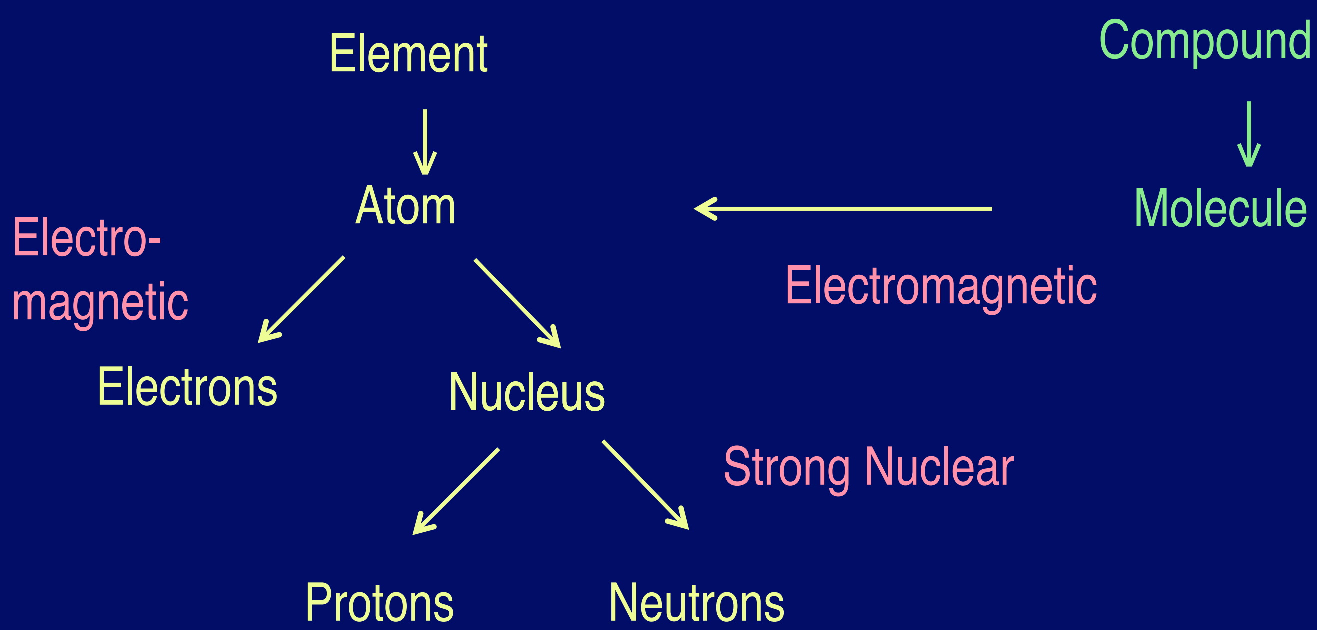
Cosmic Evolution, Part II

Heavy Elements to Molecules

First a review of terminology:



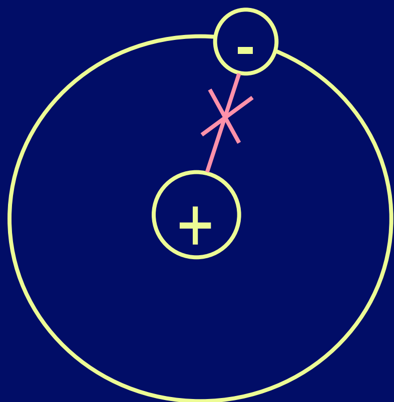
Neutral atom: # Electrons = # protons

ion: $\neq$

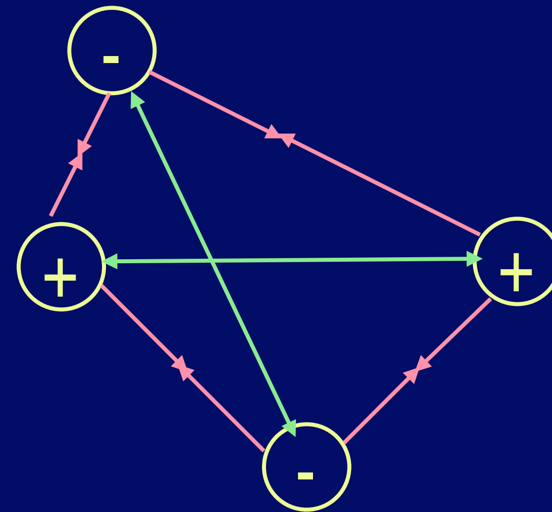
e.g. C^{+2} Carbon nucleus + 4 (6-2) electrons

Forces

H atom



H_2
Molecule



Attractive   Repulsive

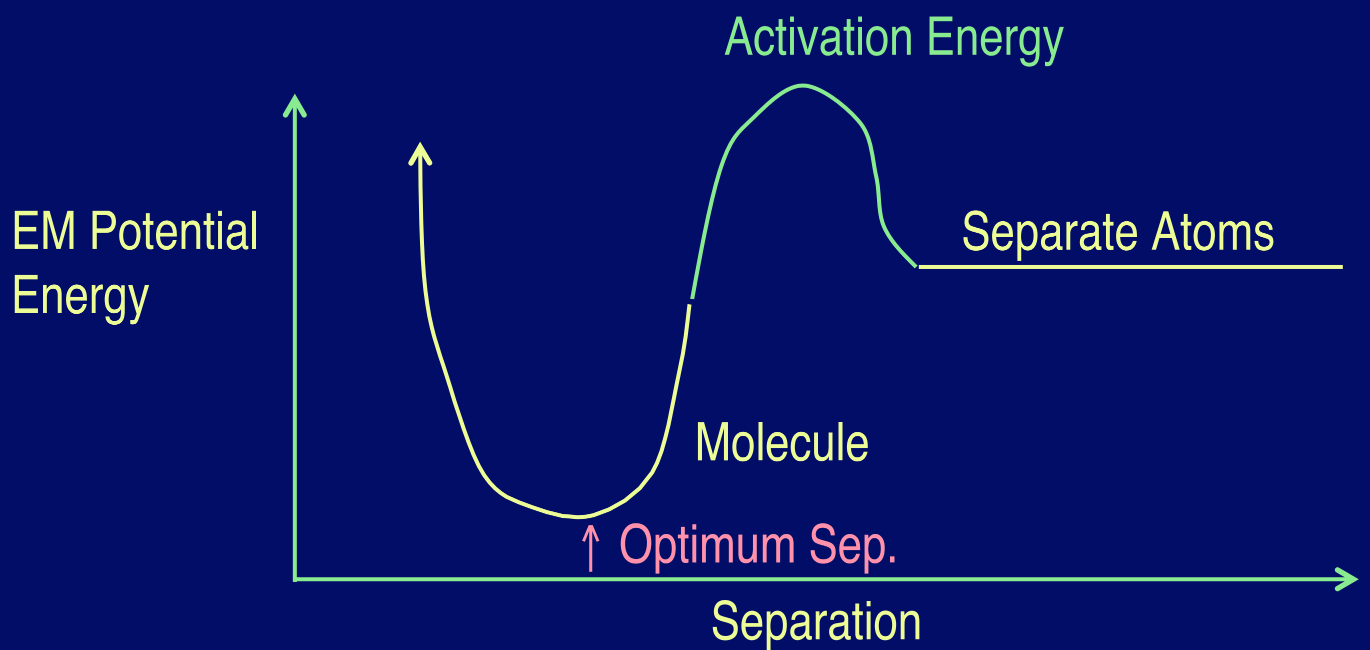
Molecule: Repulsive ~ Attractive

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 → 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

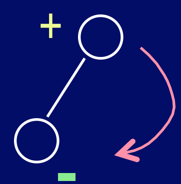
Interstellar Molecules

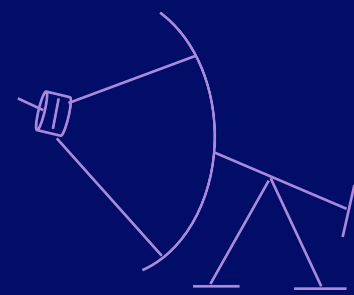
Exist as gas (individual molecules)

