

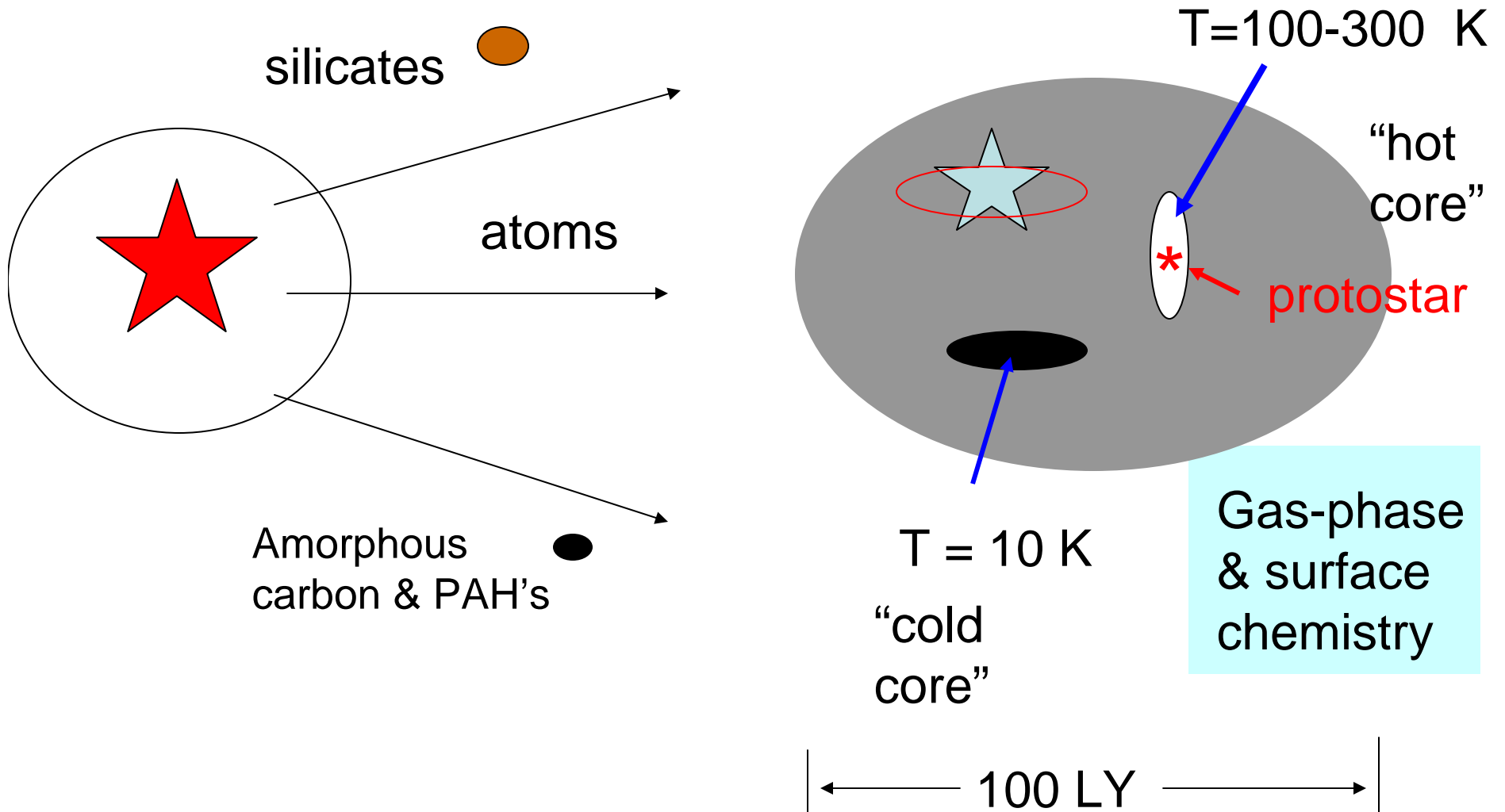
# Molecular Complexity and Star Formation



