Cosmic Evolution, Part II

Heavy Elements to Molecules

Heavy elements → molecules

First a review of terminology:

Element → Atom

Compound → Molecule → Atom (Electromagnetic)

Atom → Electrons, Nucleus (Electro-magnetic)

Nucleus → Protons, Neutrons (Strong Nuclear)

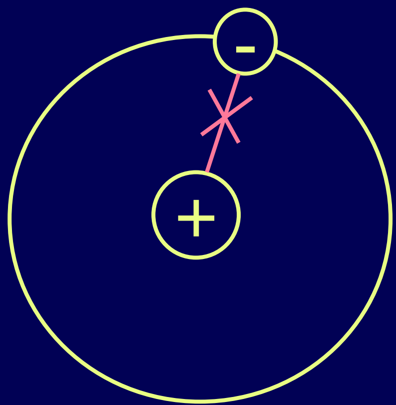
Neutral atom: # Electrons = # protons

ion: $\neq$

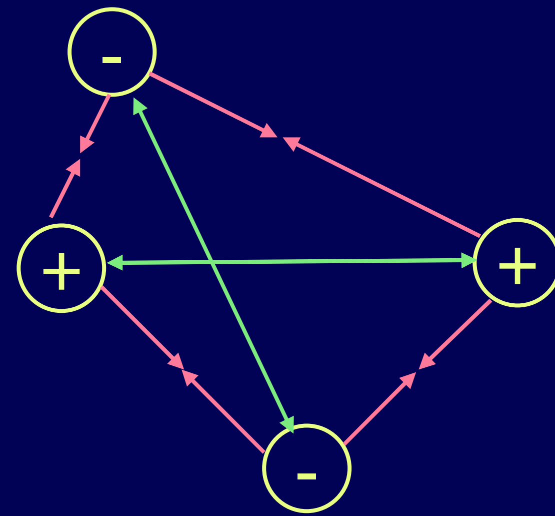
e.g. C^{+2} Carbon nucleus + 4 (6-2) electrons

