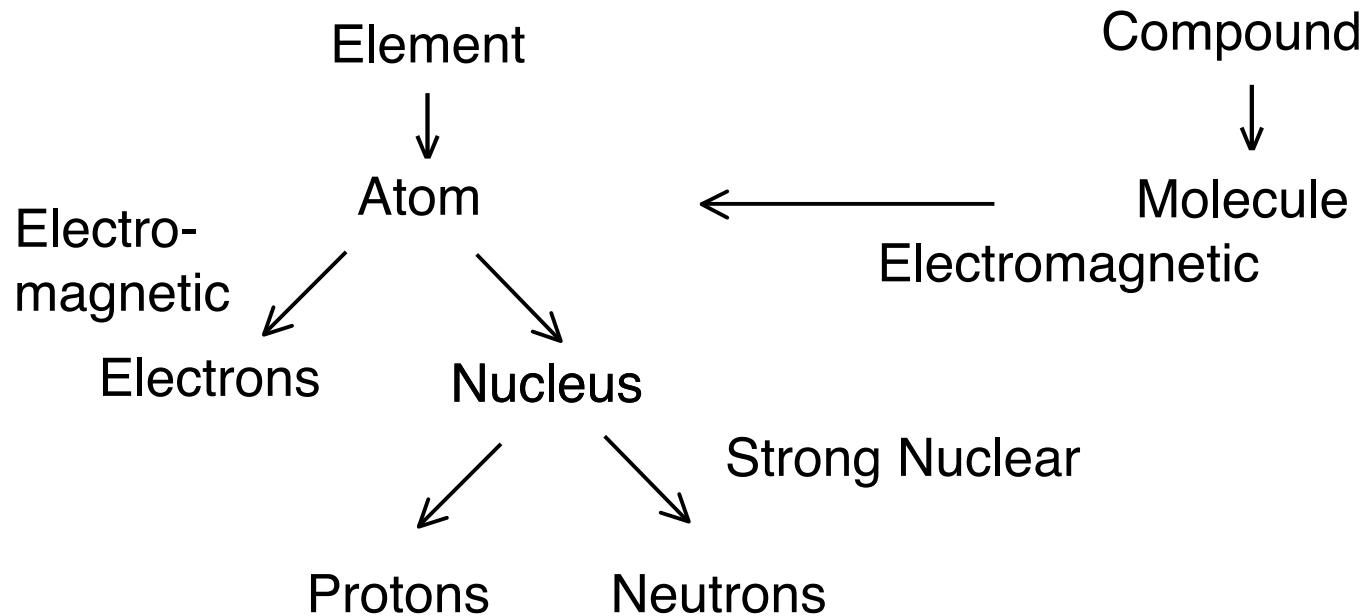


Cosmic Evolution, Part II

Heavy elements → molecules

First a review of terminology:



Neutral atom:
ion:

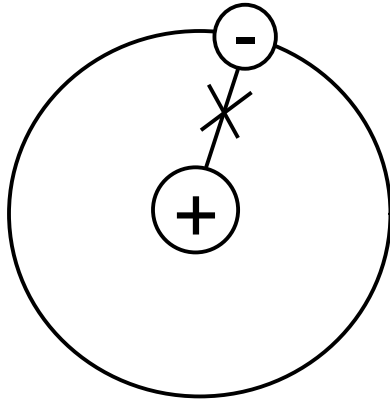
e.g. C^{+2}

Electrons = # protons

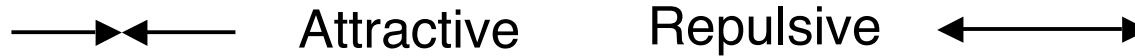
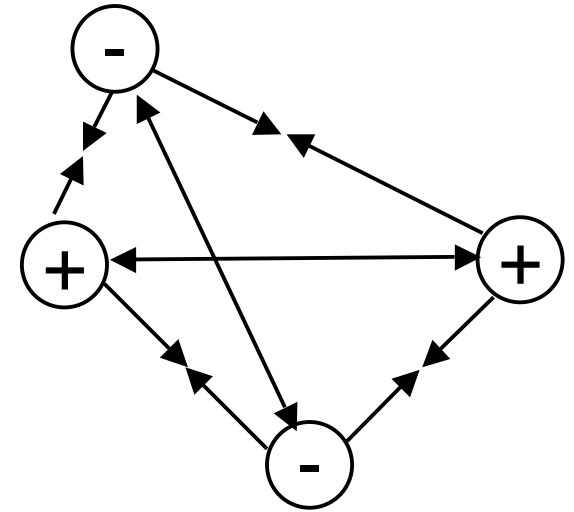


Carbon nucleus + 4 (6-2) electrons

H atom



H₂
Molecule



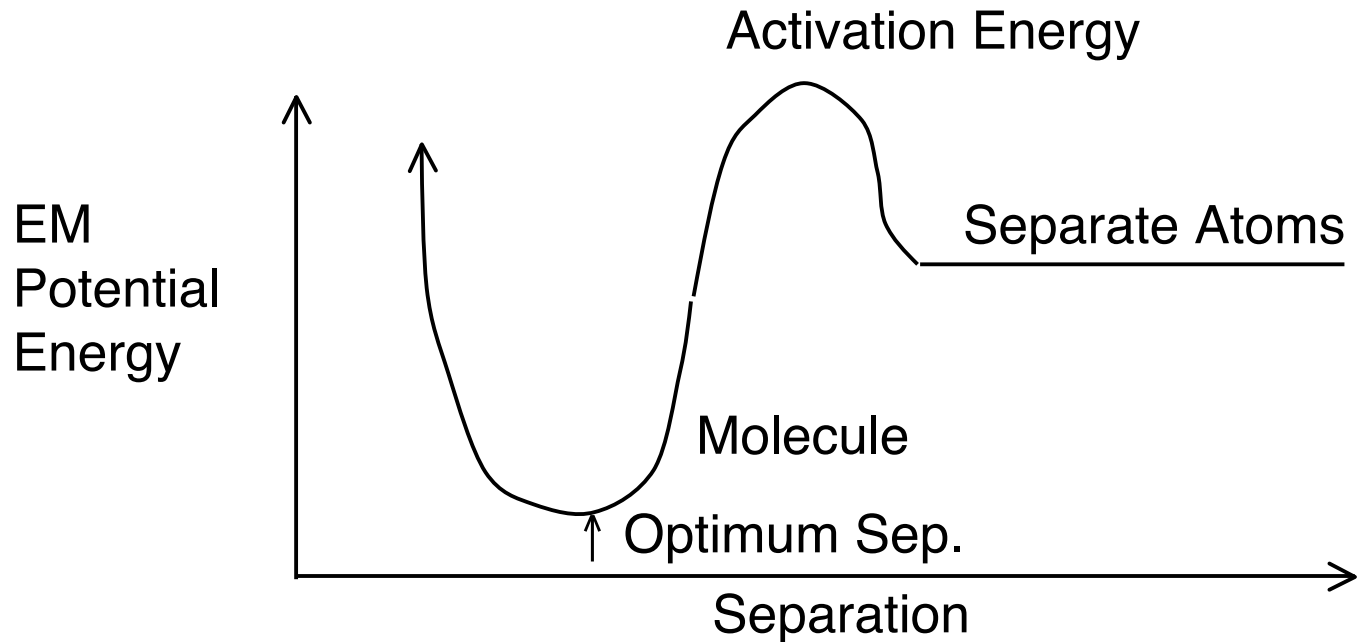
Molecule: Repulsive ~ Attractive

More delicate than atoms
can be much more complex

“Bond” sharing of electrons

Is molecule stable?

Yes, if EM potential energy less than separate atoms

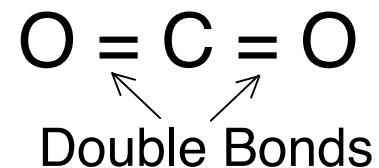
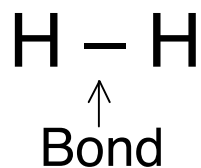
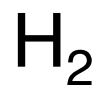


Activation energy lower \rightarrow $T \sim 100 - 1000$ K
(Room Temperature)

Questions

- Why is room temperature around 300 K?

