Cosmic Evolution, Part II

Heavy Elements to Molecules

First a review of terminology:

Element → Atom

Compound → Molecule

Molecule ← Atom (Electromagnetic)

Atom → Electrons (Electro-magnetic)

Atom → Nucleus

Nucleus → Protons, Neutrons (Strong Nuclear)

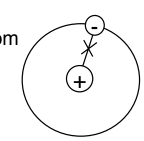
Neutral atom: # Electrons = # protons

ion: # Electrons ≠ # protons

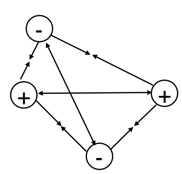
e.g. C^{+2} Carbon nucleus + 4 (6-2) electrons

Forces

H atom



H_2 Molecule

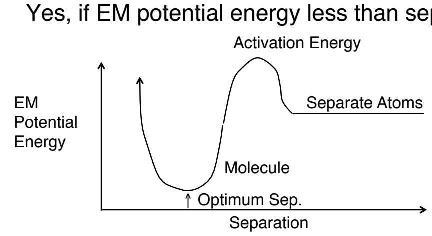


Attractive →← Repulsive ←→

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 → 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 (Bond) CO_2 O = C = O (Double Bonds)

Maximum # of Bonds:

H	1
O	2
N	3
C	4

Carbon very versatile
→ Complex chemistry

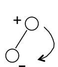
Interstellar Molecules

Exist as gas (individual molecules)

A few known in 1930's

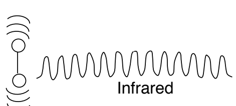
Many more since 1968 - Radio astronomy

Rotation

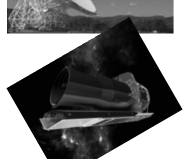


Radio Telescope

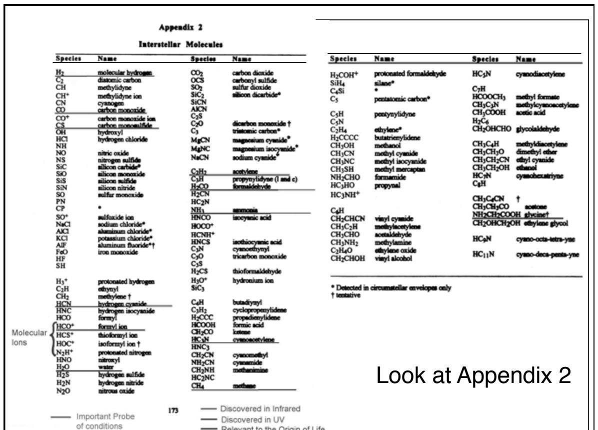
Vibration



Infrared



Infrared Telescope



Appendix 2

Interstellar Molecules

Species	Name
H_2	molecular hydrogen
C_2	diatomic carbon
CH	methylidyne
CH^+	methylidyne ion
CN	cyanogen
CO	carbon monoxide
CO^+	carbon monoxide ion
CS	carbon monosulfide
OH	hydroxyl
HCl	hydrogen chloride
NH	
NO	nitric oxide
NS	nitrogen sulfide
SiC	silicon carbide*
SiO	silicon monoxide
SiS	silicon sulfide
SiN	silicon nitride
SO	sulfur monoxide
PN	
CP	*
SO^+	sulfoxide ion
NaCl	sodium chloride*
AlCl	aluminum chloride*
KCl	potassium chloride*
AlF	aluminum fluoride*†
FeO	iron monoxide
HF	
SH	
H_3^+	protonated hydrogen
C_2H	ethynyl
CH_2	methylene †
HCN	hydrogen cyanide
HNC	hydrogen isocyanide
HCO	formyl
HCO^+	formyl ion
HCS^+	thioformyl ion
HOC^+	isoformyl ion †
N_2H^+	protonated nitrogen
HNO	nitroxyl
H_2O	water
H_2S	hydrogen sulfide
H_2N	hydrogen nitride
N_2O	nitrous oxide