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THE OHIO STATE UNIVERSITY**

# From Star to Cloud



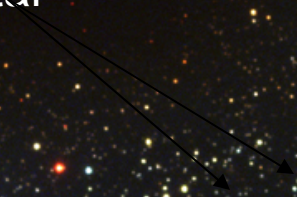
# Dense Interstellar Cloud Cores

10 K

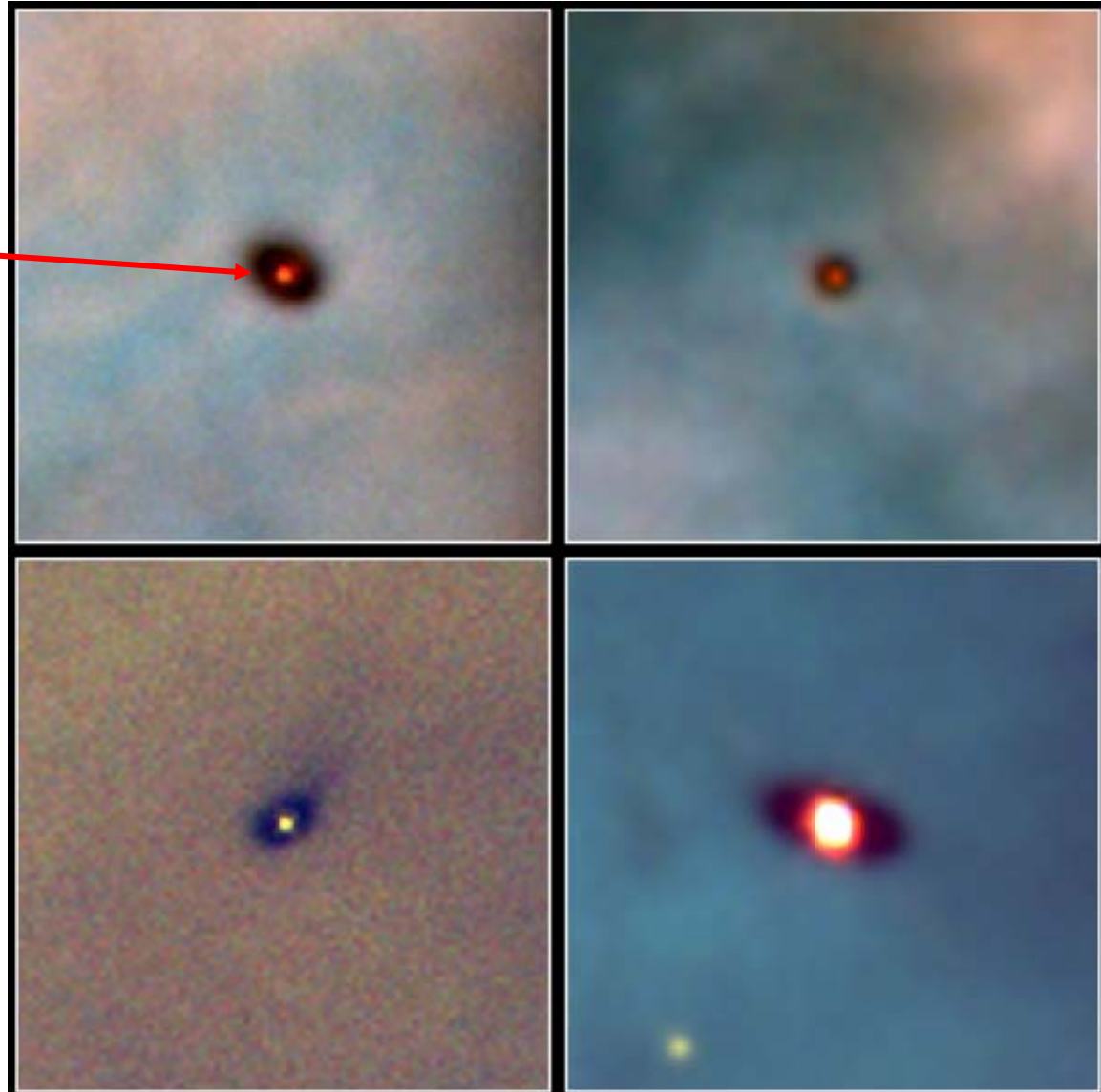