Conventions:



Maximum # of Bonds:

H 1

O 2

N 3

C 4

Carbon very versatile
→ Complex chemistry

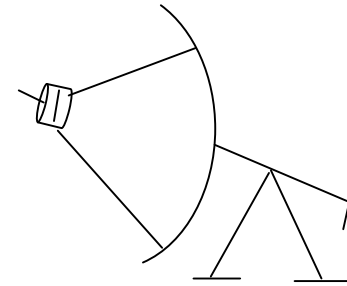
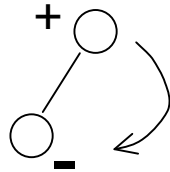
Interstellar Molecules

Exist as gas (individual molecules)

A few known in 1930's

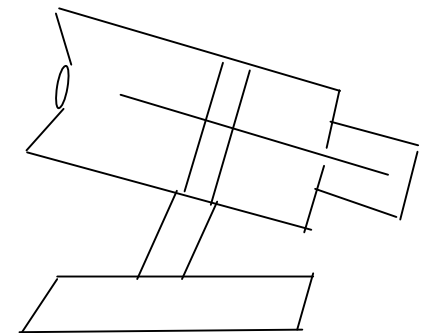
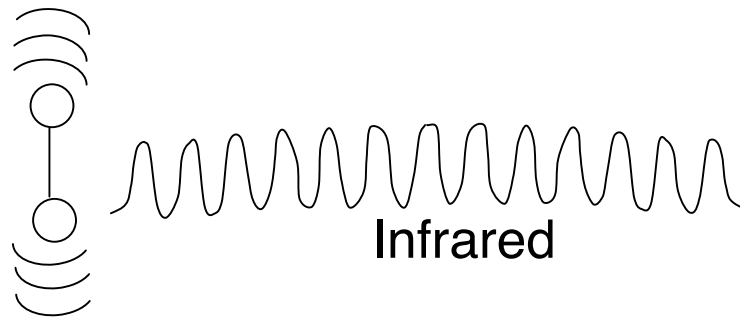
Many more since 1968 - Radio astronomy

Rotation



Radio Telescope

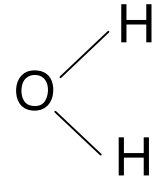
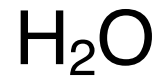
Vibration



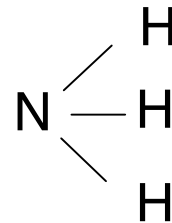
Optical Telescope

Important Examples:

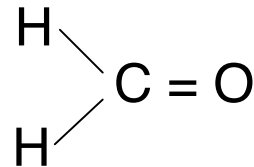
Water



Ammonia



Formaldehyde



Others of Note: CO Most common after H_2

HCN , HC_3N , ... HC_{11}N → Carbon chains

CH_4 (Methane)

PAHs (Polycyclic aromatic hydrocarbons)

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 ₂ S	
CS	carbon monosulfide	C ₂ O	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 ₂ H ₂	acetylene
SiC	silicon carbide*	C ₃ H	propynylidyne (l and c)
SiO	silicon monoxide	H ₂ CO	formaldehyde
SiS	silicon sulfide	H ₂ CN	
SiN	silicon nitride	HC ₂ N	
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 ₃ N	cyclopropynyl
KCl	potassium chloride*	C ₃ O	tricarbon monoxide
AlF	aluminum fluoride*†	C ₃ S	
FeO	iron monoxide	H ₂ CS	thioformaldehyde
HF		H ₃ O ⁺	hydronium ion
SH		SiC ₃	
H ₃ ⁺	protonated hydrogen	C ₄ H	butadiynyl
C ₂ H	ethynyl	C ₃ H ₂	cyclopropenylidene
CH ₂	methylene †	H ₂ CCC	propadienylidene
HCN	hydrogen cyanide	HCOOH	formic acid
HNC	hydrogen isocyanide	CH ₂ CO	ketene
HCO	formyl	HC ₃ N	cycanoacetylene
HCO ⁺	formyl ion	HNC ₃	
HCS ⁺	thioformyl ion	CH ₂ CN	cyanomethyl
HOC ⁺	isoformyl ion †	NH ₂ CN	cyanamide
N ₂ H ⁺	protonated nitrogen	CH ₂ NH	methanimine
HNO	nitroxyl	HC ₂ NC	
H ₂ O	water	CH ₄	methane
H ₂ S	hydrogen sulfide		
H ₂ N	hydrogen nitride		
N ₂ O	nitrous oxide		

Molecular Ions

Species	Name	Species	Name
H ₂ COH ⁺	protonated formaldehyde	HC ₅ N	cyanodiacetylene
SiH ₄	silane*	C ₇ H	
C ₄ Si	*	HCOOCH ₃	methyl formate
C ₅	pentatomic carbon*	CH ₃ C ₃ N	methylcyanoacetylene
C ₅ H	pentynylidyne	CH ₃ COOH	acetic acid
C ₅ N		H ₂ C ₆	
C ₂ H ₄	ethylene*	CH ₂ OHCHO	glycolaldehyde
H ₂ CCCC	butatrienylidene	CH ₃ C ₄ H	methylidiacetylene
CH ₃ OH	methanol	CH ₃ CH ₃ O	dimethyl ether
CH ₃ CN	methyl cyanide	CH ₃ CH ₂ CN	ethyl cyanide
CH ₃ NC	methyl isocyanide	CH ₃ CH ₂ OH	ethanol
CH ₃ SH	methyl mercaptan	HC ₇ N	cyanohexatriyne
NH ₂ CHO	formamide	C ₈ H	
HC ₃ HO	propynal	CH ₃ C ₄ CN	† acetone
HC ₃ NH ⁺		CH ₃ CH ₃ CO	† glycine†
C ₆ H		NH ₂ CH ₂ COOH	† ethylene glycol
CH ₂ CHCN	vinyl cyanide	CH ₂ OHCH ₂ OH	
CH ₃ C ₂ H	methylacetylene	HC ₉ N	cyano-octa-tetra-yne
CH ₃ CHO	acetaldehyde	HC ₁₁ N	cyano-deca-penta-yne
CH ₃ NH ₂	methylamine		
C ₂ H ₄ O	ethylene oxide		
CH ₂ CHOH	vinyl alcohol		

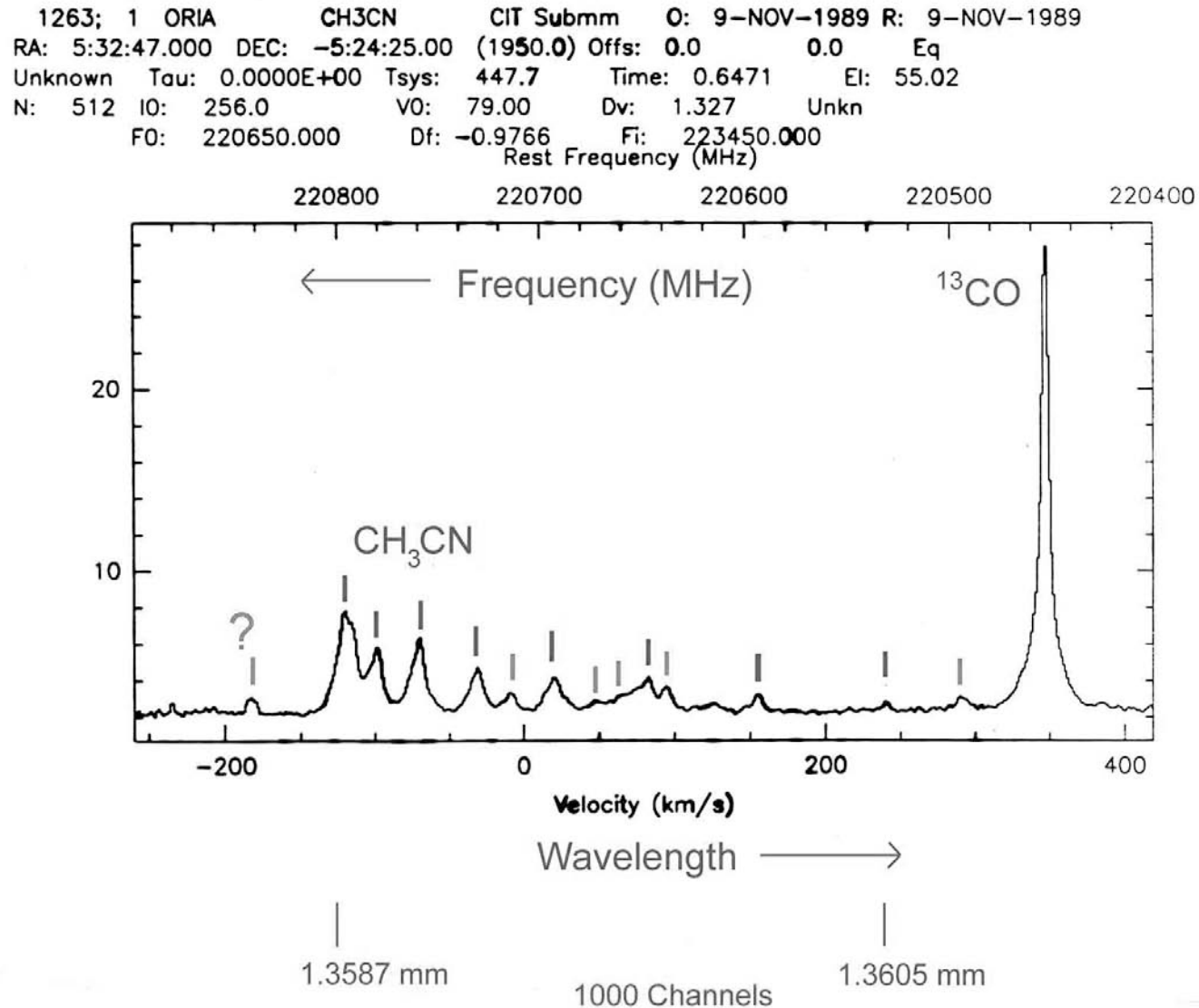
* Detected in circumstellar envelopes only
† tentative

