Physics and chemistry of molecular regions in the interstellar medium

Lecture on the Origins of the solar system
30th of June 2009

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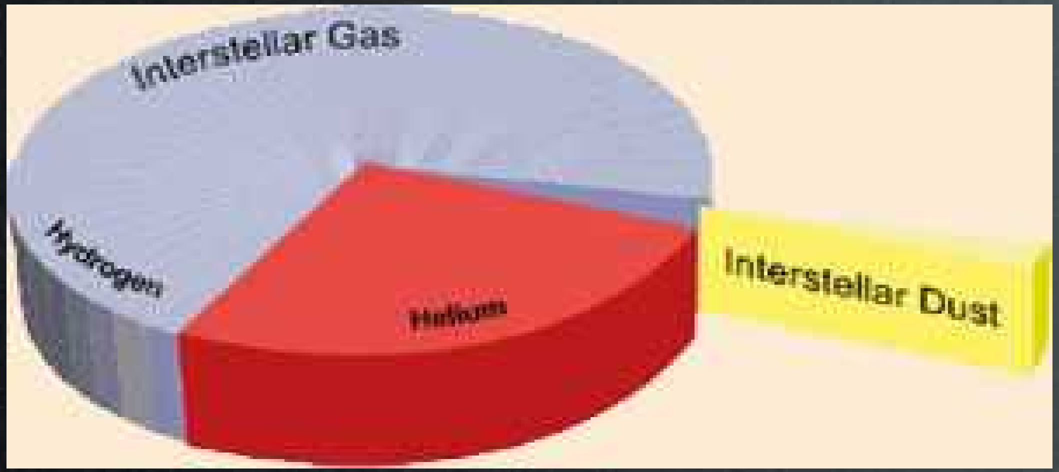
Overview

- The Interstellar Medium
- Molecular Clouds
- Observations
- Interstellar Chemistry
- Photodissociation Regions
- Summary

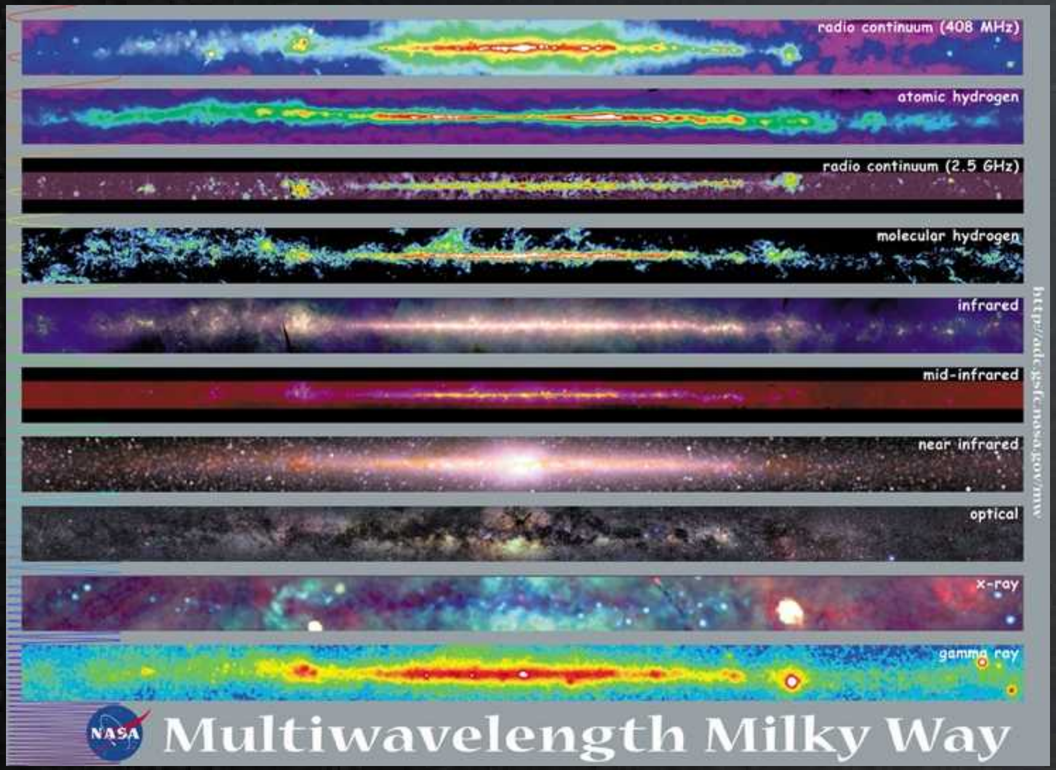
- Van Dishoek, Ewine F.; et.al. "***The chemical evolution of protostellar and protoplanetary matter***". Protostars and planets III (A93-42937 17-90), p. 163-241.
  => Introduction + Appendix
- Steven W. Stahler, Francesco Palla. "***The Formation of Stars***", Wiley, John & Sons, 2005
  => Chapter, I 1-2, II 5-7
- Tielens A.G.G.M., "***The physics and chemistry of the interstellar medium***", Cambridge, 2005
  => Introduction + Chapter, 9
- Hollenbach, D.J.; Tielens, A.G.G.M. (1999). "***Photodissociation regions in the interstellar medium of galaxies***". Review of Modern Physics 71: 173.
  => Chapter, 1-3
- Lequeux J., "***The interstellar medium***", Springer 2005
  => Overview + Chapter, 9-10

The Interstellar Medium

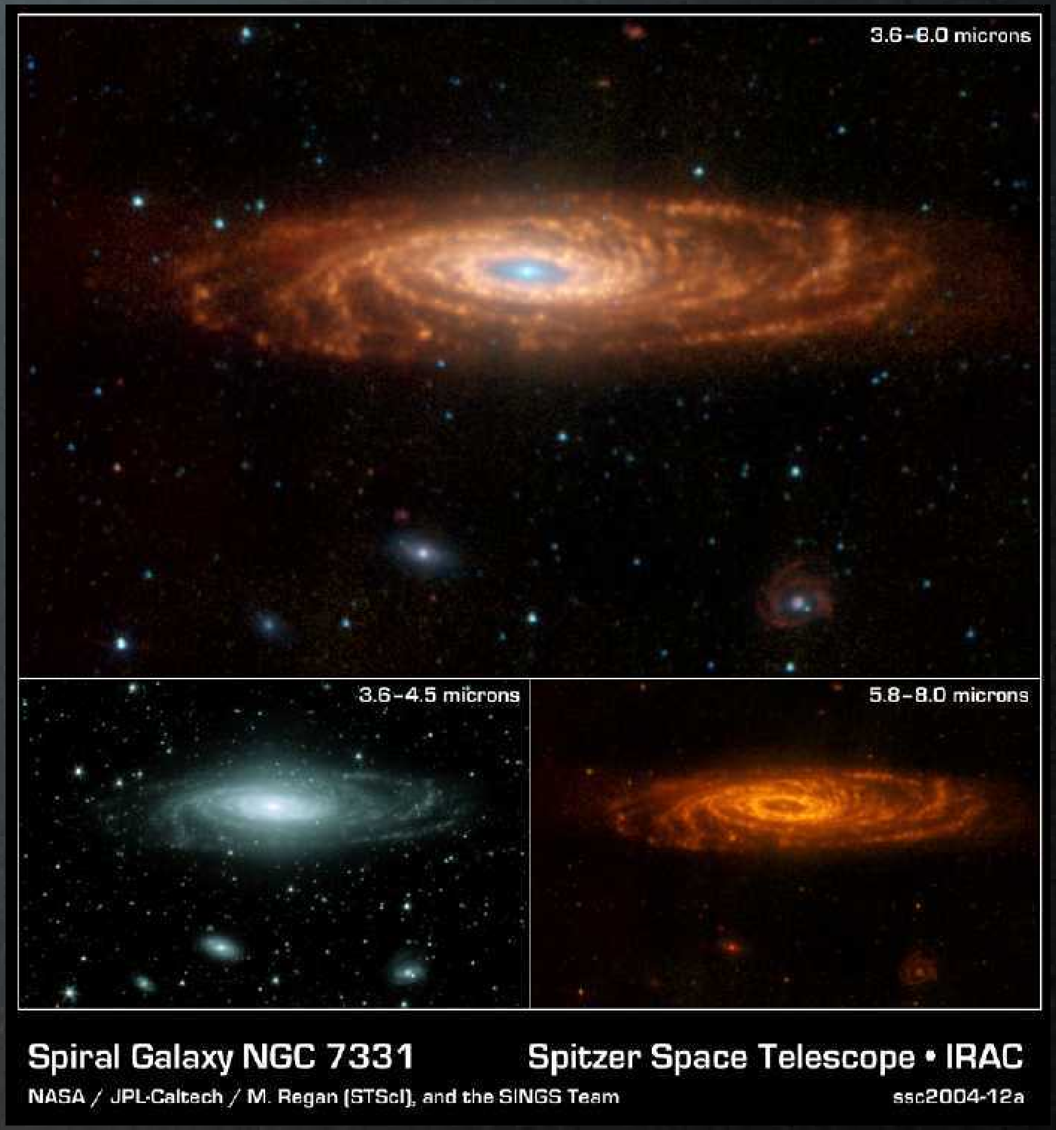
The Interstellar Medium (ISM)



70% Hydrogen, 28% Helium and
2% of heavier elements (C,N,O,Mg,Si)



≈0.5% of the total mass of the Galaxy

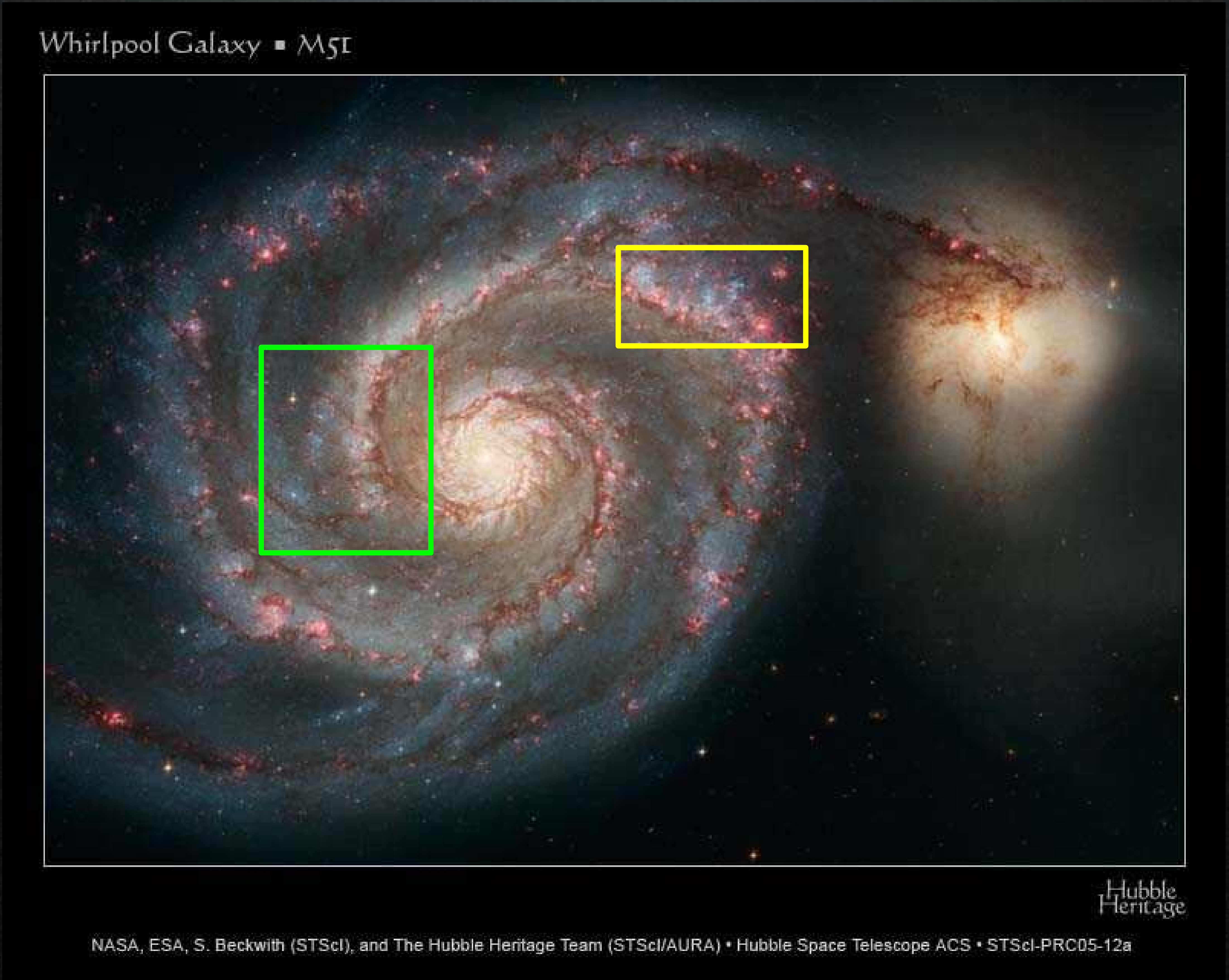


- ‘Empty space’ between the stars
- 99 % gas, 1% dust

Example

- NGC 7331 (Pegasus constellation, 50 Million light years)
- Shorter wavelengths (3.6 to 4.5 µm): older and cooler stars than the sun
- Longer wavelengths (5 to 8 µm) : glow from dust of interstellar dust

Another one: M51



Molecular Clouds

Molecular Clouds

- Diffuse Molecular Clouds
  - No star formation (from observation)
- Translucent Clouds
  - No star formation (from observation)
- Dark Molecular Clouds (DMC)
  - Low mass star formation
- Giant Molecular Clouds (GMC)
  - Low and Massive star formation

?   The Sun was formed in DMC or GMC   ?