Forces

H atom



H_2
Molecule



Attractive Repulsive

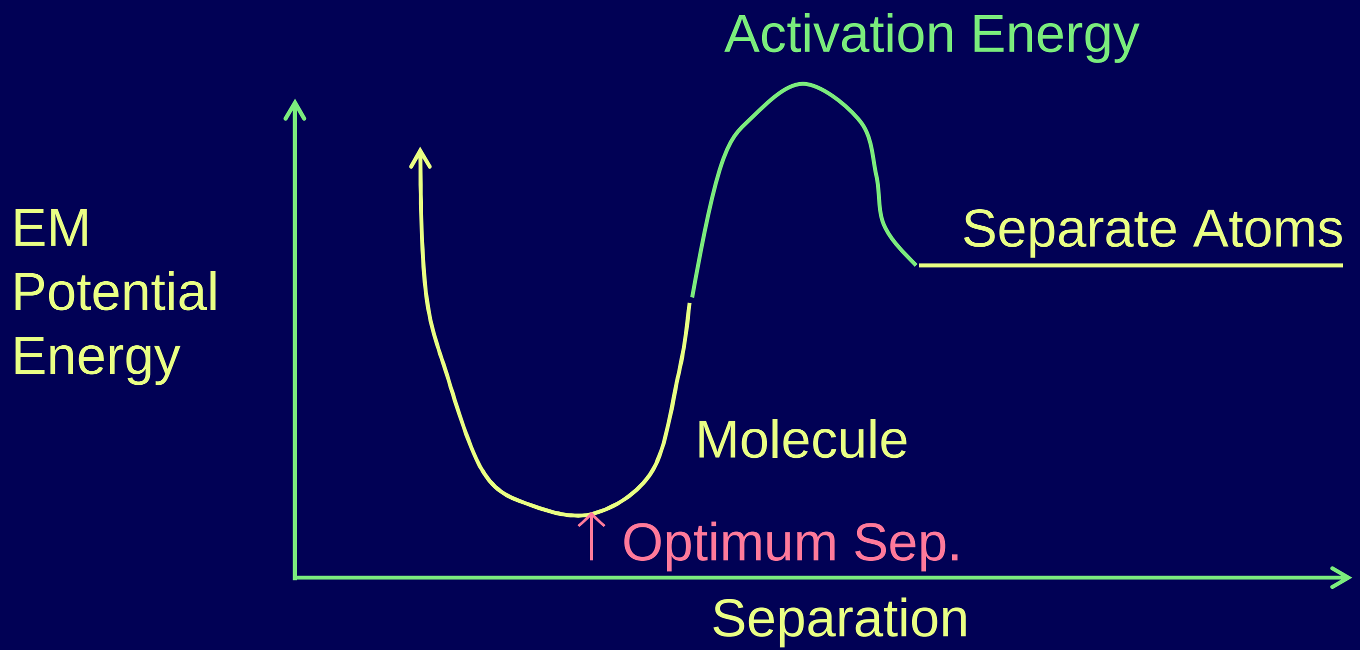
Molecule: Repulsive ~ Attractive

More delicate than atoms,
can be <u>much</u> more complex

“Bond” is sharing of electrons

Is molecule stable?

Yes, if EM potential energy less than separate atoms



Activation energy lower $\rightarrow$ T ~ 100 - 1000 K

(Room Temperature)

Questions

- Why is room temperature around 300 K?
- How commonly is this temperature found in the Universe?

Conventions:

H_2	$H - H$	CO_2	$O = C = O$
	Bond		Double Bonds

Maximum # of Bonds:

H	1
O	2
N	3
C	4

Carbon very versatile

$\rightarrow$ Complex chemistry

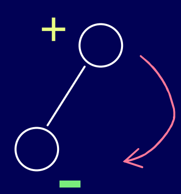
Interstellar Molecules

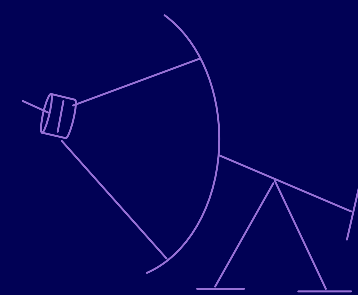
Exist as gas (individual molecules)

