Cosmic Evolution, Part II

Heavy elements → molecules

First a review of terminology:

Element
↓
Atom

Electro-
magnetic

Electrons

Nucleus

Strong Nuclear

Protons

Neutrons

Compound
↓
Molecule

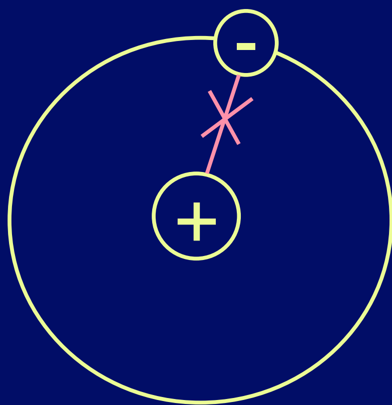
Electromagnetic

Neutral atom: # Electrons = # protons

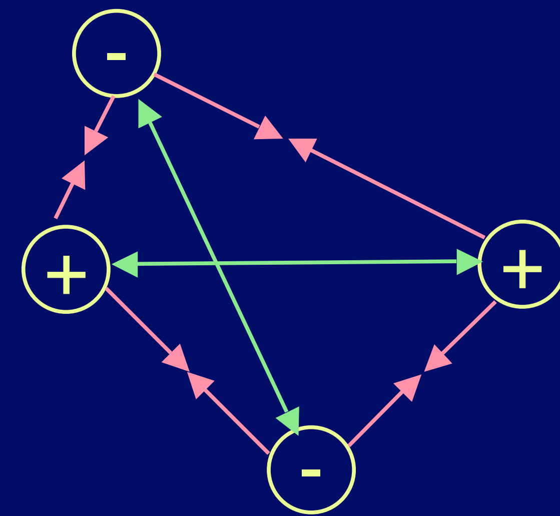
ion: ≠

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

H atom



H_2
Molecule



Attractive   Repulsive

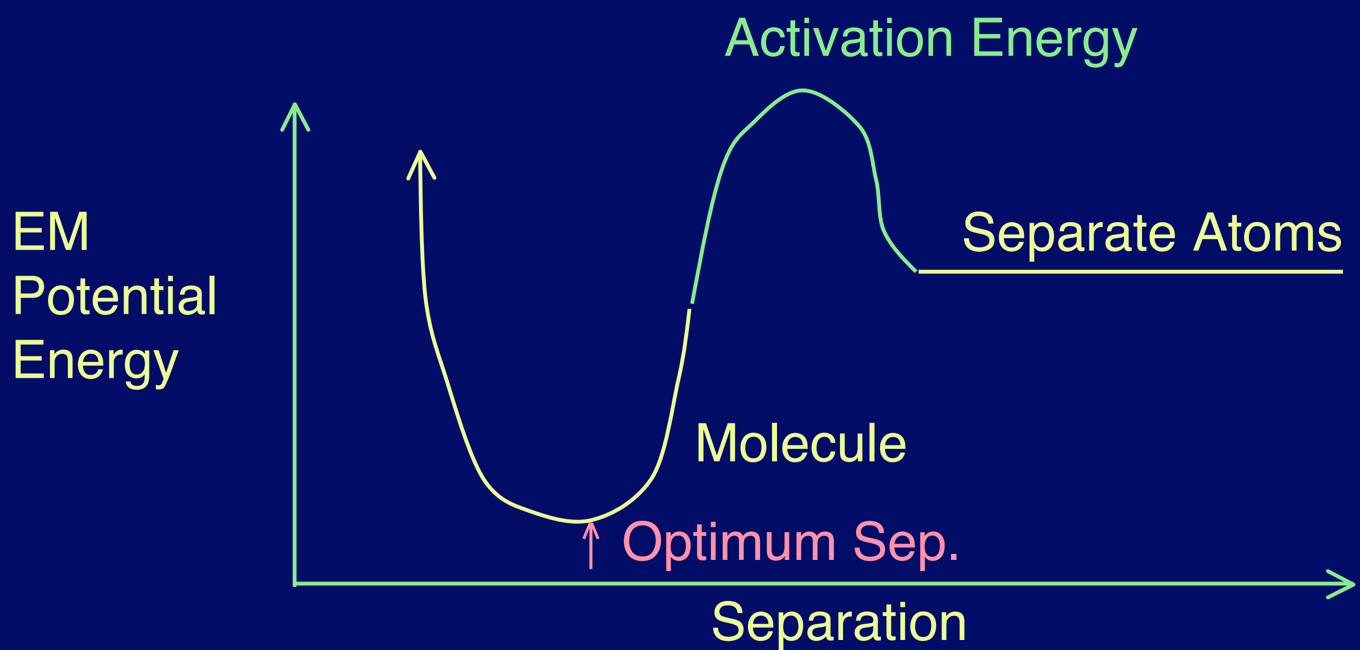
Molecule: Repulsive ~ Attractive

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

“Bond” 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?

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

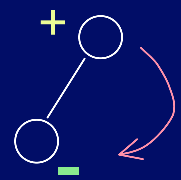
Interstellar Molecules

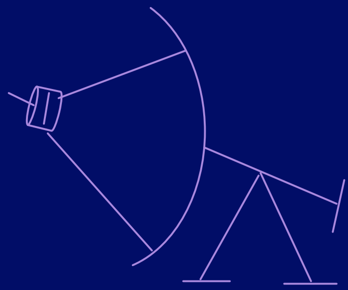
Exist as gas (individual molecules)

A few known in 1930's

Many more since 1968 - Radio astronomy

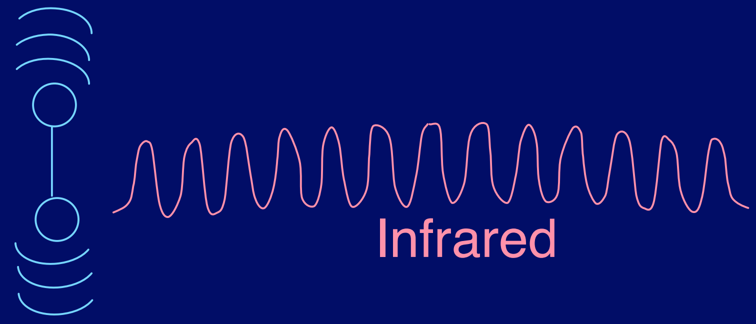
Rotation

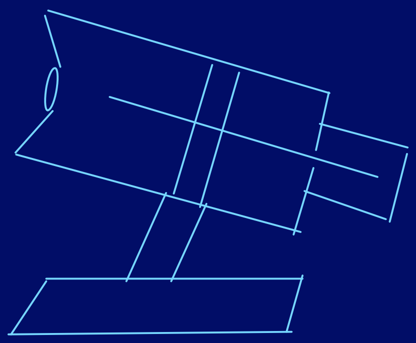




Radio Telescope

Vibration

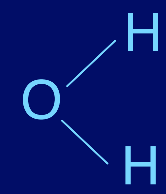




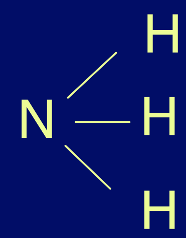
Optical Telescope

Important Examples:

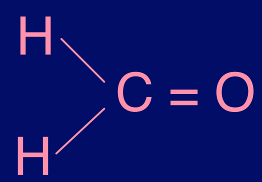
Water H_2O



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)