=> Both scenarios need to be investigated

Dark Molecular Clouds (DMC)

- Observation:

  Visible as dark patches on the sky

  Show a complex morphology

- Places for stars formation with low mass
- Sites of many complex molecules
- EX: Taurus

Cold, Dark Clouds	Density (cm^{-3})	T (K)	Mass $M_\odot$	A_V (mag)	Size (pc)	ΔV ($km\ s^{-1}$)	Examples
complex	$10^2 - 10^3$	$\gtrsim 10$	$10^3 - 10^4$	$1 - 2$	$6 - 20$	$1 - 3$	Taurus-Auriga
clouds	$10^2 - 10^4$	$\gtrsim 10$	$10 - 10^3$	$2 - 5$	$0.2 - 4$	$0.5 - 1.5$	B1, B5
cores/clumps	$10^4 - 10^5$	≈ 10	$0.3 - 10$	$5 - 25$	$0.05 - 0.4$	$0.2 - 0.4$	TMC-1, B335

Giant Molecular Cloud

- Similarity complex morphology
- Similarity density
- More Massive
- More warm
- Place for Low and Massive-star formation
- Eg: Orion Molecular Cloud

Giant Molecular Clouds	Density (cm^{-3})	T (K)	Mass $M_\odot$	A_V (mag)	Size (pc)	ΔV ($km\ s^{-1}$)	Examples
complex	100 – 300	15 – 20	10^5–3×10^6	1 – 2	20 – 80	6 – 15	M 17, Orion
clouds	$10^2 - 10^4$	$\gtrsim 20$	$10^3 - 10^5$	$\gtrsim 2$	3 – 20	3 – 12	Orion OMC-1, W3 A
warm clumps	$10^4 - 10^7$	25 – 70	$1 - 10^3$	5 – 1000	0.05 – 3	1 – 3	M 17 clumps, Orion 1.'5 S
hot cores	$10^7 - 10^9$	100 – 200	$10 - 10^3$	50 – 1000	0.05 – 1	1 – 10	Orion hot core

Molecular Clouds

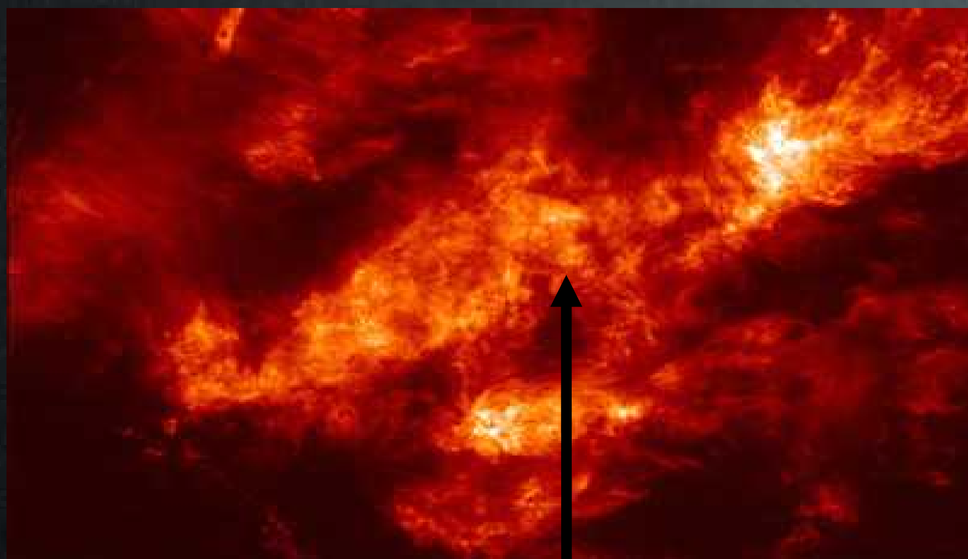


Table 3.1 Physical Properties of Molecular Clouds

Cloud Type	A_V (mag)	n_{tot} (cm^{-3})	L (pc)	T (K)	M ($M_\odot$)	Examples
Diffuse	1	500	3	50	50	ζ Ophiuchi
Giant Molecular Clouds	2	100	50	15	10^5	Orion
Dark Clouds						
Complexes	5	500	10	10	10^4	Taurus-Auriga
Individual	10	10^3	2	10	30	B1
Dense Cores/Bok Globules	10	10^4	0.1	10	10	TMC–1/B335

The Formation of Stars. Steven W. Stahler and Francesco Palla

ISBN: 3-527-40559-3

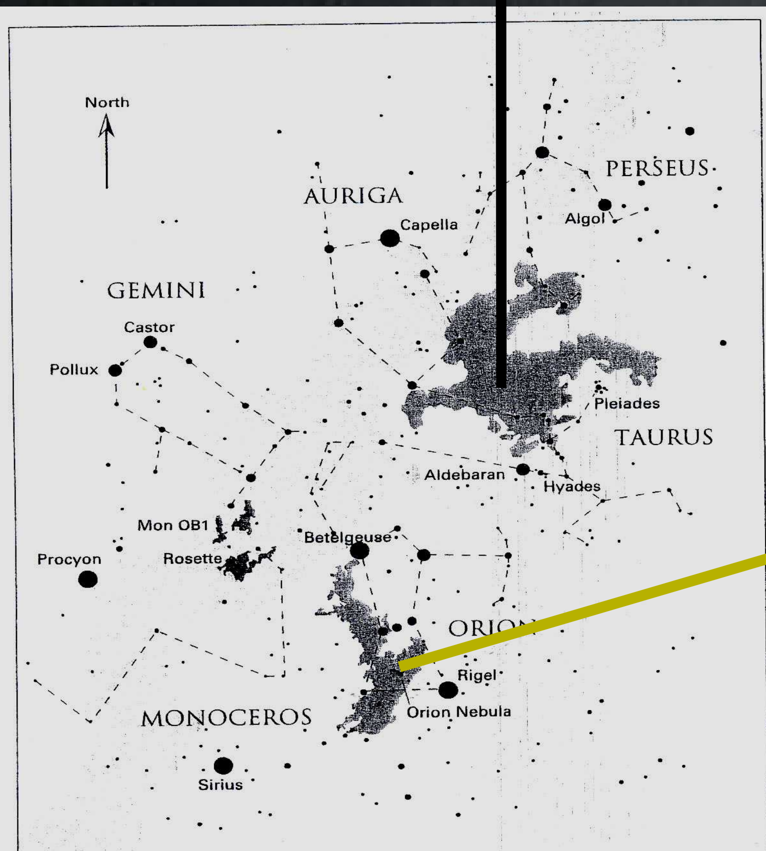
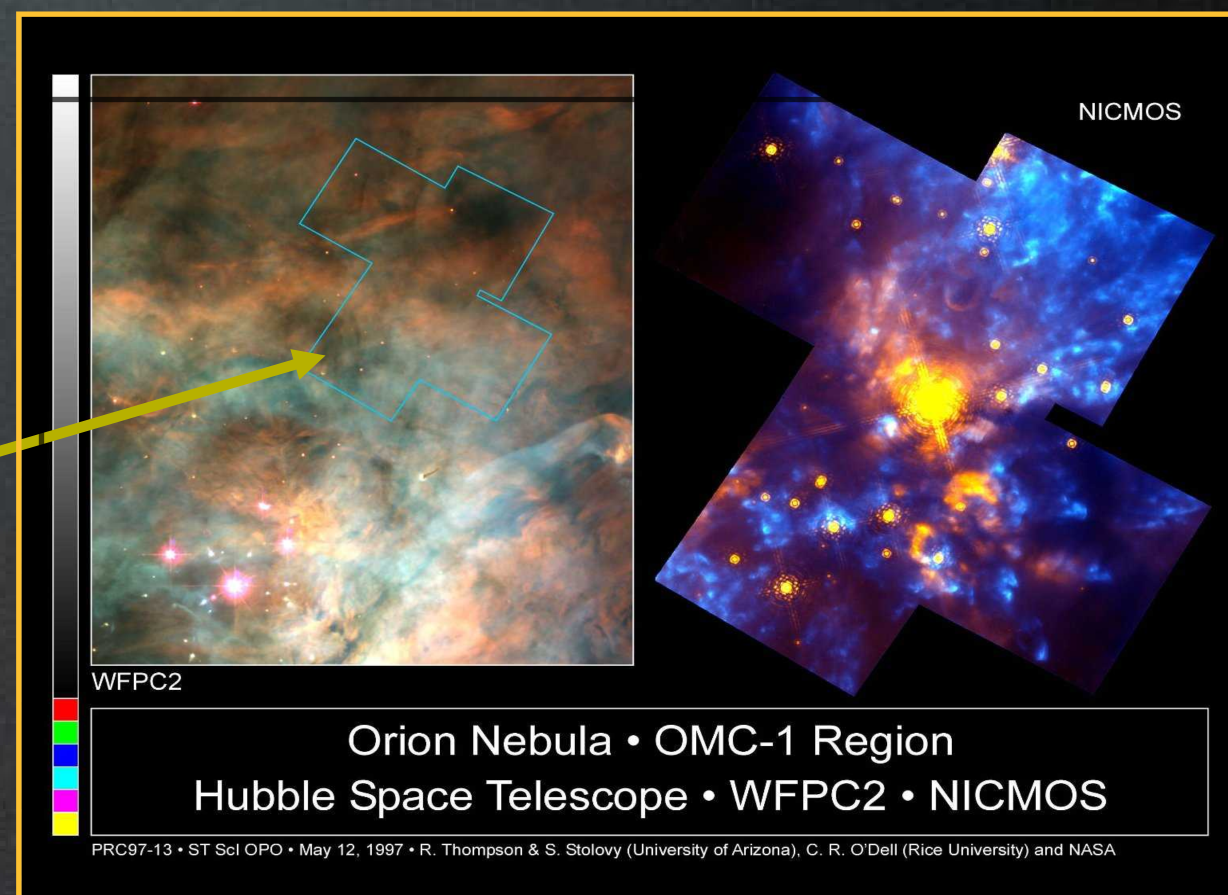


Figure 1.1 A portion of the Northern sky. The Milky Way is depicted as light grey, while the darker patches indicate giant molecular clouds. Also shown, according to their relative brightness, are the more prominent stars, along with principle constellations.



Molecular Clouds

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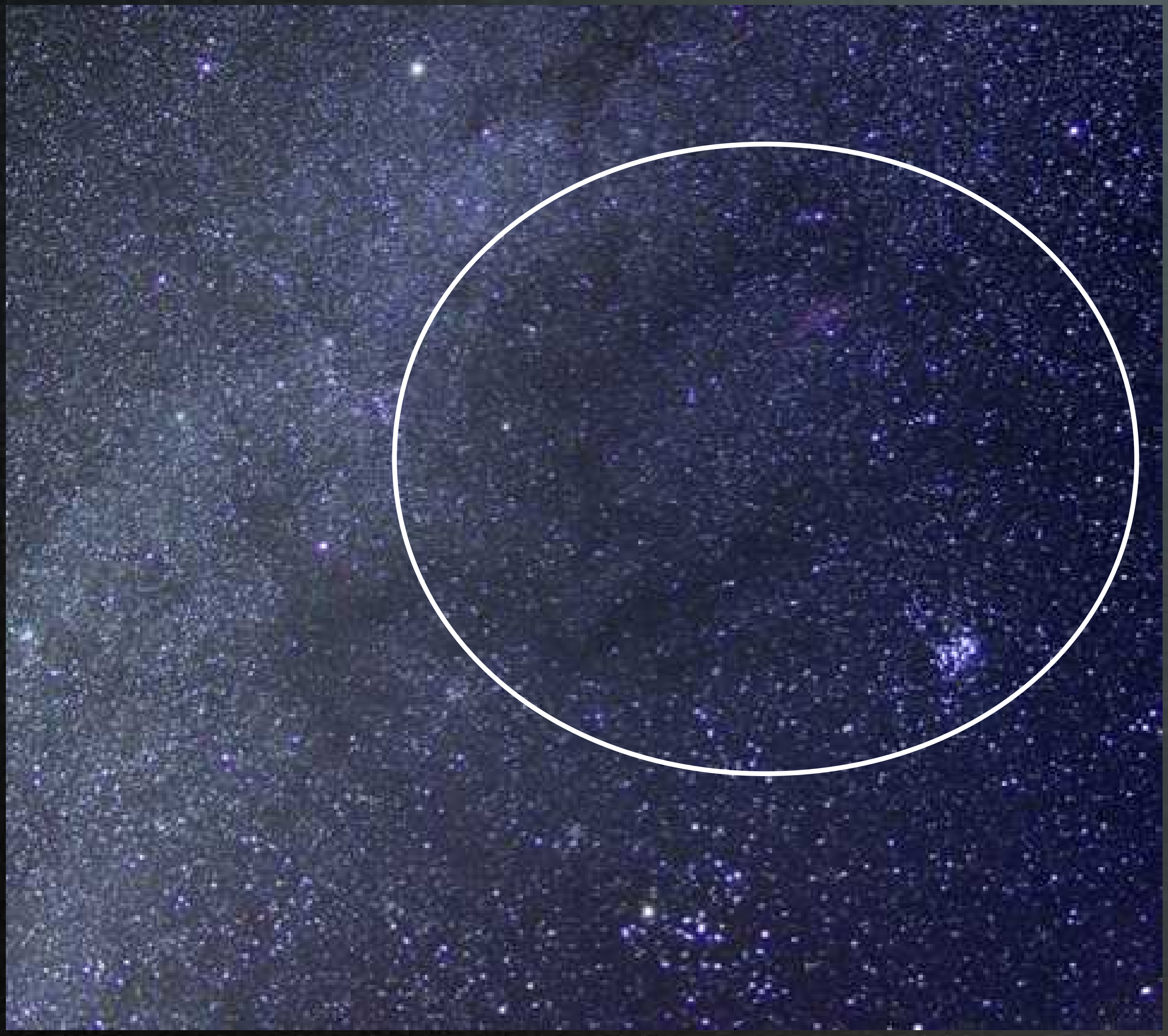
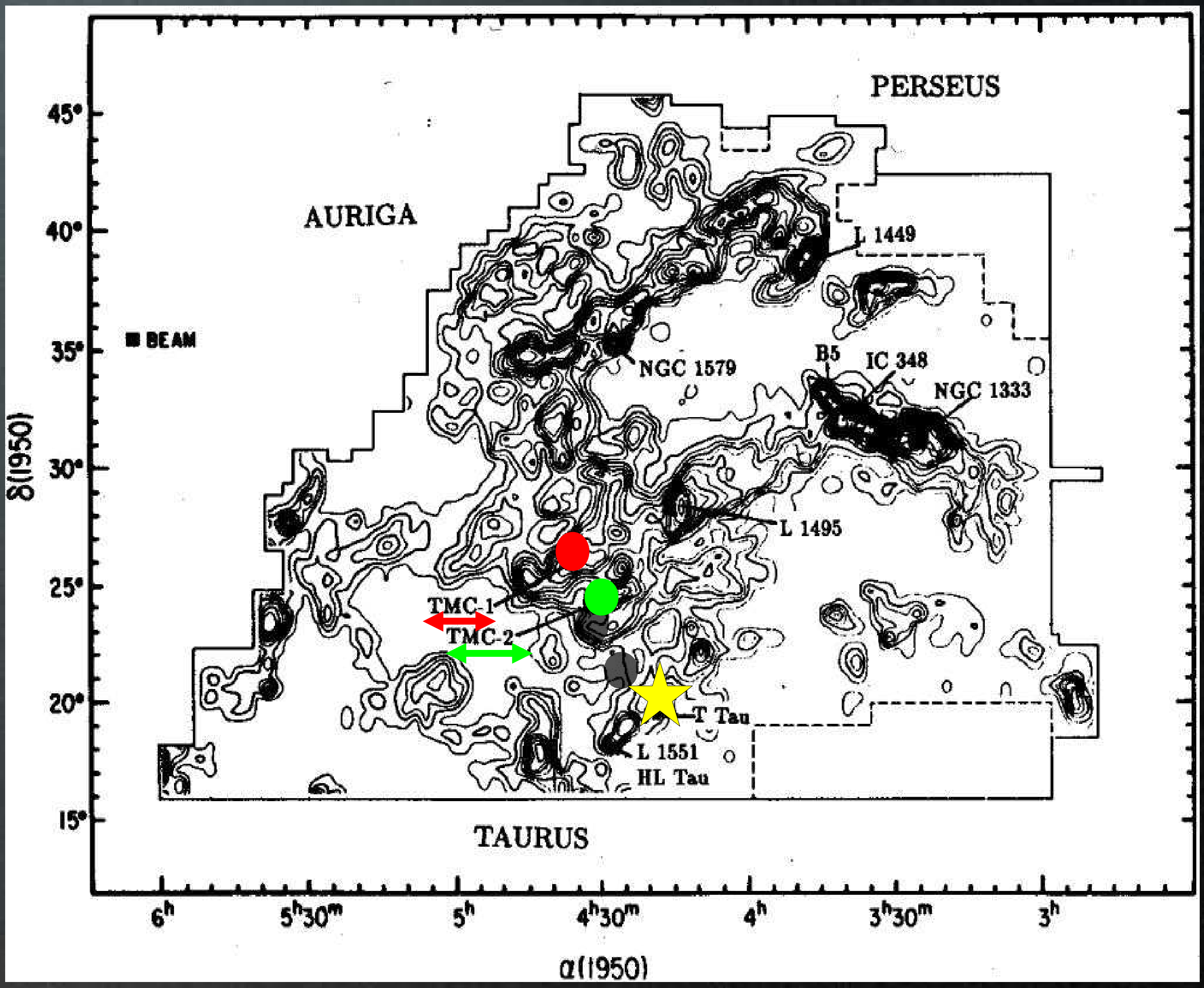
Diffuse Cloud