A few known in 1930's

Many more since 1968 - Radio astronomy

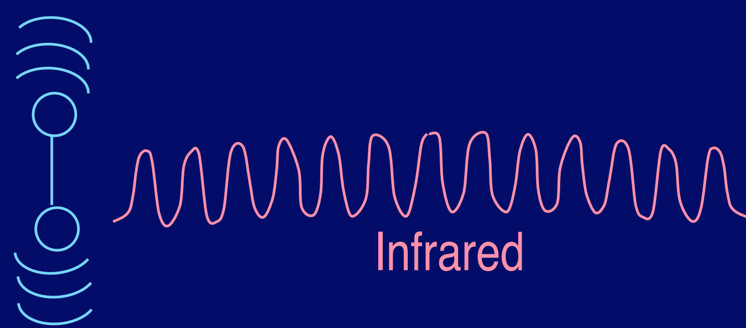
Rotation

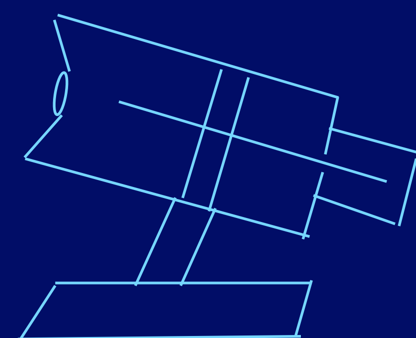




Radio Telescope

Vibration



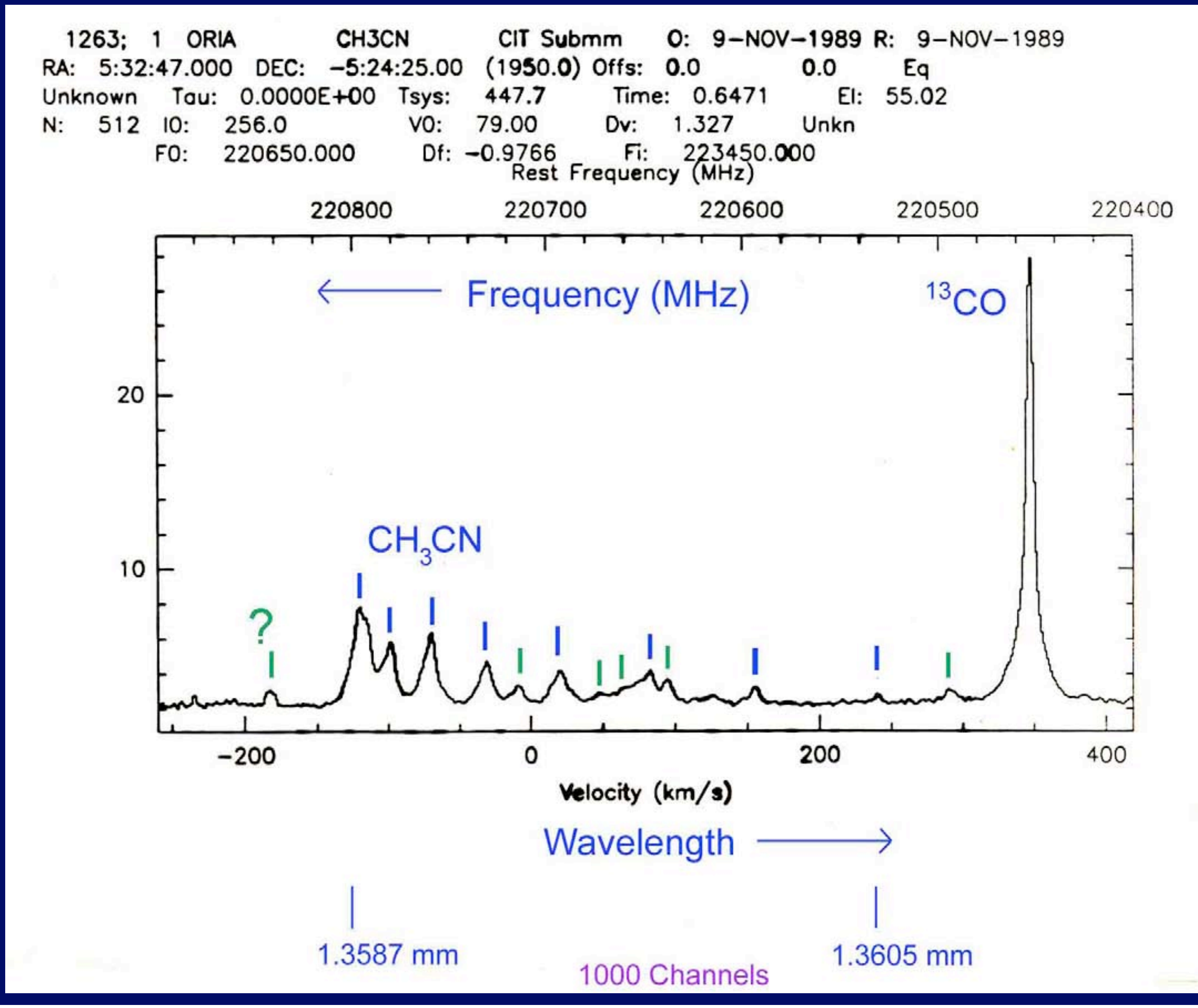


Optical Telescope

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
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
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
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
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

Molecular Ions

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Important Probe of conditions

Discovered in Infrared

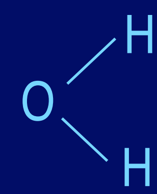
Discovered in UV

Relevant to the Origin of Life

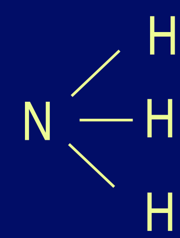
Look at Appendix 2

Important Examples:

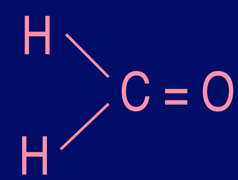
Water H_2O



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 ? 1994 so far, not confirmed

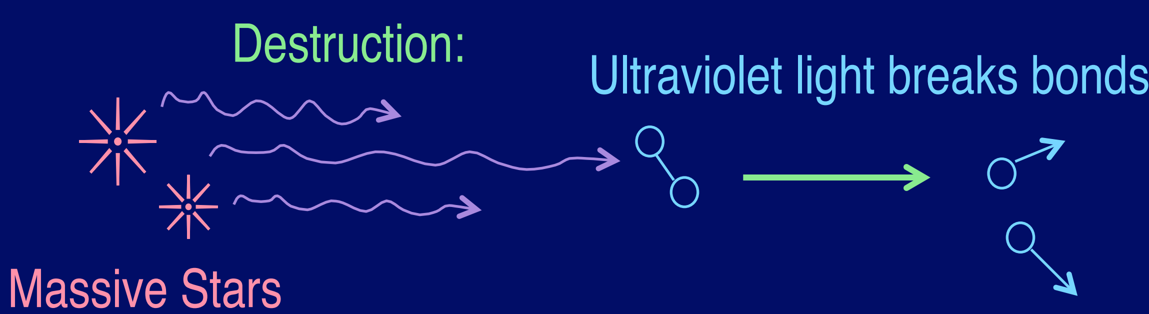
   Polycyclic Aromatic Hydrocarbons (PAHs)

   (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 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