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

Important Probe of conditions

Discovered in Infrared

Discovered in UV

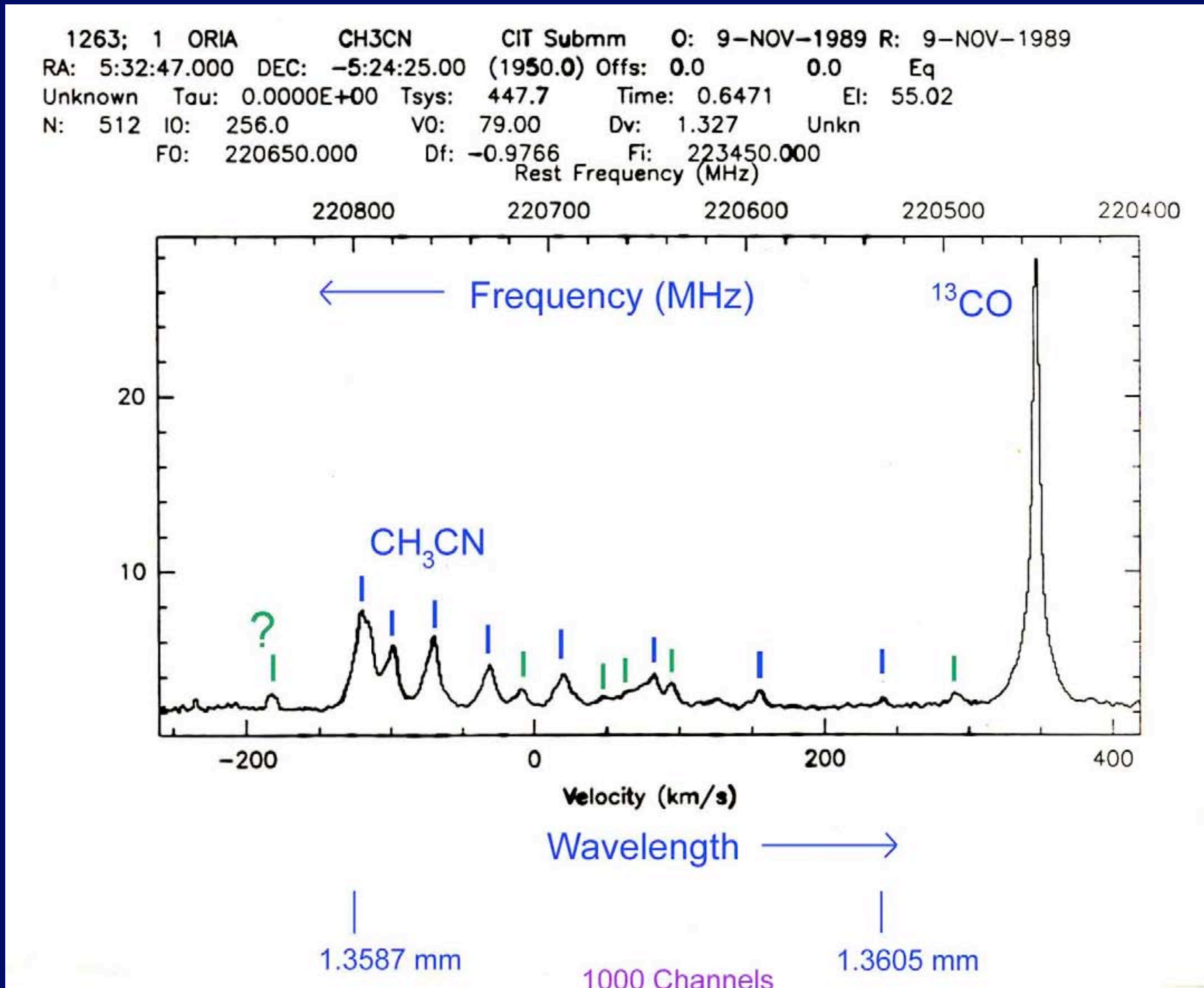
Relevant to the Origin of Life

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

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 → 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. 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

$T \sim 10$ K $\ll$ Barrier

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

e.g. Molecular ions, like HCO^+

Cosmic Ray

$\xrightarrow{\hspace{3em}} H_2 \rightarrow H_2^+$

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

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

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

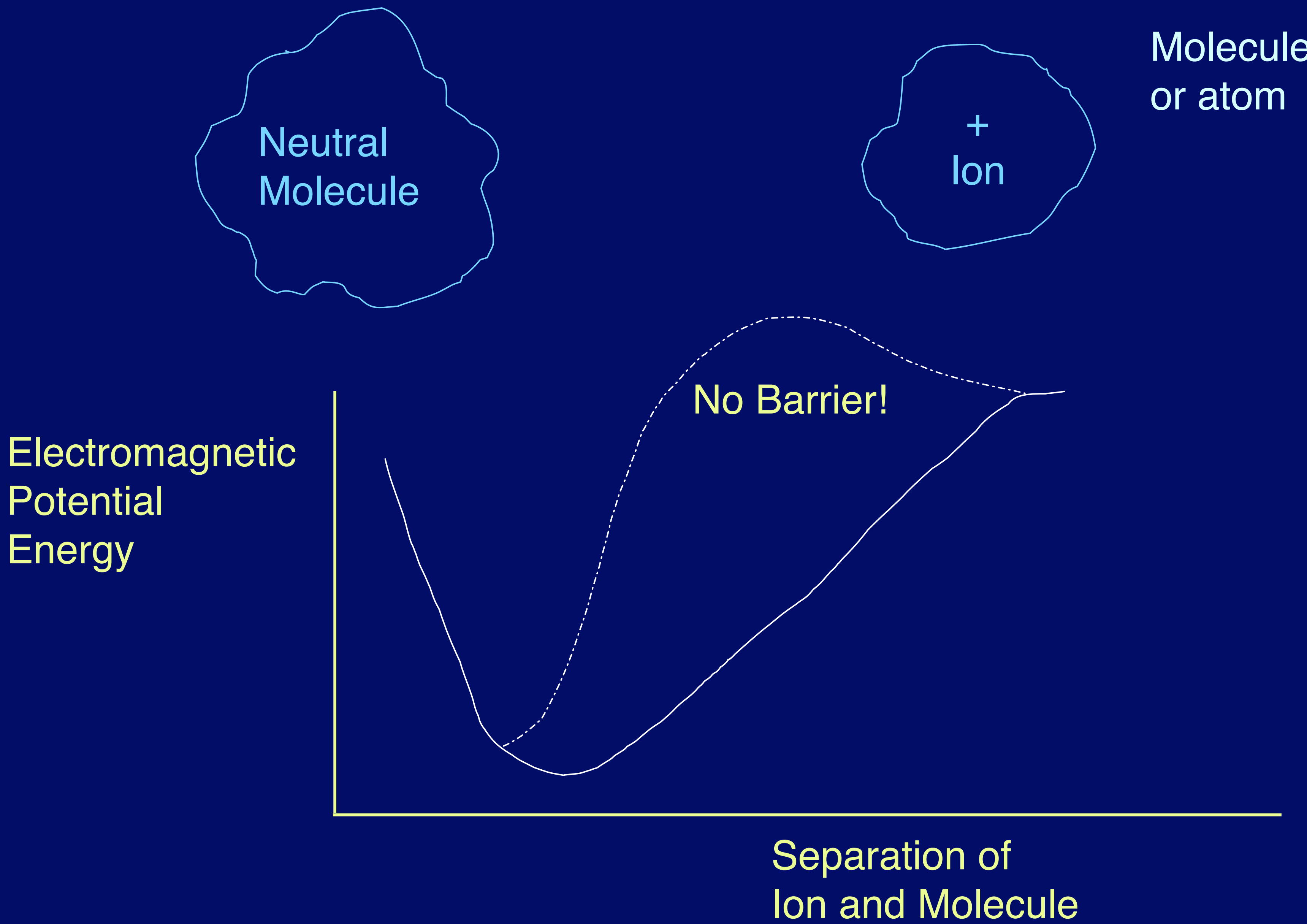
Energy + simple mol.