Dark Cloud

Molecular Clouds





- Taurus Molecular cloud seen in:
  - visible (Left side)
  - the CO line (right side)

Molecular Clouds

- Some other examples of Dark Molecular cloud:
  - -Right Picture: DMC in the plane of the Milky-Way
  - -Left Picture: DMC in the Eagle nebulae (M16)

Molecular Clouds

Table 3.1 Physical Properties of Molecular Clouds

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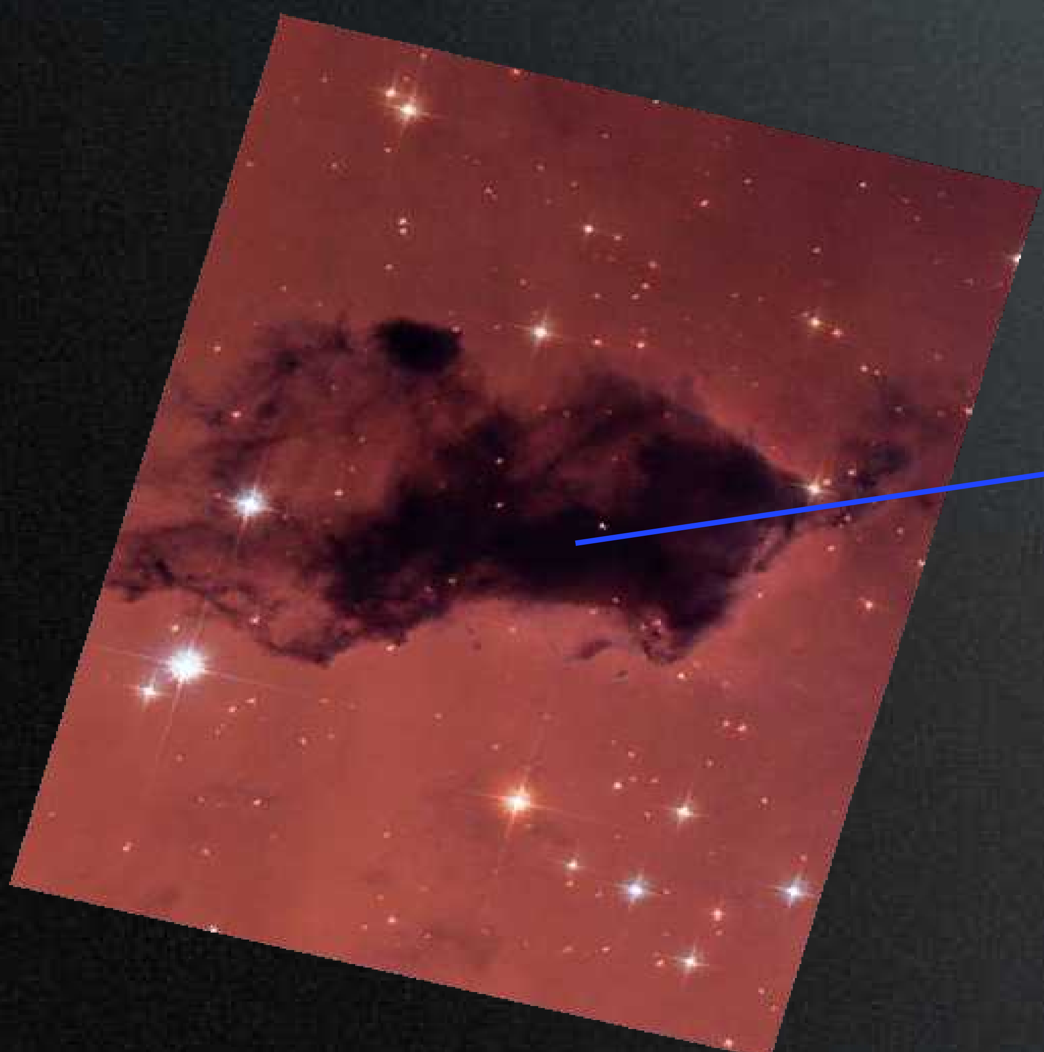
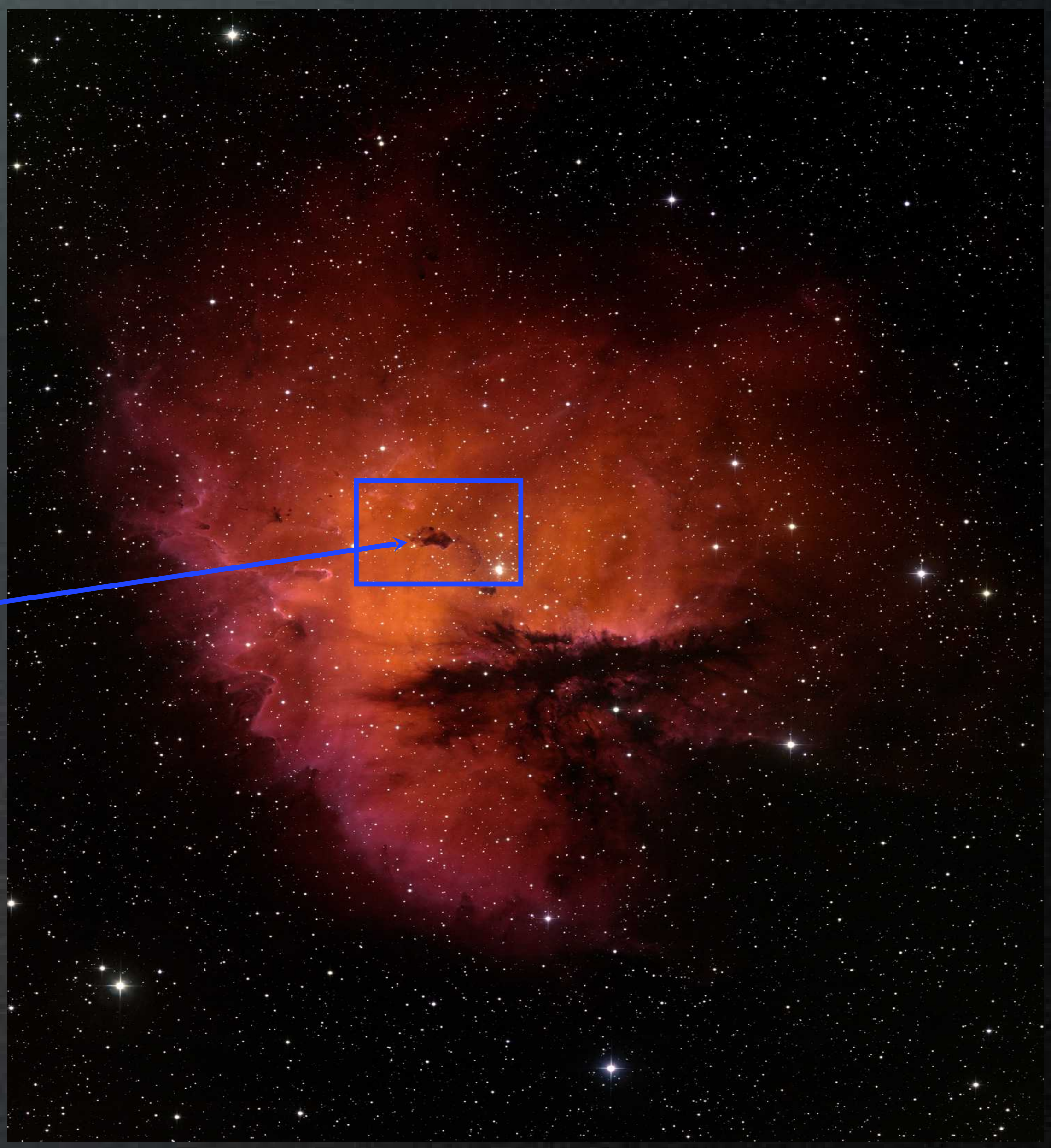
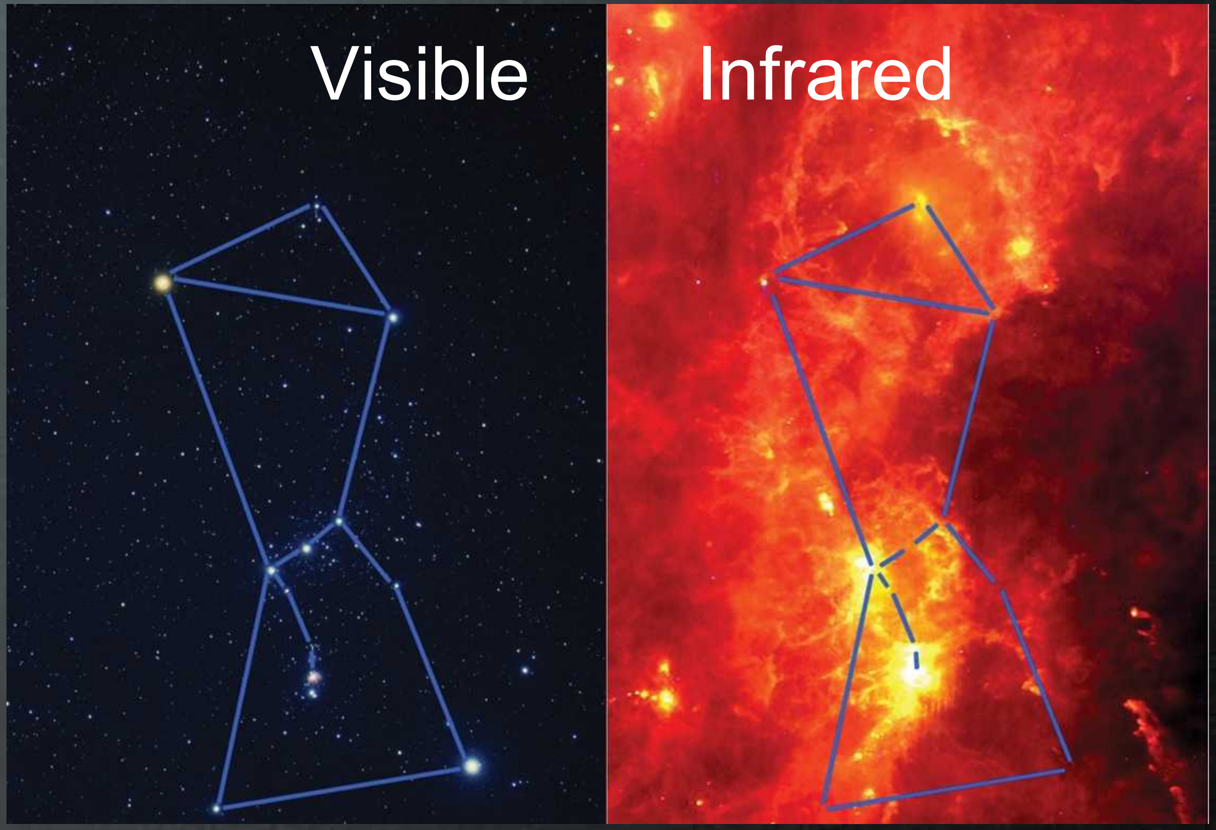


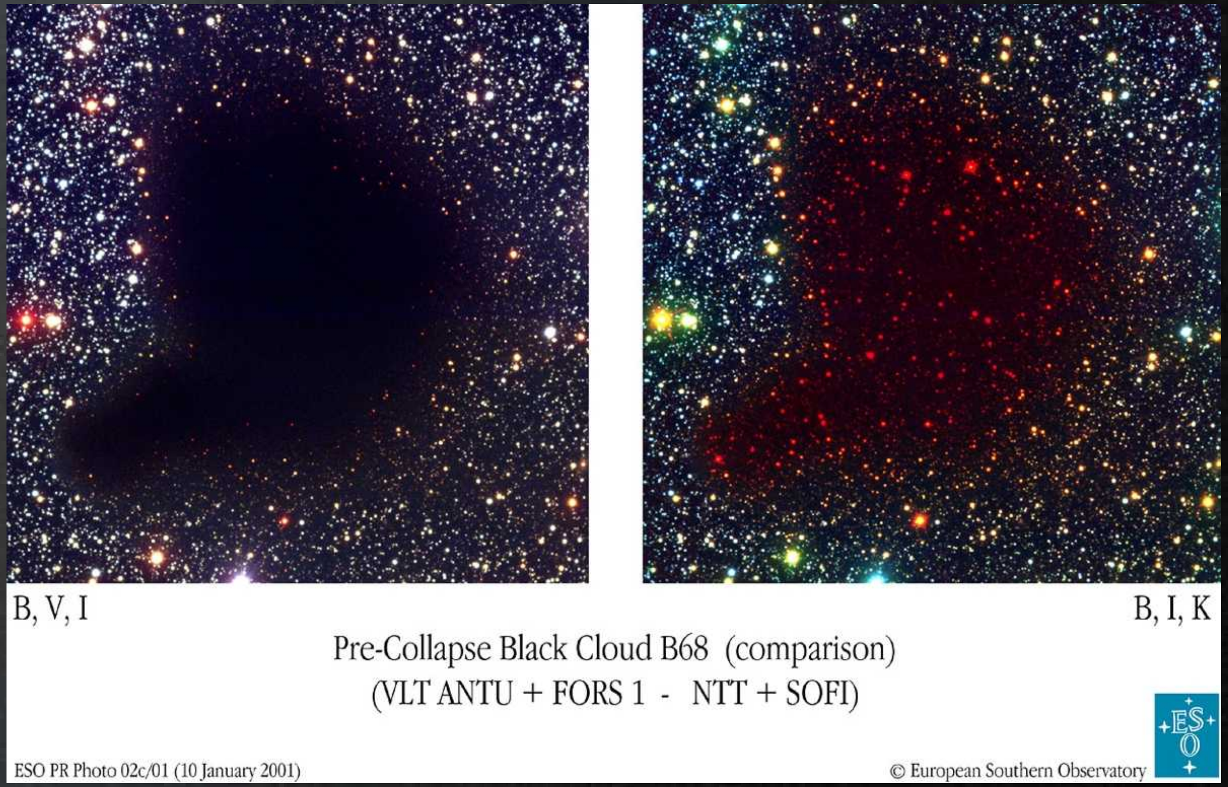


Observations

Observations

- Detection of DMC:
  - ✦Infra-Red
  - ✦Microwave
  - ✦millimeter and submillimeter
- Examples:
  - ➡Orion Region
  - ➡DMC B68 in Ophiuchus