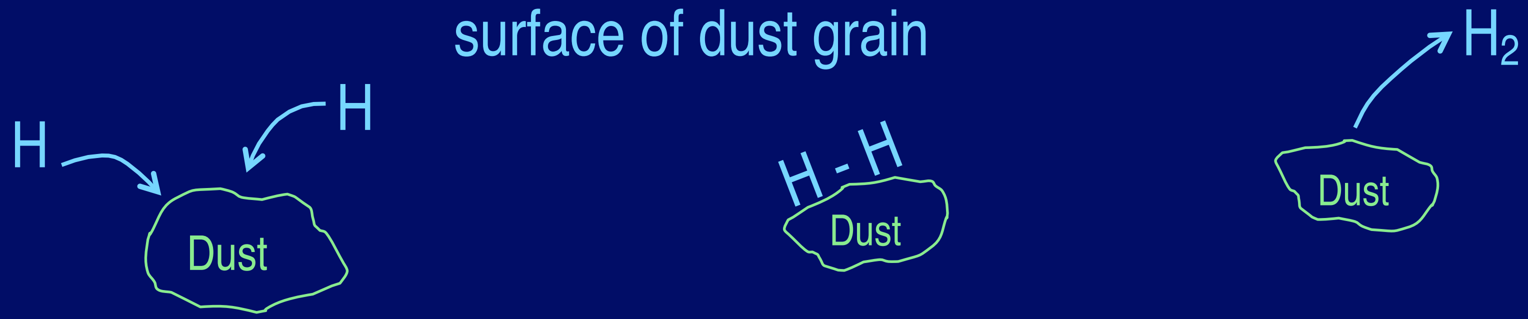
Must lose the potential energy difference before it falls apart (~ 10^{-14} s)

Collisions: OK in lab, too slow in space

Emit photon: very 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 **without** activation energies

e.g. Molecular ions, like HCO^+

Cosmic Ray

$$\xrightarrow{\hspace{6em}} H_2 \rightarrow H_2^+$$

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

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

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

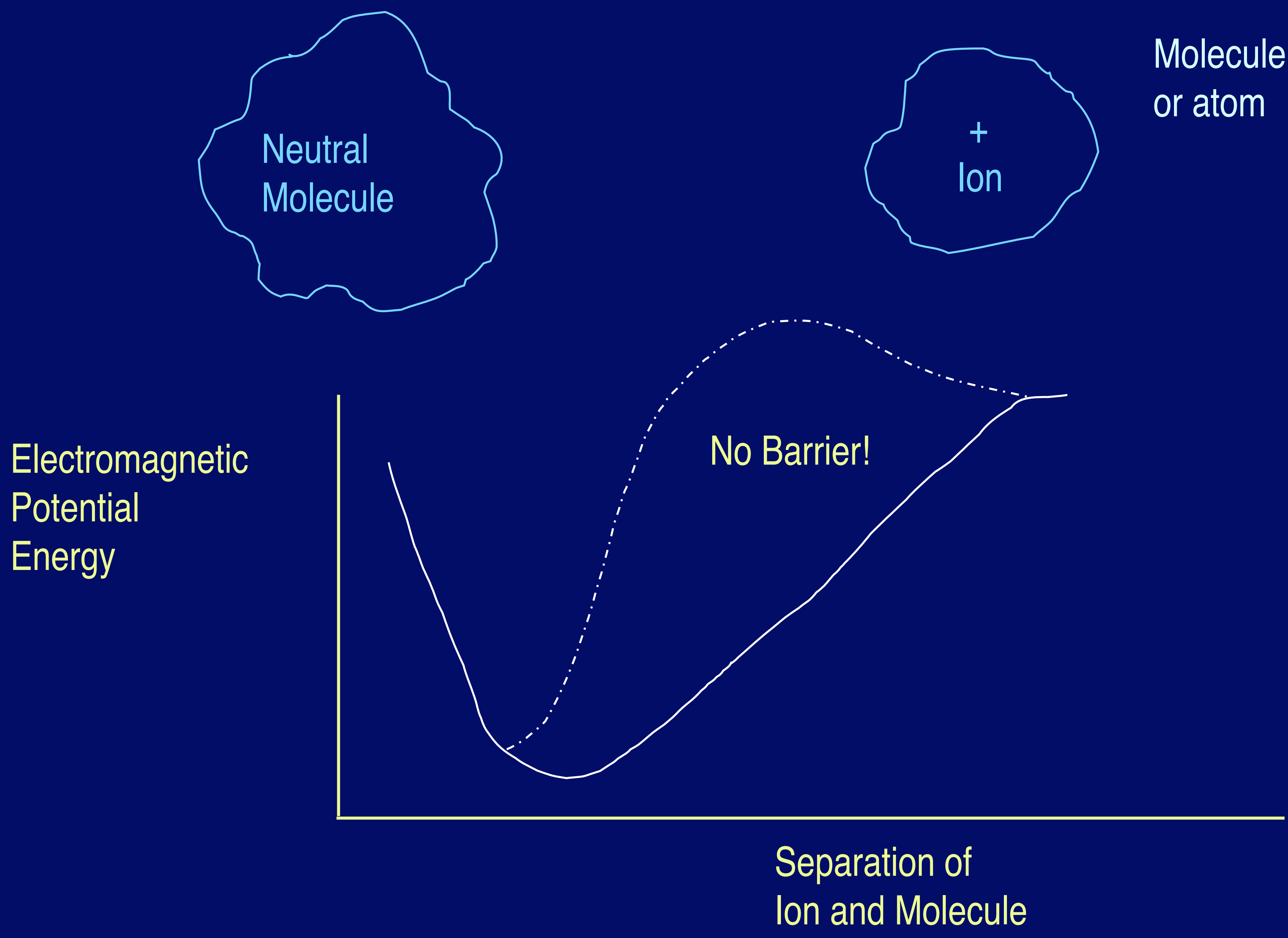
Energy + simple mol.

→ Reactive mol.

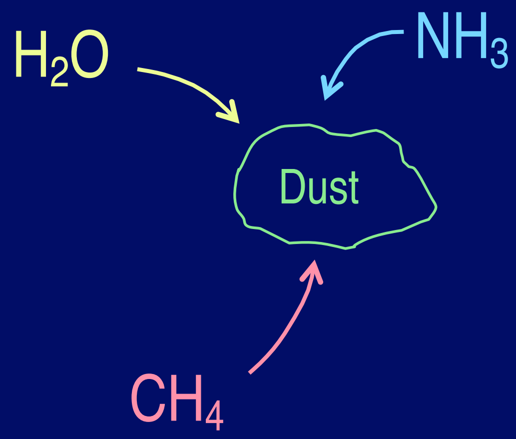
↓

More complex

Ion - Molecule Reactions



Molecules on Dust Grains



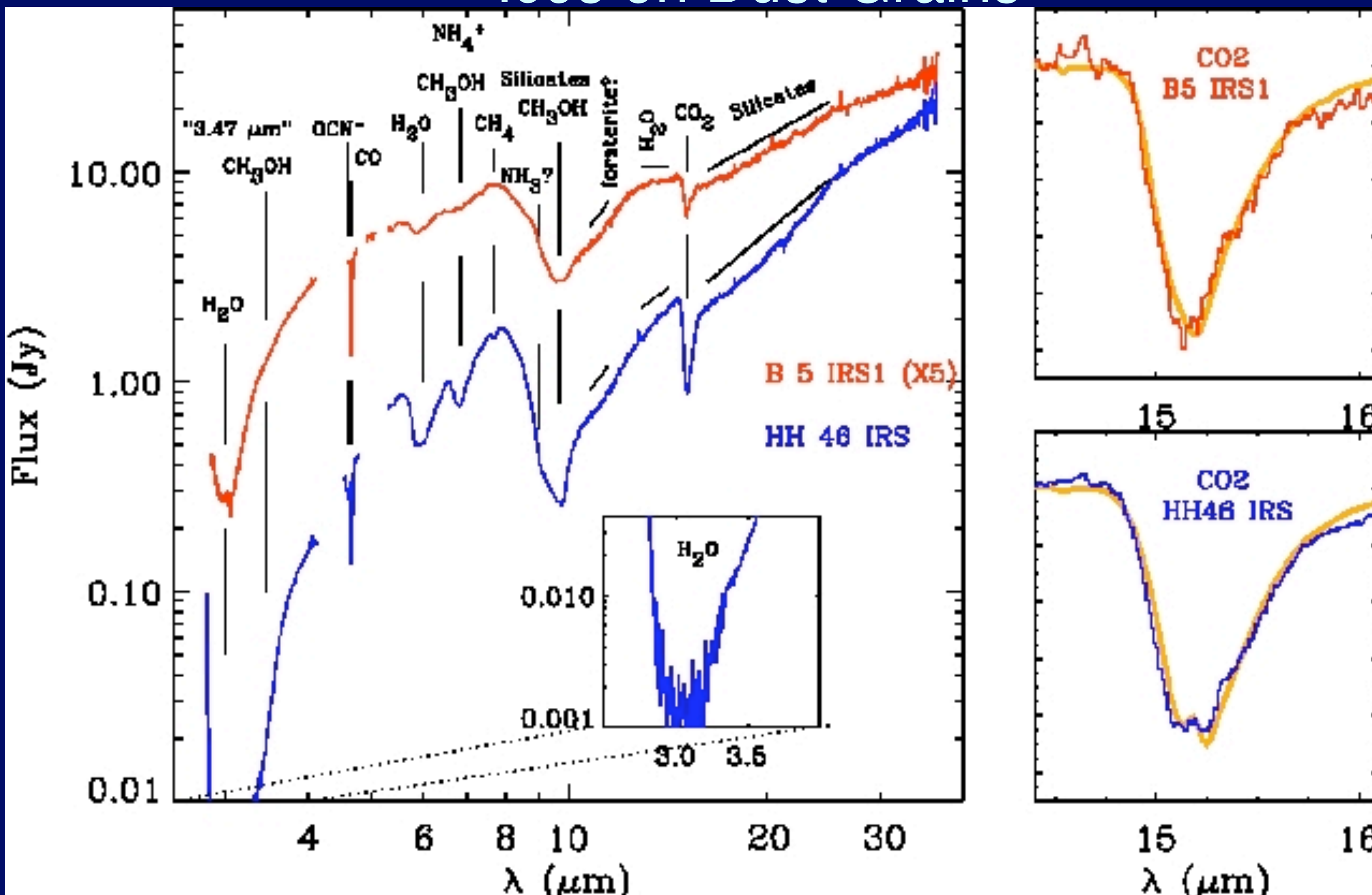
Stick on grains
"ice"

