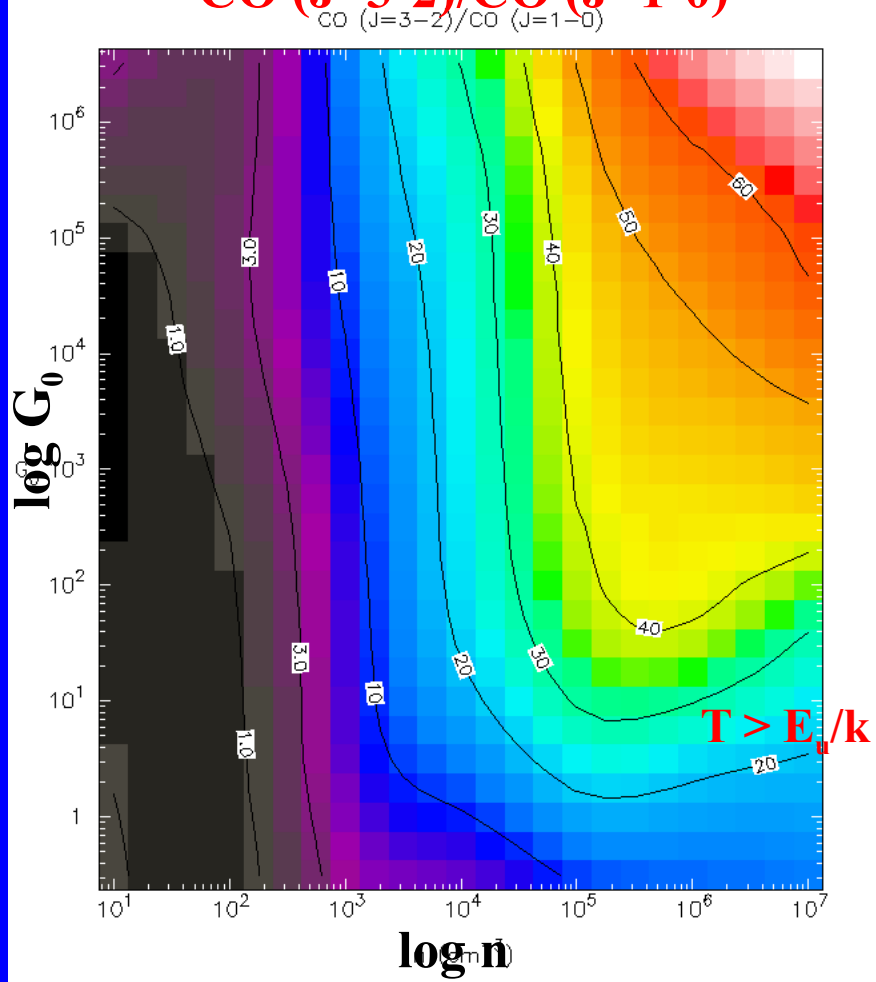
Density Indicator

[OI]/[CII]



Wolfire, Tielens, & Hollenbach 1990
Kaufman, Wolfire, Hollenbach & Luhman 1999
Kaufman, Wolfire, & Hollenbach 2006

Molecular Gas Tracers
CO (J=3-2)/CO (J=1-0)