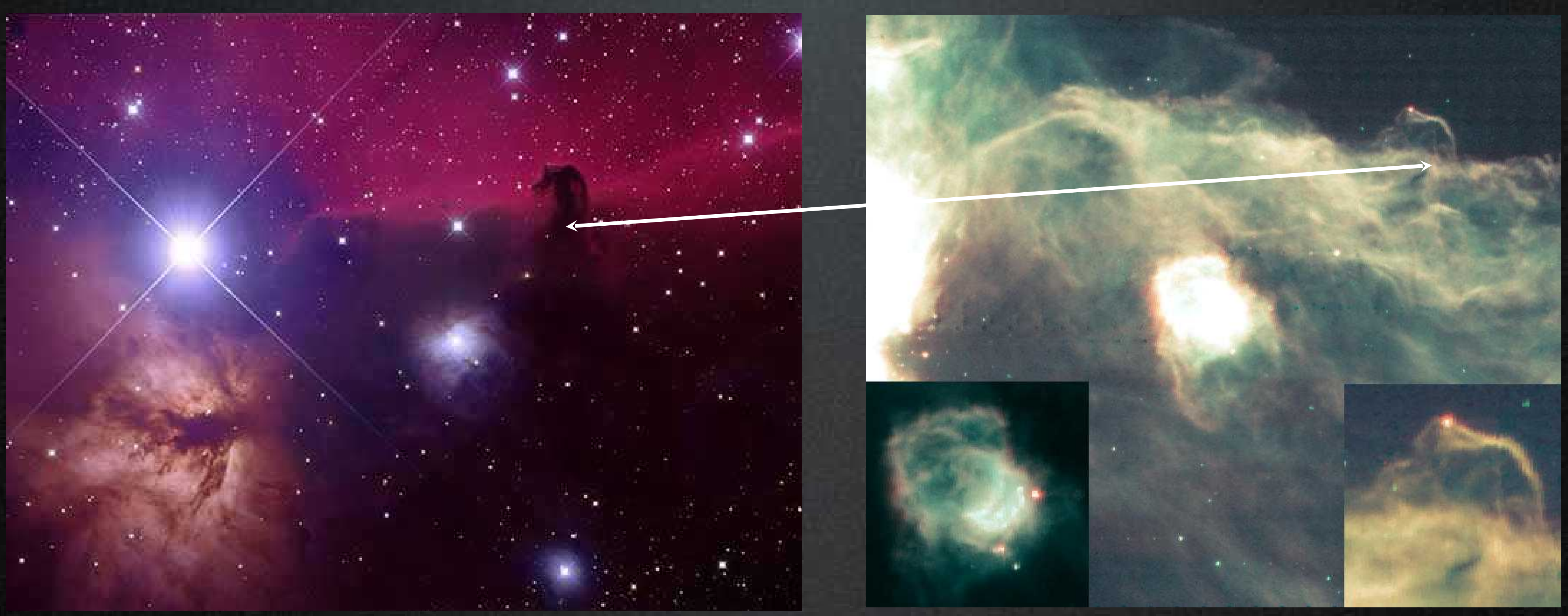




Observations

Why DMC are detected in Infrared?

- Presence of dust
  - ➡ Absorption more in shorter wavelengths than in Infrared wavelengths
- The dust reemit in the Infrared



Horsehead nebula in Orion: visible (left), infrared (right)

Observations

- Spitzer (2003) :
  - IRAC: InfraRed Array Camera
  - MIPS: Multiband Imaging Photometer for Spitzer
- IRAM: 30m radiotelescope
- Odin (2001):
  - OSIRIS: Odin Spectrometer and InfraRed Imaging System
- And others ...

Interstellar Chemistry

Interstellar Chemistry
What are the processes involved?

TABLE A1
Classes of Chemical Reactions

Type	Process	Rate Coefficient
	Formation Processes	
Radiative association	$X + Y \rightarrow XY + h\nu$	10^{-16}–10^{-9}
Grain surface formation	$X + Y{:}g \rightarrow XY + g$	$\sim 10^{-18}$
	Destruction Processes	
Photodissociation	$XY + h\nu \rightarrow X + Y$	$\sim 10^{-10}$–$10^{-8}\ s^{-1}$
Dissociative recombination	$XY^+ + e \rightarrow X + Y$	$\sim 10^{-6}$
Collisional dissociation	$XY + M \rightarrow X + Y + M$	—
	Chemical Processes	
Ion-molecule exchange	$X^+ + YZ \rightarrow XY^+ + Z$	$\sim 10^{-9}$
Charge-transfer	$X^+ + YZ \rightarrow X + YZ^+$	$\sim 10^{-9}$
Neutral-neutral	$X + YZ \rightarrow XY + Z$	$\sim 10^{-12}$

[a] Approximate rate coefficients appropriate for cold dark clouds. All rate coefficients are sensitive to temperature. For photodissociation, the rates in s^{-1} in the unattenuated interstellar radiation field are listed.

Interstellar Chemistry
Build-up of complex molecules

- Essential facts and assumptions:
  - H_2 is the most abundant constituent
  - Presence of sufficient amount of reactive ions (e.g C, S, Si in diffuse clouds)
- <u>Cosmic Rays are the most important source of ionization in DMC</u>
  - Cosmic Rays penetrate into molecular clouds up to column density 10^{24} cm^{-2}.
- Cosmic Rays ionize Hydrogen at rates 10^{-17} to 10^{-16} s^{-1}.
- $H_2^+ + H_2 \rightarrow H_3^+ + H$
  $X + H_3^+ \rightarrow XH^+ + H_2$ Neutral atom X (X=O, C, S)
- ***H_3^+*** is the key to molecule formation in Dark Molecular Clouds

Interstellar Chemistry

But why?

- Gas phase reactions with O:

  $H^+ + O \rightarrow O^+ + H$

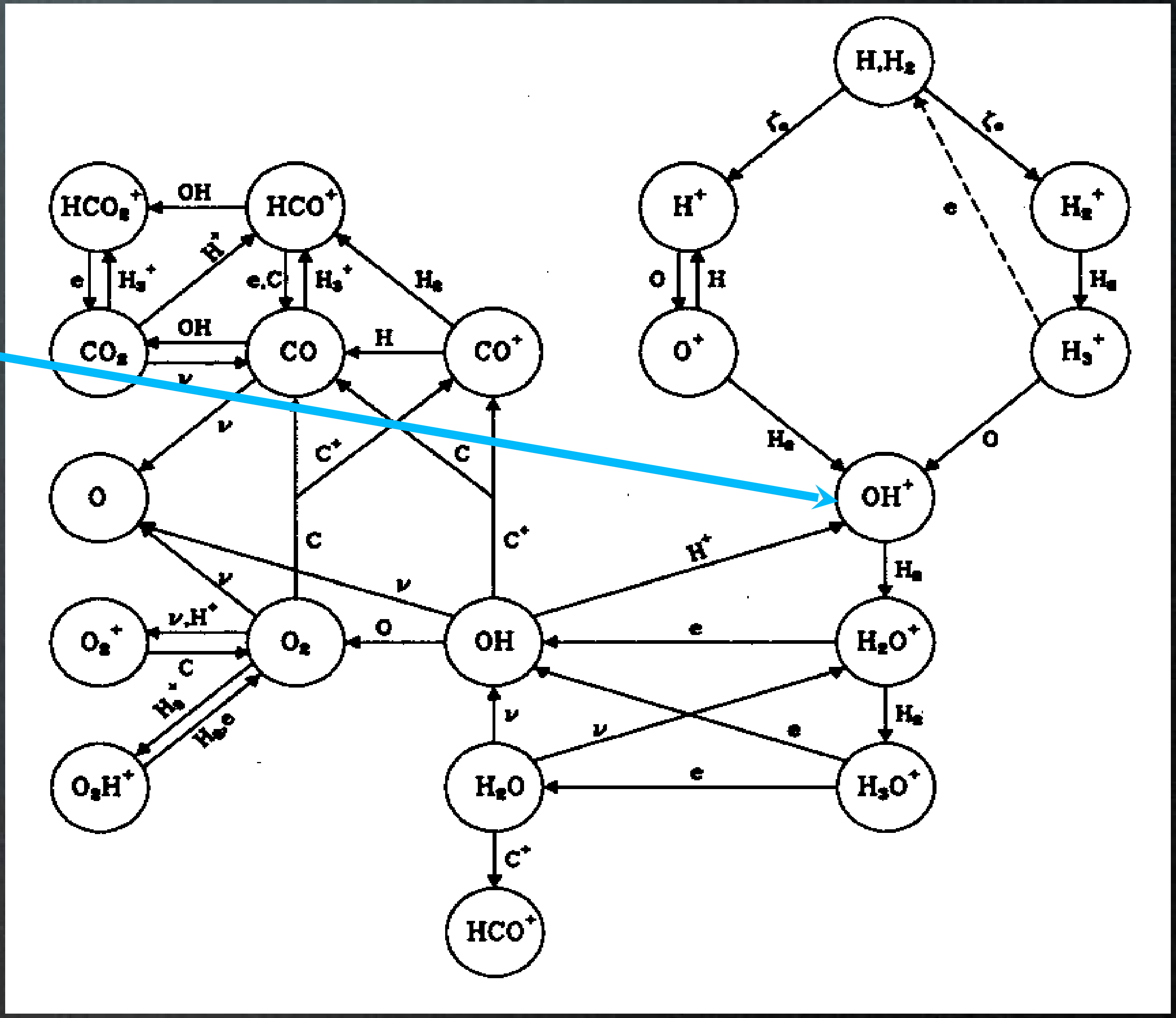
  $O^+ + H_2 \rightarrow OH^+ + H$
- or:

  $H_3^+ + O \rightarrow OH^+ + H_2$

  $\rightarrow$ exothermal
- Similar reactions are possible with C.
- N reactions must proceed in a different way as

  $N + H_3^+ \rightarrow NH^+ + H_2$ is endothermic.

  N^+ must be formed first.



Chemical Network of O

Interstellar Chemistry

Interstellar molecules are involved and formed

Table 1. Interstellar molecules (September 1993).

Number of atoms: 2	2	3	4	5	6	7	8	9	10	11	13
H_2	NS	H_2O	NH_3	SiH_4							
OH	HCl	H_2S	H_3O^+								
SO	NaCl	N_2H^+									
NO	KCl	SO_2									
SiO	AlCl	HNO									
SiS	AlF	SiH_2?									
SiN	PN	H_2D^+?									
	NH										
CH^+		HCN	H_2CO	HC_3N	CH_3OH	HC_5N	$HCOOCH_3$	HC_7N	CH_3C_5N?	HC_9N	$HC_{11}N$
CH		HNC	HNCO	C_4H	CH_3CN	CH_3CCH	CH_3C_3N	$(CH_3)_2O$	$(CH_3)_2CO$?		
CC		C_2H	H_2CS	H_2CNH	CH_3NC	CH_3NH_2		CH_3CH_2OH			
CN		C_2S	HNCS	H_2C_2O	CH_3SH	CH_3CHO		CH_3CH_2CN			
CO		SiC_2	C_3N	NH_2CN	NH_2CHO	H_2CCHCN		CH_3C_4H			
CSi		HCO	C_3H^{lin}	HCOOH	H_2CCH_2	C_6H					
CS		HCO^+	C_3H^{ring}	CH_4	C_5H						
CP		HOC^+?	C_3O	$H_2C_3^{ring}$	HC_2COH						
		OCS	C_3S	$H_2C_3^{lin}$	$H_2C_4^{lin}$						
		HCS^+	$HOCO^+$	CH_2CN							
		CO_2	HCCH	C_4Si							
		C_2O	$HCNH^+$	HCCNC							
		MgNC	HCCN	HNCCC							
		CaNC	H_2CN	CCCCC							
		CCC									

Interstellar Chemistry

H_2 not directly observed in DMC !

- H_2 is the most abundant molecule in space
- Vibrational transition v= 1-> 0; S(1) at 2.1μm
- Typical DMC Temperature ≈ 10 K

➡ No observation of rotational or vibrational transitions in DMC

106 F. Combes

Molecules in galaxies at all redshifts, in “The cold universe” Saas-Fee advanced course 32, Springer 2002, pp105-212

$h\nu = hc/\lambda = kT$
$T = hc/k\lambda$
$= 1.439/(\lambda \text{ in cm})$

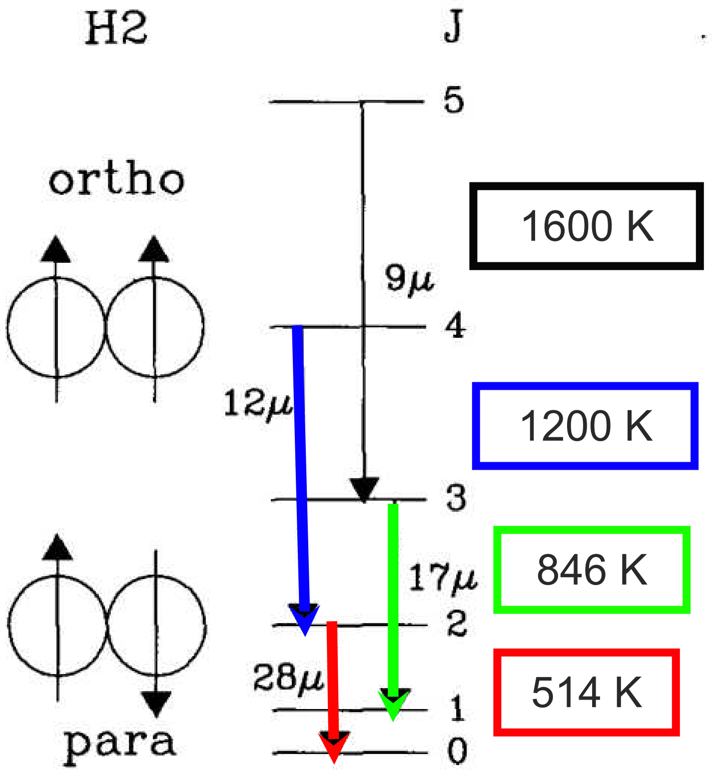


Fig. 1. Schematic of the first levels of the H_2 molecule. The even-J levels are the para-hydrogen, while the odd-J levels are from the ortho-hydrogen. The coupled levels obey $\Delta J = \pm 2$, for quadrupolar transitions, and the two species are not radiatively coupled. The four first rotational lines of hydrogen S(J) (where J is the lower state) are represented – wavelengths in μm, $S(3) = 9$, $S(2) = 12$, $S(1) = 17$ and $S(0) = 28$.