$10^4 \text{ cm}^{-3}$

Atoms →  
molecules

sites of star  
formation



Full of  
molecules



**Protoplanetary Disks  
Orion Nebula**

**HST · WFPC2**

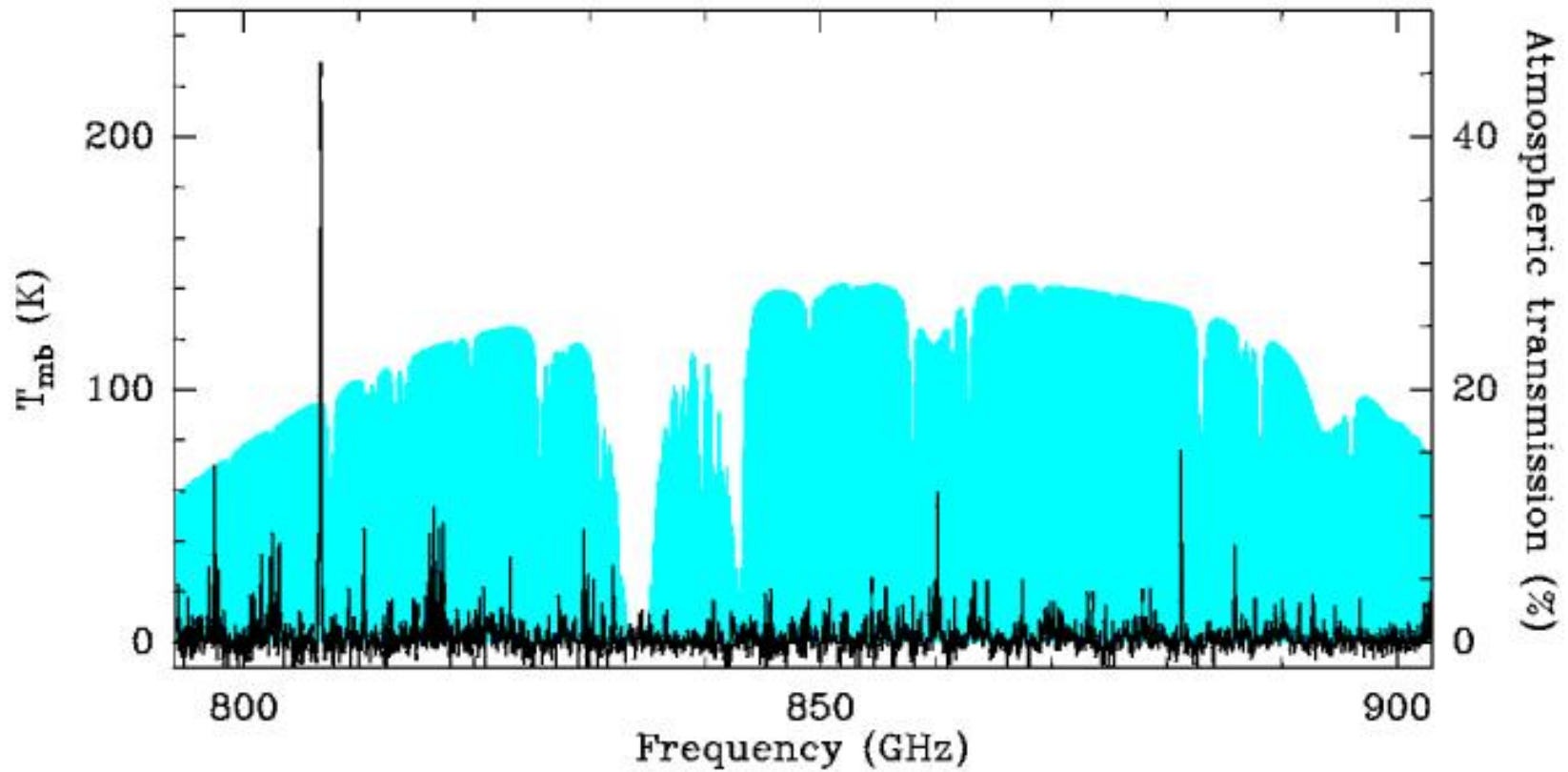
PRC95-45b · ST ScI OPO · November 20, 1995

