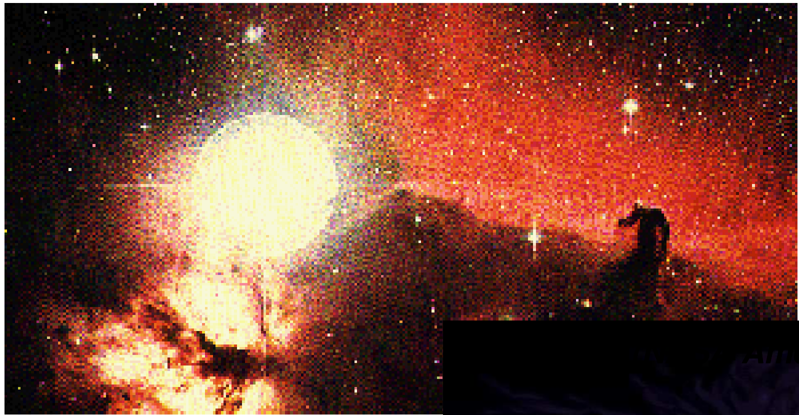
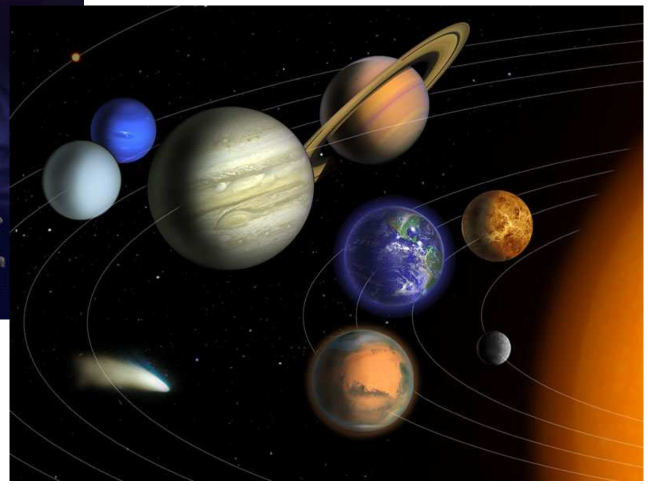
ASTROCHEMISTRY & ASTROBIOLOGY: ISM, COMETS & METEORITES