Look at Appendix 2

How we detect Interstellar Molecules

Radio Spectroscopy (Mostly $\lambda \sim 1-3$ mm)

+ Precise knowledge of wavelengths for different molecules

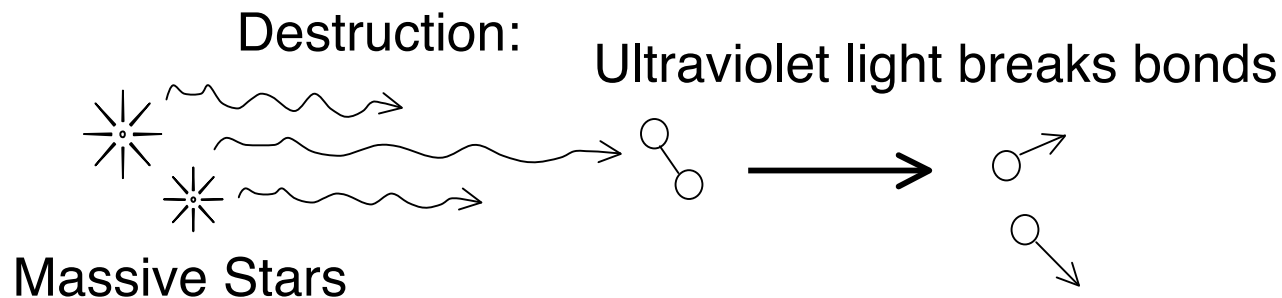


3 Lessons

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



Protection by dust grains: scatter and absorb ultraviolet

Dust

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

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

Carbon

PAHs → Graphite

~ Soot

Silicates

Si + O + Mg, Fe, ...

Both Produced by old stars

Formation of Interstellar Molecules

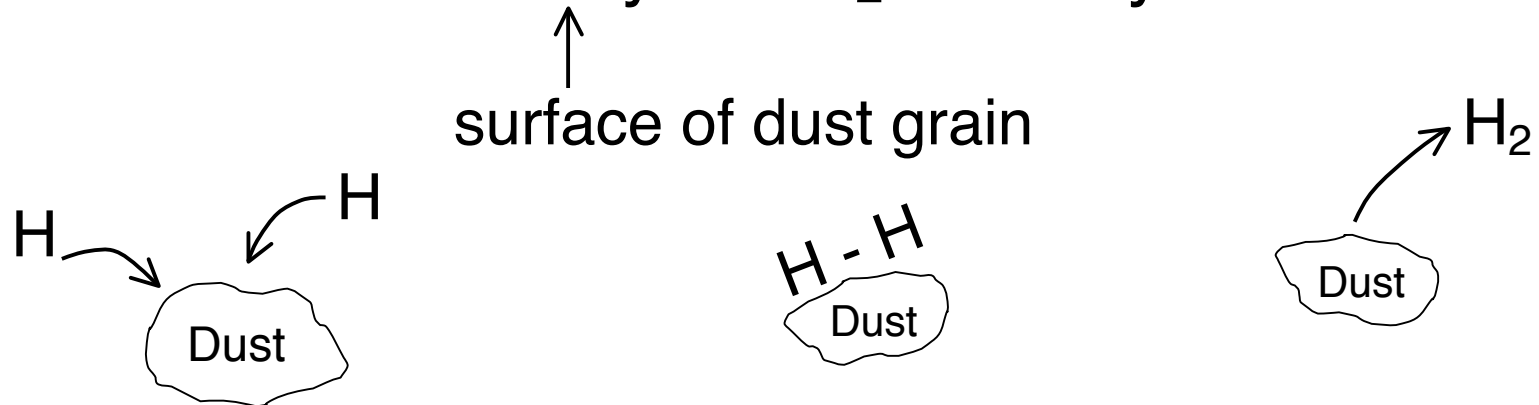
1. H₂

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

Collisions: OK in lab, too slow in space

Emit photon: very slow for H₂ (10^7 s)

H + H + catalyst = H₂ + catalyst



Formation of Interstellar Molecules

2. More complex molecules

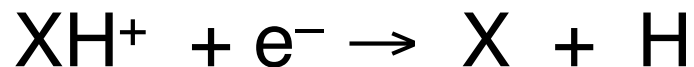
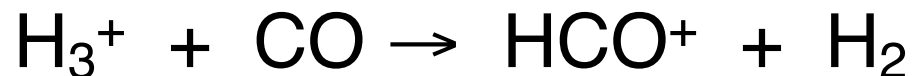
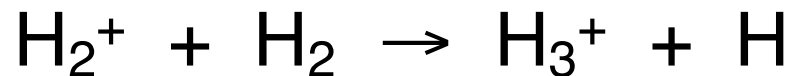
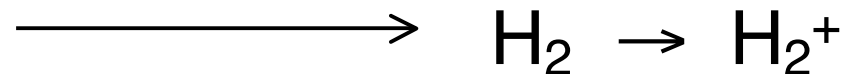
Problem is activation energy barrier

$T \sim 10 \text{ K} \ll \text{Barrier}$

Use reactions without activation energies

e.g. Molecular ions, like HCO^+

Cosmic Ray



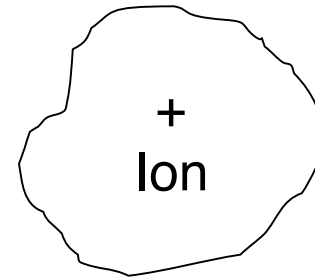
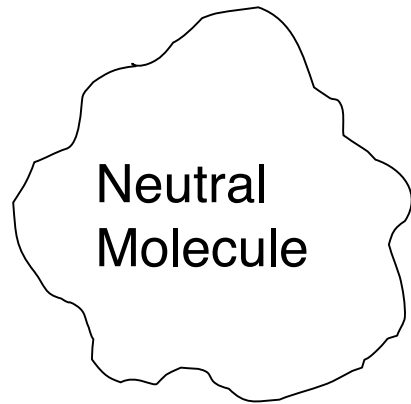
Energy + simple mol.

→ Reactive mol.