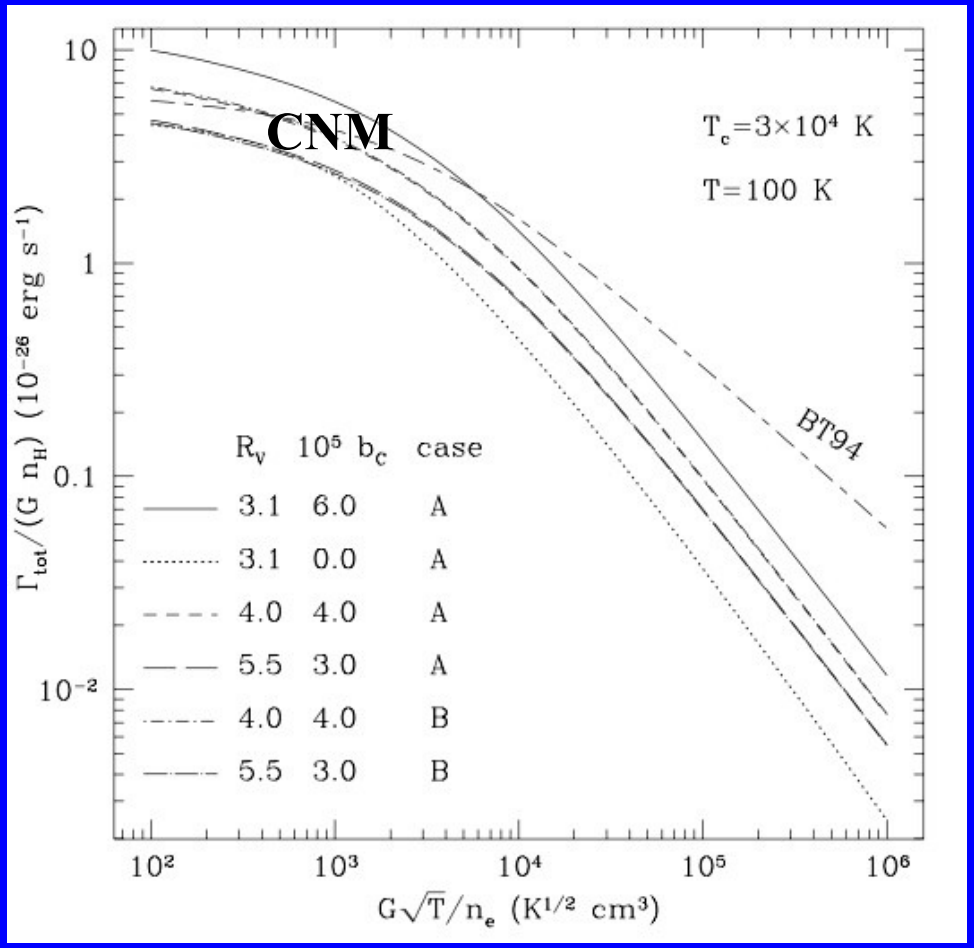


Kaufman, Wolfire, Hollenbach & Luhman 1999

Problems in PDR Modeling

1)Photoelectric Heating rate at Av = 0, and as a function of depth?

Weingartner & Draine 2000



Good agreement in CNM confirmed by observed P_{th} and I(CII)

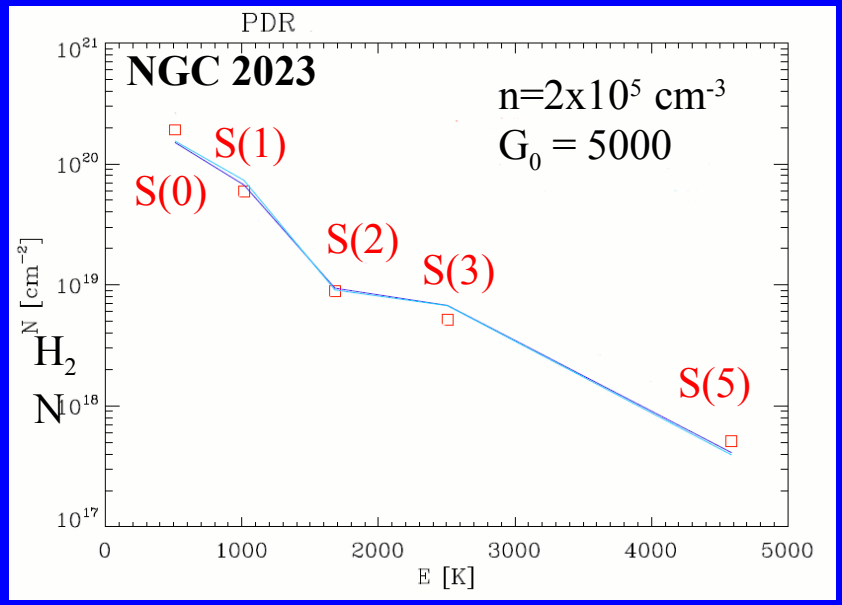
Some divergence at high G_0/n

Heating rate with Av
1)PAH and grain properties and abundances
2) Penetration of FUV