M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

# Gaseous Interstellar Molecules

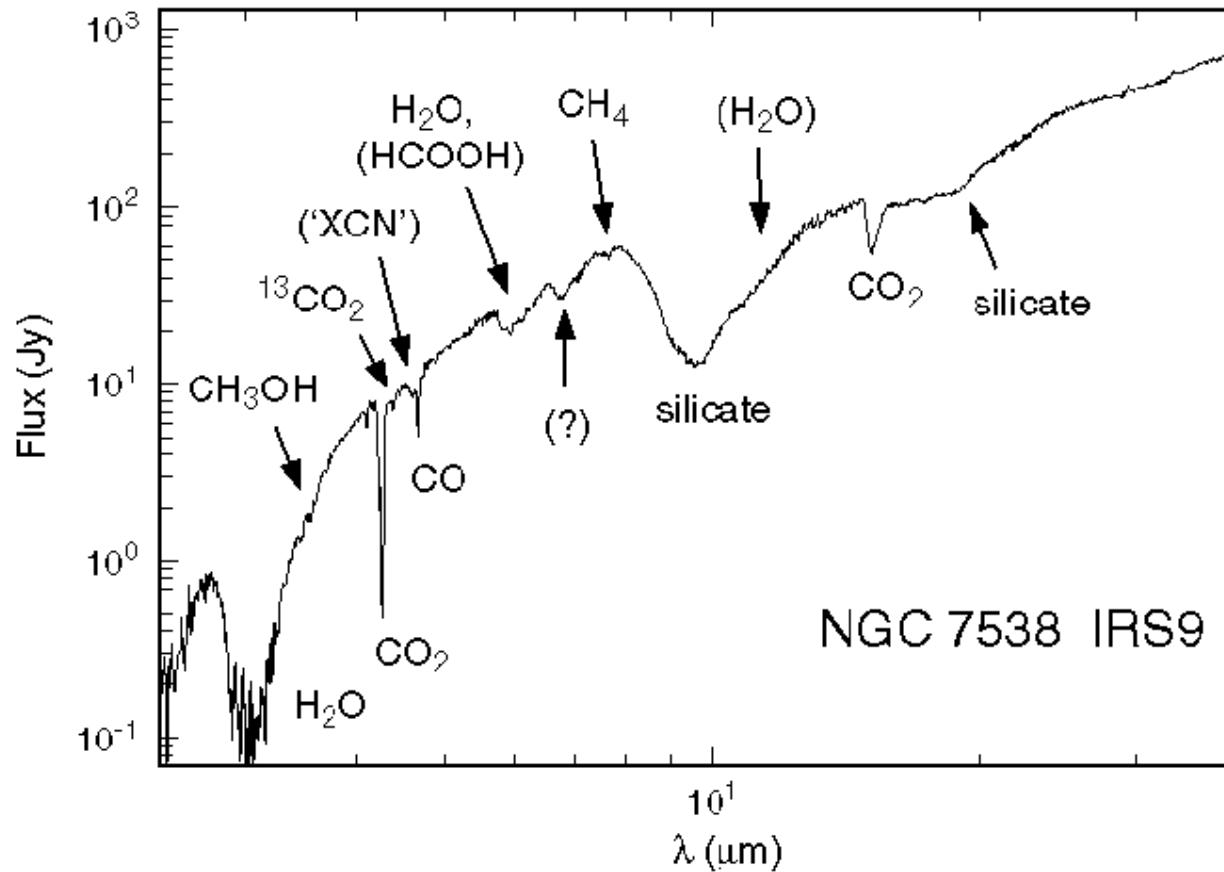
N=2	N=2	N=3	N=3	N=4	N = 5	N = 6	N = 7	N = 8	N = 9	N = 10
H <sub>2</sub>	AlCl	H <sub>3</sub> <sup>+</sup>	CO <sub>2</sub>	NH <sub>3</sub>	CH <sub>4</sub>	CH <sub>3</sub> OH	CH <sub>3</sub> NH <sub>2</sub>	HCOOCH <sub>3</sub>	(CH <sub>3</sub> ) <sub>2</sub> O	(CH <sub>3</sub> ) <sub>2</sub> CO
CH	PN	CH <sub>2</sub>	OCS	H <sub>3</sub> O <sup>+</sup>	SiH <sub>4</sub>	CH <sub>3</sub> SH	CH <sub>3</sub> CCH	CH <sub>3</sub> C <sub>2</sub> CN	C <sub>2</sub> H <sub>5</sub> OH	CH <sub>3</sub> C <sub>4</sub> CN
CH <sup>+</sup>	SiN	NH <sub>2</sub>	MgCN	H <sub>2</sub> CO	CH <sub>2</sub> NH	C <sub>2</sub> H <sub>4</sub>	CH <sub>3</sub> CHO	C <sub>6</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>5</sub> CN	?glycine?
NH	SiO	H <sub>2</sub> O	MgNC	H <sub>2</sub> CS	H <sub>2</sub> C <sub>3</sub>	CH <sub>3</sub> CN	c-CH <sub>2</sub> OCH <sub>2</sub>	C <sub>7</sub> H	CH <sub>3</sub> C <sub>4</sub> H	CH <sub>3</sub> CH <sub>2</sub> CHO
OH	SiS	H <sub>2</sub> S	NaCN	<i>l</i> -C <sub>3</sub> H	<i>l</i> -C <sub>3</sub> H <sub>2</sub>	CH <sub>3</sub> NC	CH <sub>2</sub> CHCN	HOCH <sub>2</sub> CHO	C <sub>8</sub> H	(CH <sub>2</sub> OH) <sub>2</sub>
HF	CO <sup>+</sup>	C <sub>2</sub> H	SO <sub>2</sub>	c-C <sub>3</sub> H	c-C <sub>3</sub> H <sub>2</sub>	H <sub>2</sub> CCHO	HC <sub>4</sub> CN	CH <sub>3</sub> COOH	HC <sub>6</sub> CN	
C <sub>2</sub>	SO <sup>+</sup>	HCN	N <sub>2</sub> O	HCCH	H <sub>2</sub> CCN	NH <sub>2</sub> CHO	C <sub>6</sub> H	H <sub>2</sub> CCCHCN	CH <sub>3</sub> CONH <sub>2</sub>	
CN	PO	HNC	SiCN	HCNH <sup>+</sup>	H <sub>2</sub> NCN	HC <sub>3</sub> NH <sup>+</sup>	H <sub>2</sub> CCHOH	H <sub>2</sub> C <sub>6</sub>		
CO	SH	HCO	AlNC	H <sub>2</sub> CN	CH <sub>2</sub> CO	H <sub>2</sub> C <sub>4</sub>		CH <sub>2</sub> CHCHO		N = 11
CS	AlF	HCO <sup>+</sup>	c-SiC <sub>2</sub>	c-C <sub>3</sub> H	HCOOH	C <sub>5</sub> H	C <sub>6</sub> H <sup>-</sup>			HC <sub>8</sub> CN
CP	FeO	HOC <sup>+</sup>	SiNC	HCCN	C <sub>4</sub> H	C <sub>5</sub> N				CH <sub>3</sub> C <sub>6</sub> H
NO	SiC	HN <sub>2</sub> <sup>+</sup>		HNCO	HC <sub>2</sub> CN	C <sub>5</sub> O				N = 12
NS	CF <sup>+</sup>	HNO	H <sub>2</sub> D <sup>+</sup>	HOCO <sup>+</sup>	HC <sub>2</sub> NC	C <sub>5</sub> S				C <sub>6</sub> H <sub>6</sub>
SO	? N <sub>2</sub> ?	HCS <sup>+</sup>	HD <sub>2</sub> <sup>+</sup>	HNCS	C <sub>4</sub> Si	CH <sub>2</sub> CNH				
HCl		C <sub>3</sub>	DCO <sup>+</sup>	C <sub>2</sub> CN	C <sub>5</sub>	c-H <sub>2</sub> C <sub>3</sub> O				N = 13
NaCl		C <sub>2</sub> O		C <sub>3</sub> O	C <sub>4</sub> N					HC <sub>10</sub> CN
KCl		C <sub>2</sub> S		C <sub>3</sub> S	H <sub>2</sub> COH <sup>+</sup>					
				SiC <sub>3</sub>						