$\rightarrow$ Reactive mol.

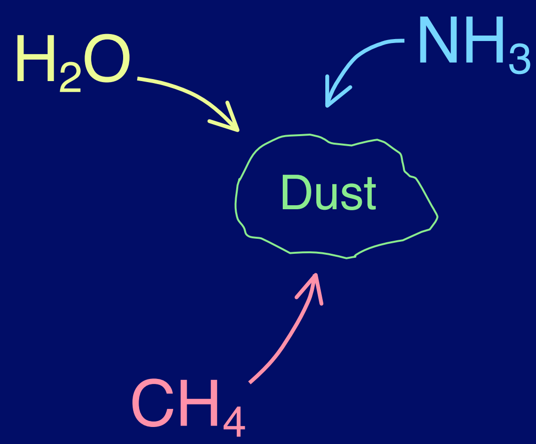
$\downarrow$

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

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. H_2 Formation
3. Depletion → Mantles of Ice
   H_2O, NH_3, CH_4, CO_2, HCOOH, …
   ↑ Methane

Estimate of Average Star Formation Rate (R_*)

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

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

$$\frac{1}{2} M_\odot v^2 = \frac{1}{2} \frac{G M_g M_\odot}{R_g}$$

R_g ← 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 ly) $\rightarrow$ $M_g = 1.0 \times 10^{11}\ M_\odot$