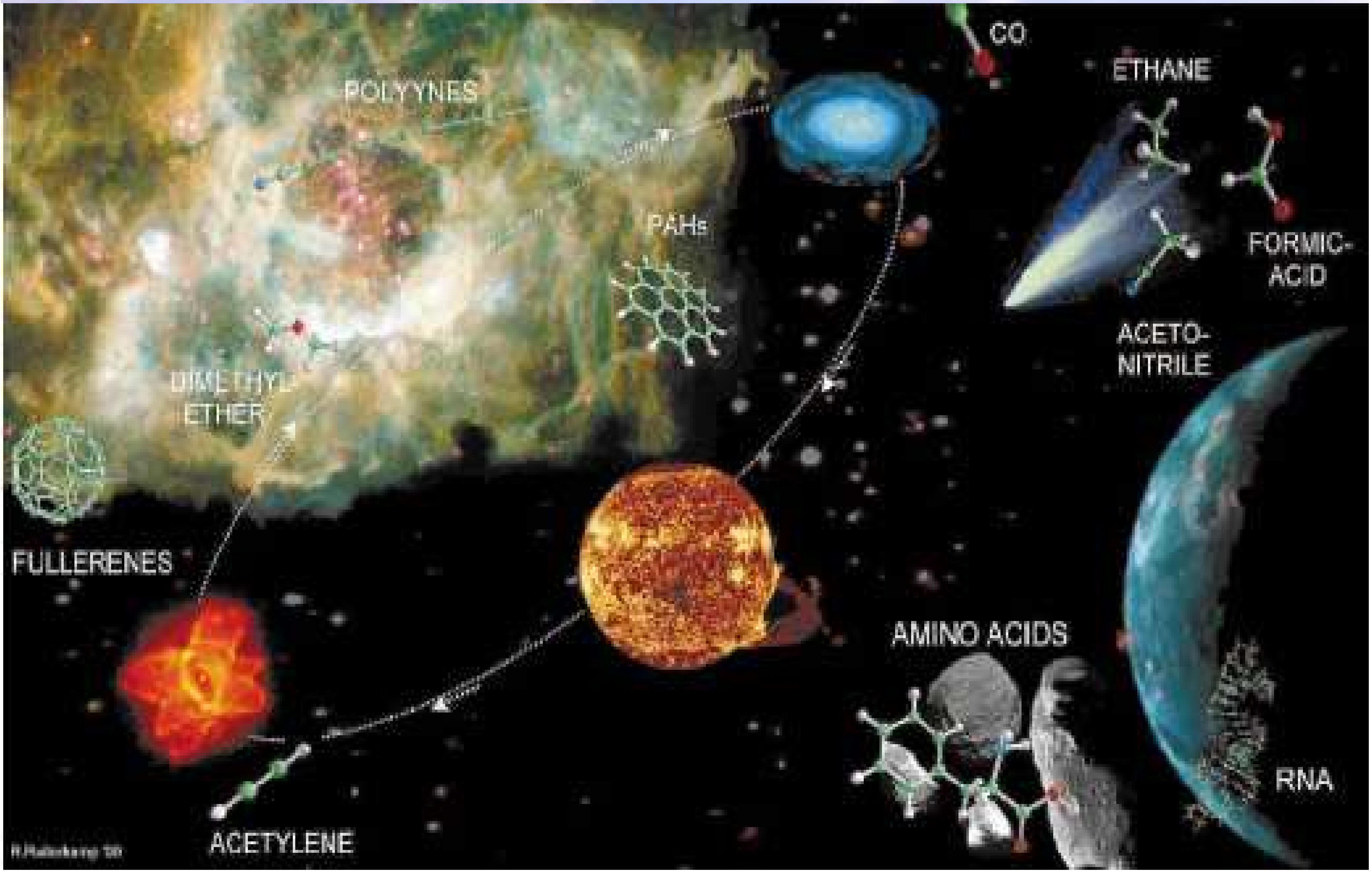


Steven Charnley

NASA Ames Research Center

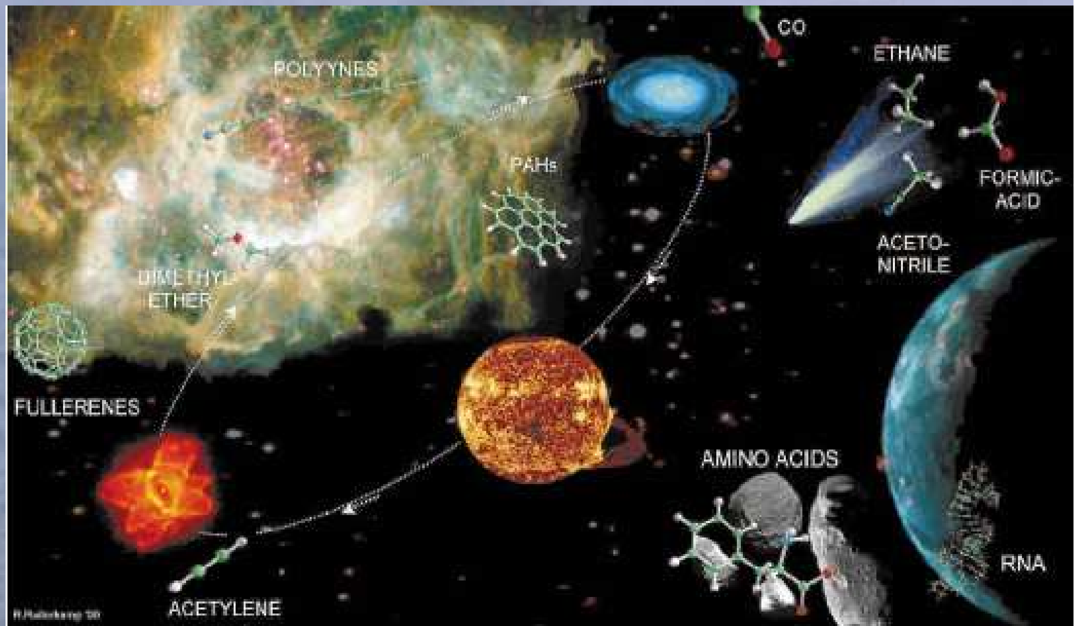
XII IAG/USP Advanced School on Astrophysics

Organic Molecules in the Universe



Course Outline

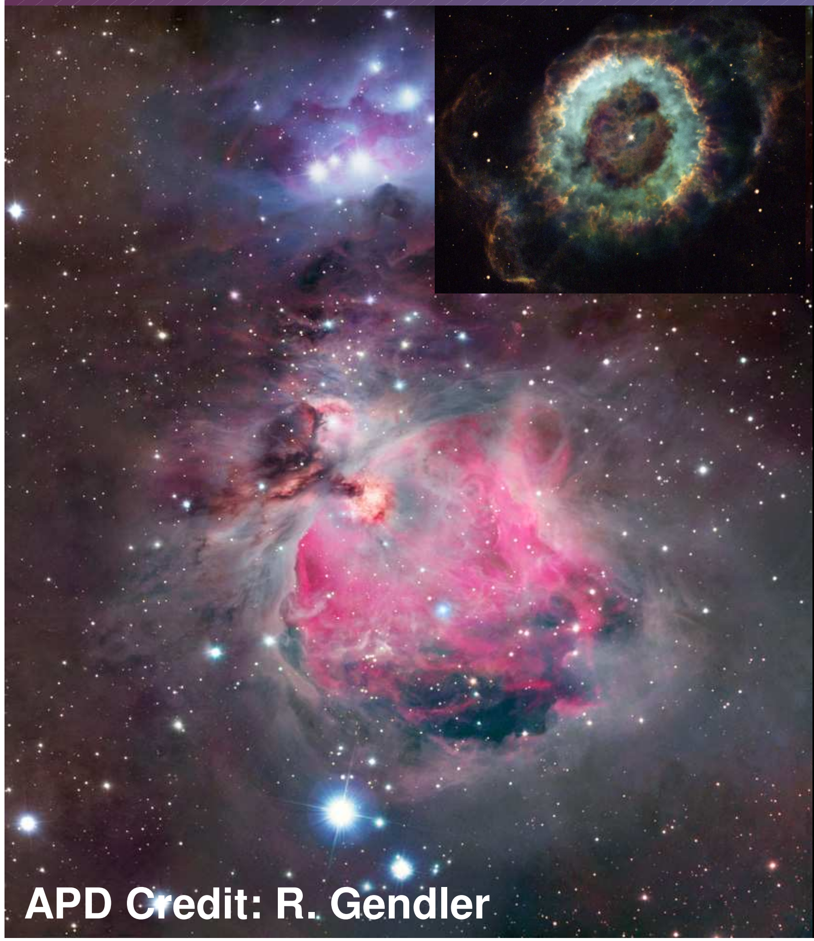
1. Overview - Molecules in the ISM
2. Astrochemical Processes
3. Chemistry of Star Formation
4. Comets & Meteorites
5. Astrochemistry & Astrobiology