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



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. 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_*)

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

N_* : Count them? No

Use Gravity (Newton's Laws)

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

update: 269 km s^{-1} reported in Jan. 2009

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

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

← 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) $\longrightarrow$ $M_g = 1.0 \times 10^{11} M_\odot$

Update: 28,000 ly gives $1.4 \times 10^{11} M_\odot$

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

Update: $2.0 \times 10^{11} M_\odot$

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

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

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

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.

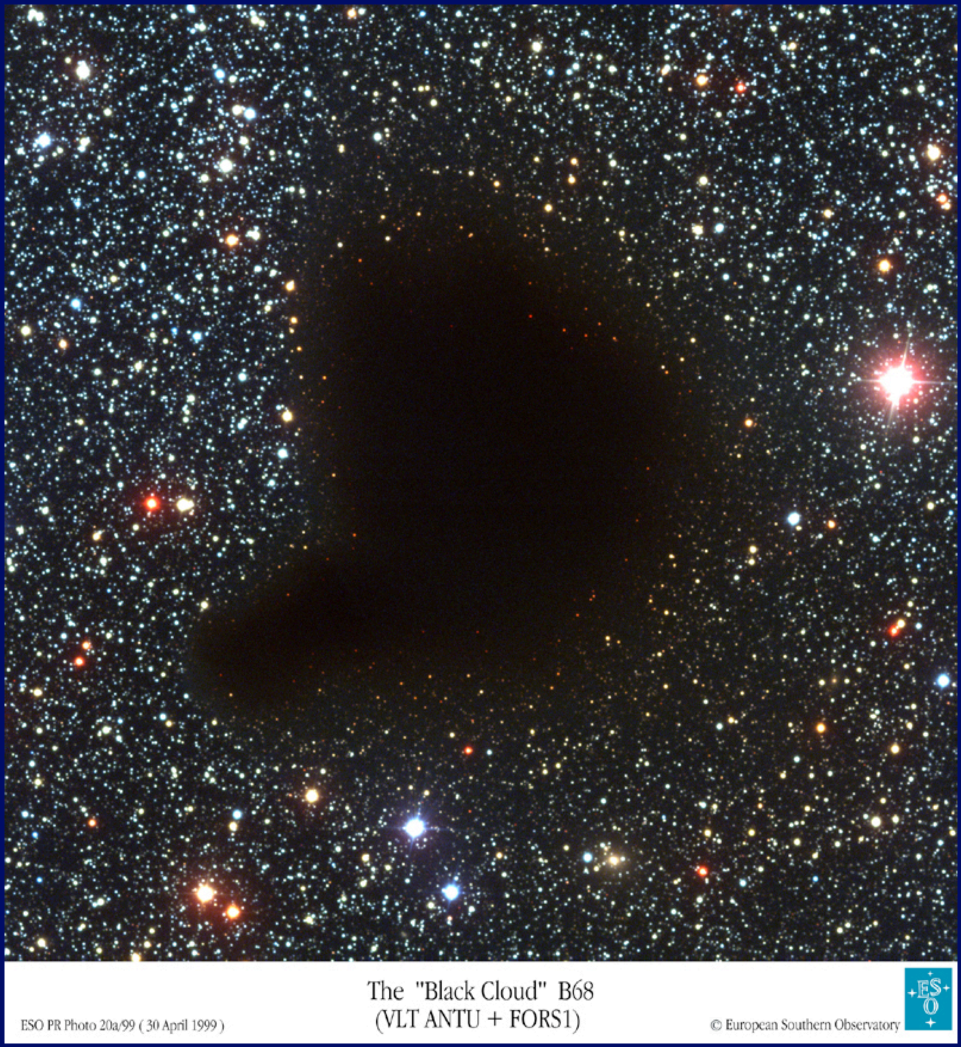
Star Formation

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)
  - ~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