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

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

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

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

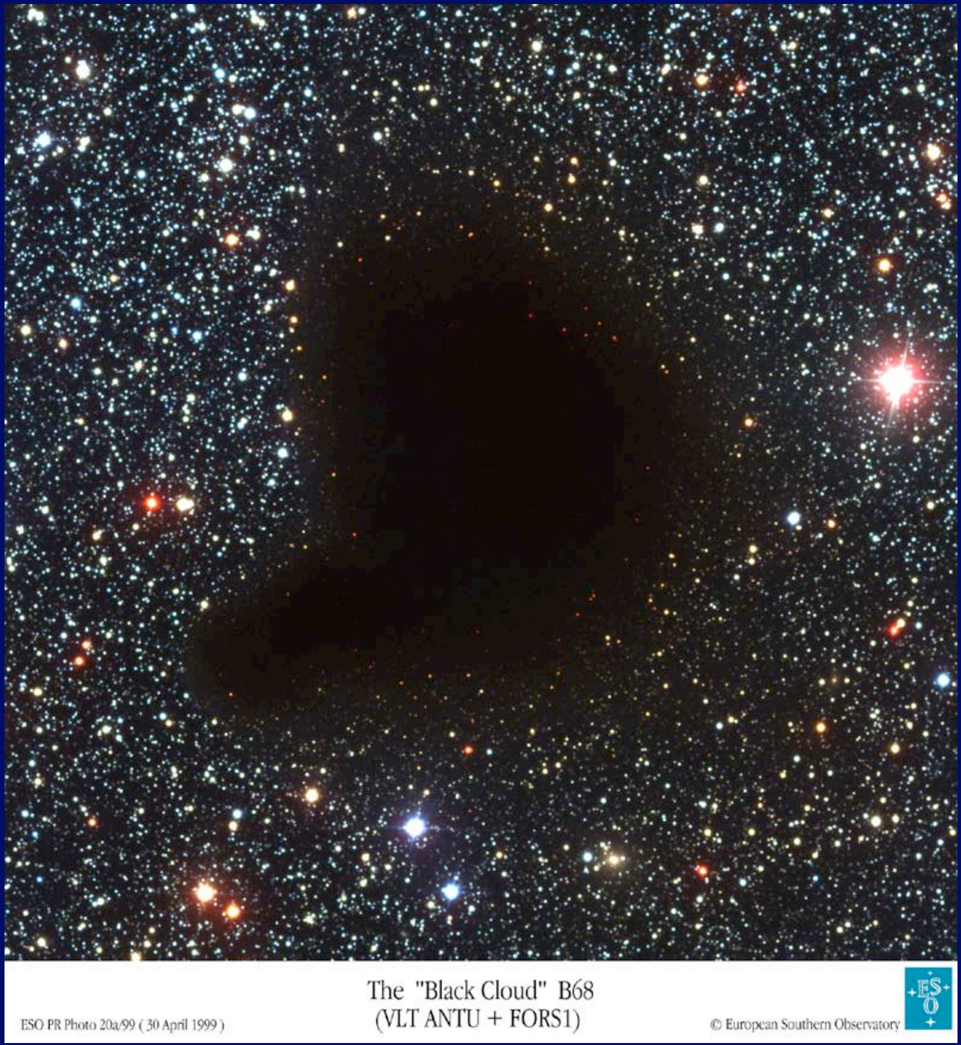
Star Formation

Current Star Formation

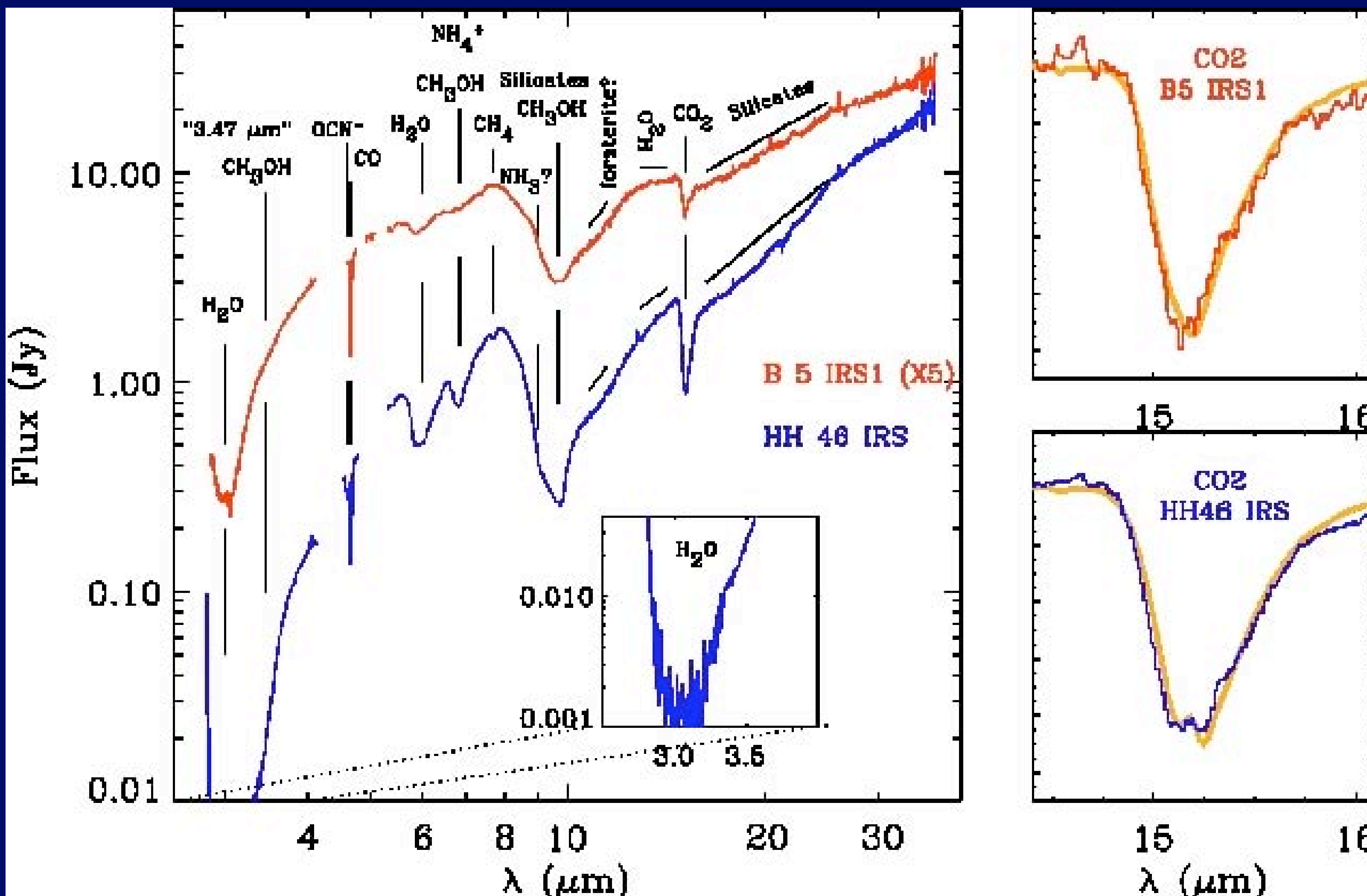
Molecular Clouds

- Composition
  - 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 x 10^{22} cm^{-3}
- Size 1-300 ly
- Mass 1 to 10^6 M_{sun}