# A Core in Orion



Gas-phase rotational emission spectra

# IR Absorption Spectrum through Cold Dense Cloud Core

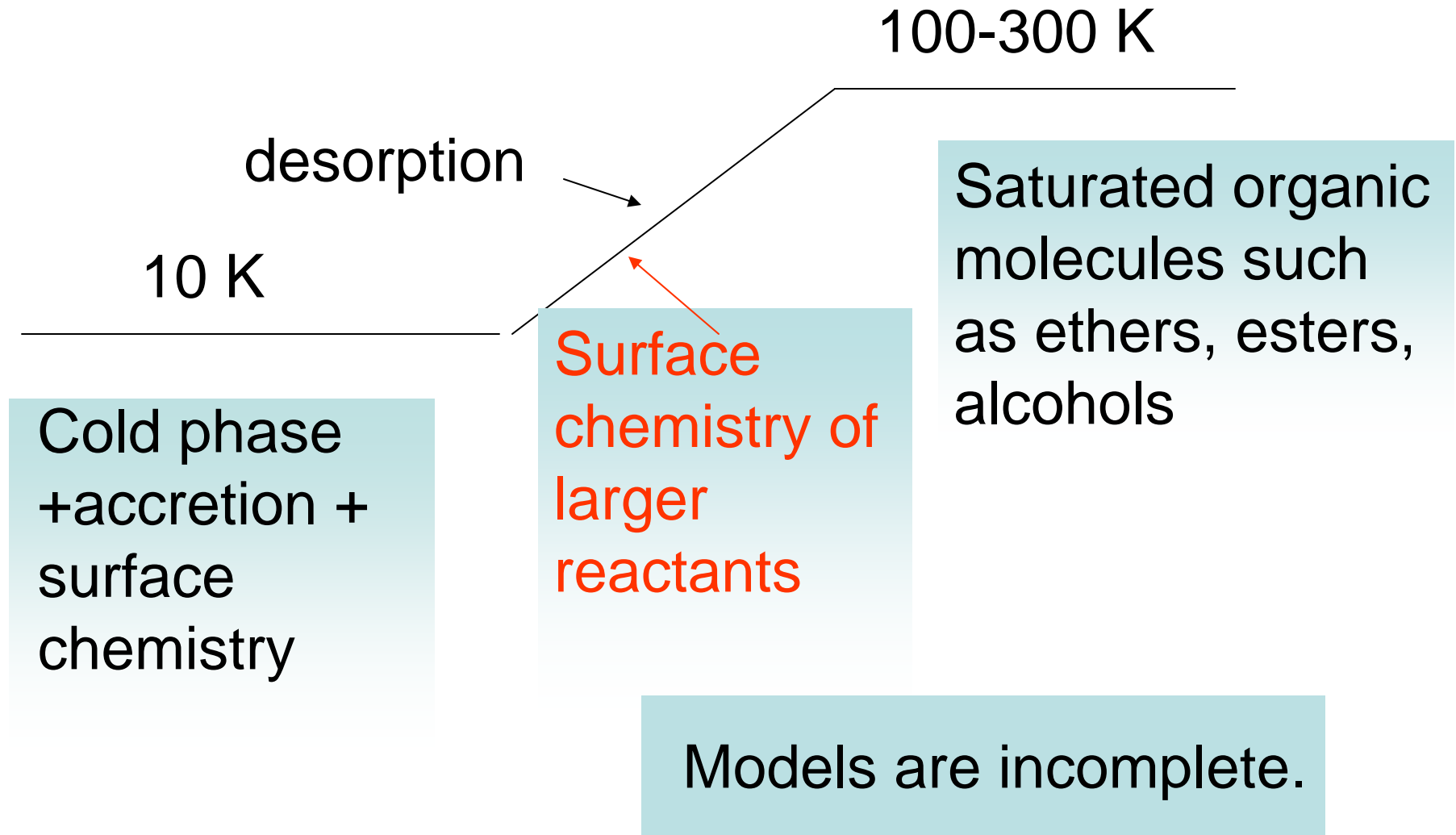


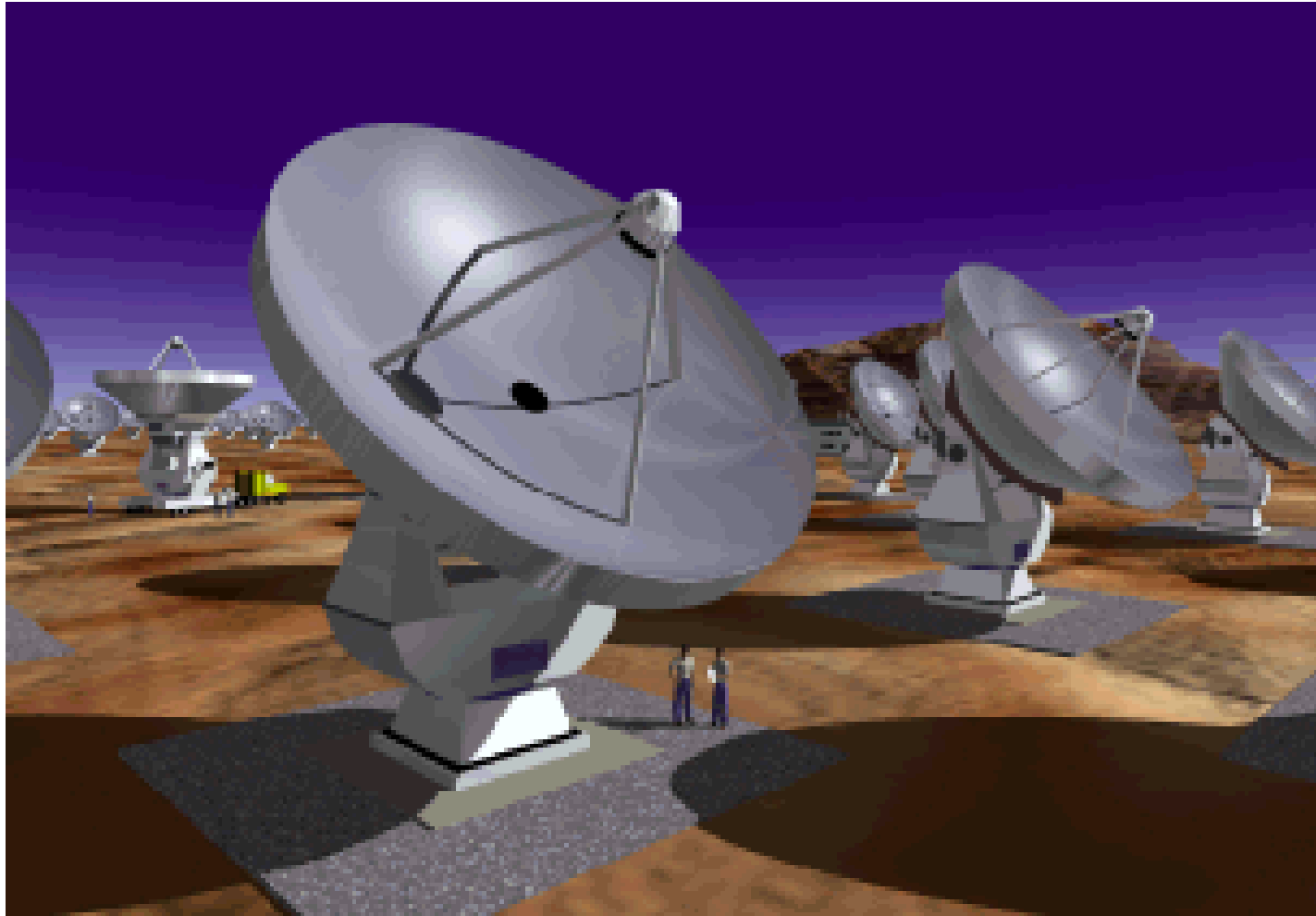
Dominant Mantle Species: water,  $\text{CO}_2$ , CO,  $\text{CH}_3\text{OH}$

## Highlights of Cold Phase Chemistry

- Ion-molecule gas-phase chemistry leading to **exotic and unsaturated (H-poor species)**; these reactions have no activation energy and can occur at 10 K. Ionization is caused by cosmic rays.
- Surface chemistry leading to H<sub>2</sub> and ices, including water and methanol (**H-rich**).
- Large models can simulate chemistry successfully.