Molecular Ions

Species	Name
CO_2	carbon dioxide
OCS	carbonyl sulfide
SO_2	sulfur dioxide
SiC_2	silicon dicarbide*
SiCN	
AlCN	
C_2S	
C_2O	dicarbon monoxide †
C_3	triatomic carbon*
MgCN	magnesium cyanide*
MgNC	magnesium isocyanide*
NaCN	sodium cyanide*
C_2H_2	acetylene
C_3H	propynylidyne (l and c)
H_2CO	formaldehyde
H_2CN	
HC_2N	
NH_3	ammonia
HNCO	isocyanic acid
$HOCO^+$	
$HCNH^+$	
HNCS	isothiocyanic acid
C_3N	cyanoethynyl
C_3O	tricarbon monoxide
C_3S	
H_2CS	thioformaldehyde
H_3O^+	hydronium ion
SiC_3	
C_4H	butadiynyl
C_3H_2	cyclopropenylidene
H_2CCC	propadienylidene
HCOOH	formic acid
CH_2CO	ketene
HC_3N	cyanoacetylene
HNC_3	
CH_2CN	cyanomethyl
NH_2CN	cyanamide
CH_2NH	methanimine
HC_2NC	
CH_4	methane

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Important Probe of conditions

Discovered in Infrared

Discovered in UV

Relevant to the Origin of Life

Species	Name
H_2COH^+	protonated formaldehyde
SiH_4	silane*
C_4Si	*
C_5	pentatomic carbon*
C_5H	pentynylidyne
C_5N	
C_2H_4	ethylene*
H_2CCCC	butatrienylidene
CH_3OH	methanol
CH_3CN	methyl cyanide
CH_3NC	methyl isocyanide
CH_3SH	methyl mercaptan
NH_2CHO	formamide
HC_3HO	propynal
HC_3NH^+	
C_6H	
CH_2CHCN	vinyl cyanide
CH_3C_2H	methylacetylene
CH_3CHO	acetaldehyde
CH_3NH_2	methylamine
C_2H_4O	ethylene oxide
CH_2CHOH	vinyl alcohol

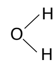
Species	Name
HC_5N	cyanodiacetylene
C_7H	
$HCOOCH_3$	methyl formate
CH_3C_3N	methylcyanoacetylene
CH_3COOH	acetic acid
H_2C_6	
CH_2OHCHO	glycolaldehyde
CH_3C_4H	methyldiacetylene
CH_3CH_3O	dimethyl ether
CH_3CH_2CN	ethyl cyanide
CH_3CH_2OH	ethanol
HC_7N	cyanohexatriyne
C_8H	
CH_3C_4CN	†
CH_3CH_3CO	acetone
NH_2CH_2COOH	glycine†
CH_2OHCH_2OH	ethylene glycol
HC_9N	cyano-octa-tetra-yne
$HC_{11}N$	cyano-deca-penta-yne

* Detected in circumstellar envelopes only
† tentative

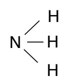
Look at Appendix 2

Important Examples:

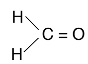
Water H_2O



Ammonia NH_3



Formaldehyde H_2CO



Others of Note: CO Most common after H_2

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

CH_4 (Methane)

PAHs (Polycyclic aromatic hydrocarbons)

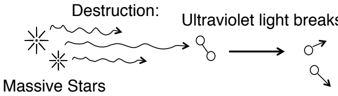
3 Lessons

1. Complexity (Up to 13 - atoms) is extraterrestrial
   May be more complex (Hard to detect)
   Glycine claimed in 1994, but, so far, not confirmed
   Polycyclic Aromatic Hydrocarbons (PAHs)
   (Infrared evidence)

2. Dominance of Carbon
   Carbon Chemistry not peculiar to Earth

3. Formation & Destruction <u>Analogous</u> to early Earth

Destruction: Ultraviolet light breaks bonds



Massive Stars

Protection by dust grains: scatter and absorb ultraviolet

Dust particles

Studies of how they scatter and absorb light
(Ultraviolet → Visible → Infrared)

⇒ Two types, range of sizes up to 10^{-6} m

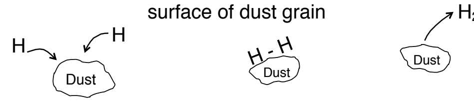
Carbon	Silicates
PAHs → Graphite	Si + O + Mg, Fe, …
~ Soot	

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 + catalyst = H_2 + catalyst
   ↑ surface of dust grain



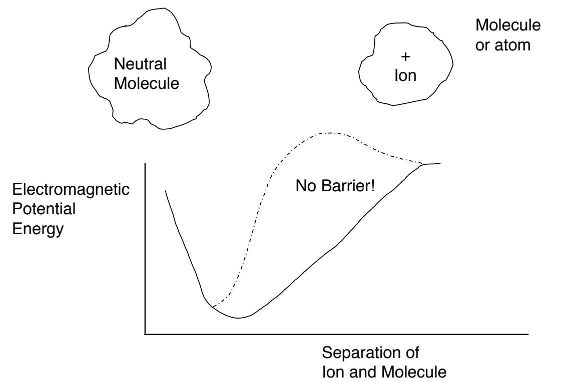
Formation of Interstellar Molecules

2. More complex molecules
   Problem is activation energy barrier
   T ~ 10 K << Barrier
   Use reactions **without** activation energies
   e.g. Molecular ions, like HCO^+