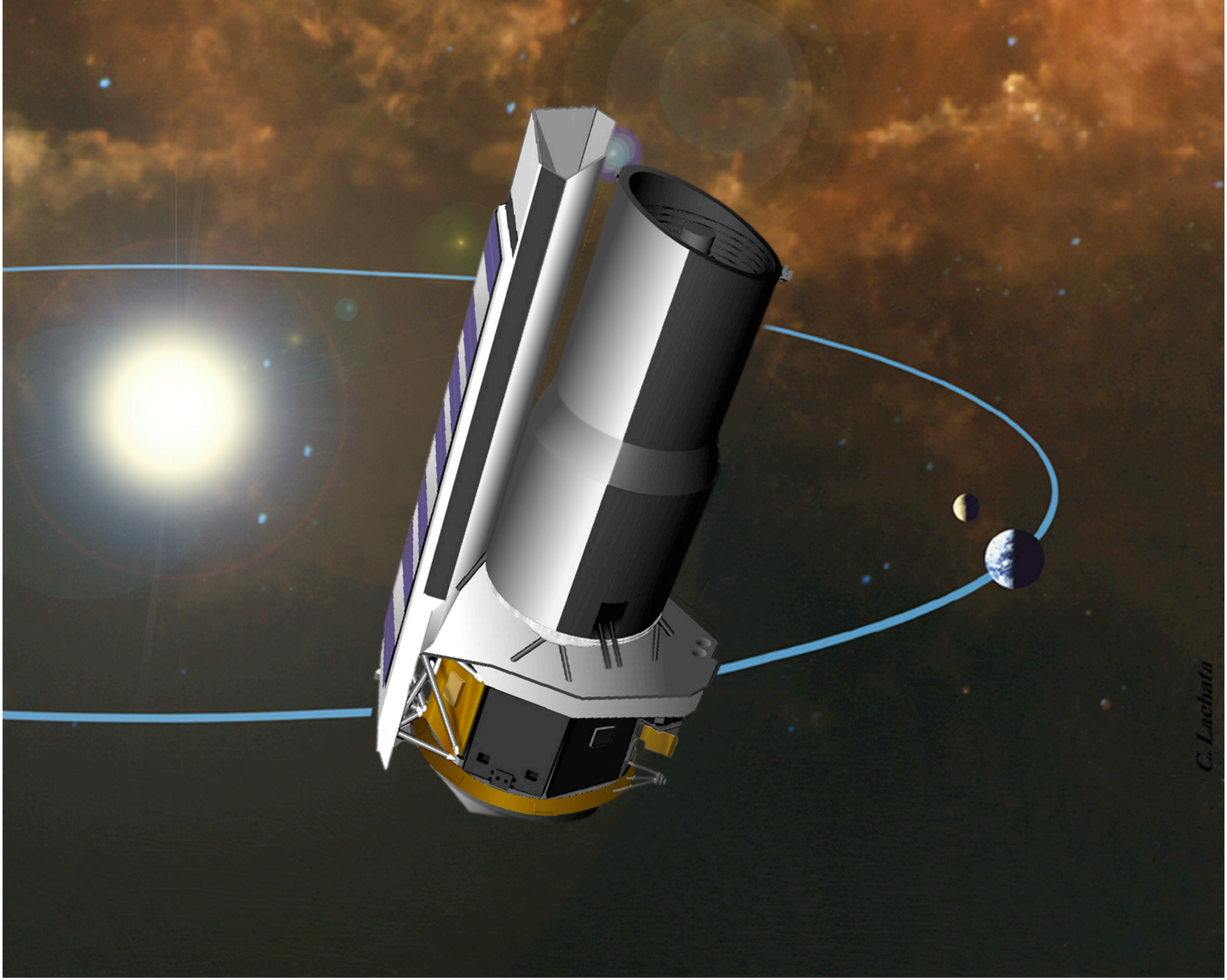


Current Star Formation

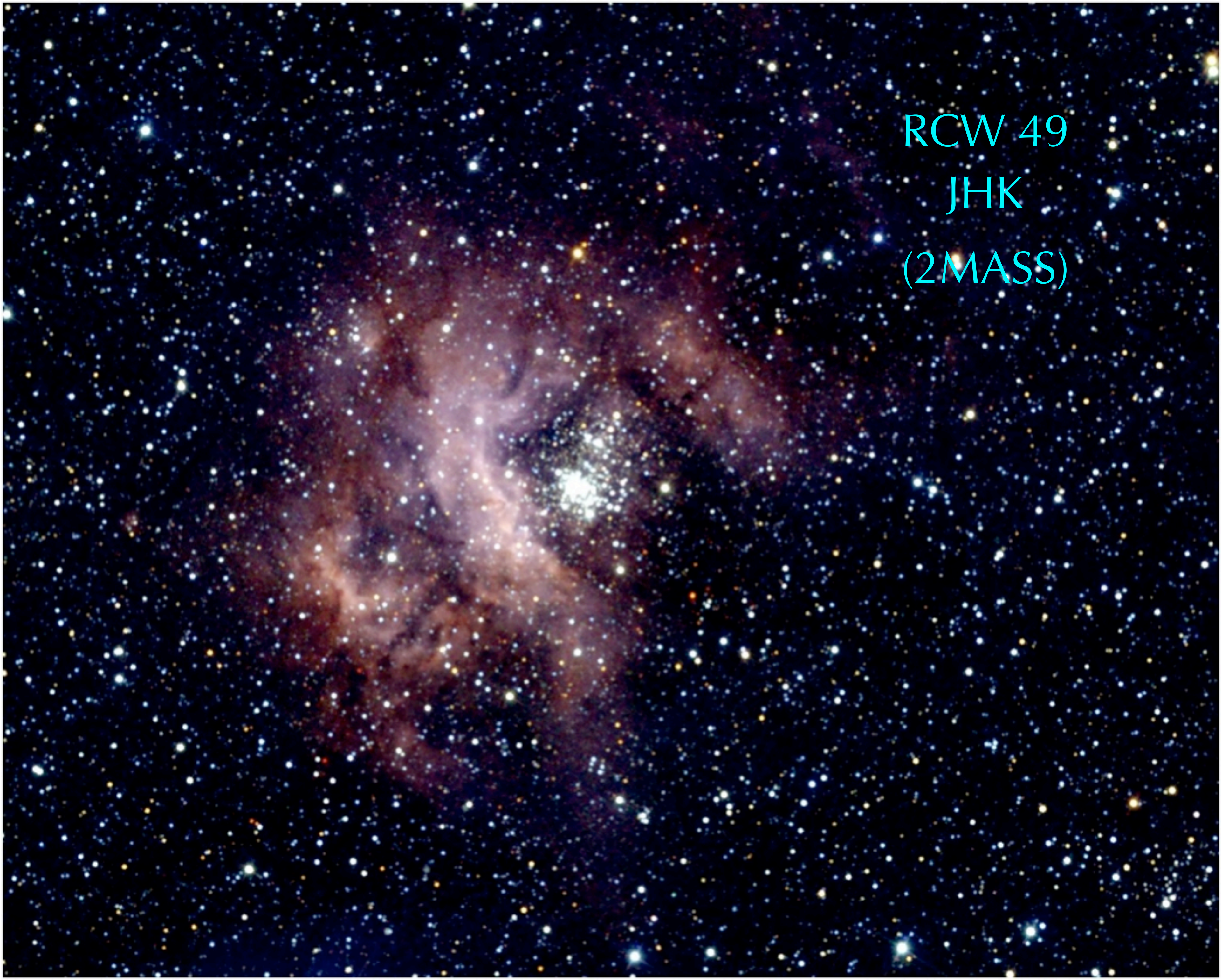
- Occurs in gas with heavy elements
  - Molecules and dust keep gas cool
  - Radiate energy released by collapse
  - Stars of lower mass can form
  - Mass needed for collapse increases with T
- Star formation is ongoing in our Galaxy
  - Massive stars are short-lived
  - Star formation observed in infrared

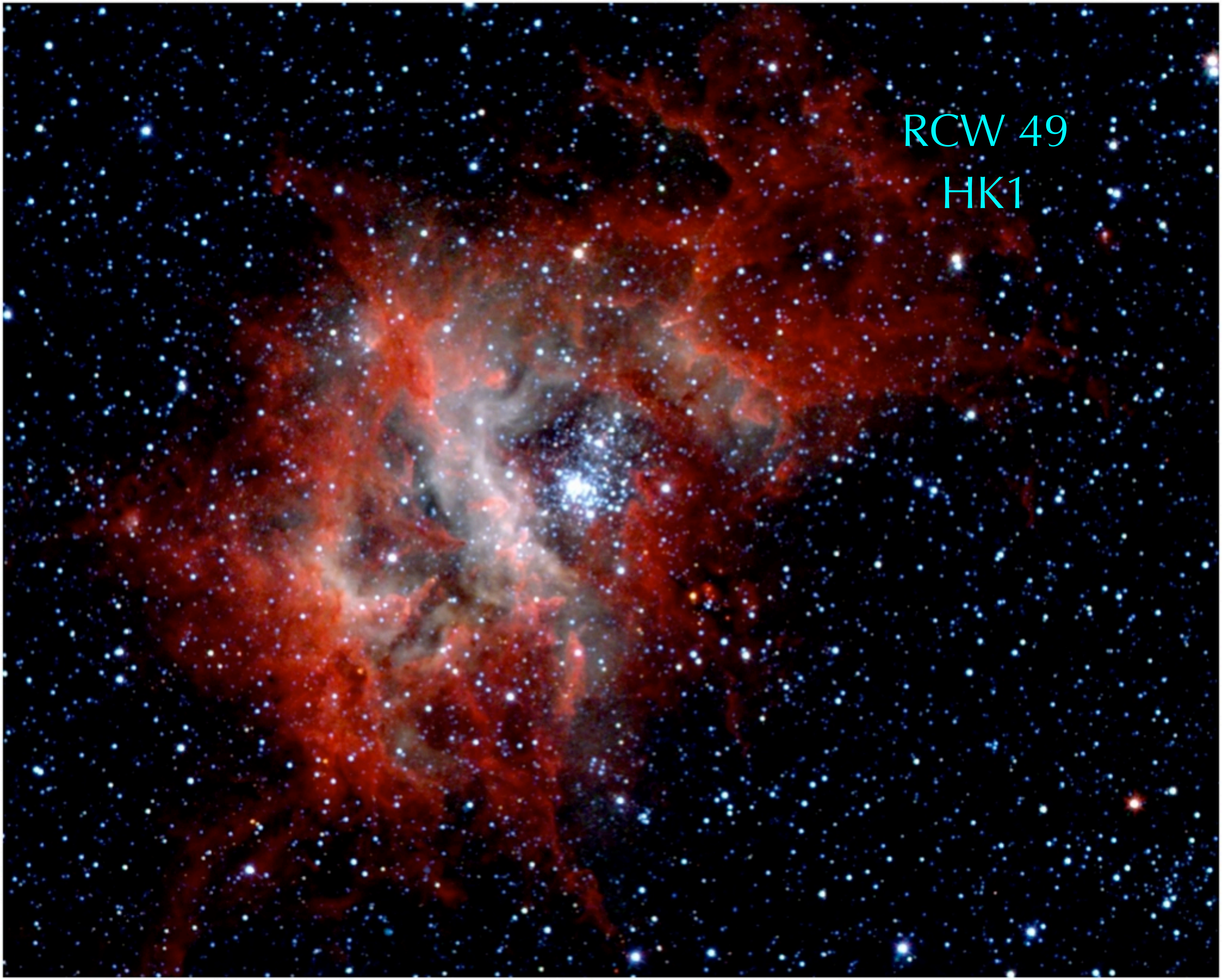
The Launch of The Spitzer Space Telescope