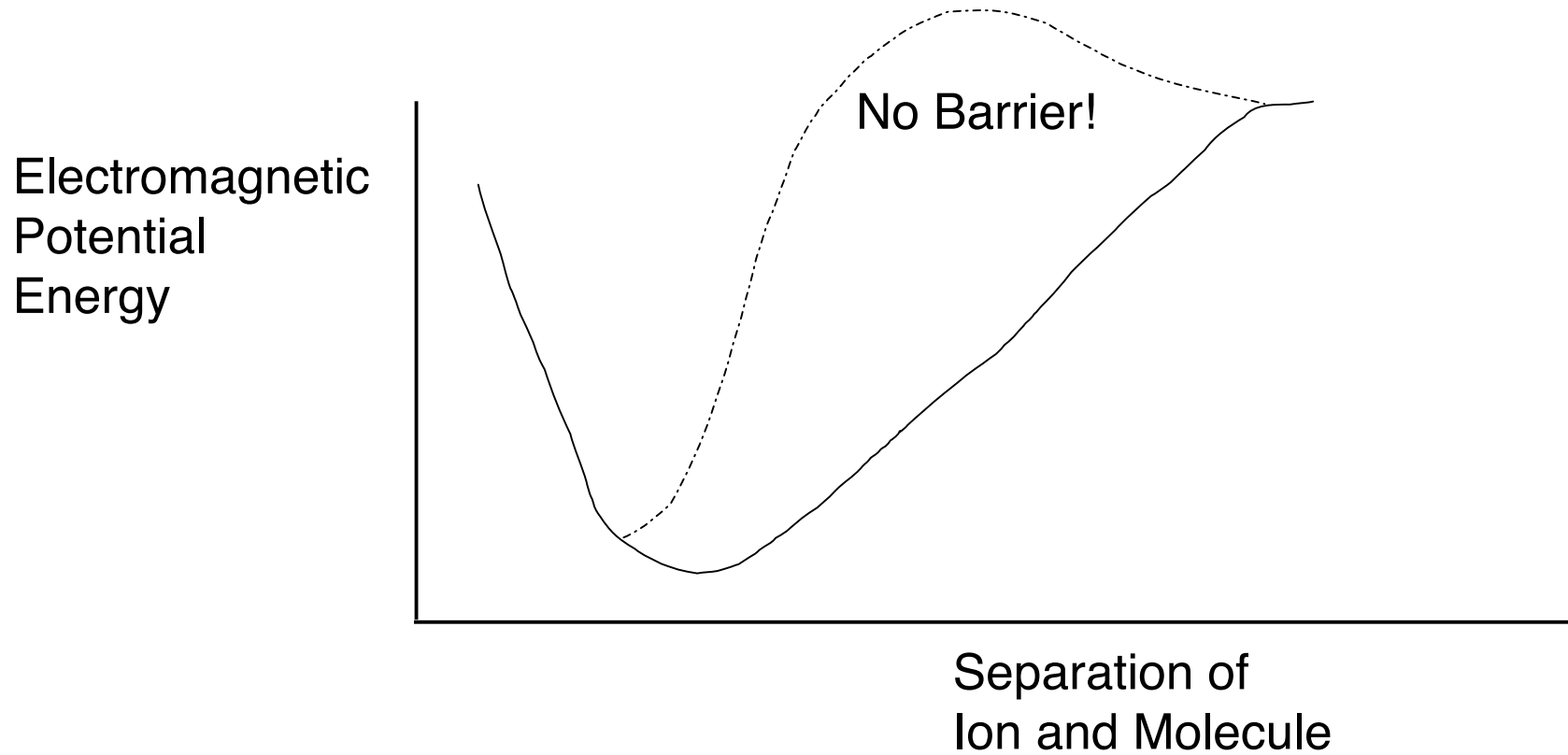
↓

More complex

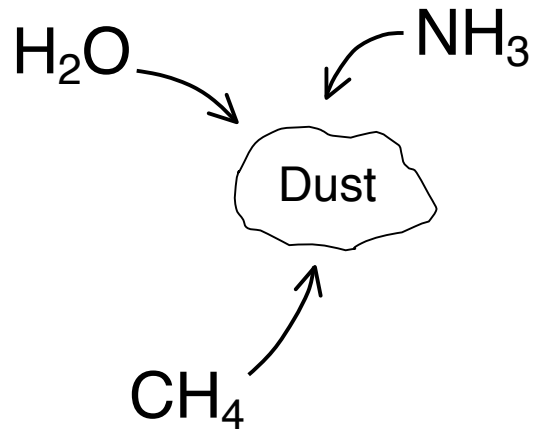
Ion - Molecule Reactions



Molecule
or atom



Molecules on Dust Grains



Stick on grains
“ice”

Infrared observations show this: as molecules
Vibrate, absorb infrared

e.g. H₂O absorbs at 3×10^{-6} m

CH₄ absorbs at 8×10^{-6} m

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

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. H₂ Formation
3. Depletion → Mantles of Ice
H₂O, NH₃, CH₄, CO₂, HCOOH, ...
↑
Methane

Estimate of Average Star Formation Rate (R_*)

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

N_* : Count them? No

Use Gravity (Newton's Laws)

Sun orbiting center of galaxy at 250 km s^{-1} (155 miles per second)

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

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

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

Estimate of Average Star Formation Rate (R_*)

$$(R_g = 25,000 \text{ ly}) \rightarrow M_g = 1.0 \times 10^{11} M_\odot$$

$$\text{Add stars outside Sun's orbit} \rightarrow M_g \simeq 1.6 \times 10^{11} M_\odot$$

$$N_* \simeq \frac{M_g}{\text{Avg. mass of star}} = \frac{1.6 \times 10^{11}}{0.4} = 4 \times 10^{11}$$

$$T_{\text{gal}} \simeq 10^{10} \text{ yr} \quad (\text{studies of old stars})$$

$$R_* \simeq \frac{4 \times 10^{11}}{10^{10}} \text{ stars} = 40 \text{ stars per year} \quad (5 - 50)$$

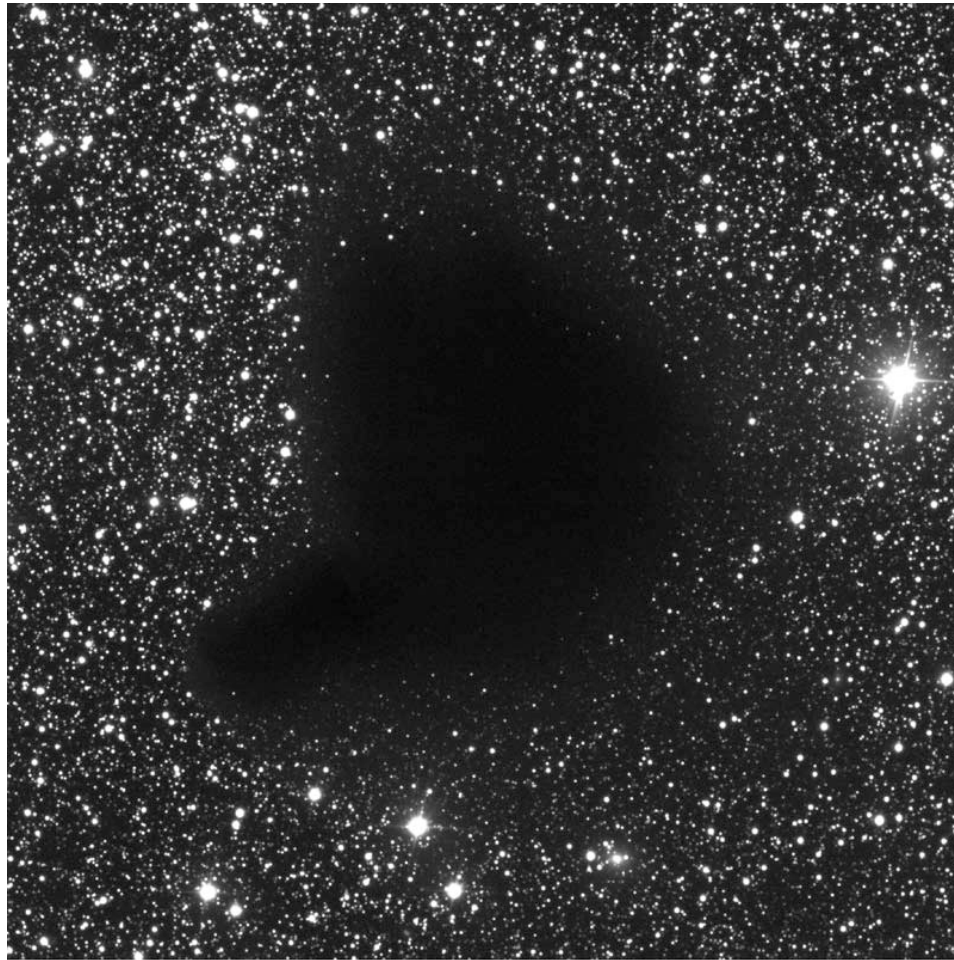
Star Formation

Current Star Formation

Molecular Clouds

- Composition
 - H₂ (93%), He (6%)
 - Dust and other molecules (~1%)
 - CO next most common after H₂, He
- Temperature about 10 K
- Density (particles per cubic cm)
 - ~100 cm⁻³ to 10⁶ cm⁻³
 - Air has about 10¹⁹ cm⁻³
 - Water about 3 x 10²² cm⁻³
- Size 1-300 ly
- Mass 1 to 10⁶ M_{sun}