A few known in 1930's

Many more since 1968 - Radio astronomy

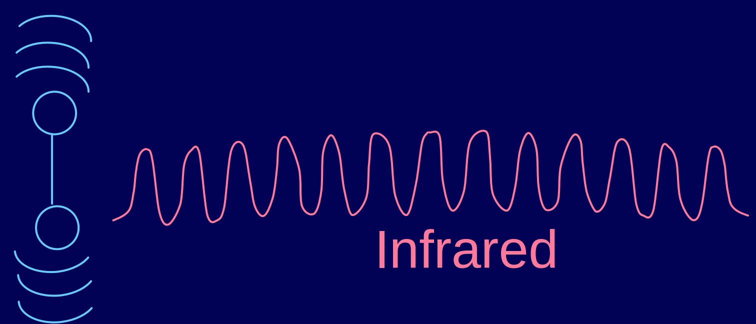
Rotation

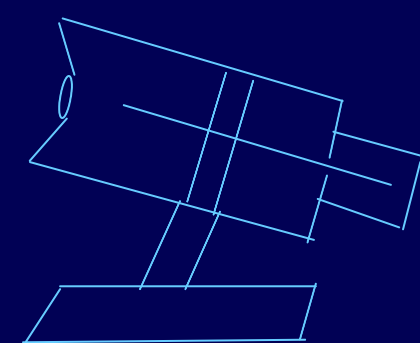




Radio Telescope

Vibration



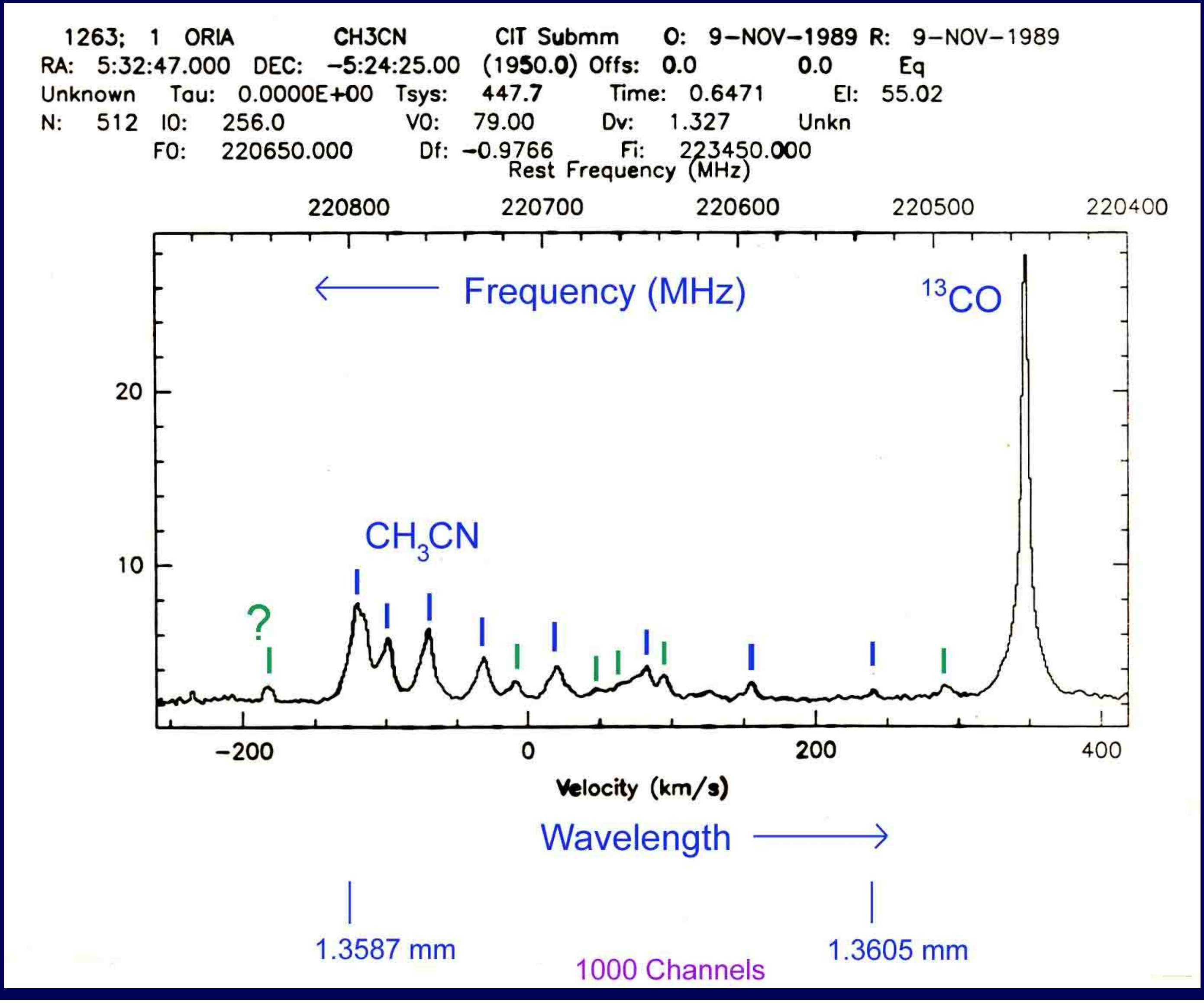


Optical Telescope

How we detect Interstellar Molecules

Radio Spectroscopy (Mostly λ ~ 1- 3 mm)