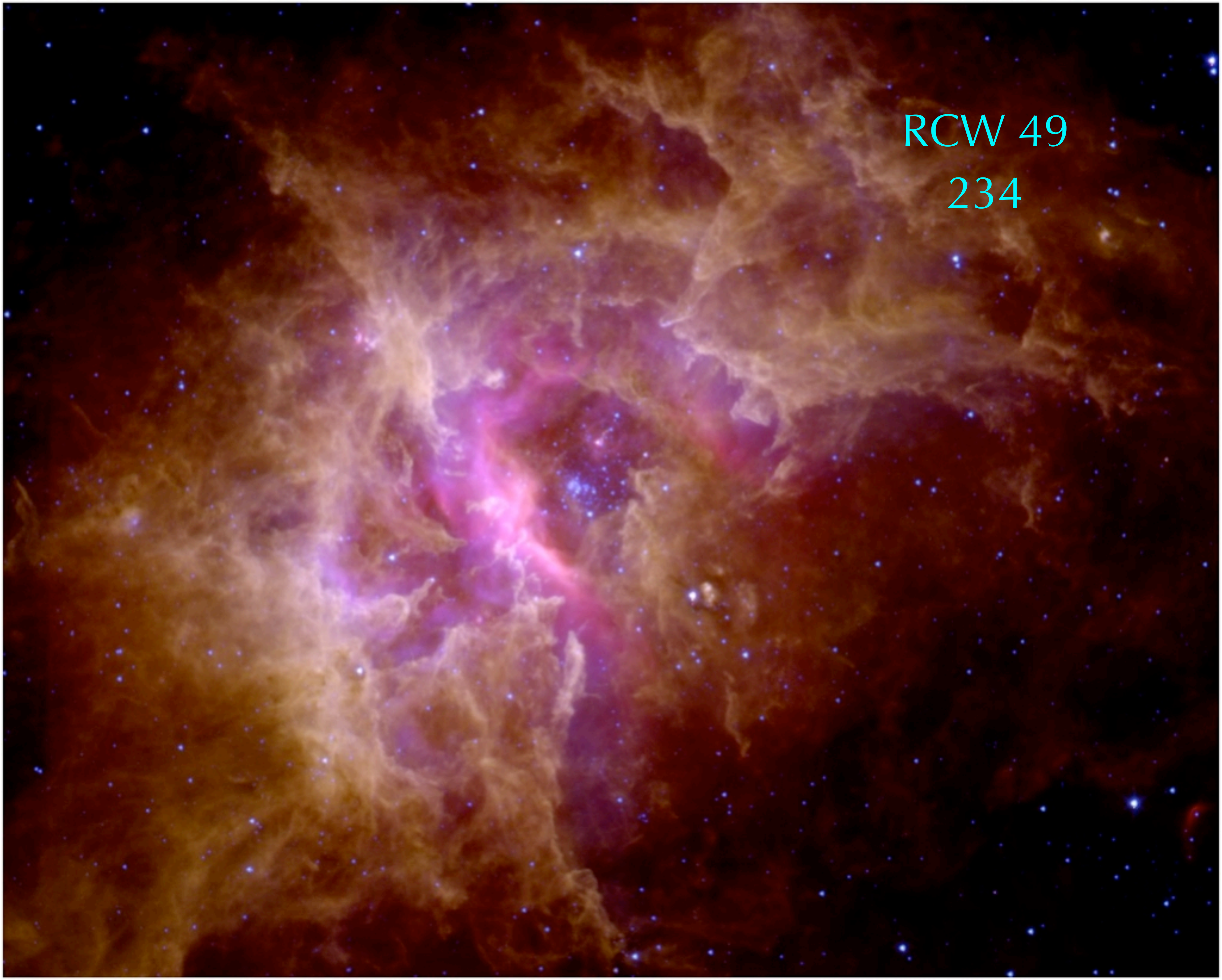
Spitzer Space Telescope Launched Aug. 2003, expect a 5 yr life.


C. Lachata

Visible to Infrared Views


RCW 49
JHK
(2MASS)


RCW 49
HK1


RCW 49
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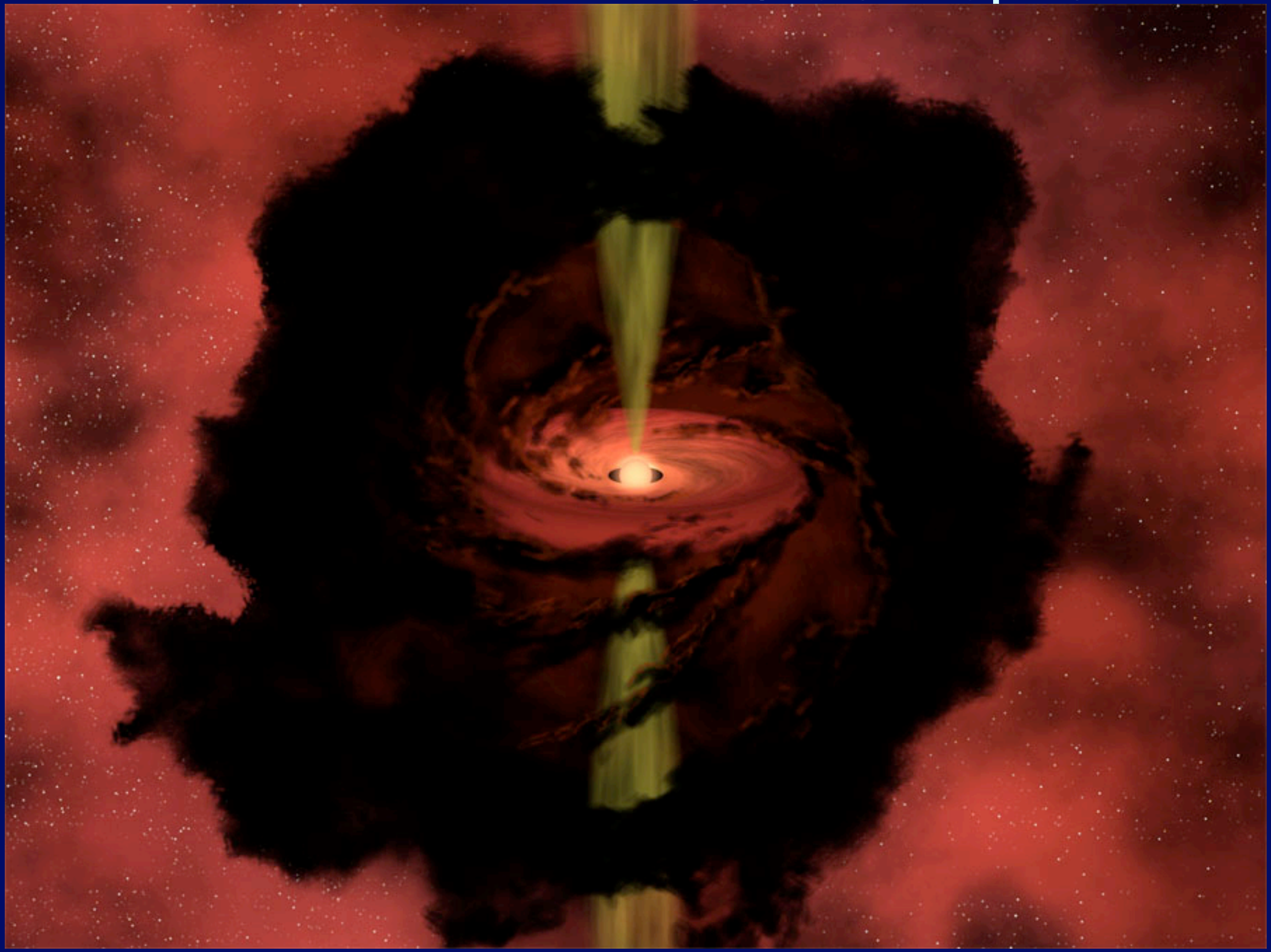
Artist's Conception