A Small Molecular Cloud



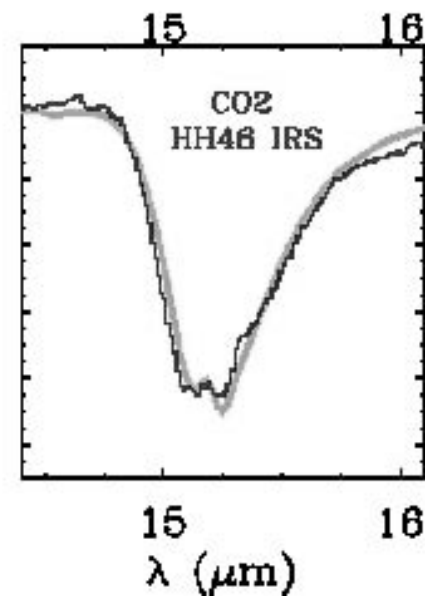
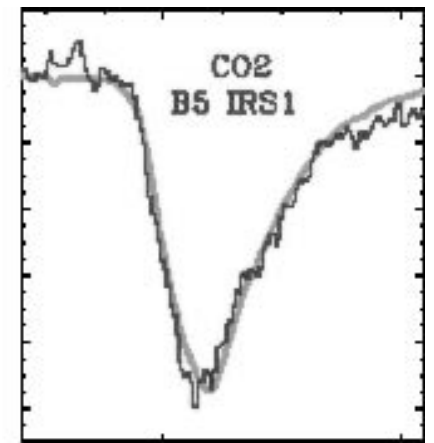
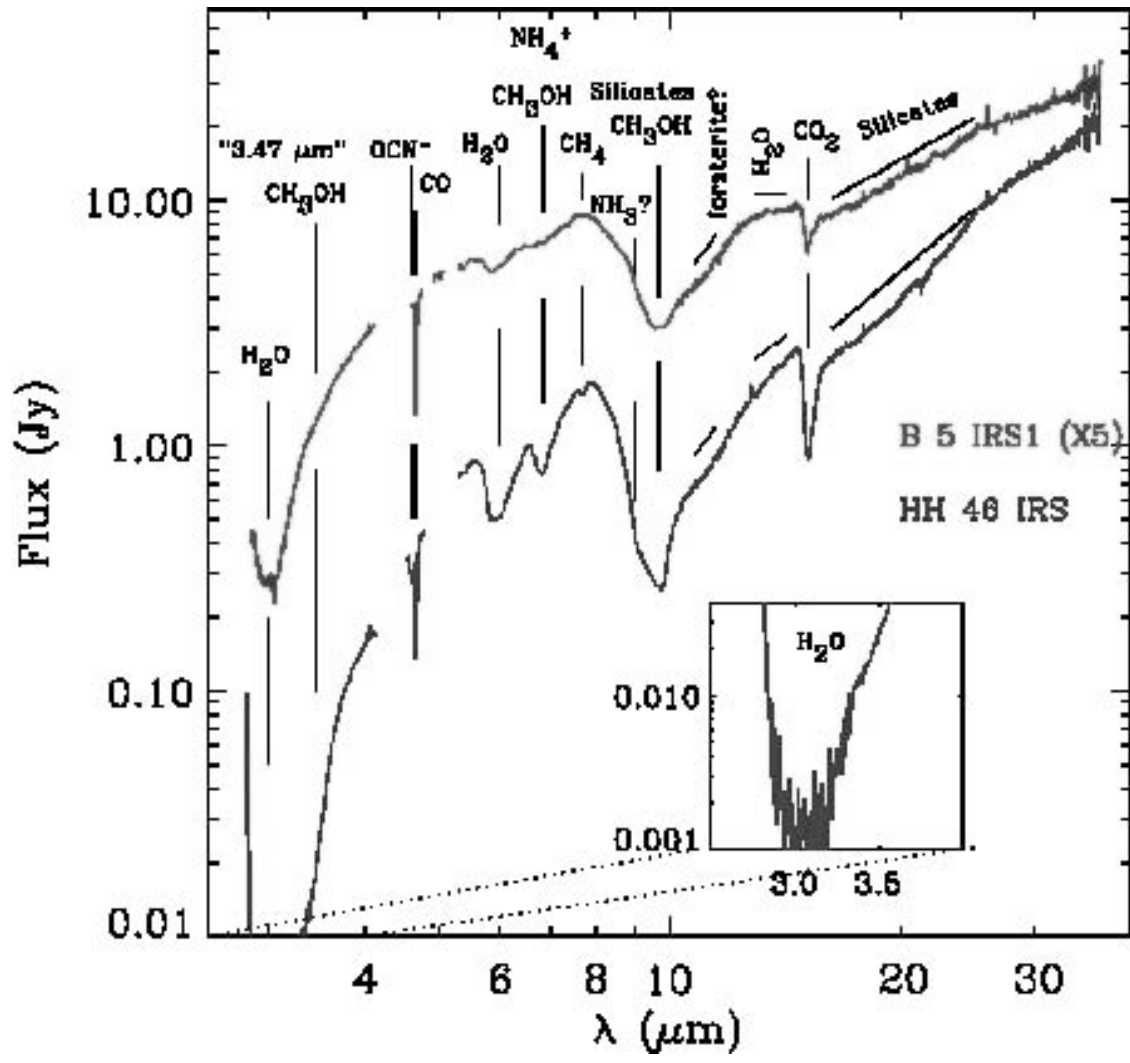
ESO PR Photo 20a/99 (30 April 1999)

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

© European Southern Observatory



Ices on Dust Grains



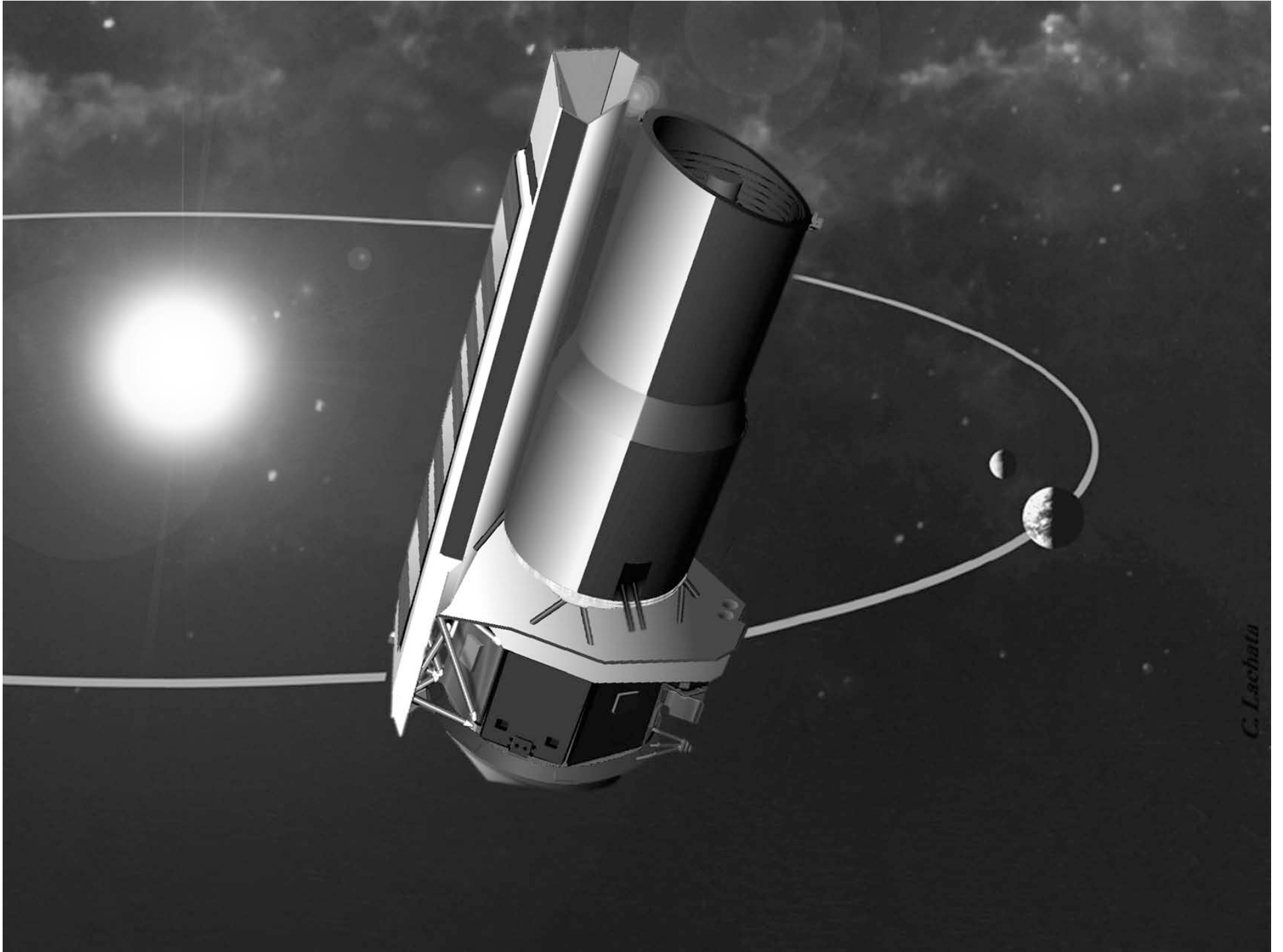
Current Star Formation

- 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

The Launch of The Spitzer Space Telescope



Spitzer Space Telescope Launched Aug. 2003, expect a 5 yr life.