# Protostellar Chemistry





ALMA: Higher spatial resolution & intensity

# CONCLUSIONS

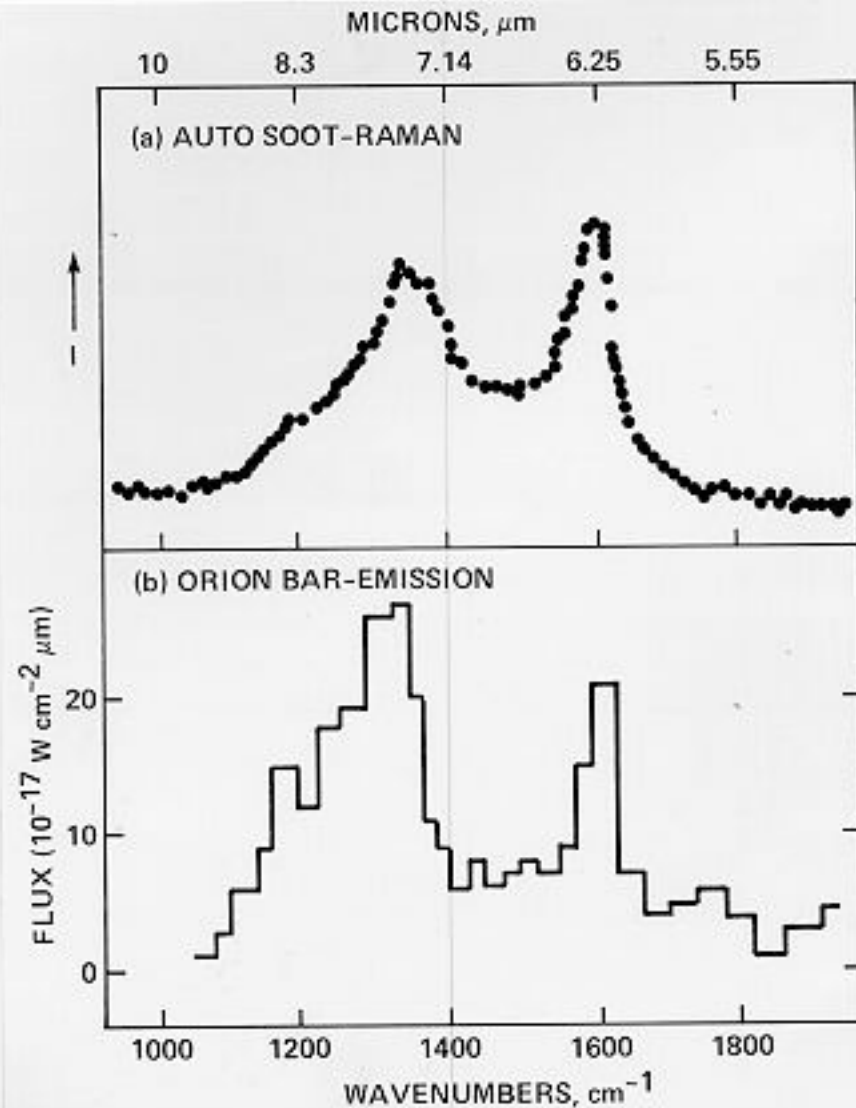
- The chemistry of the interstellar medium is a precursor of terrestrial chemistry.
- The exotic chemistry of cold cores is well understood.
- The formation of saturated organic molecules in protostellar regions is not well understood.
- New telescopes such as ALMA will detect complex molecules on small spatial scales!



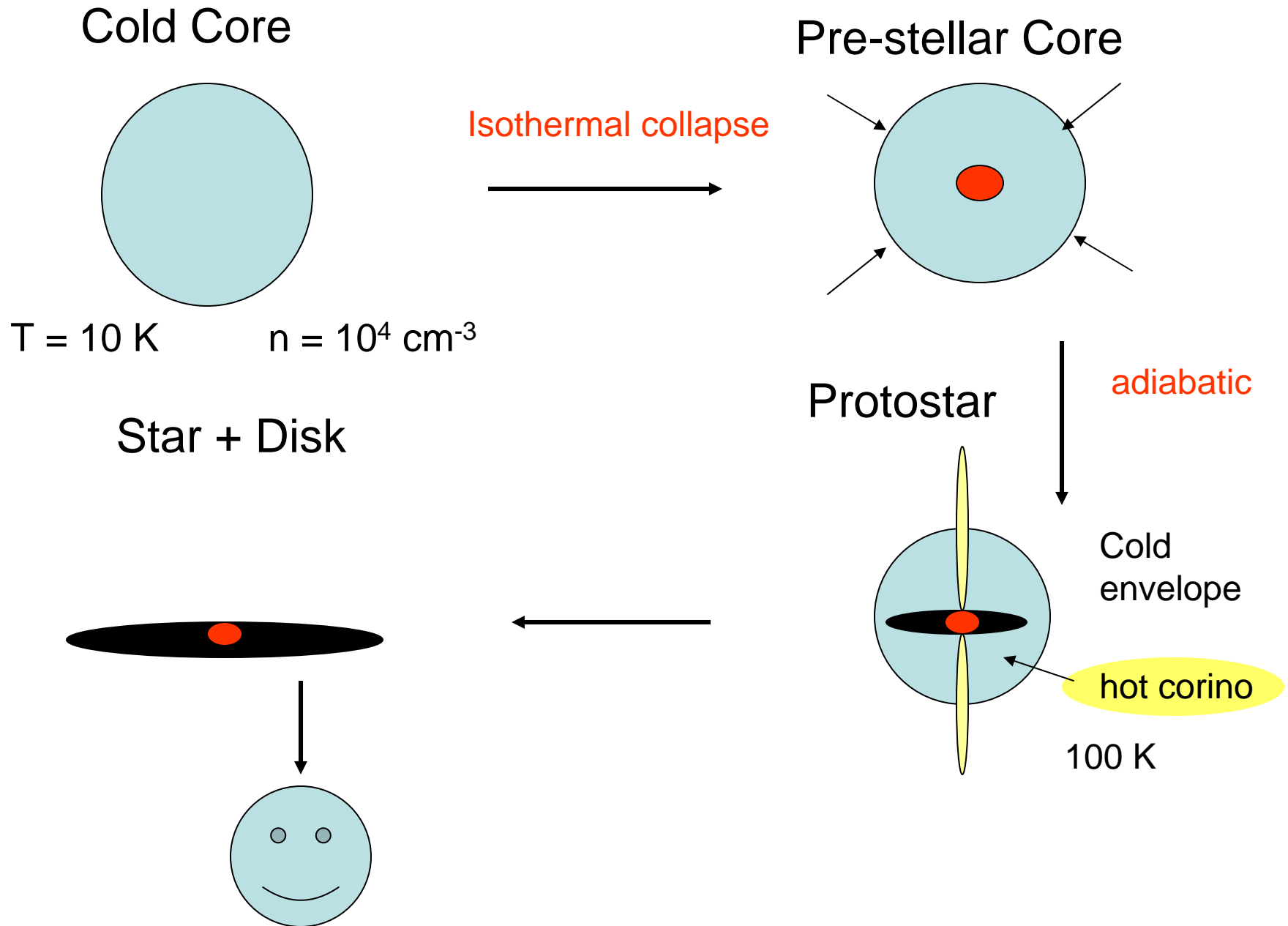
Low resolution IR spectra:  
PAH's found near sources of visible and UV radiation.