+ Precise knowledge of wavelengths for different molecules



Appendix 2

Interstellar Molecules

Species	Name	Species	Name
H_2	molecular hydrogen	CO_2	carbon dioxide
C_2	diatomic carbon	OCS	carbonyl sulfide
CH	methylidyne	SO_2	sulfur dioxide
CH^+	methylidyne ion	SiC_2	silicon dicarbide*
CN	cyanogen	SiCN	
CO	carbon monoxide	AlCN	
CO^+	carbon monoxide ion	C_2S	
CS	carbon monosulfide	C_2O	dicarbon monoxide †
OH	hydroxyl	C_3	triatomic carbon*
HCl	hydrogen chloride	MgCN	magnesium cyanide*
NH		MgNC	magnesium isocyanide*
NO	nitric oxide	NaCN	sodium cyanide*
NS	nitrogen sulfide	C_2H_2	acetylene
SiC	silicon carbide*	C_3H	propynylidyne (l and c)
SiO	silicon monoxide	H_2CO	formaldehyde
SiS	silicon sulfide	H_2CN	
SiN	silicon nitride	HC_2N	
SO	sulfur monoxide	NH_3	ammonia
PN		HNCO	isocyanic acid
CP	*	$HOCO^+$	
SO^+	sulfoxide ion	$HCNH^+$	
NaCl	sodium chloride*	HNCS	isothiocyanic acid
AlCl	aluminum chloride*	C_3N	cyanoethynyl
KCl	potassium chloride*	C_3O	tricarbon monoxide
AlF	aluminum fluoride*†	C_3S	
FeO	iron monoxide	H_2CS	thioformaldehyde
HF		H_3O^+	hydronium ion
SH		SiC_3	
H_3^+	protonated hydrogen	C_4H	butadiynyl
C_2H	ethynyl	C_3H_2	cyclopropenylidene
CH_2	methylene †	H_2CCC	propadienylidene
HCN	hydrogen cyanide	HCOOH	formic acid
HNC	hydrogen isocyanide	CH_2CO	ketene
HCO	formyl	HC_3N	cyanoacetylene
HCO^+	formyl ion	HNC_3	
HCS^+	thioformyl ion	CH_2CN	cyanomethyl
HOC^+	isoformyl ion †	NH_2CN	cyanamide
N_2H^+	protonated nitrogen	CH_2NH	methanimine
HNO	nitroxyl	HC_2NC	
H_2O	water	CH_4	methane
H_2S	hydrogen sulfide		
H_2N	hydrogen nitride		
N_2O	nitrous oxide		

Molecular Ions

Species	Name	Species	Name
H_2COH^+	protonated formaldehyde	HC_5N	cyanodiacetylene
SiH_4	silane*	C_7H	
C_4Si	*	$HCOOCH_3$	methyl formate
C_5	pentatomic carbon*	CH_3C_3N	methylcyanoacetylene
C_5H	pentynylidyne	CH_3COOH	acetic acid
C_5N		H_2C_6	
C_2H_4	ethylene*	CH_2OHCHO	glycolaldehyde
H_2CCCC	butatrienylidene	CH_3C_4H	methyldiacetylene
CH_3OH	methanol	CH_3CH_3O	dimethyl ether
CH_3CN	methyl cyanide	CH_3CH_2CN	ethyl cyanide
CH_3NC	methyl isocyanide	CH_3CH_2OH	ethanol
CH_3SH	methyl mercaptan	HC_7N	cyanohexatriyne
NH_2CHO	formamide	C_8H	
HC_3HO	propynal	CH_3C_4CN	†
HC_3NH^+		CH_3CH_3CO	acetone
C_6H		NH_2CH_2COOH	glycine†
CH_2CHCN	vinyl cyanide	CH_2OHCH_2OH	ethylene glycol
CH_3C_2H	methylacetylene	HC_9N	cyano-octa-tetra-yne
CH_3CHO	acetaldehyde	$HC_{11}N$	cyano-deca-penta-yne
CH_3NH_2	methylamine		
C_2H_4O	ethylene oxide		
CH_2CHOH	vinyl alcohol		

* Detected in circumstellar envelopes only
† tentative

Look at Appendix 2

Important Probe of conditions

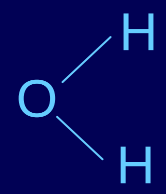
Discovered in Infrared

Discovered in UV

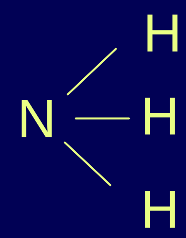
Relevant to the Origin of Life

Important Examples:

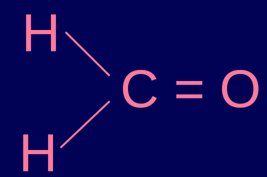
Water H_2O



Ammonia NH_3



Formaldehyde H_2CO



Others of Note: CO Most common after H_2

HCN, HC_3N, … $HC_{11}N$ $\rightarrow$ Carbon chains

CH_4 (Methane)

PAHs (Polycyclic aromatic hydrocarbons)