C. Lachata

Visible to Infrared Views





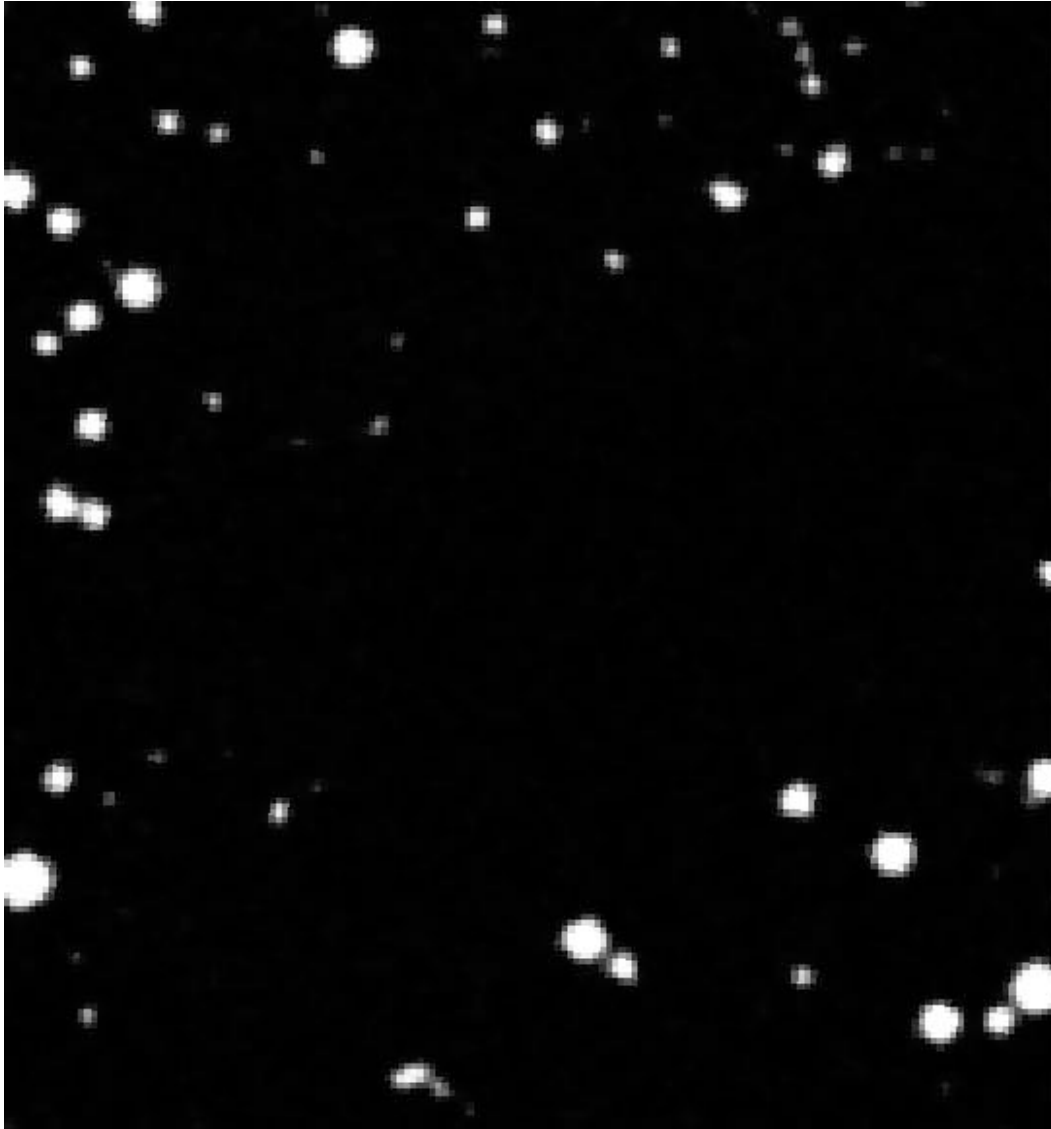




RCW 49

234

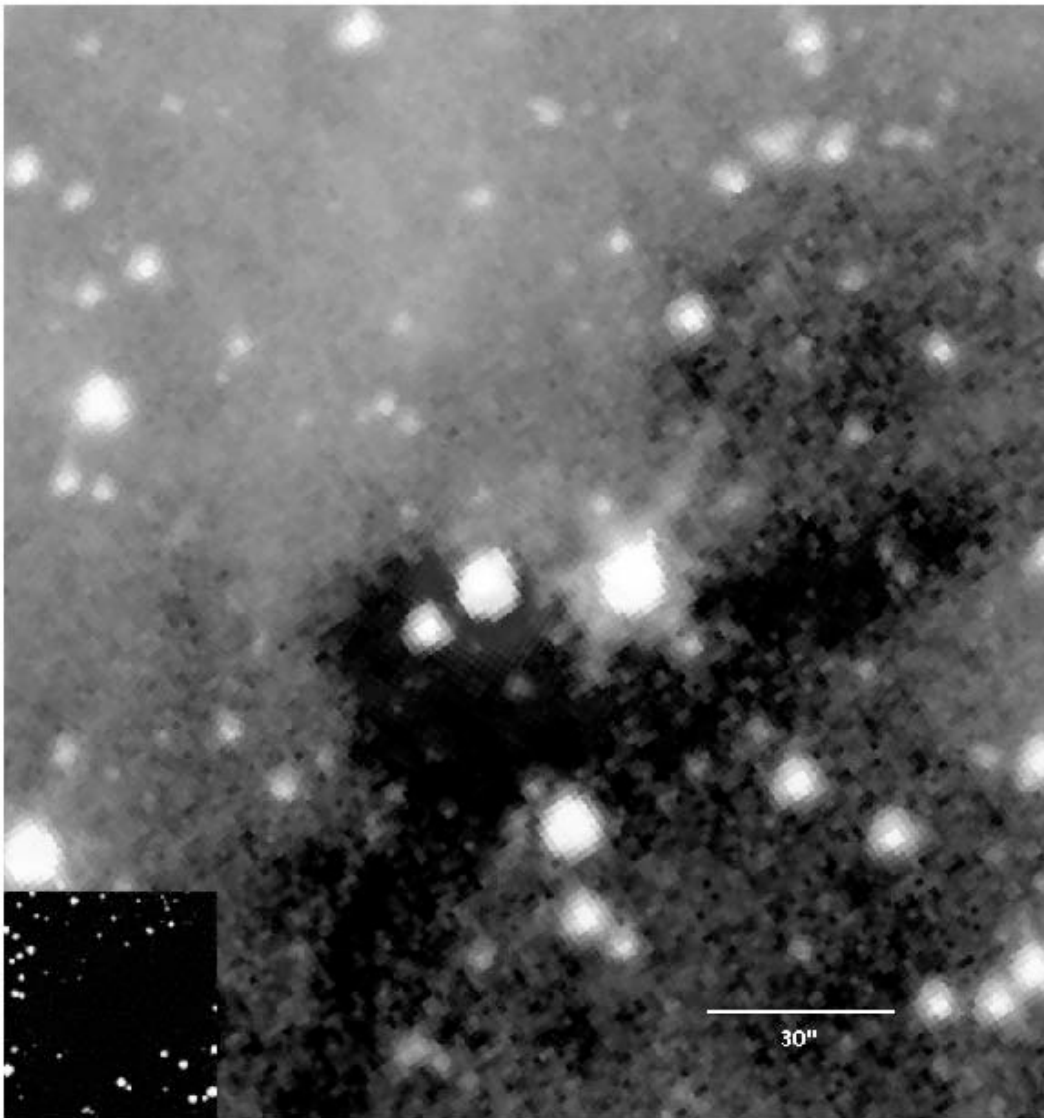
A Dark Molecular Cloud



L1014 distance ~ 600 ly, but somewhat uncertain.