Features:

Dusty envelope

Rotation

Disk

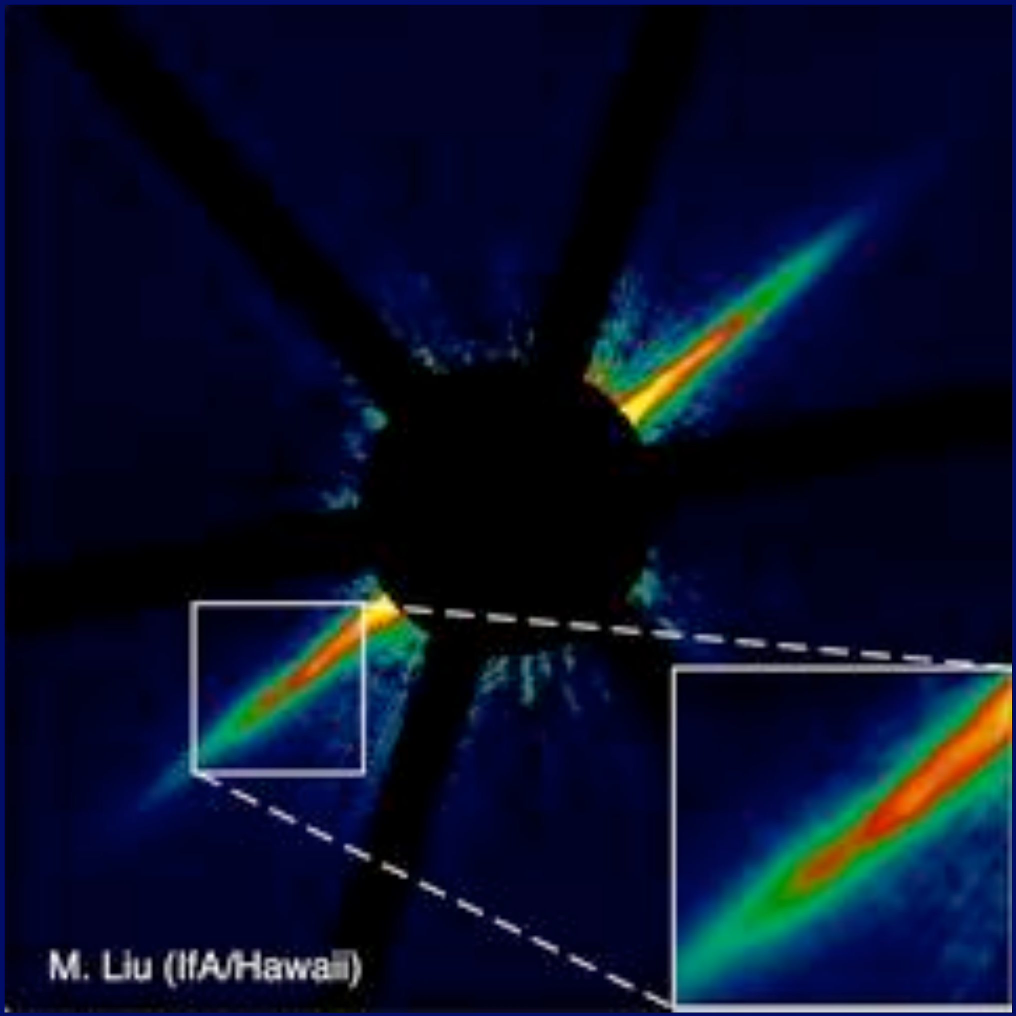
Bipolar outflow

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.