3 Lessons

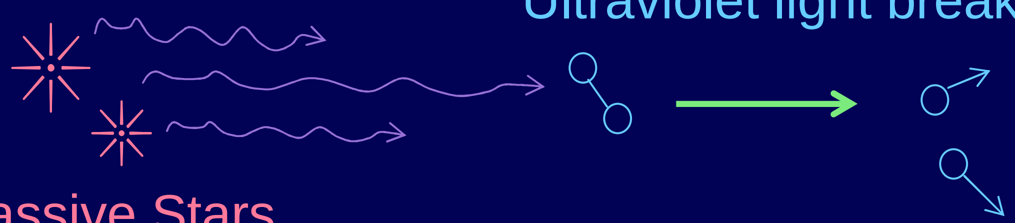
1. Complexity (Up to 13 - atoms) is extraterrestrial
   May be more complex (Hard to detect)
   Glycine ? 1994
   Polycyclic Aromatic Hydrocarbons (PAHs)
   (Infrared evidence)

2. Dominance of Carbon
   Carbon Chemistry not peculiar to Earth

3. Formation & Destruction   Analogous to early Earth

Destruction:

Ultraviolet light breaks bonds



Massive Stars

Protection by dust grains: scatter and absorb ultraviolet

Dust

Studies of how they scatter and absorb light

(Ultraviolet $\longrightarrow$ Visible $\longrightarrow$ Infrared)

$\Longrightarrow$ Two types, range of sizes up to 10^{-6} m

Carbon	Silicates
PAHs $\longrightarrow$ Graphite	Si + O + Mg, Fe, …
~ Soot	

Both Produced by old stars

Formation of Interstellar Molecules

1. H_2

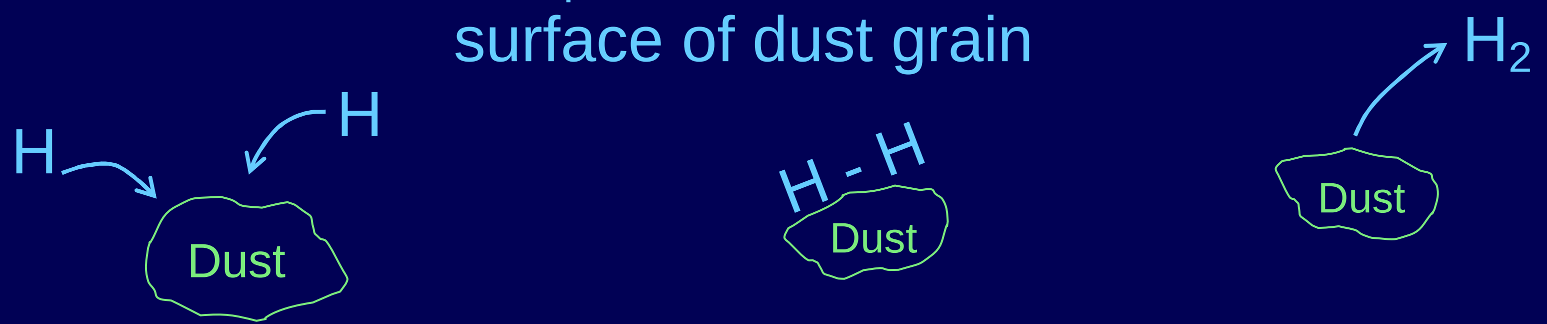
   Must lose the potential energy difference before it falls apart (~ 10^{-14} s)

   Collisions: OK in lab, too slow in space

   Emit photon: <u>very</u> slow for H_2 (10^7 s)

   $H + H + \text{catalyst} = H_2 + \text{catalyst}$

   ↑ surface of dust grain



Formation of Interstellar Molecules

2. More complex molecules

Problem is activation energy barrier

T ~ 10 K << Barrier

Use reactions <u>without</u> activation energies

e.g. Molecular ions, like HCO^+

Energy + simple mol.

$\rightarrow$ Reactive mol.