Interstellar Chemistry

Which Molecules !

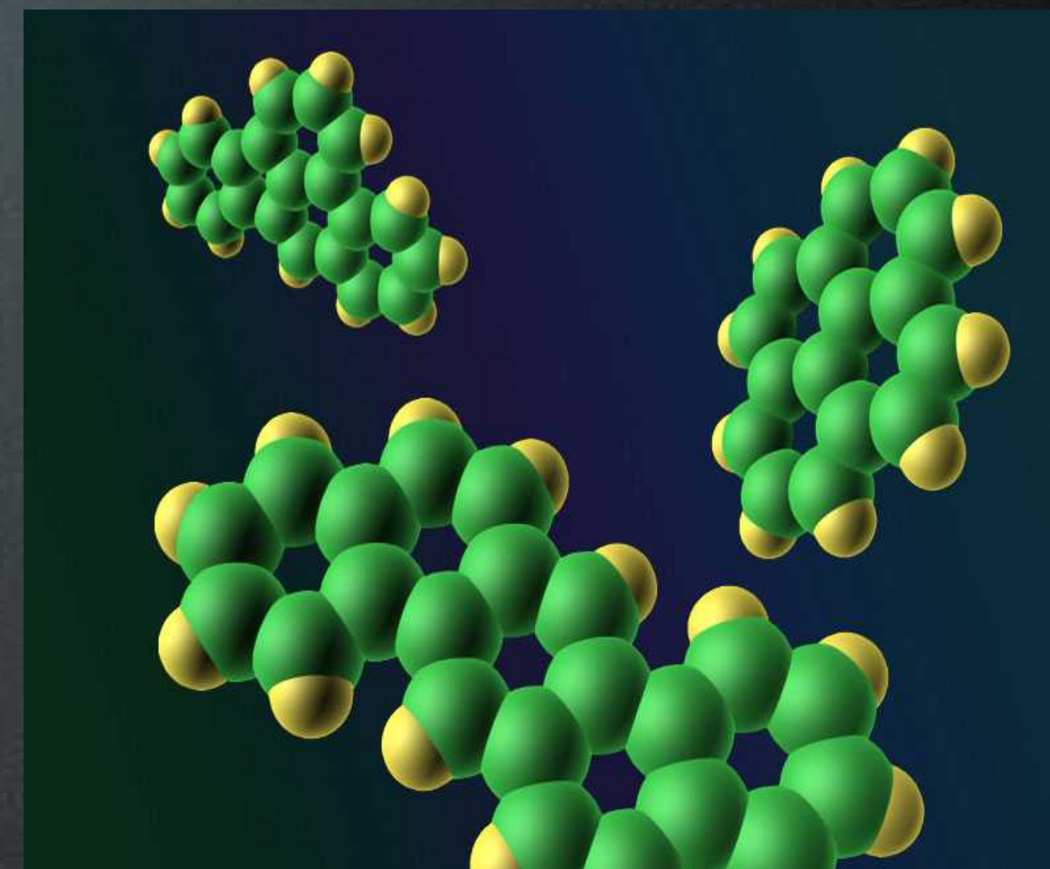
Table 5.1 Some Useful Molecules

molecule	abundance[a]	transition	type	λ	$T_\circ^b$ (K)	A_{ul} (s^{-1})	n_{crit}^c (cm^{-3})	comments
H_2	1	$1 \rightarrow 0$ S(1)	vibrational	2.1 μm	6600	8.5×10^{-7}	7.8×10^{7}	shock tracer
CO	8×10^{-5}	$J=1 \rightarrow 0$	rotational	2.6 mm	5.5	7.5×10^{-8}	3.0×10^{3}	low density probe
OH	3×10^{-7}	$^2\Pi_{3/2}$;J=3/2	Λ-doubling	18 cm	0.08	7.2×10^{-11}	1.4×10^{0}	magnetic field probe
NH_3	2×10^{-8}	(J,K)=(1,1)	inversion	1.3 cm	1.1	1.7×10^{-7}	1.9×10^{4}	temperature probe
H_2CO	2×10^{-8}	$2_{12} \rightarrow 1_{11}$	rotational	2.1 mm	6.9	5.3×10^{-5}	1.3×10^{6}	high density probe
CS	1×10^{-8}	$J=2 \rightarrow 1$	rotational	3.1 mm	4.6	1.7×10^{-5}	4.2×10^{5}	high density probe
HCO^+	8×10^{-9}	$J=1 \rightarrow 0$	rotational	3.4 mm	4.3	5.5×10^{-5}	1.5×10^{5}	tracer of ionization
H_2O		$6_{16} \rightarrow 5_{23}$	rotational	1.3 cm	1.1	1.9×10^{-9}	1.4×10^{3}	maser
//	$<7\times10^{-8}$	$1_{10} \rightarrow 1_{11}$	rotational	527 μm	27.3	3.5×10^{-3}	1.7×10^{7}	warm gas probe

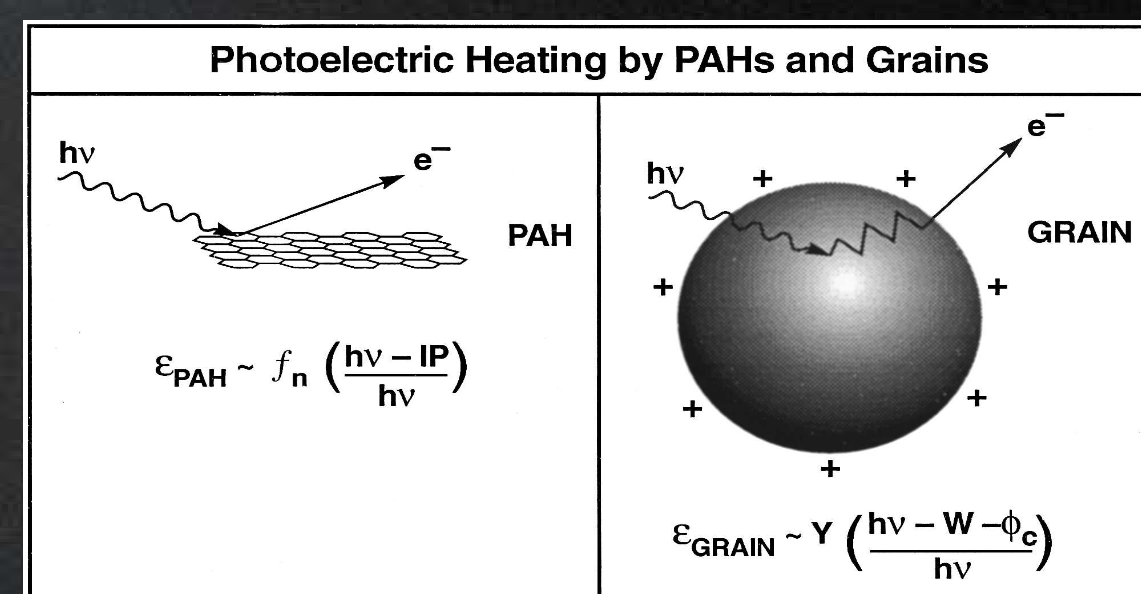
[a] number density of main isotope relative to hydrogen, as measured in the dense core TMC–1
[b] equivalent temperature of the transition energy; $T_\circ \equiv \Delta E_{ul}/k_B$
[c] evaluated at T=10 K, except for H_2 (T=2000 K) and H_2O at 527 μm (T=20 K)

Polycyclic Aromatic Hydrocarbon (PAH)

- Large robust organic molecules
- Found in interstellar medium, in comets, and in meteorites.
- PAHs with grains play an important role in the heating of interstellar gas
- Candidate molecule to act as a basis for the earliest forms of life.



=> *<u>The PAH world hypothesis</u> (biological hypothesis) PAH was a means for a pre-RNA World basis for the origin of life. As yet it is untested, though in 2007 Cassini spacecraft found the presence of heavy negative ions of tholin in the upper regions of Titan's atmosphere.*



Photodissociation Regions

Photodissociation Regions (PDRs)

- Part of the interstellar medium where the ultraviolet radation field is strong enough to photodissociate molecules: **XY + h*v* -> X + Y**

- Heating and chemistry are regulated by farultraviolet photons.

- The study of the PDRs is understanding

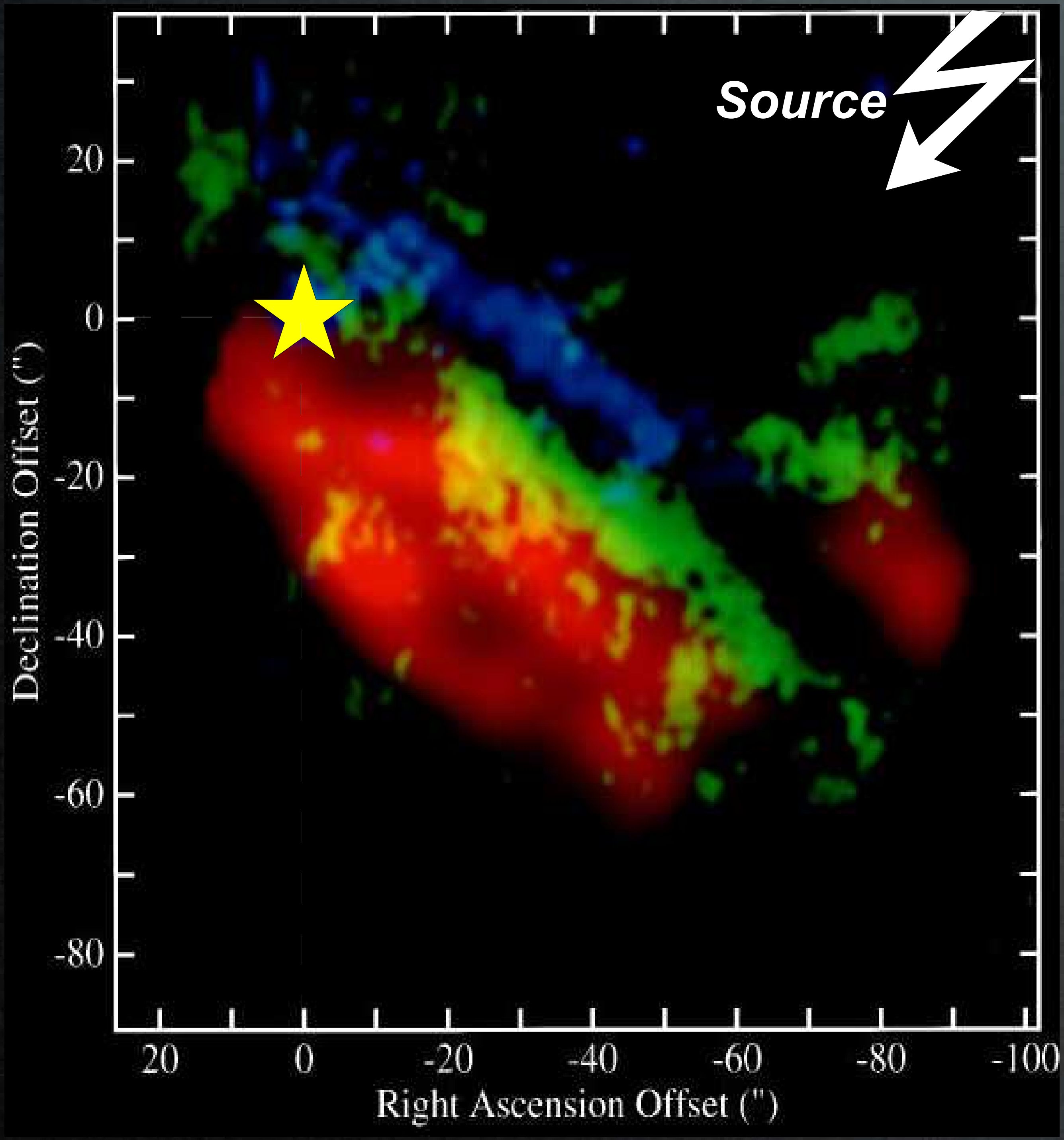
  - The effects of stellar far-ultraviolet photons on the structure, chemistry and thermal balance

  - The evolution of the neutral interstellar medium.

  - Understanding the process of star formation: *Farultraviolet photons illuminate star-forming regions, causing them to glow in infrared emission, and play an important role in regulating the star formation process*

Photodissociation Regions (PDRs)

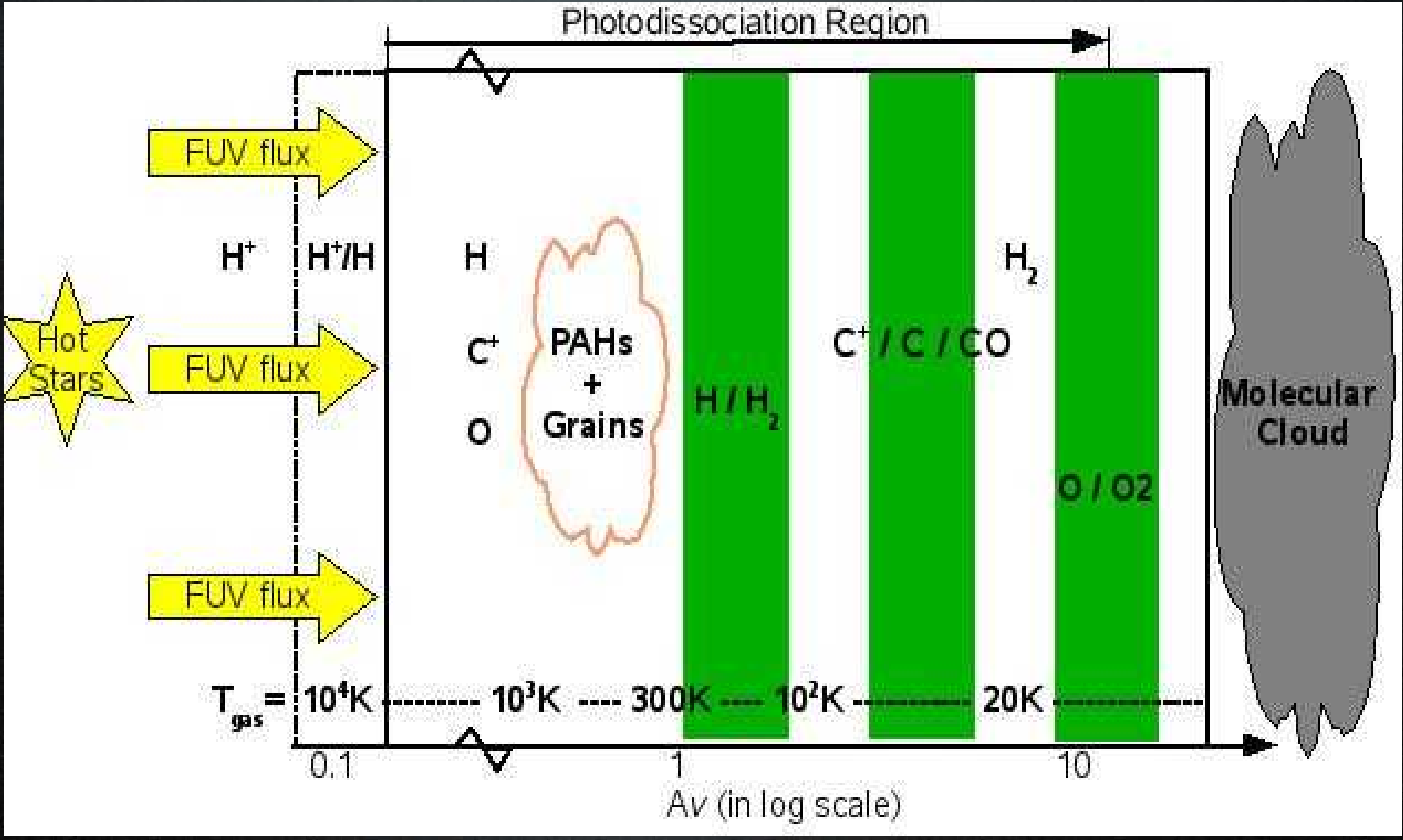
Orion Bar Region



- PAH feature (blue),
- H2 emission (yellow),
- CO emission (red).
- The PDR is seen edge on (Green).
- Position (0,0) corresponds to the a star.
- The illuminating source, the star and the ionized gas are in upper right