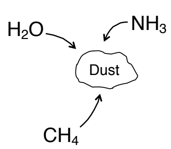
Cosmic Ray
$\xrightarrow{\hspace{2cm}}$ $H_2 \rightarrow H_2^+$
$H_2^+ + H_2 \rightarrow H_3^+ + H$
$H_3^+ + CO \rightarrow HCO^+ + H_2$
$XH^+ + e^- \rightarrow X + H$

Energy + simple mol.
$\rightarrow$ Reactive mol.
$\downarrow$
More complex

Ion - Molecule Reactions



Molecules on Dust Grains

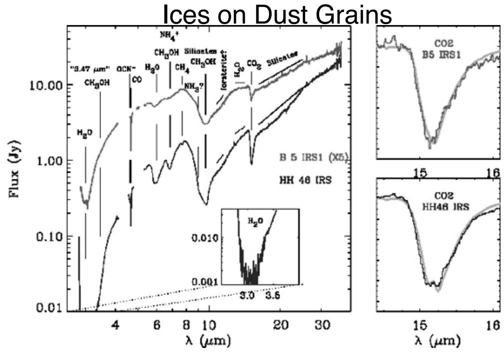


Stick on grains
"ice"

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



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. Freeze-out → Mantles of Ice
   H_2O, NH_3, CH_4, CO_2, HCOOH, …
   ↑ Methane

Star Formation

First factor in Drake Equation: The rate of star formation

Estimate of Average Star Formation Rate ($R_\star$)

$R_\star = \dfrac{\text{\# of stars in galaxy}}{\text{lifetime of galaxy}} = \dfrac{N_\star}{t_{gal}}$

$N_\star$: Count them? No
Use Gravity (Newton's Laws)

Sun orbiting center of galaxy at 250 km s^{-1} (155 miles per second)
update: 269 km s^{-1} reported in Jan. 2009

Kinetic energy = $\frac{1}{2}$ gravitational potential energy

$\frac{1}{2} M_\odot v^2 = \frac{1}{2} \frac{G M_g M_\odot}{R_g}$ ← Distance of Sun from center of galaxy

$\frac{R_g v^2}{G} = M_g$

Estimate of Average Star Formation Rate ($R_\star$)

(R_g = 25,000 ly) → $M_g = 1.0 \times 10^{11} M_\odot$
Update: 28,000 ly gives $1.4 \times 10^{11} M_\odot$

Add stars outside Sun's orbit → $M_g \simeq 1.6 \times 10^{11} M_\odot$
Update: $2.0 \times 10^{11} M_\odot$

$N_\star \simeq \dfrac{M_g}{\text{Avg. mass of star}} = \dfrac{1.6 \times 10^{11}}{0.4} = 4 \times 10^{11}$ (5×10^{11})

$t_{gal} \simeq 10^{10}$ yr (studies of old stars)

$R_\star \simeq \dfrac{4 \times 10^{11}}{10^{10}}$ stars = 40 stars per year (5 - 50)
Update: 50 stars per year

Complicating factors

50 stars per year is an average over history of Milky Way. Current rate is about 5 stars per year. Probably stars formed more rapidly early in history of Milky Way. Any number between 5 and 50 may be correct for our purposes.

Recent work suggests total mass of Milky Way is 3 trillion solar masses ($3 \times 10^{12}\ M_\odot$). This is mostly dark matter outside the orbit of the Sun.

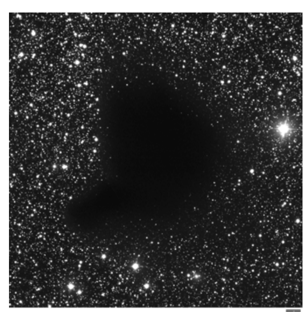
Star Formation

Current Star Formation

Molecular Clouds

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

A Small Molecular Cloud



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

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

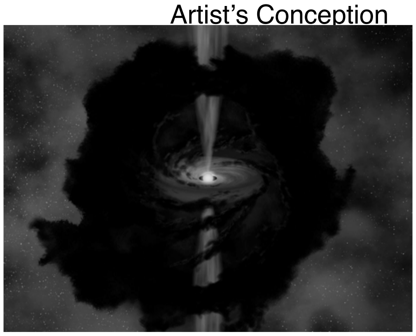
© European Southern Observatory

Current Star Formation

- Occurs in gas with heavy elements
  - Molecules and dust keep gas cool
  - Radiate energy released by collapse
  - Stars of lower mass can form
  - Mass needed for collapse increases with T
- Star formation is ongoing in our Galaxy
  - Massive stars are short-lived
  - Star formation observed in infrared