$\downarrow$

More complex

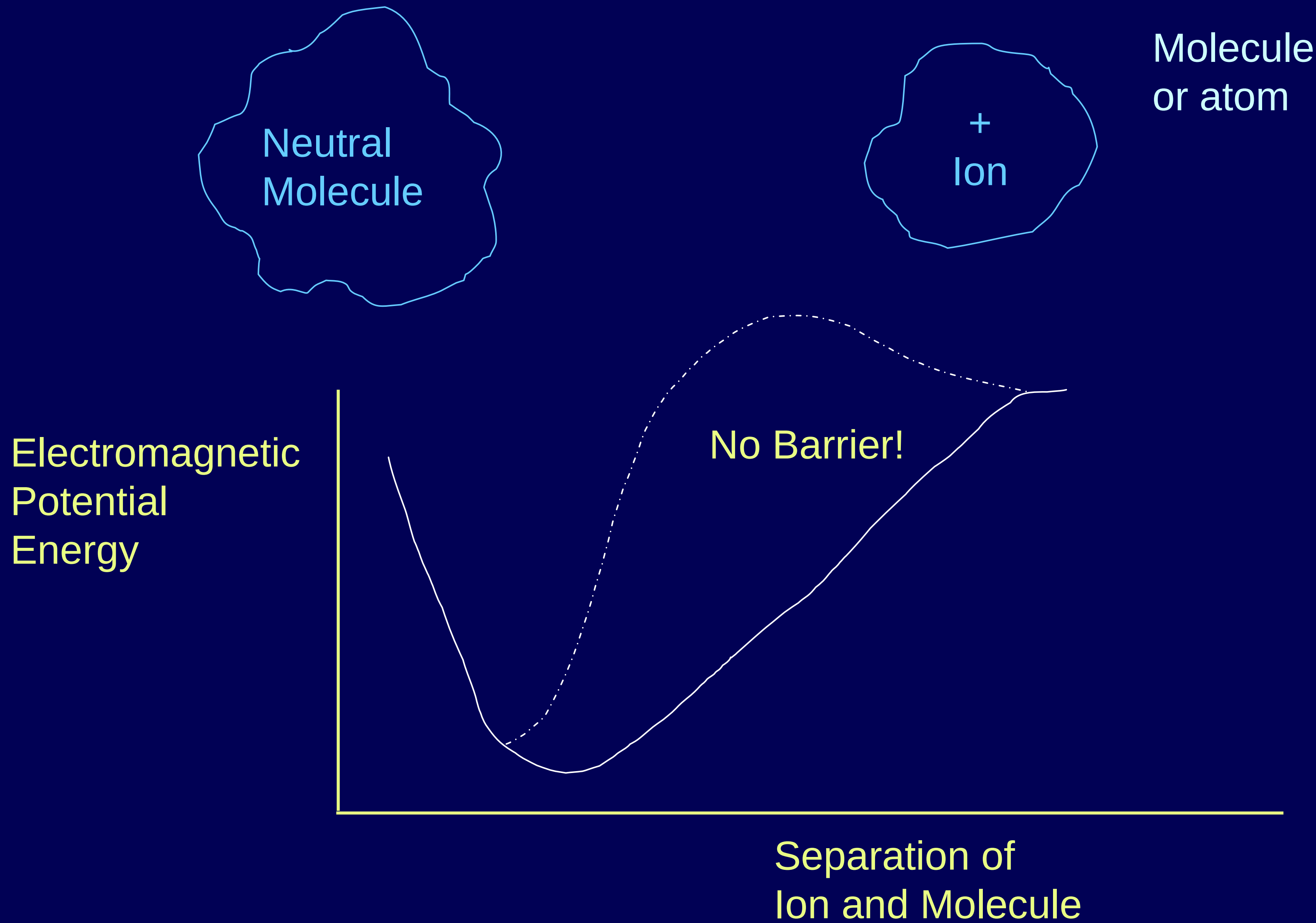
$$\xrightarrow{\text{Cosmic Ray}} \quad H_2 \rightarrow H_2^+$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

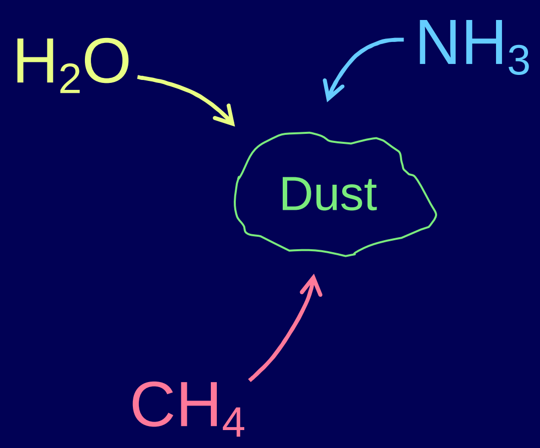
$$H_3^+ + CO \rightarrow HCO^+ + H_2$$

$$XH^+ + e^- \rightarrow X + H$$

Ion - Molecule Reactions



Molecules on Dust Grains



Stick on grains
"ice"