Models get 0.1-1% of FIR coming out in lines as observed

Need observations of species that sample a range of Av

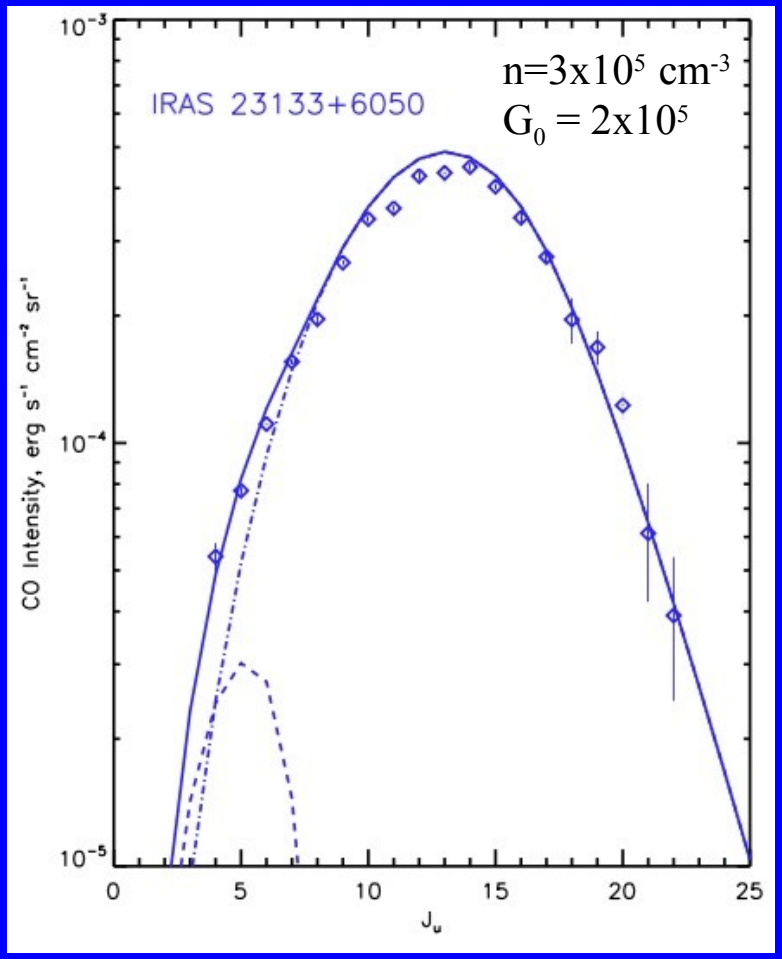
2)High-J CO and H_2 line emission



Sheffer, Wolfire, Hollenbach, Kaufman & Cordier 2011

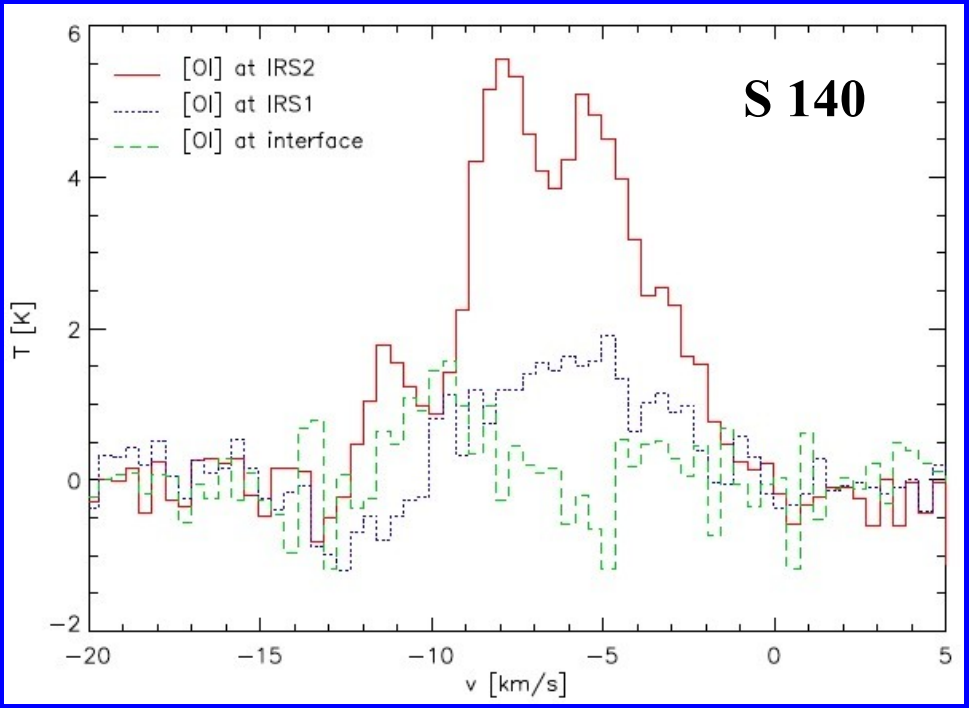
PE with depth ?, H_2 heating?

Other processes?



Stock et al. 2015

3)[OI] 63 μm ??



Ossenkopf et al. 2015

OI Self-absorption
High OI 145/63 ratios

Column of cold O depends on
1)Geometry
2)C/O ratio
3)Oxygen freeze out

4)[Si II] 35 μm ?? Models overestimate [Si II] large depletions?

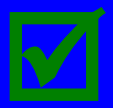
Draine & Bertoldi 2000
Kaufman et al. 2006
Sheffer et al. 2011

Photodissociation Region

or

Photon Dominated Region

Photodissociation Region



or

Photon Dominated Region

Hollenbach Shoe Store
Heidelberg Germany

Dave's birth site according to local legend.

Thanks Dave!

…for many years of stimulating and productive collaborations!