Photodissociation Regions (PDRs)

Schematic of PDRs



Photodissociation Regions (PDRs)

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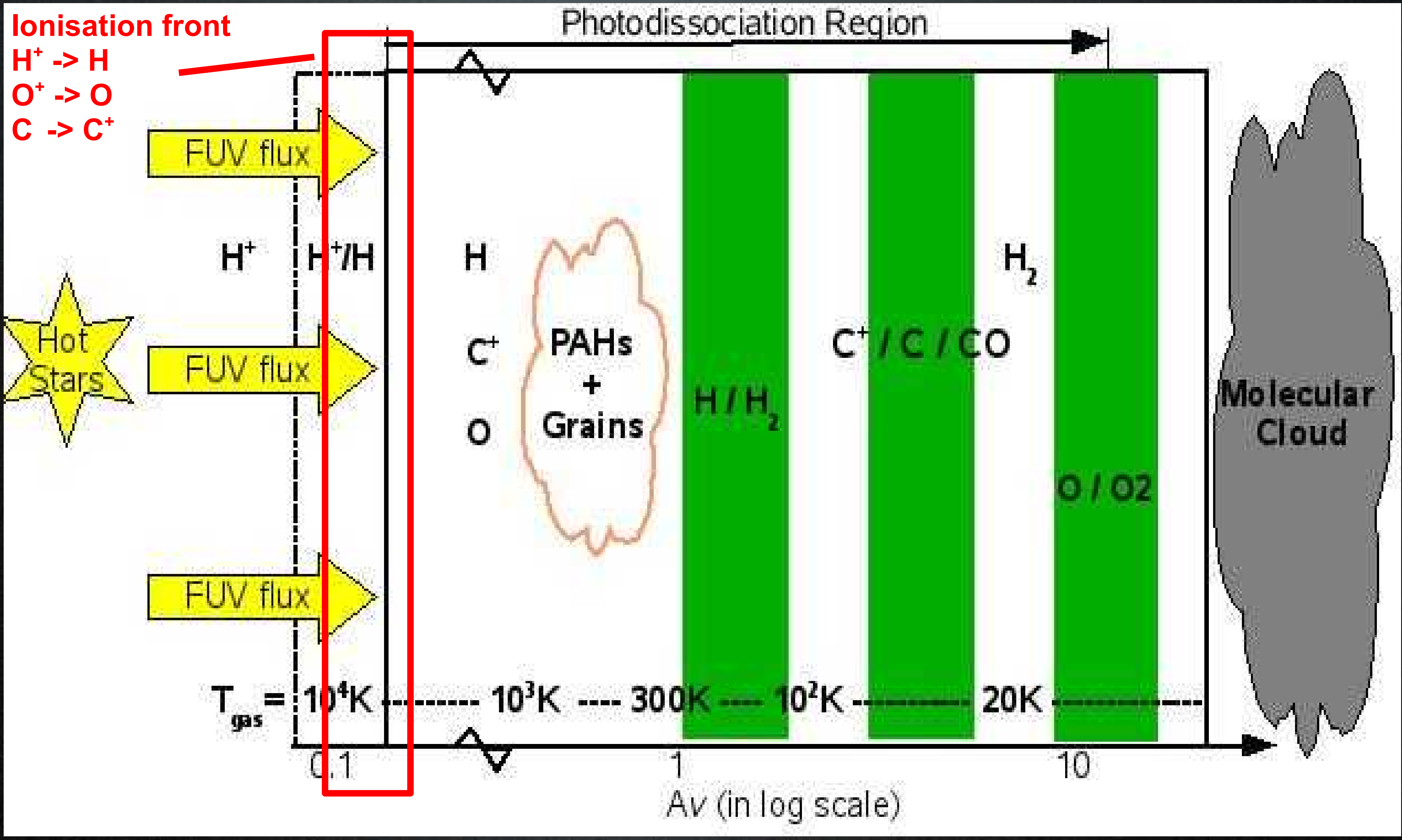


Photodissociation Regions (PDRs)

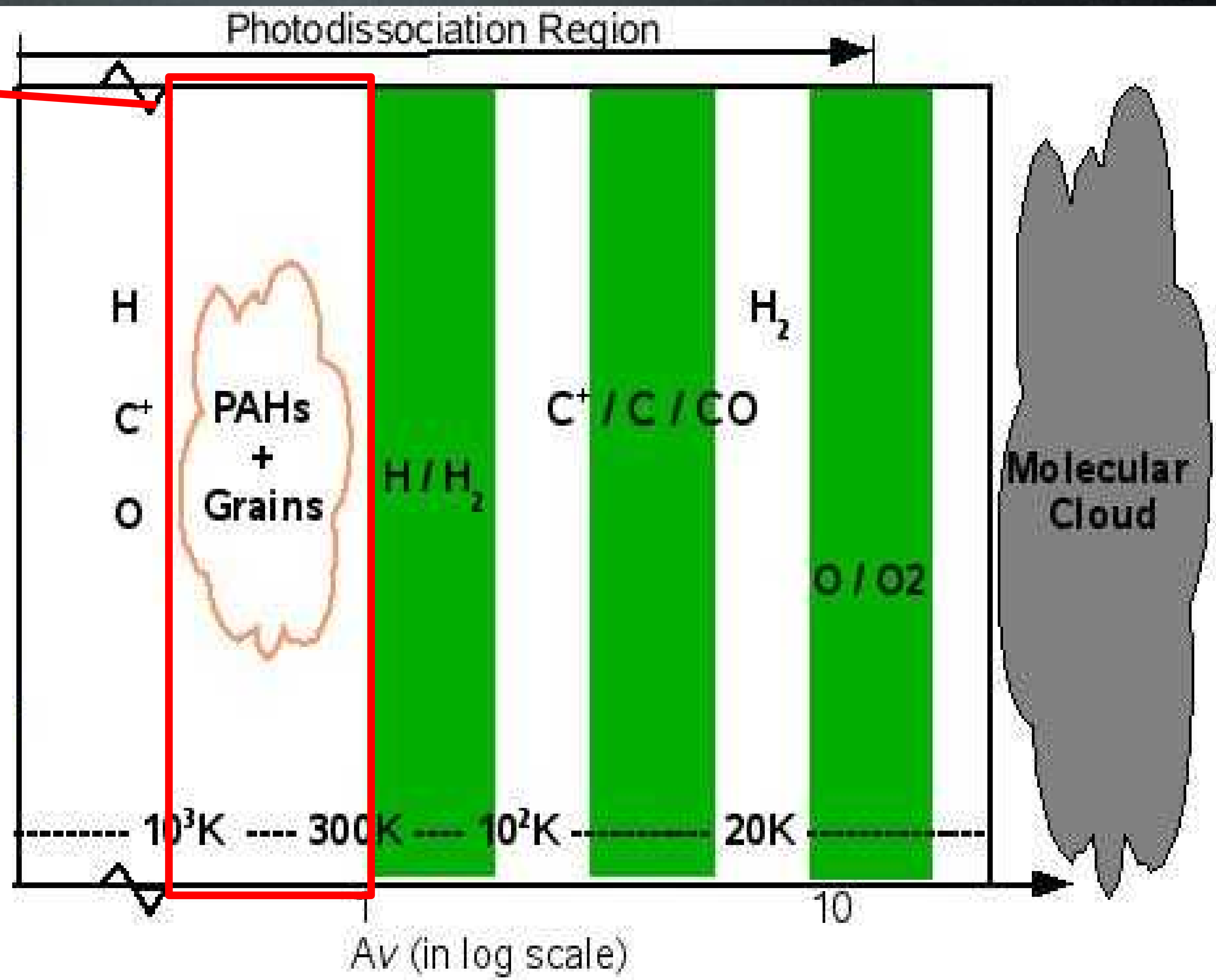
Schematic of PDRs

FUV absorbed by
- PAHs
- grains

Absorbed energy is used
- excite the PAHs
- heat the grains

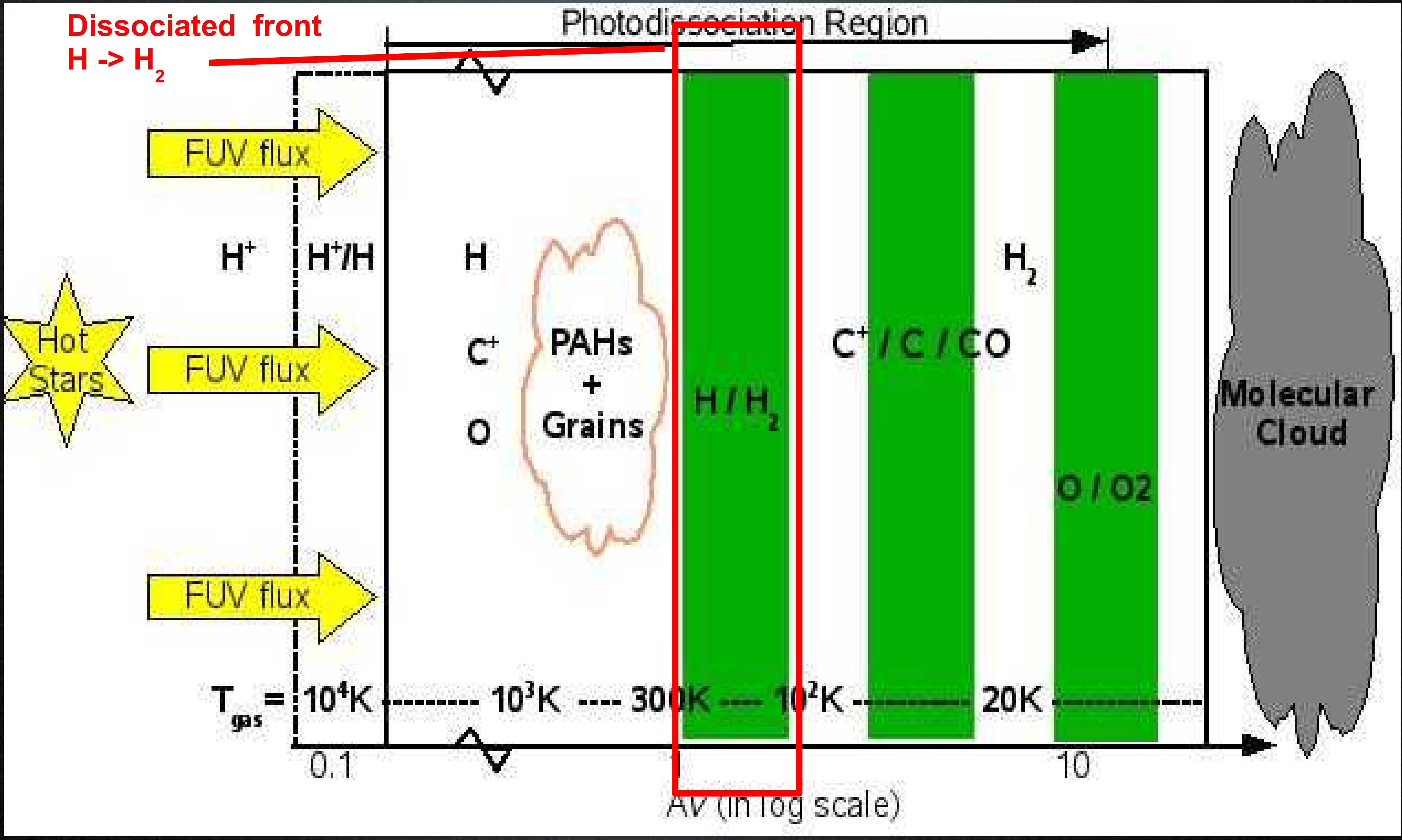
(~90%) Energy is converted to
- PAH infrared features
- Farinfrared continuum radiation of the cooling grains.

(~1%) Energy is converted to
- energetic photoelectrons that heat the gas ("photoelectric heating").