Red light image; dust blocks stars behind and our view of what goes on inside.

Forming Star Seen in Infrared



Three Color Composite:
Blue = 3.6 microns
Green = 8.0 microns
Red = 24 microns

R-band image from DSS at
Lower left.

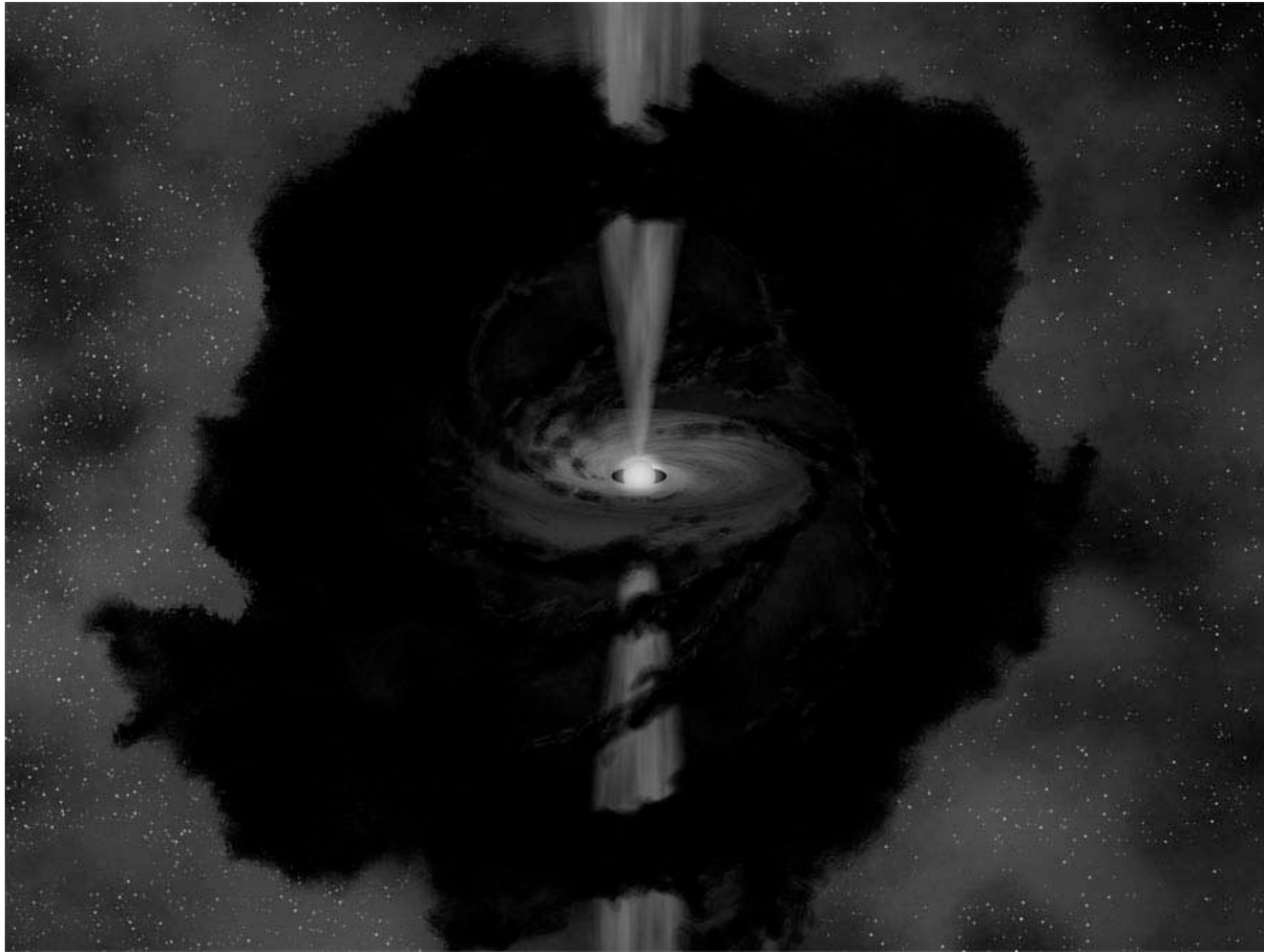
We see many stars
through the cloud not seen
in R.

The central source is NOT
a background star.

L1014 is forming a star

C. Young et al. ApJS, 154, 396

Artist's Conception



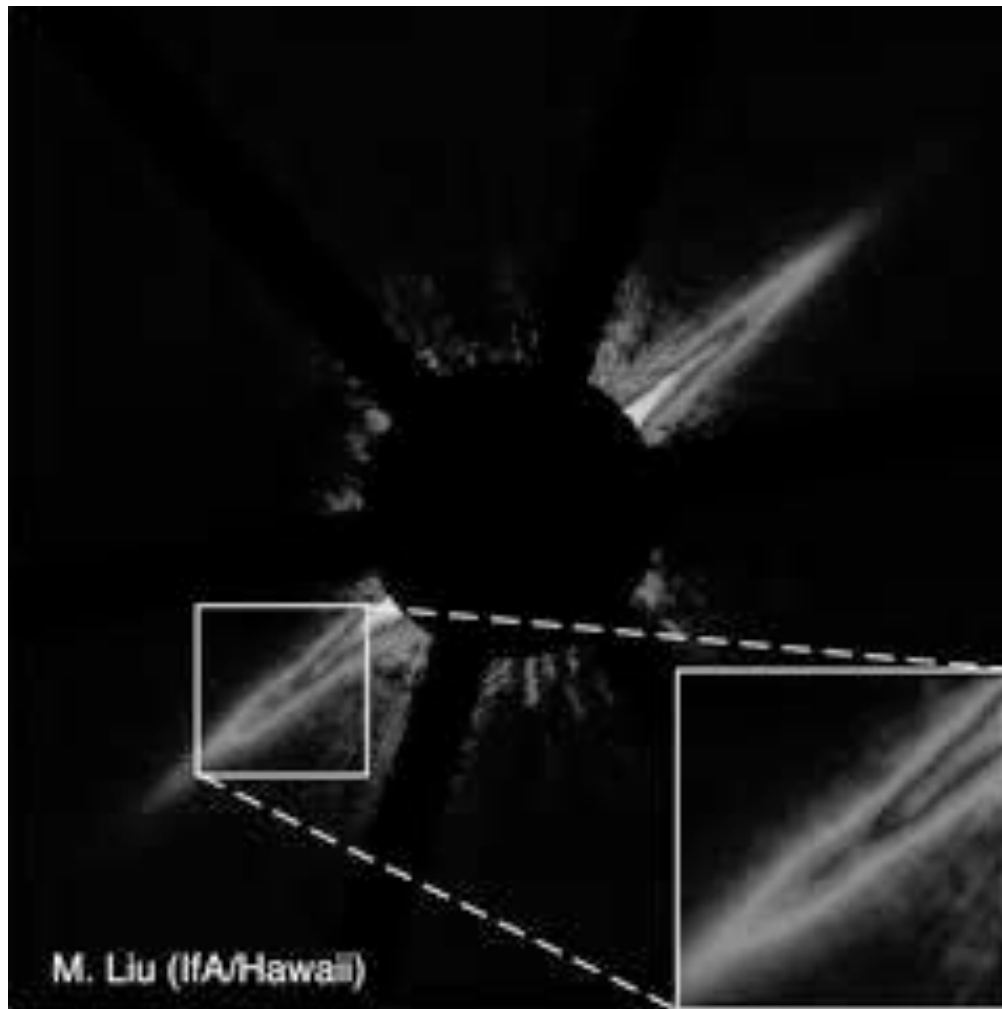
Features:
Dusty envelope
Rotation
Disk
Bipolar outflow

R. Hurt, SSC

The Protostar

- Evolution of the collapsing gas cloud
 - At first, collapsing gas stays cool
 - Dust, gas emit photons, remove energy
 - At $n \sim 10^{11} \text{ cm}^{-3}$, 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 $T \sim 10^7 \text{ K}$
 - Protostar becomes a main-sequence star