A Small Molecular Cloud



Ices on Dust Grains

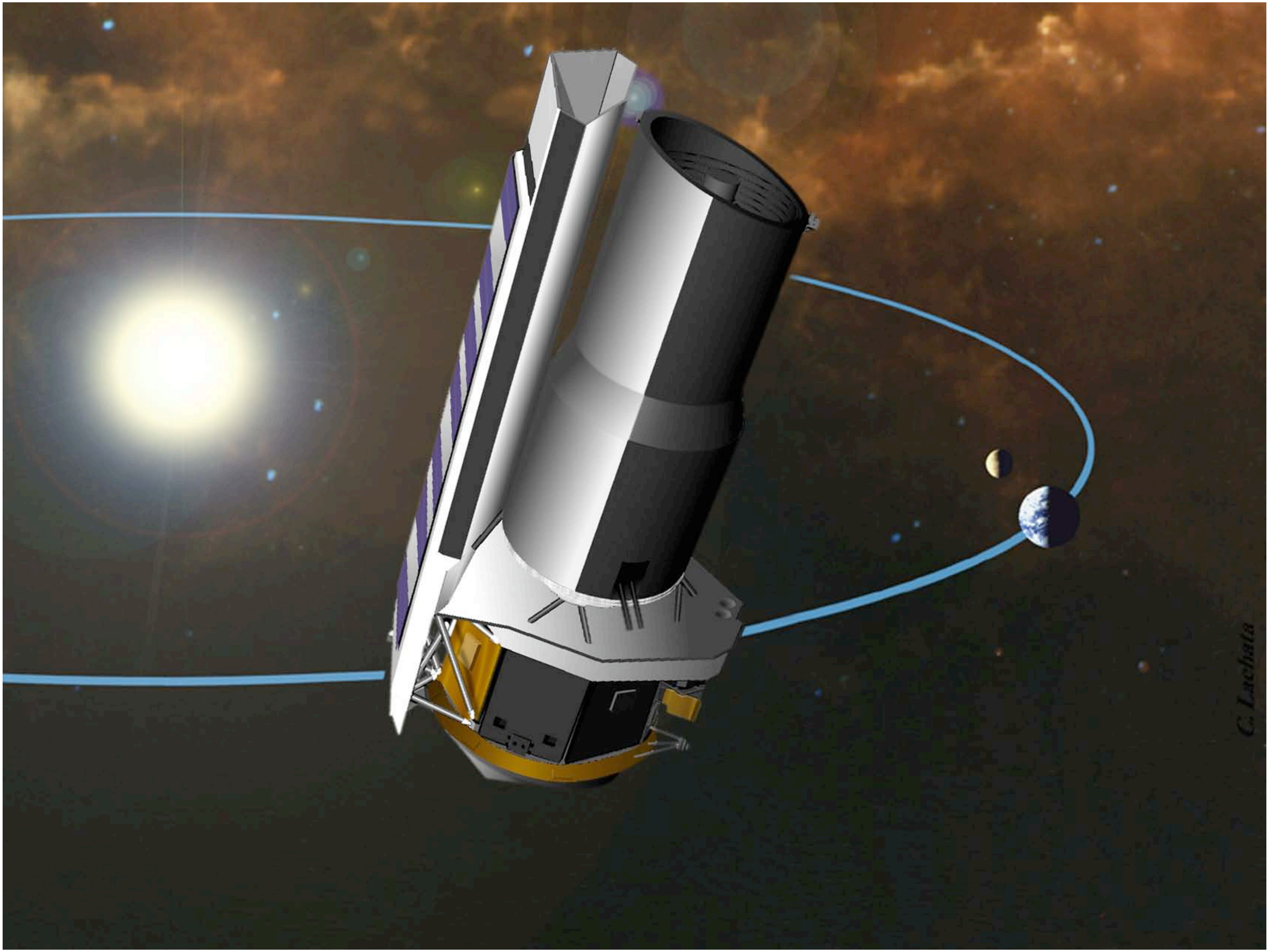


Current Star Formation

- 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

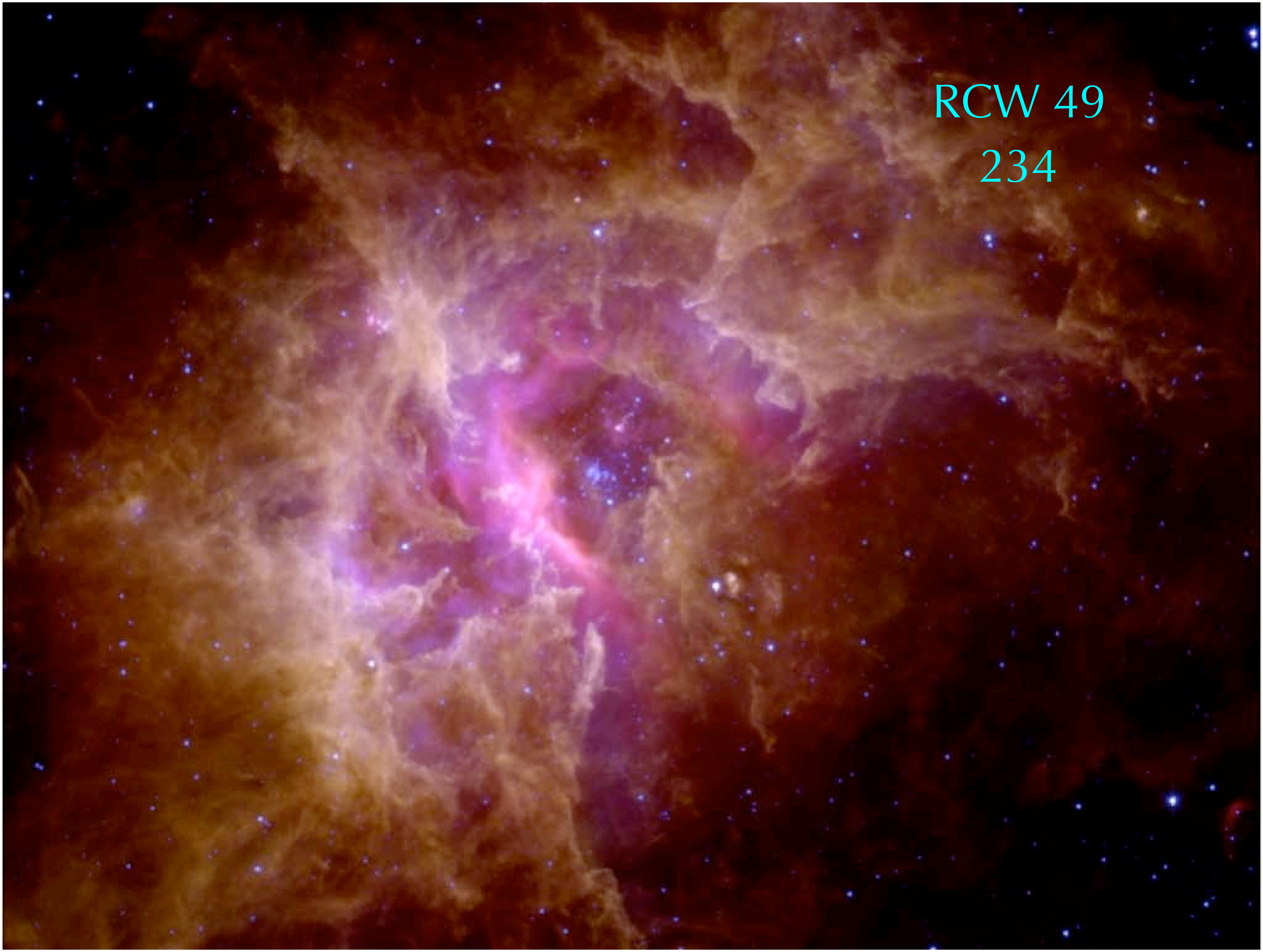
Spitzer Space Telescope Launched Aug. 2003, expect a 5 yr life.


C. Lachata

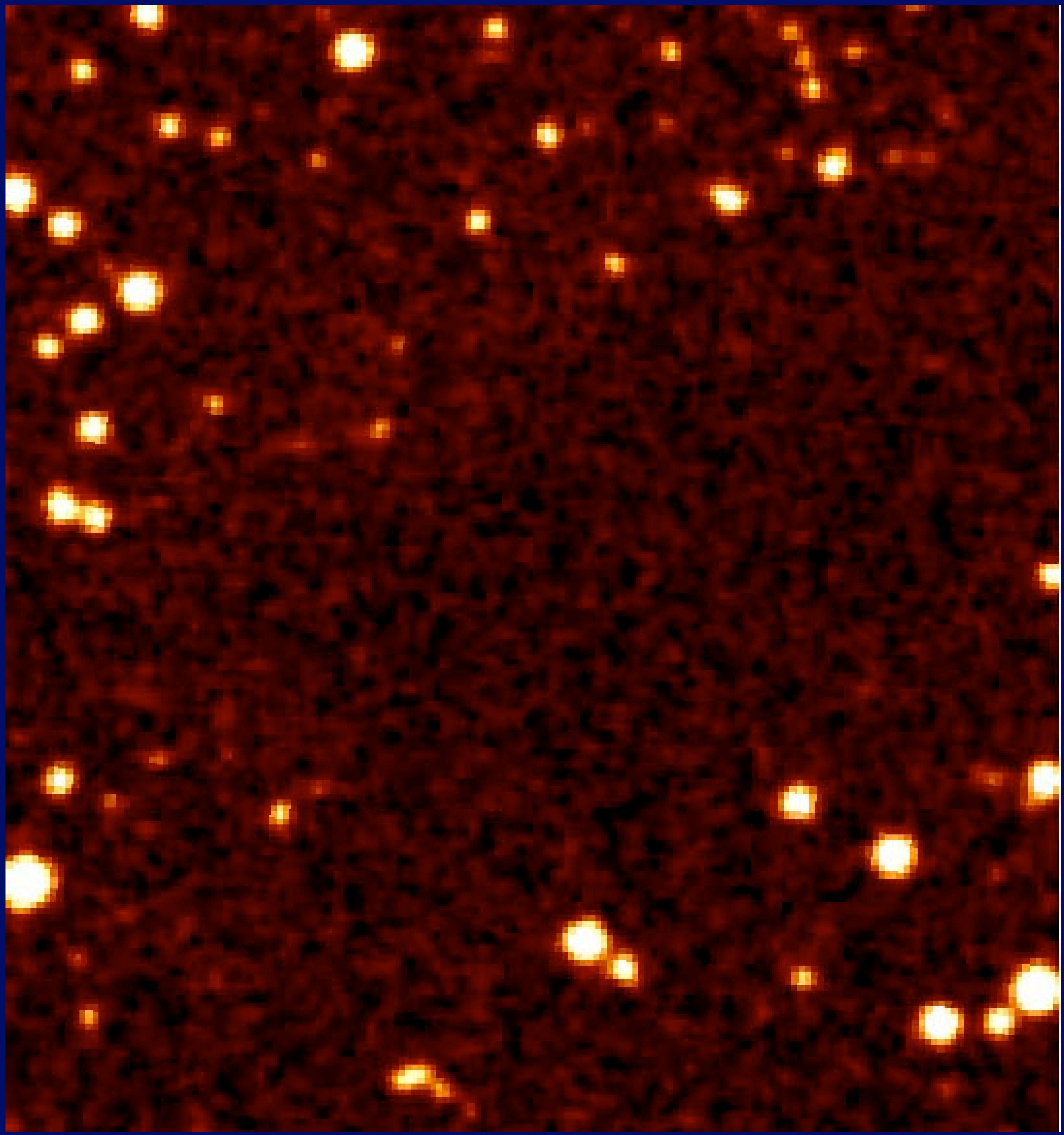
Visible to Infrared Views


RCW 49
JHK
(2MASS)