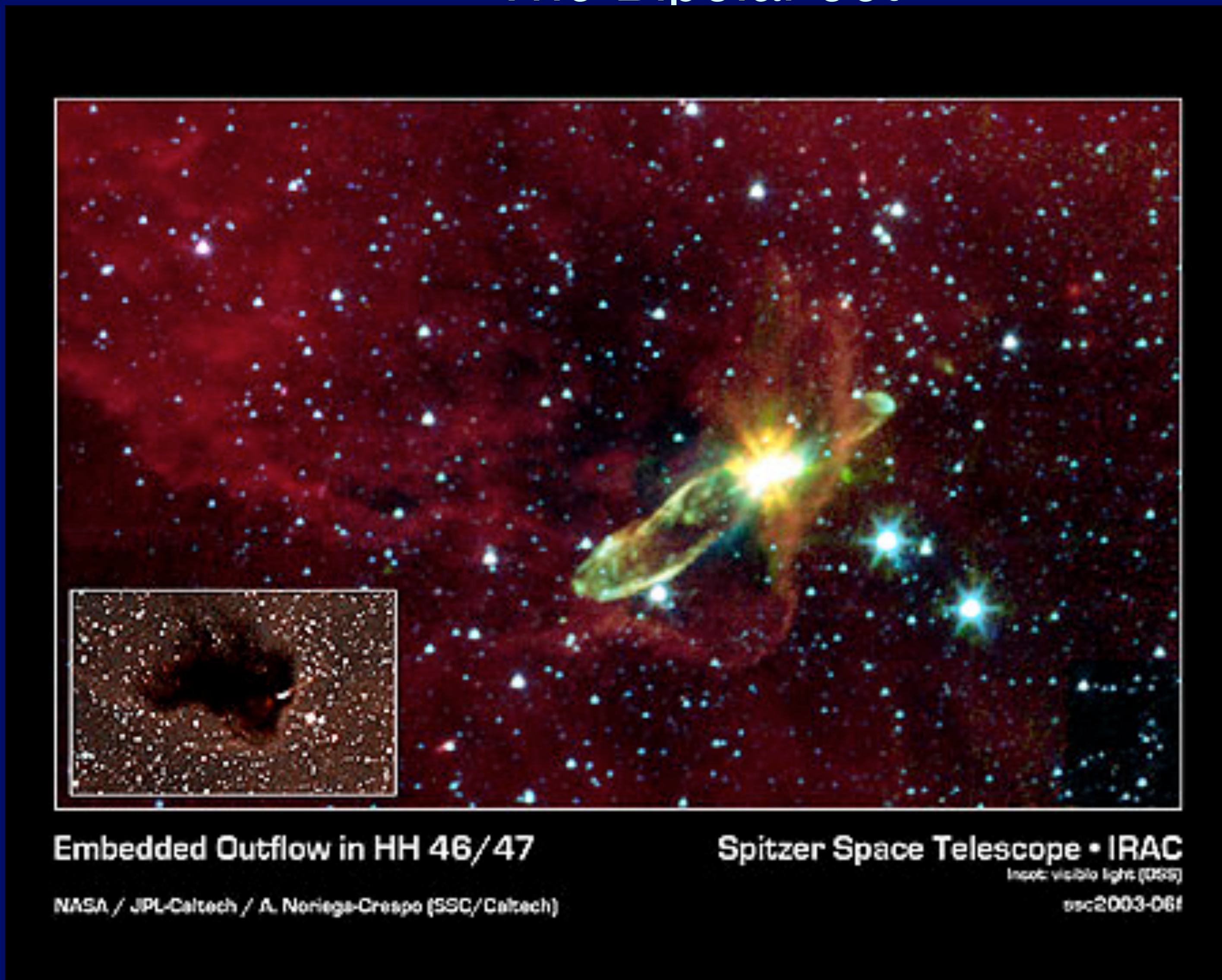
Angular Momentum

- 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

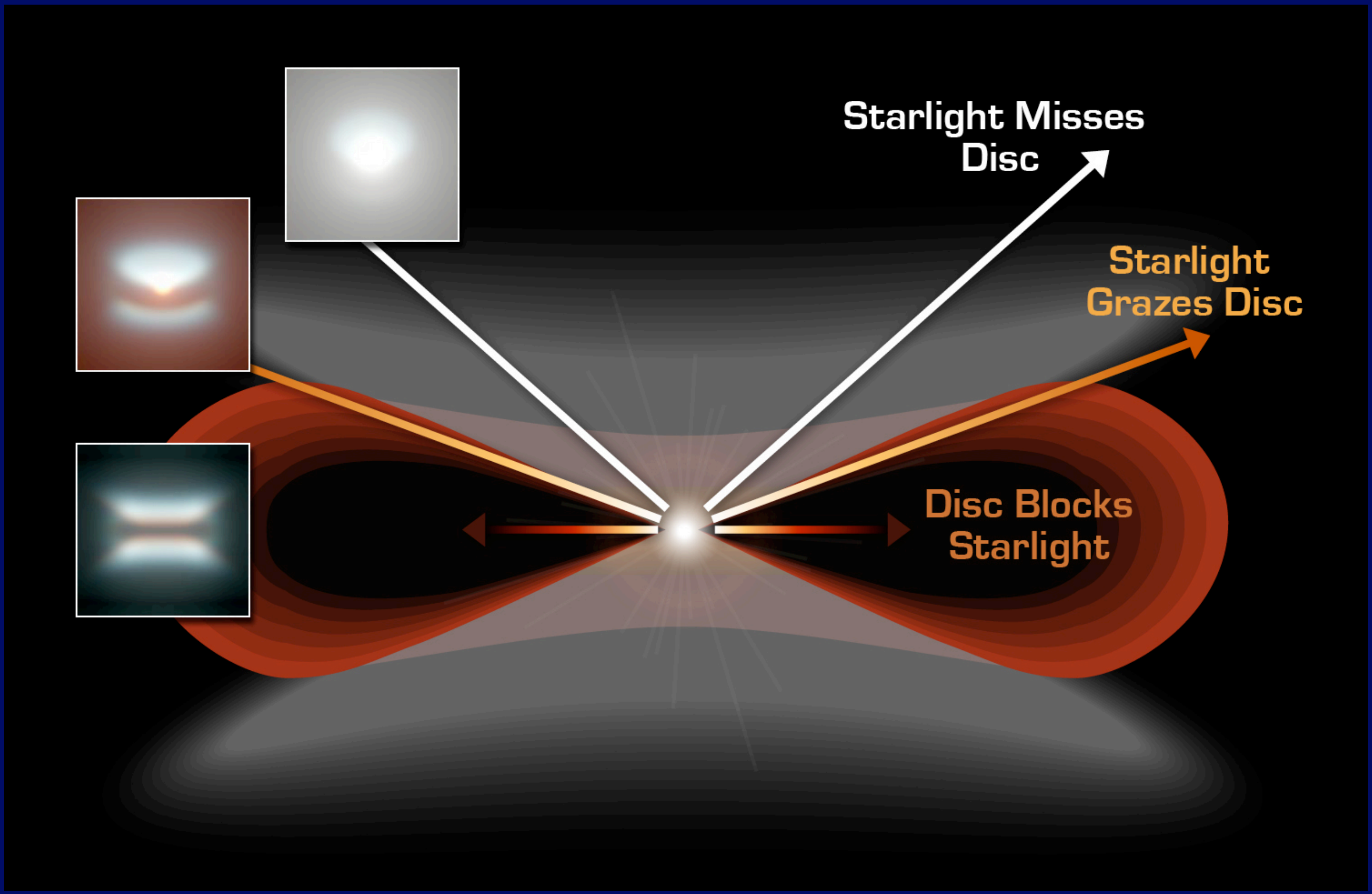
The Wind

- 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

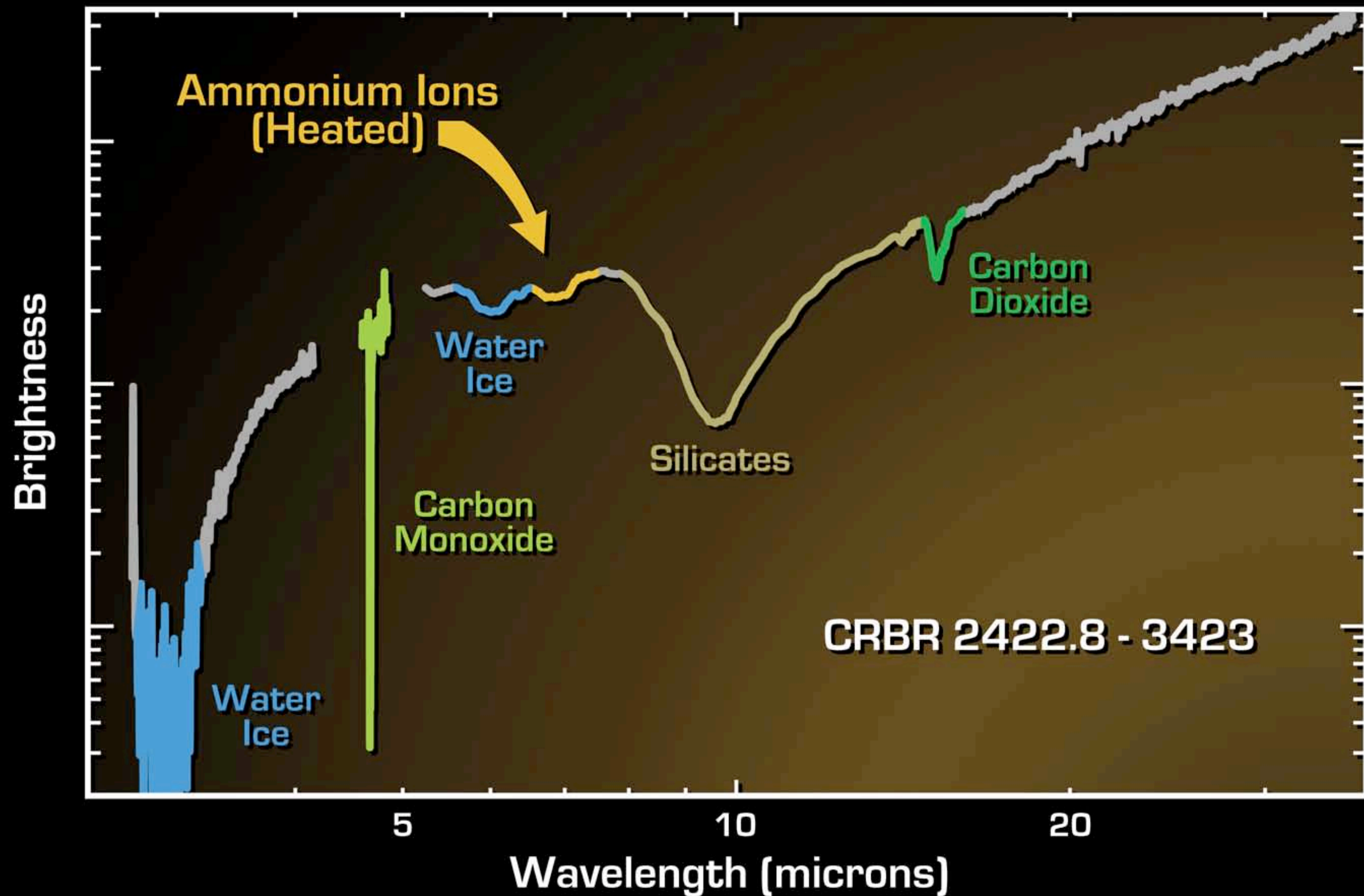


Studying the Disk



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