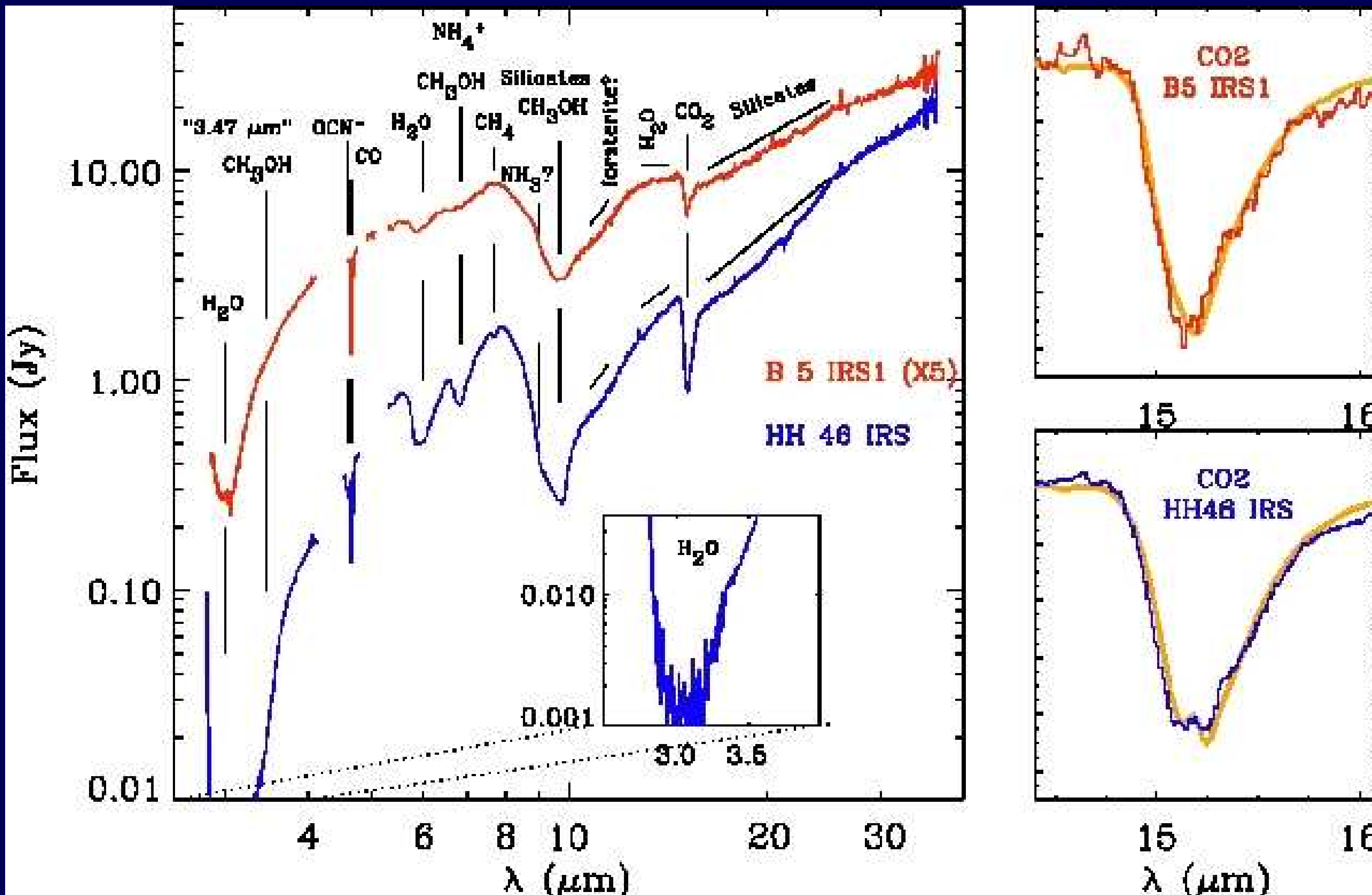
Infrared observations show this: as molecules

Vibrate, absorb infrared

e.g. H_2O absorbs at 3×10^{-6} m

CH_4 absorbs at 8×10^{-6} m

Ices on Dust Grains



Molecules on Dust Grains

Icy "mantles" contain H, O, C, N

Further reactions possible $\rightarrow$ more complex molecules (e.g. Ethanol)

$\rightarrow$ Building blocks of life ?