RCW 49
HK1


RCW 49
234

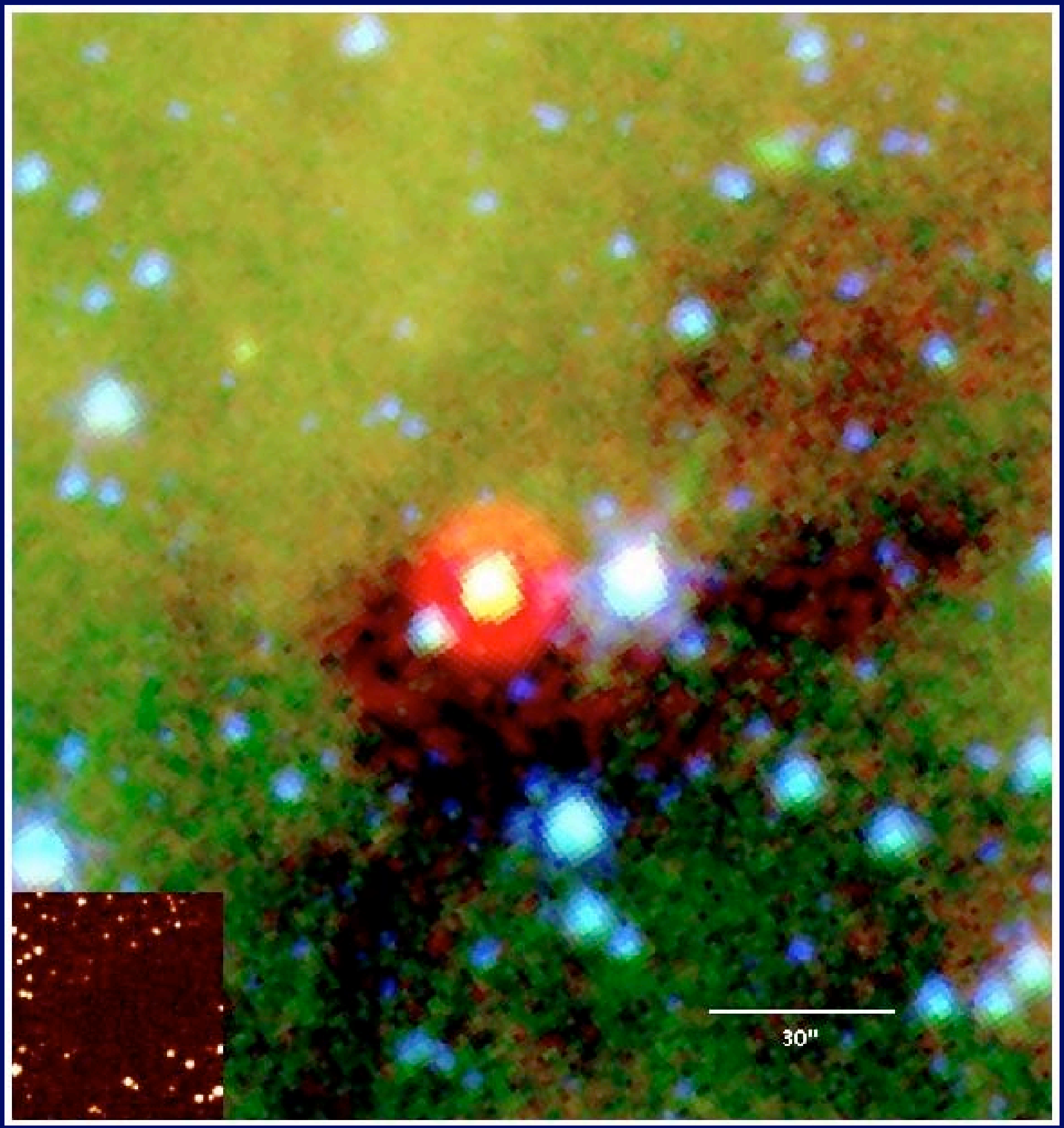
A Dark Molecular Cloud



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

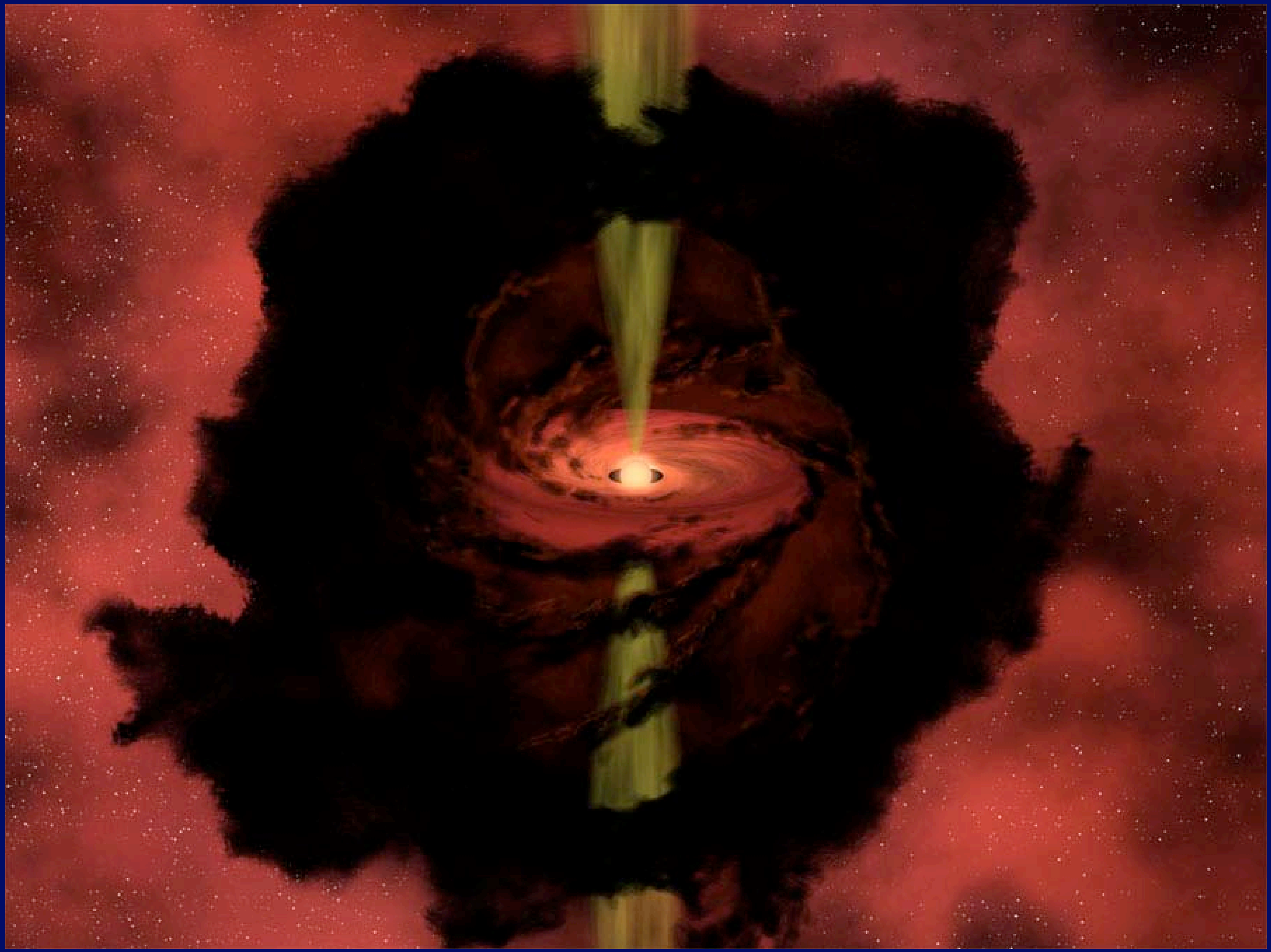
R-band image from DSS at Lower left.