The Disk



The Star (AU Mic) is blocked in a coronagraph. 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
 - $J = \text{constant}$
 - 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



Embedded Outflow in HH 46/47

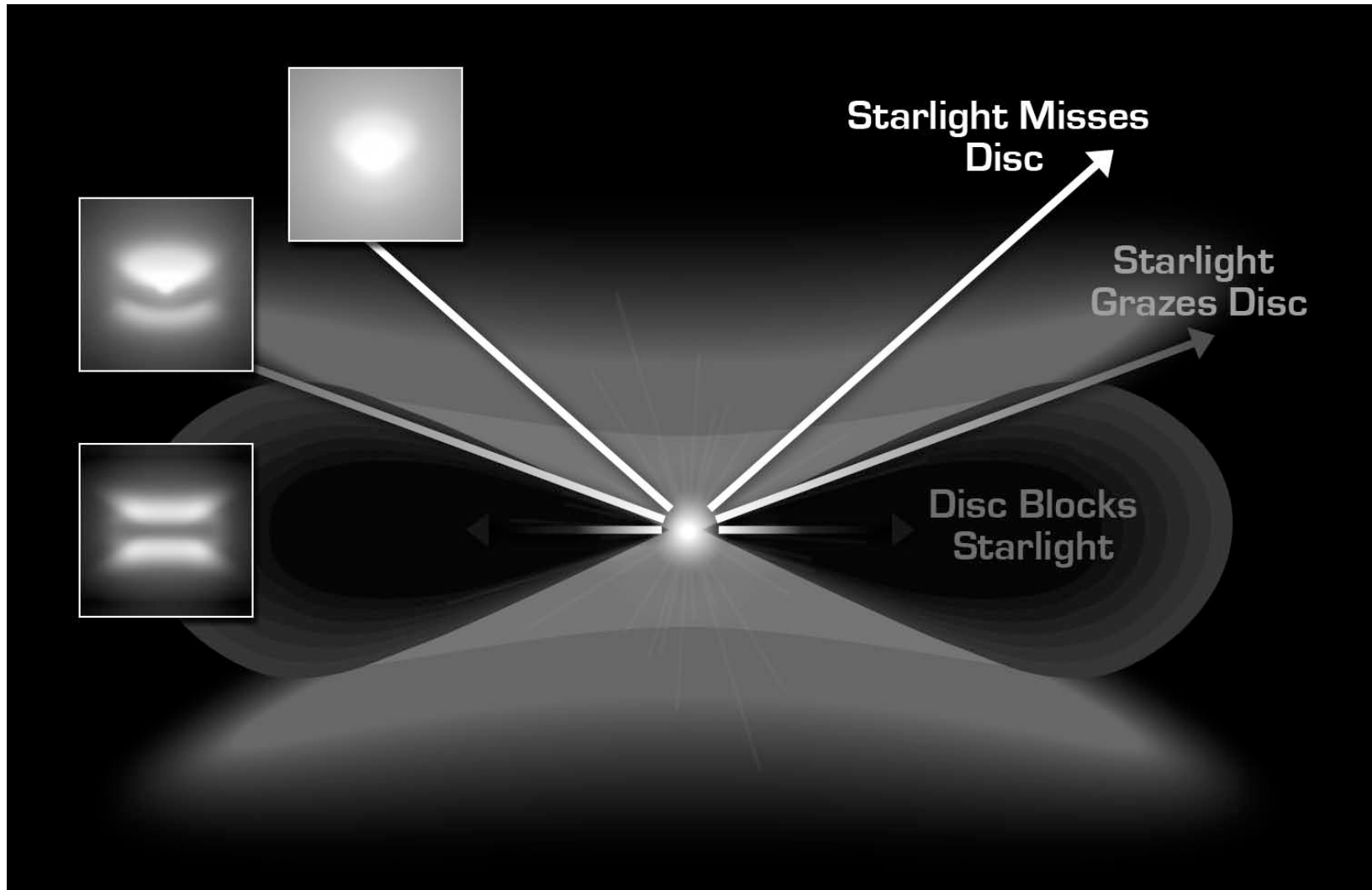
Spitzer Space Telescope • IRAC

Inset: visible light (0595)

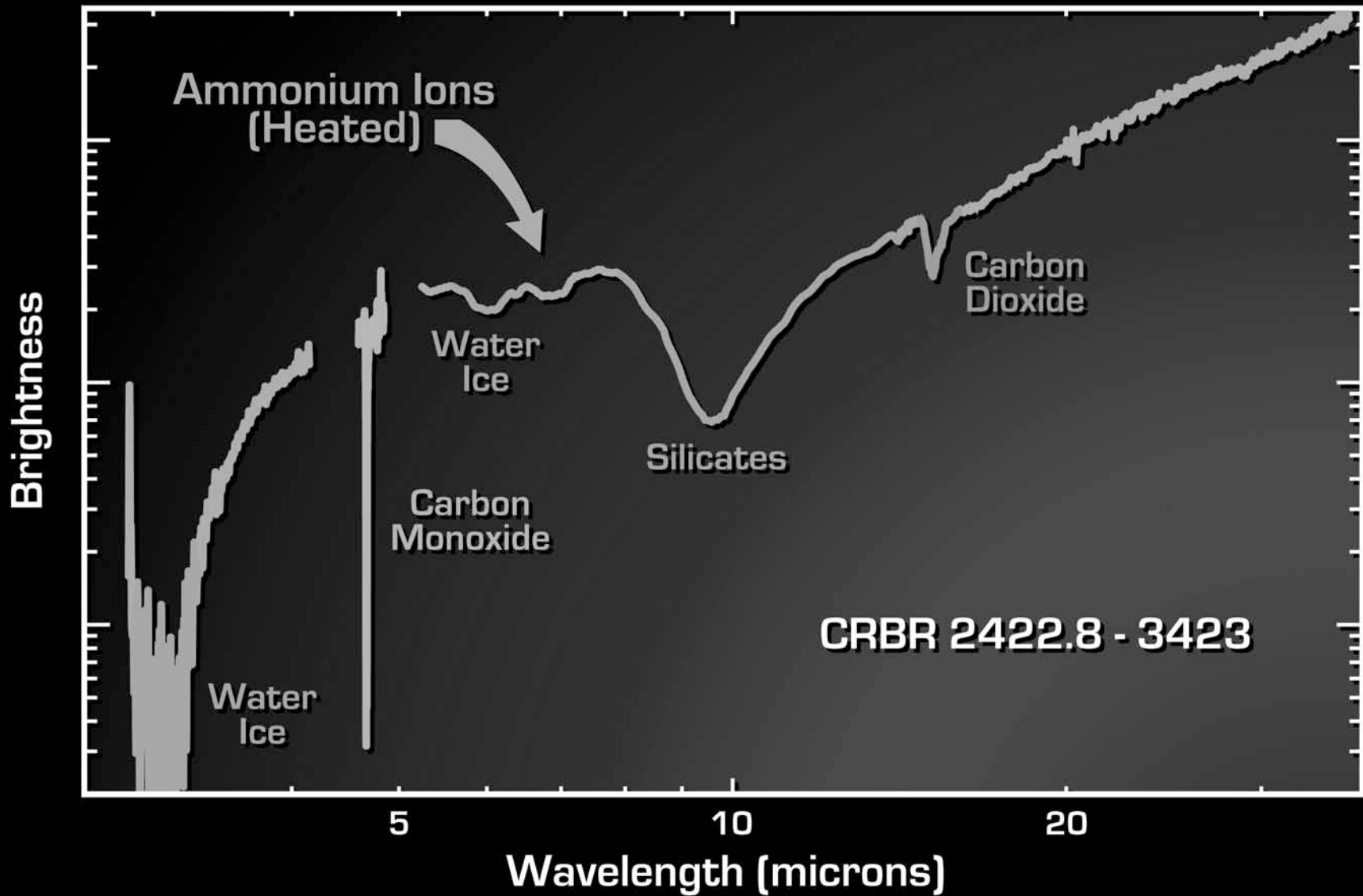
NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)

ssc2003-06f

Studying the Disk



Robert Hurt, SSC



Ices in a Protoplanetary Disc

Spitzer Space Telescope • IRS

NASA / JPL-Caltech / K. Pontoppidan [Leiden Observatory]

ESO • VLT-ISAAC
ssc2004-20c