$\rightarrow$ Life ??? Hoyle and Wickramasinghe

New stars and planets form in same regions

Implications

1. Similar (Carbon-Dominated) Chemistry

2. Direct Role in Origin of Life?

3. Formation + Destruction
   Analogous to Early Earth

Roles of Dust

1. Protection from UV
2. H_2 Formation
3. Depletion $\rightarrow$ Mantles of Ice
   H_2O, NH_3, CH_4, CO_2, HCOOH, …
   $\uparrow$
   Methane

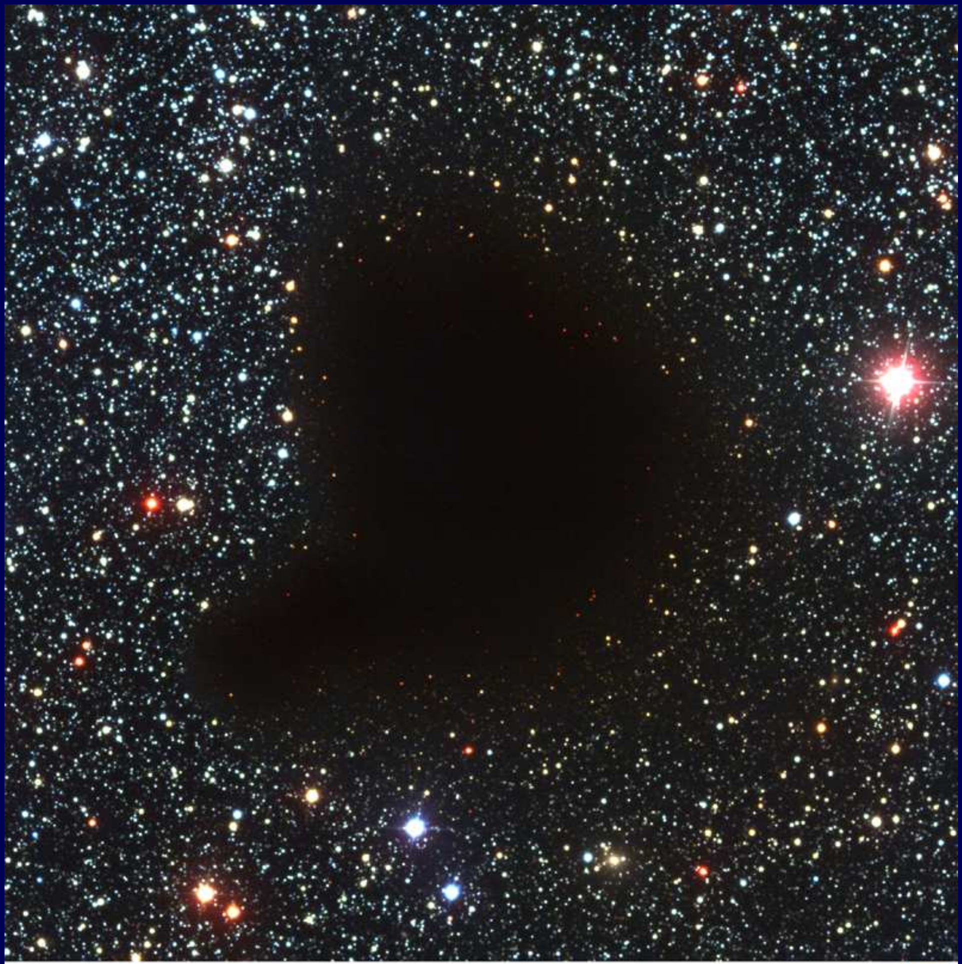
Star Formation

Current Star Formation

Molecular Clouds

- Composition
  - H_2 (93%), He (6%)
  - Dust and other molecules (~1%)
    - CO next most common after H_2, He
- Temperature about 10 K
- Density (particles per cubic cm)
  - ~100 cm^{-3} to 10^6 cm^{-3}
  - Air has about 10^{19} cm^{-3}
  - Water about 3×10^{22} cm^{-3}
- Size 1-300 ly
- Mass 1 to 10^6 M_{sun}

A Small Molecular Cloud



ESO PR Photo 20a/99 (30 April 1999)

The "Black Cloud" B68
(VLT ANTU + FORS1)

Next Class

Details of Star Formation and Rate