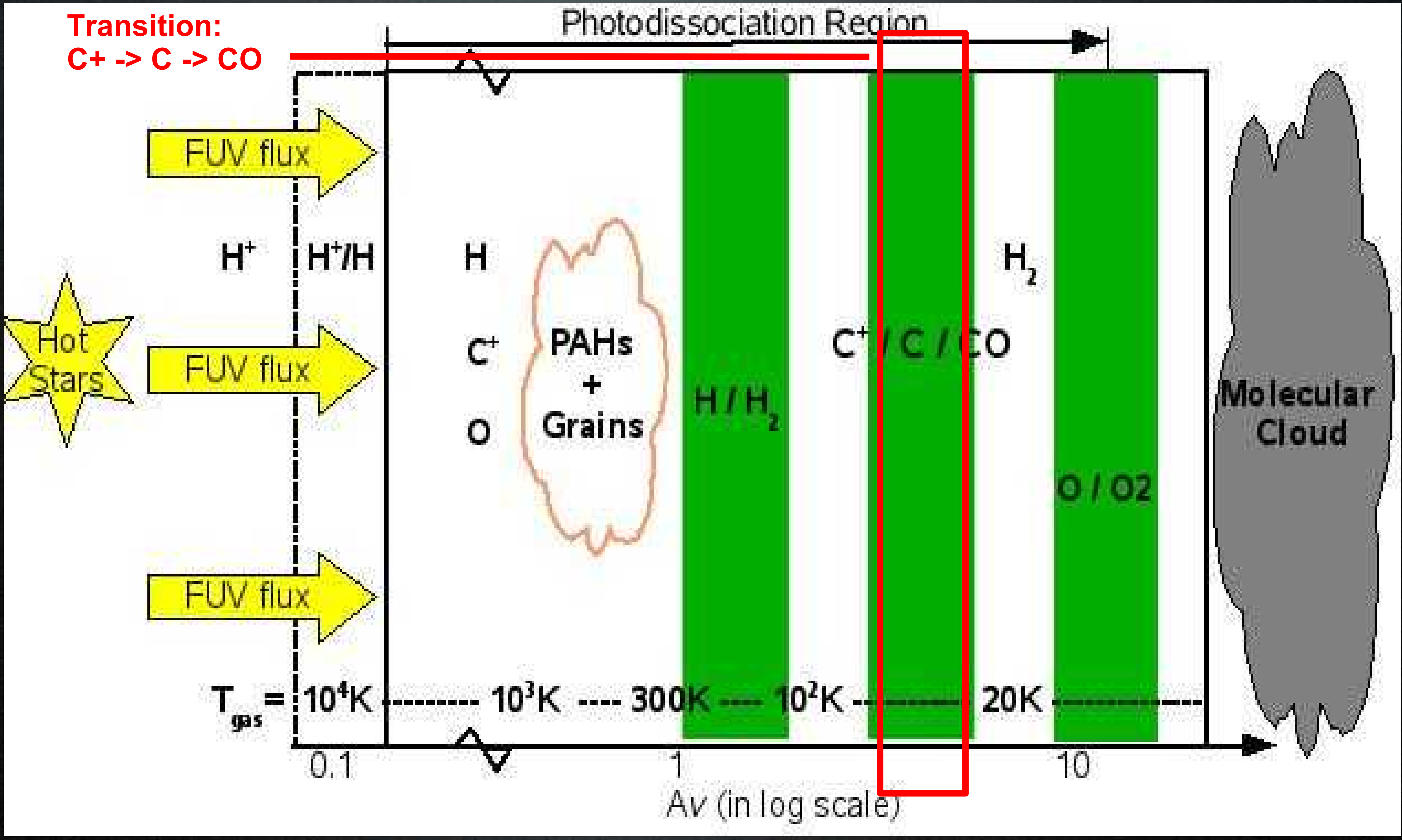
Photodissociation Regions (PDRs)

Schematic of PDRs



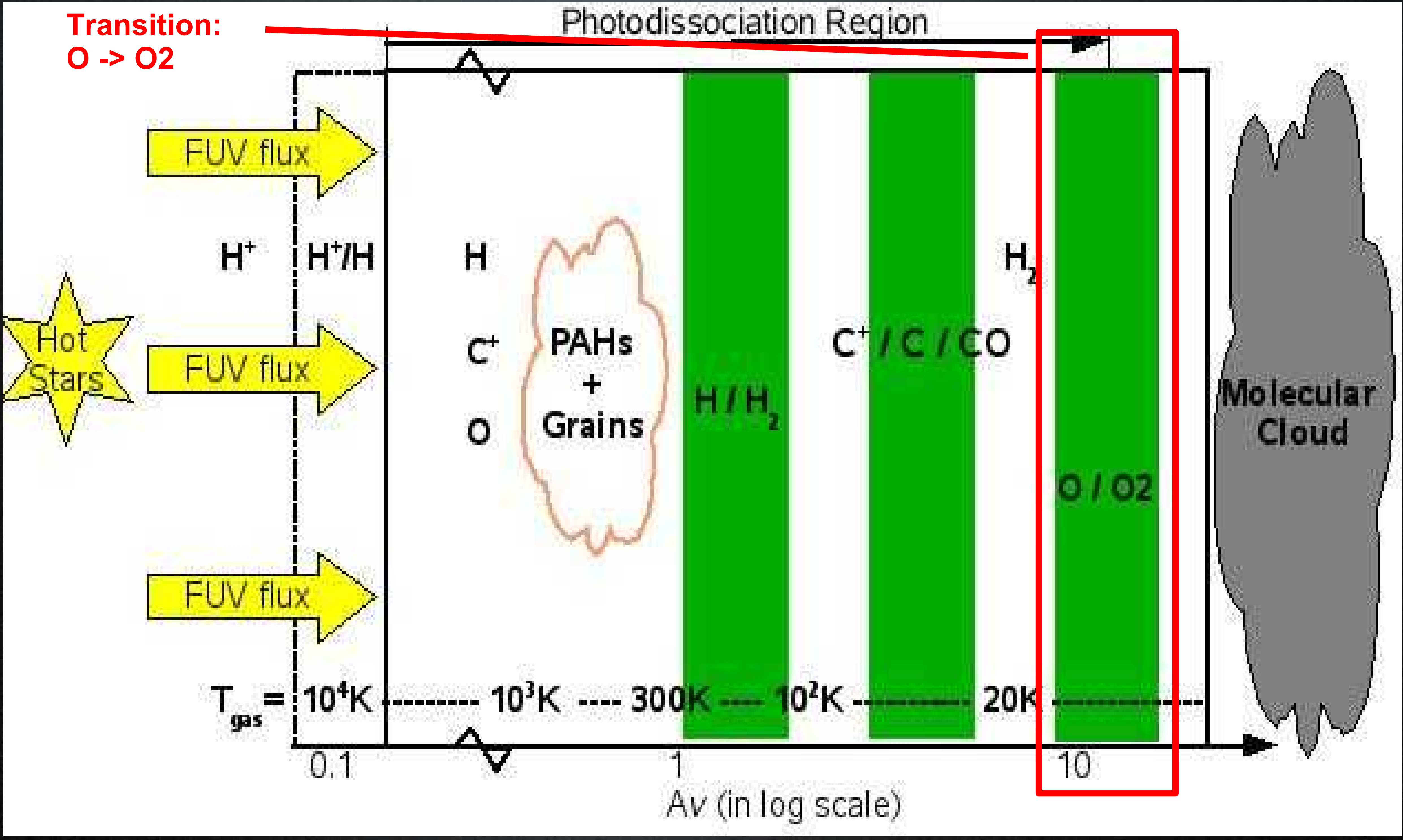
Photodissociation Regions (PDRs)

Schematic of PDRs



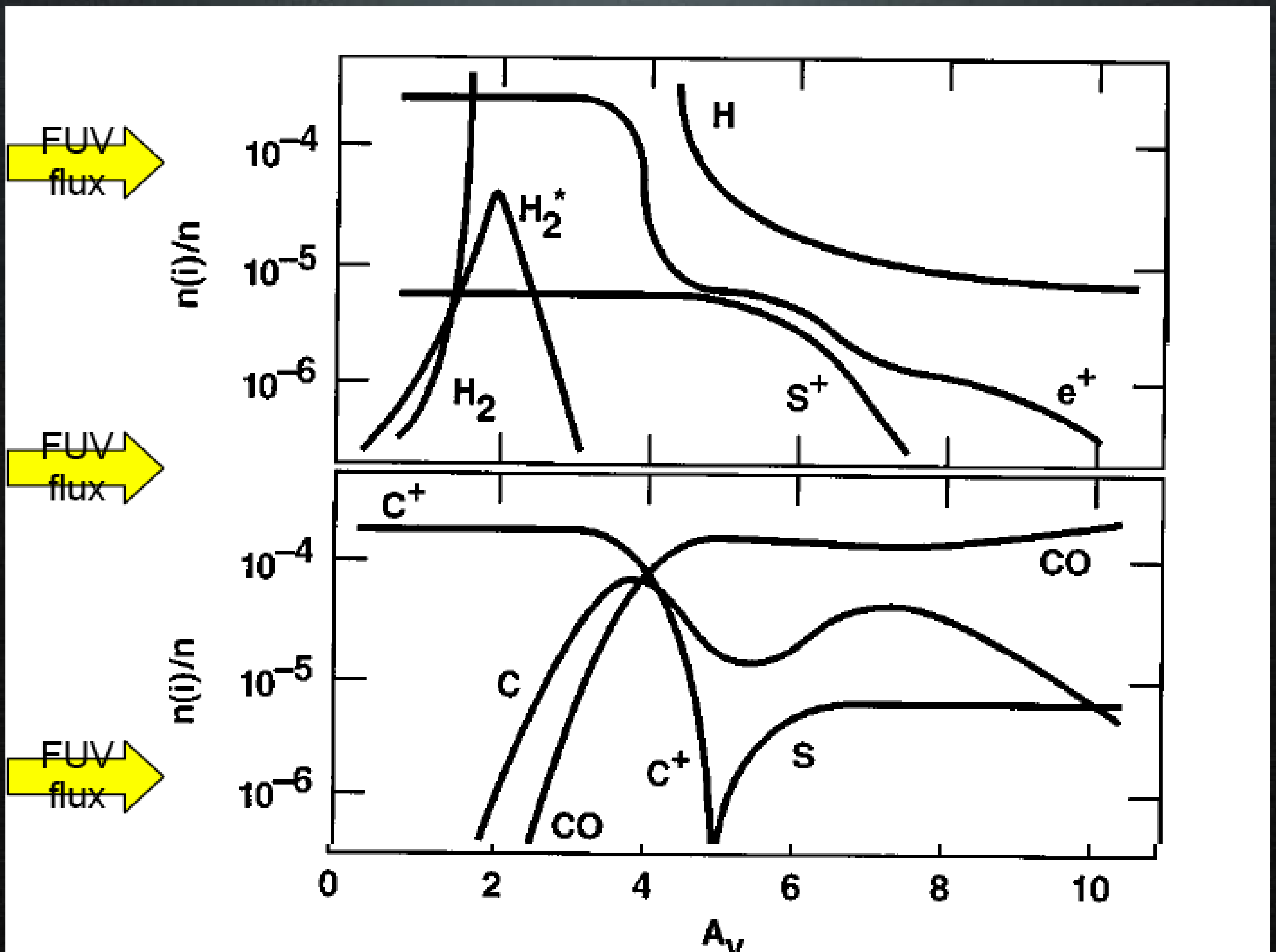
Photodissociation Regions (PDRs)

Schematic of PDRs



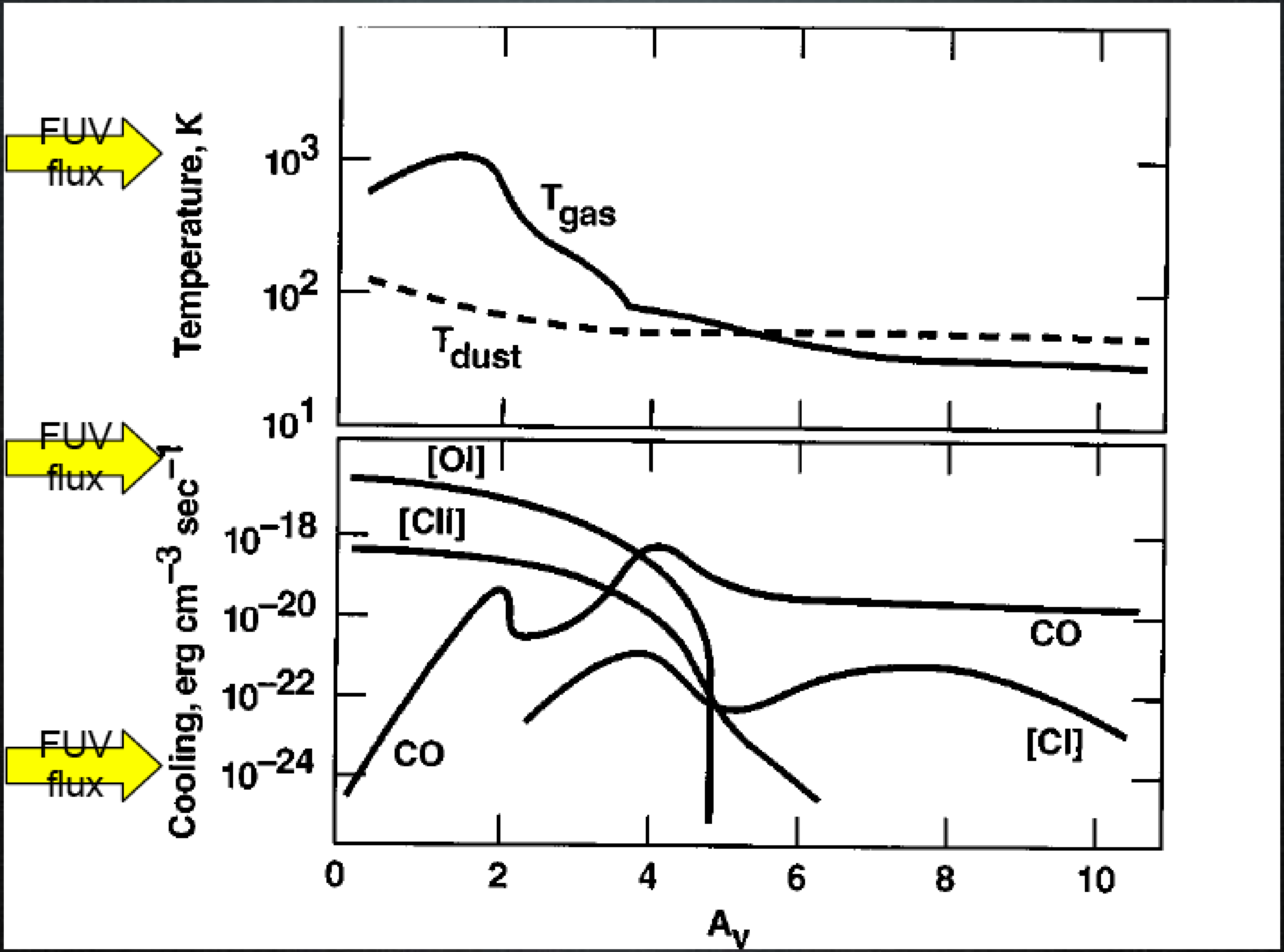
Photodissociation Regions (PDRs)

Structure of the PDR in Orion (1/2)