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



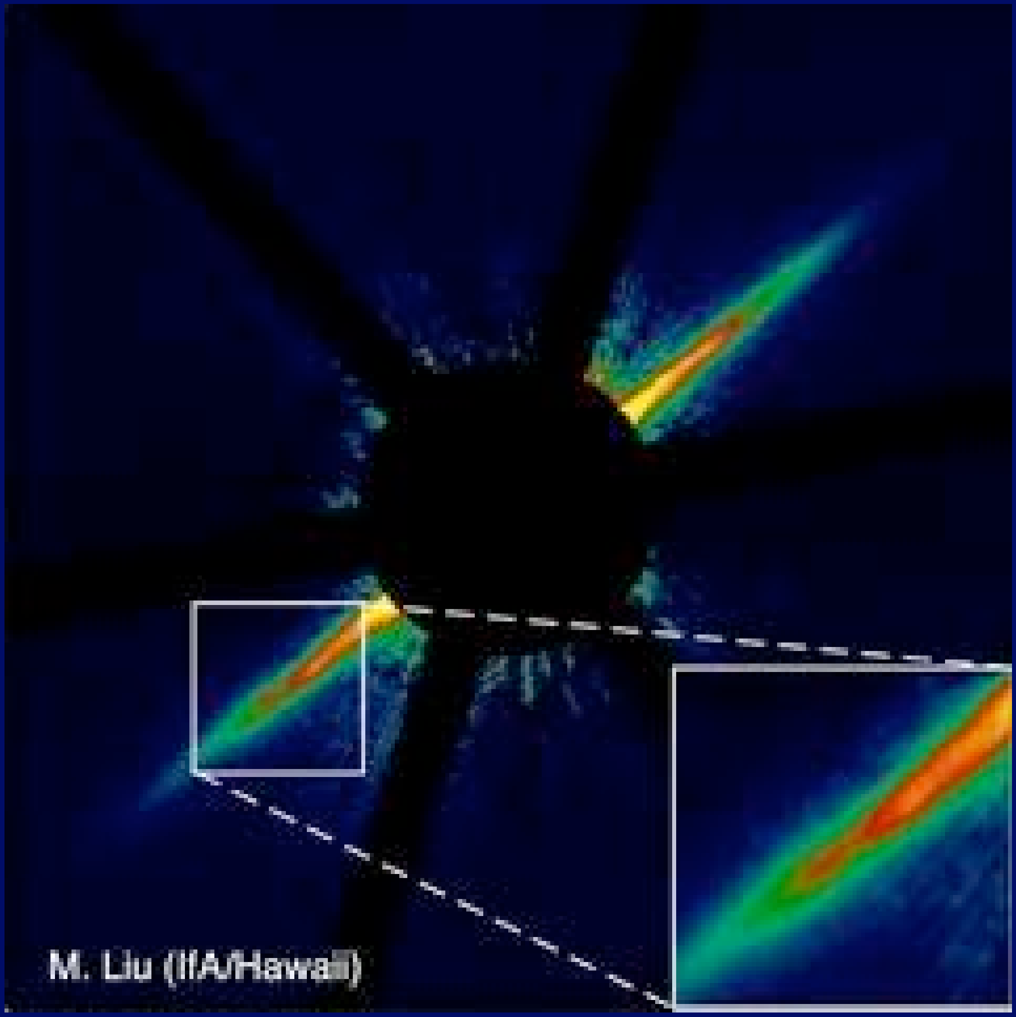
Features:
Dusty envelope
Rotation
Disk
Bipolar outflow

R. Hurt, SSC

The Protostar

- Evolution of the collapsing gas cloud
  - At first, collapsing gas stays cool
  - Dust, gas emit photons, remove energy
  - At $n \sim 10^{11}$ 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.