Visible to Infrared Views

Artist's Conception



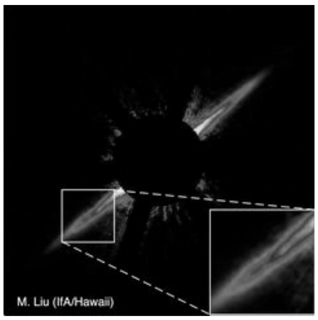
Features:
Dusty envelope
Rotation
Disk
Bipolar outflow

R. Hurt, SSC

The Protostar

- Evolution of the collapsing gas cloud
  - At first, collapsing gas stays cool
  - Dust, gas emit photons, remove energy
  - At $n \sim 10^{11}$ cm^{-3}, photons trapped
  - Gas heats up, dust destroyed, pressure rises
  - Core stops collapsing
  - The outer parts still falling in, adding mass
  - Core shrinks slowly, heats up
  - Fusion begins at $T \sim 10^7$ K
  - Protostar becomes a main-sequence star

The Disk



The Star (AU Mic) is blocked in a coronograph. Allows you to see disk. Dust in disk is heated by star and emits in infrared.

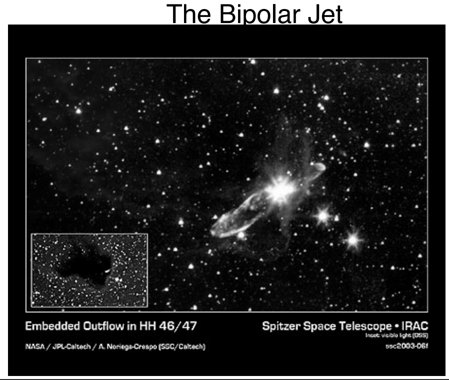
Angular Momentum

- Measure of tendency to rotate
  - J = mvr
- Angular momentum is conserved
  - J = constant
  - As gas contracts (r smaller), v increases
  - Faster rotation resists collapse
  - Gas settles into rotating disk
  - Protostar adds mass through the disk

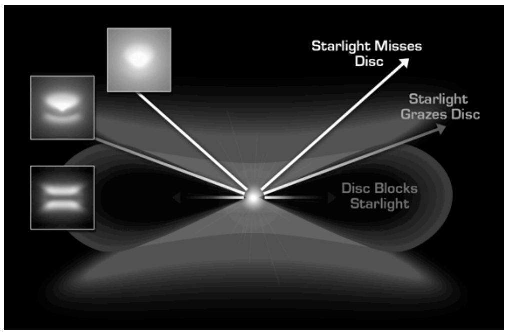
The Wind

- Accretion from disk will spin up the star
  - Star would break apart if spins too fast
- Angular momentum must be carried off
- The star-disk interaction creates a wind
- The wind carries mass to large distances
  - J = mvr, small amount of m at very large r
  - Allows star to avoid rotating too fast
- Wind turns into bipolar jet
  - Sweeps out cavity

The Bipolar Jet



Studying the Disk

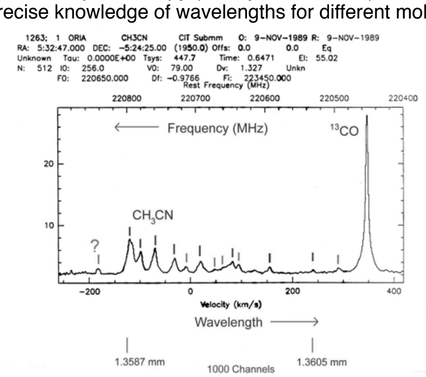


Robert Hurt, SSC

Extra Slides if Time Permits

How we detect Interstellar Molecules

Radio Spectroscopy (Mostly $\lambda \sim$ 1- 3 mm)
+ Precise knowledge of wavelengths for different molecules



Molecules on Dust Grains

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

Further reactions possible → more complex molecules (e.g. Ethanol)

→ Building blocks of life ?

→ Life ??? Hoyle and Wickramasinghe

New stars and planets form in same regions