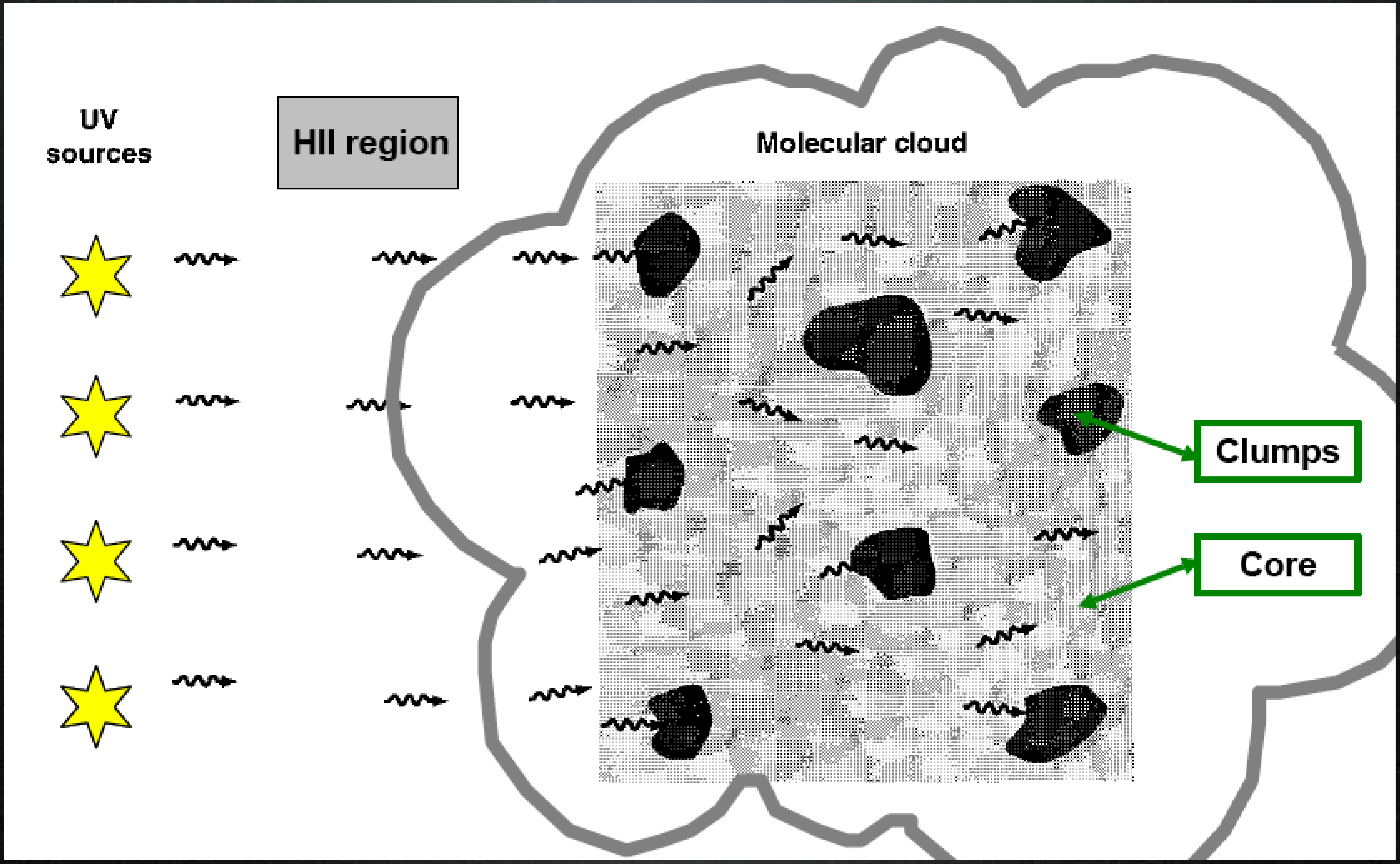
Photodissociation Regions (PDRs)

Structure of the PDR in Orion (2/2)



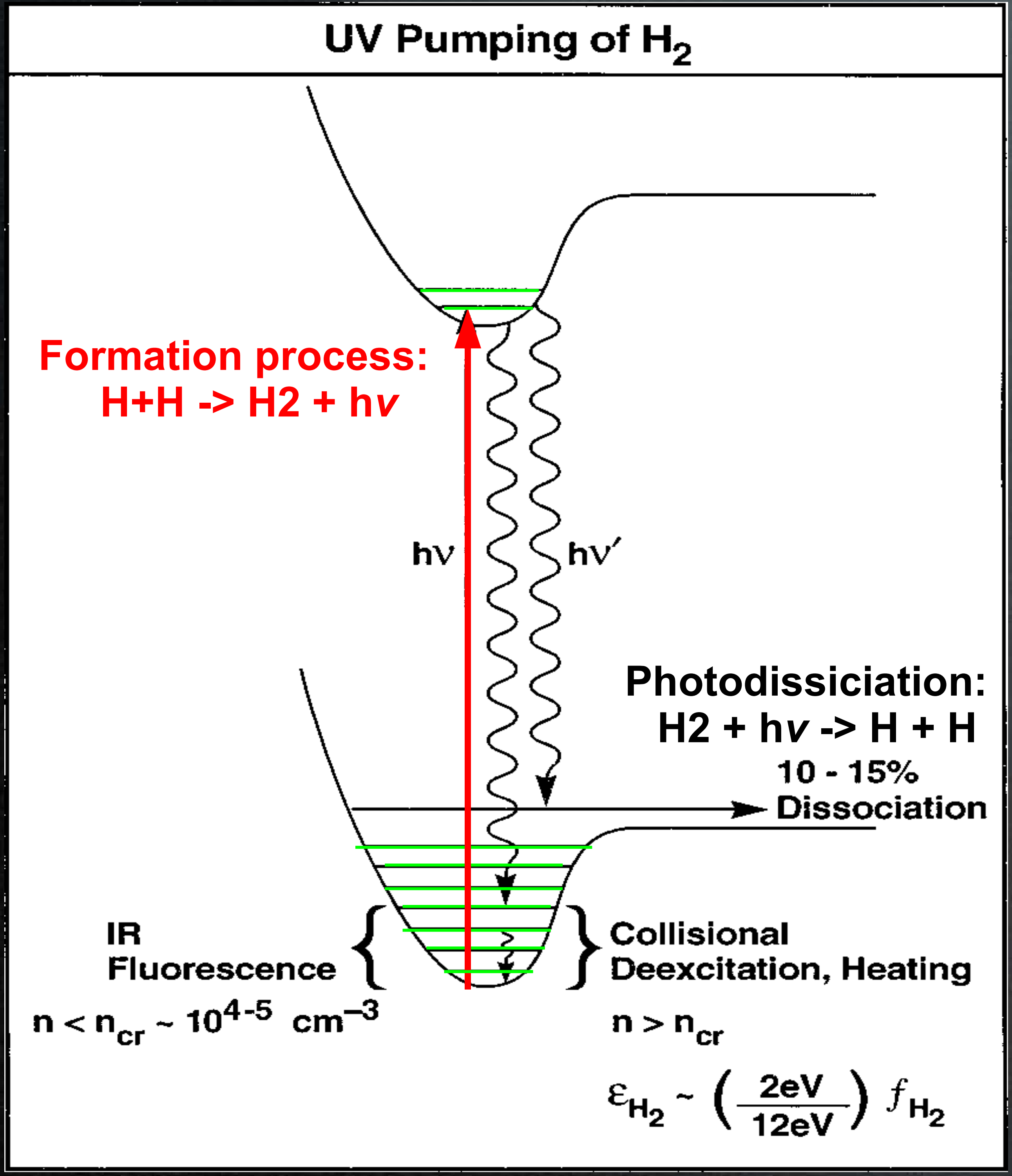
Photodissociation Regions (PDRs)

Penetration of Far-Ultraviolet radiation



Photodissociation Regions (PDRs)

Chemistry in PDRs (1/2)



Can we observe H2 in the PDR? YES

- *Pumping,*
- *Dissociation,*
- *Heating.*

Photodissiciation:

XY + h*v* -> X + Y

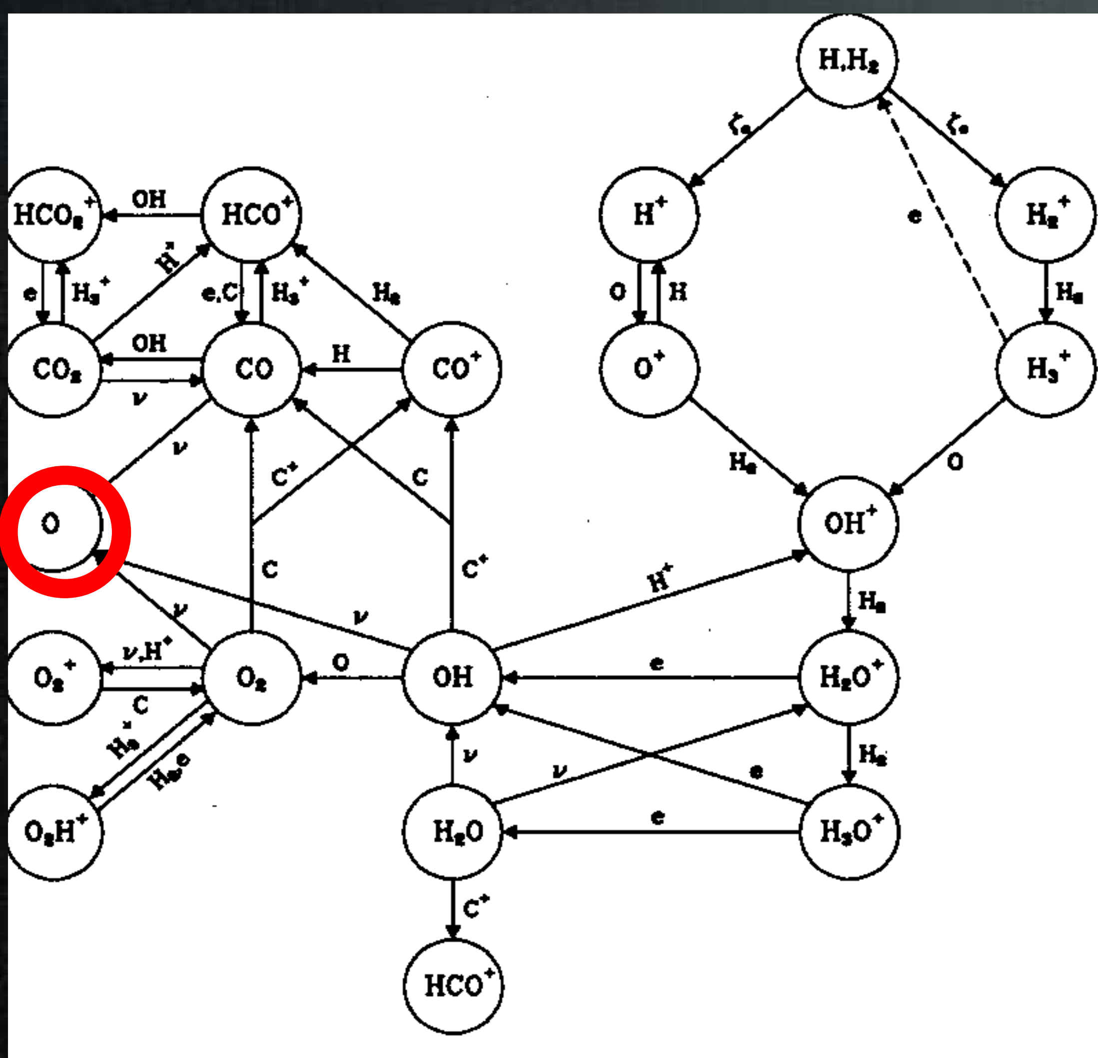
(Destruction process)

Photodissociation Regions (PDRs)

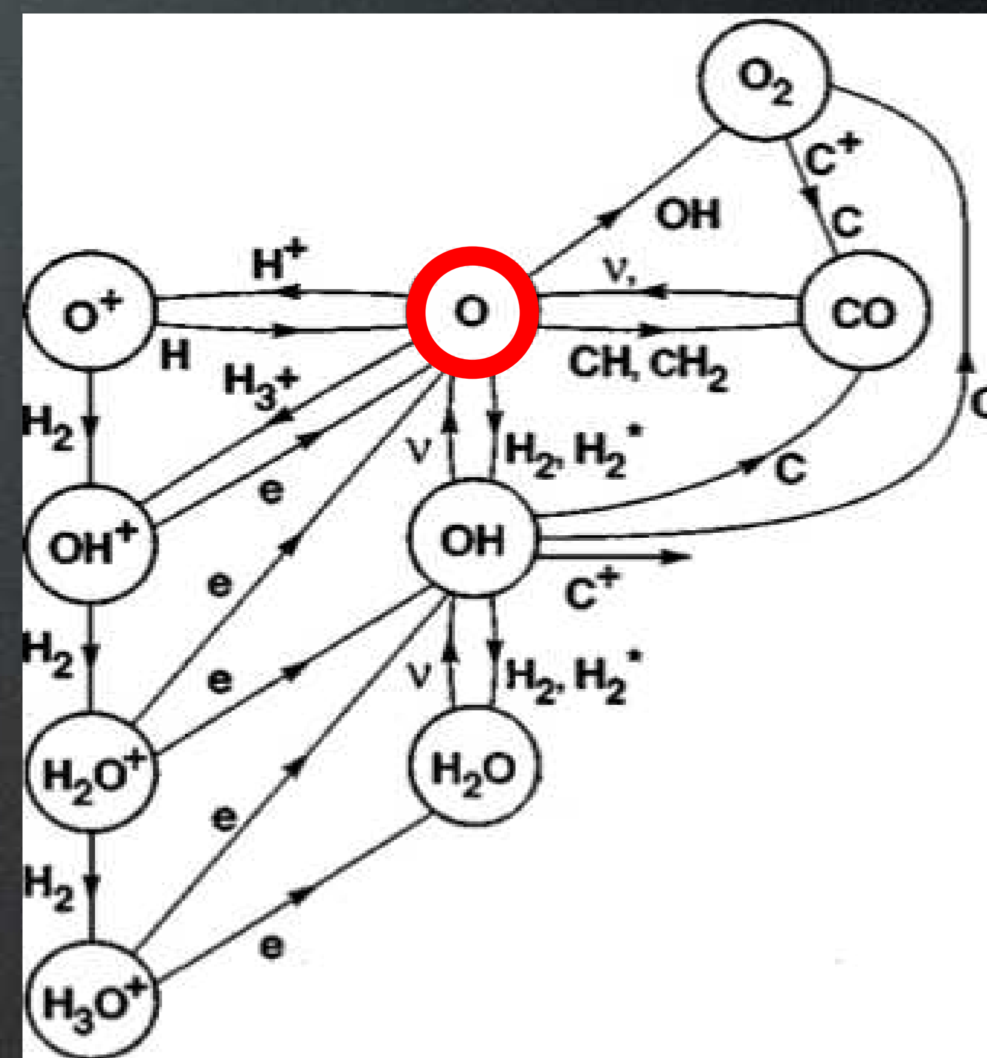
Chemistry in PDRs (2/2)

Chemical network: Example of the Oxygen

In DMC



In PDRs



Summary

- Interstellar Medium
  Hydrogen, Helium and traces of heavier elements (C,N,O,Mg,Si)
  Highly Inhomogeneous

- Molecular Clouds
  Dark molecular clouds
  Giant molecular clouds
  Observation

- Interstellar Chemistry
  Different reactions
  Molecular network
  Set of complex molecules + PAHs

- Photodissociation Regions (PDRs)
  Schema and Structure of the PDRs
  Penetration of Far-Ultraviolet radiation in the PDRs
  Chemistry, H_2 and chemical network