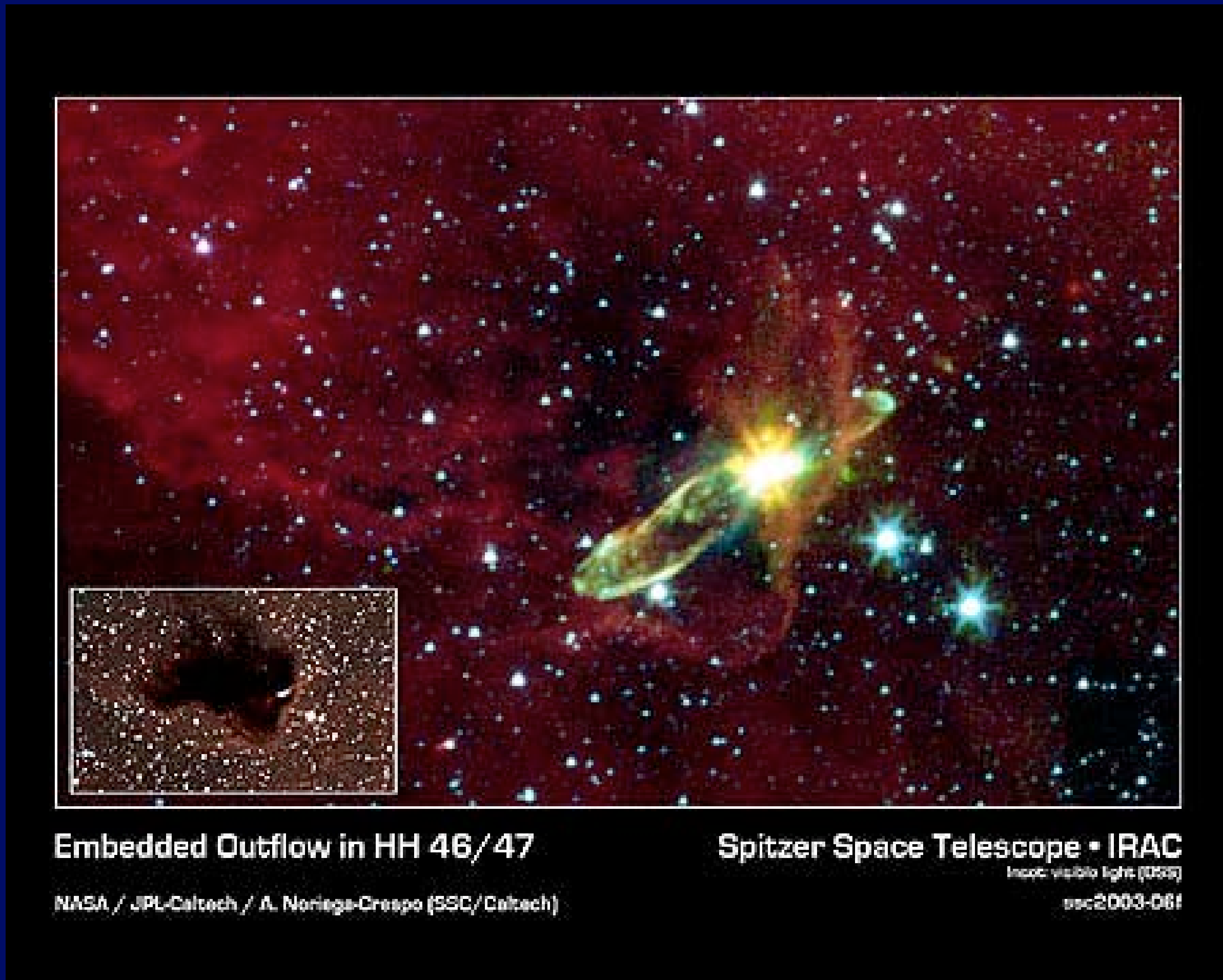
Angular Momentum

- 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

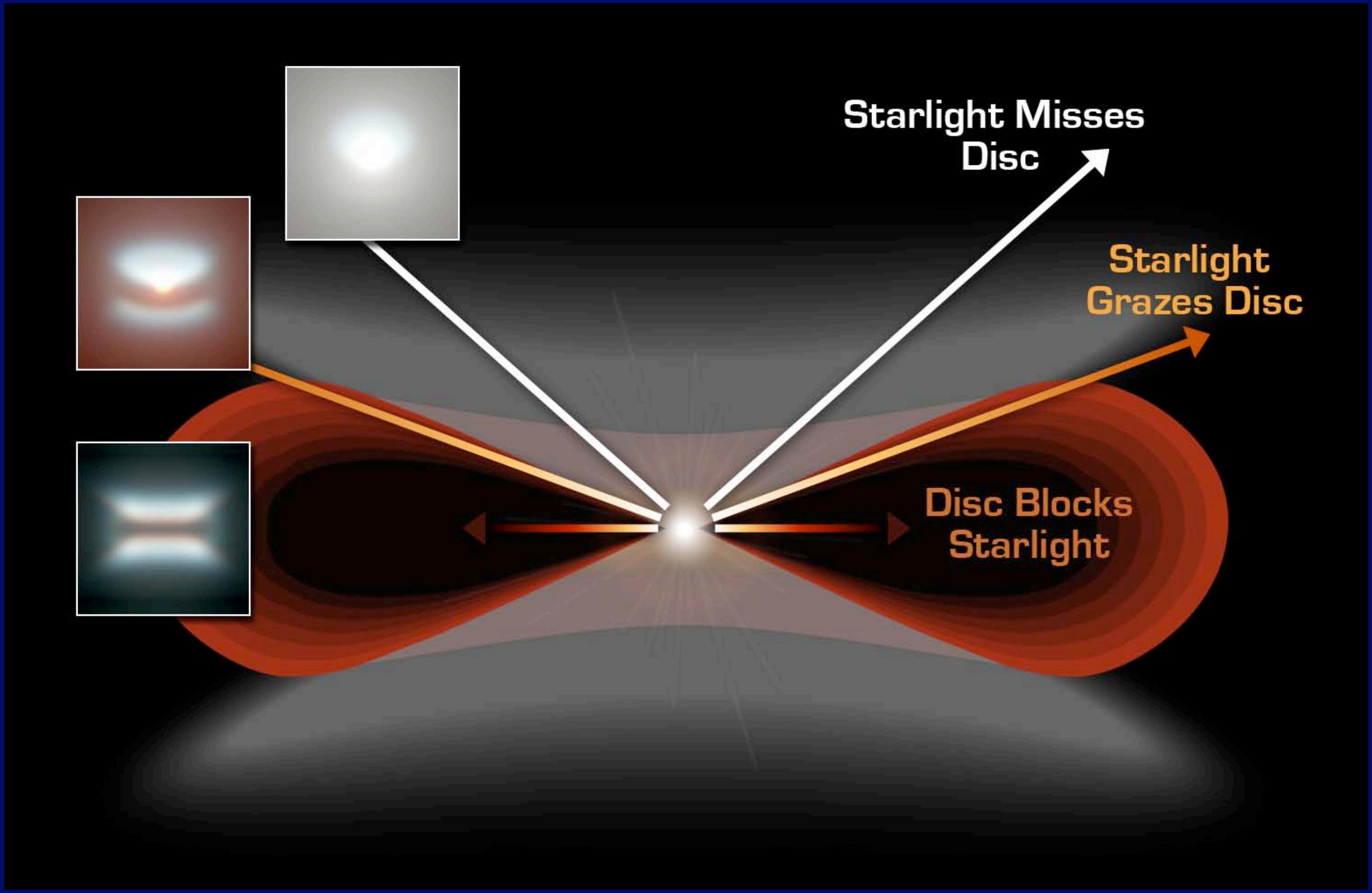
The Wind

- 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

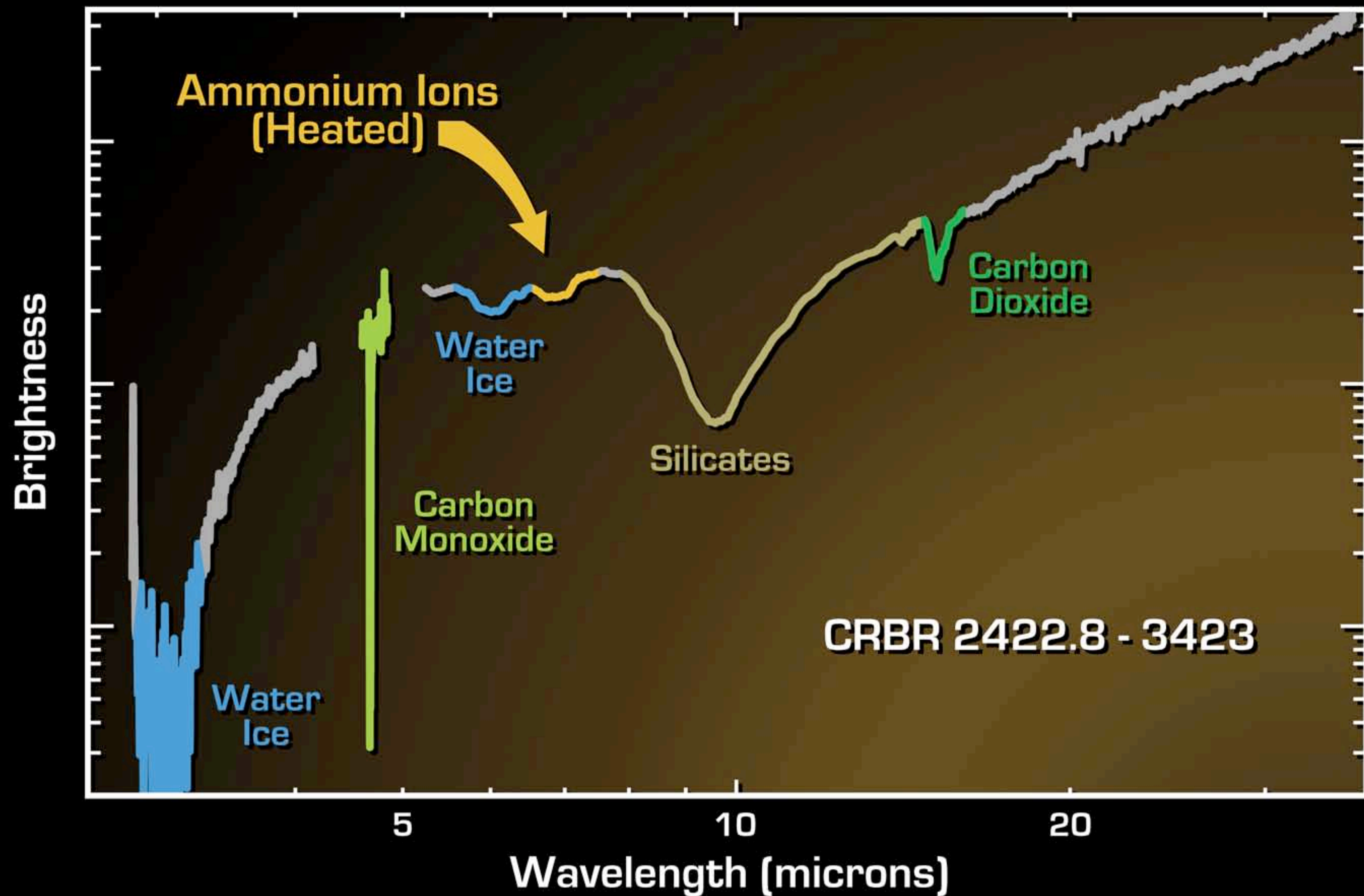


Studying the Disk



Robert Hurt, SSC

Pontoppidan et al. 2004/5, ApJ, accepted



Ices in a Protoplanetary Disc

NASA / JPL-Caltech / K. Pontoppidan (Leiden Observatory)

Spitzer Space Telescope • IRS
ESO • VLT–ISAAC
ssc2004-20c