PAH's are probably formed in C-rich stellar atmospheres and blown out into clouds.

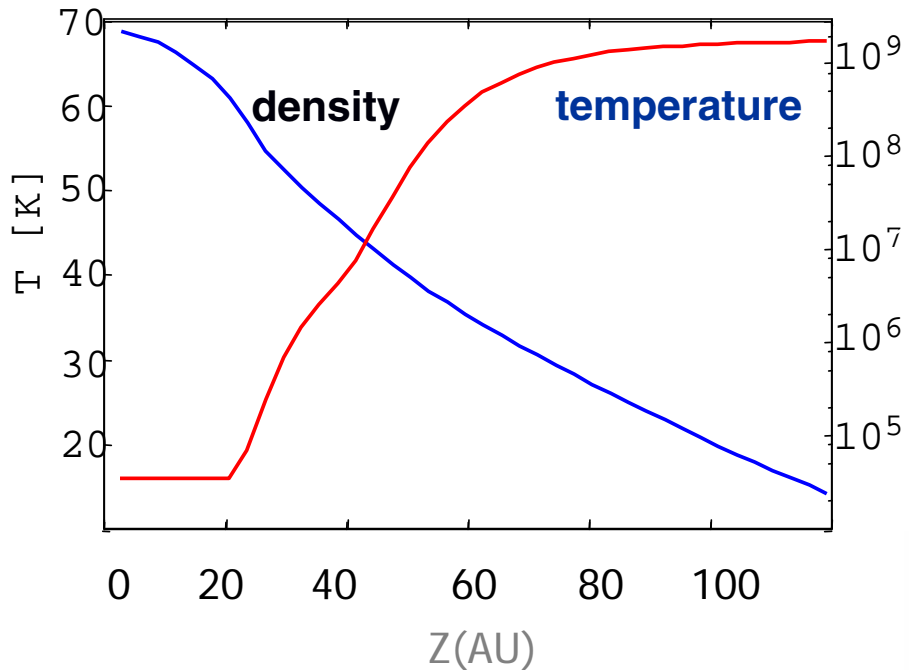
### ORION EMISSION COMPARED TO THE RAMAN SPECTRUM OF AUTO SOOT



# The Formation of a Single Solar-mass Star



# Vertical Distribution

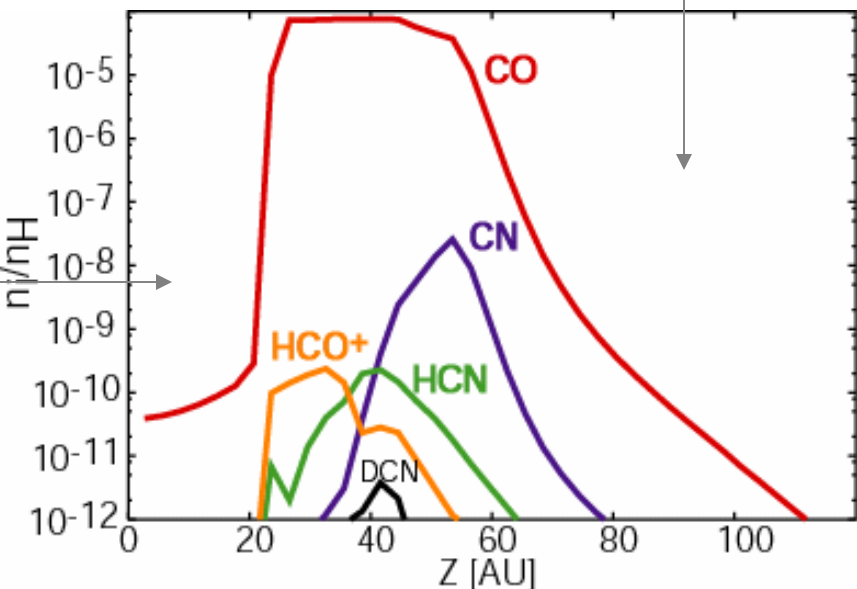


$R = 100 \text{ AU}$

photodissociation

accretion

Too detailed for observers



Icy Layer   Molecular Layer   PDR