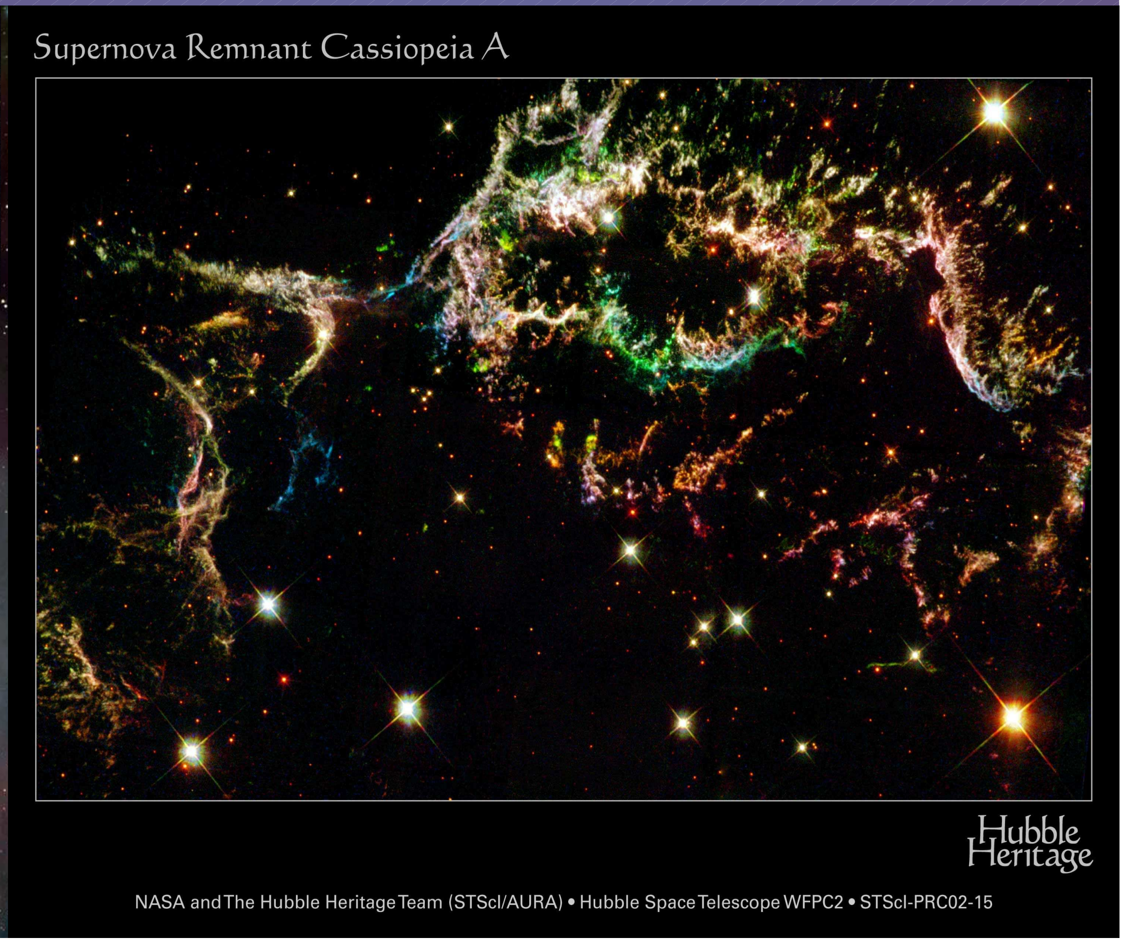


Cosmochemistry - Origin of the Elements and Dust

- **Formation of biogenic elements in stellar nucleosynthesis. Injected into ISM by supernovae and stellar winds.**

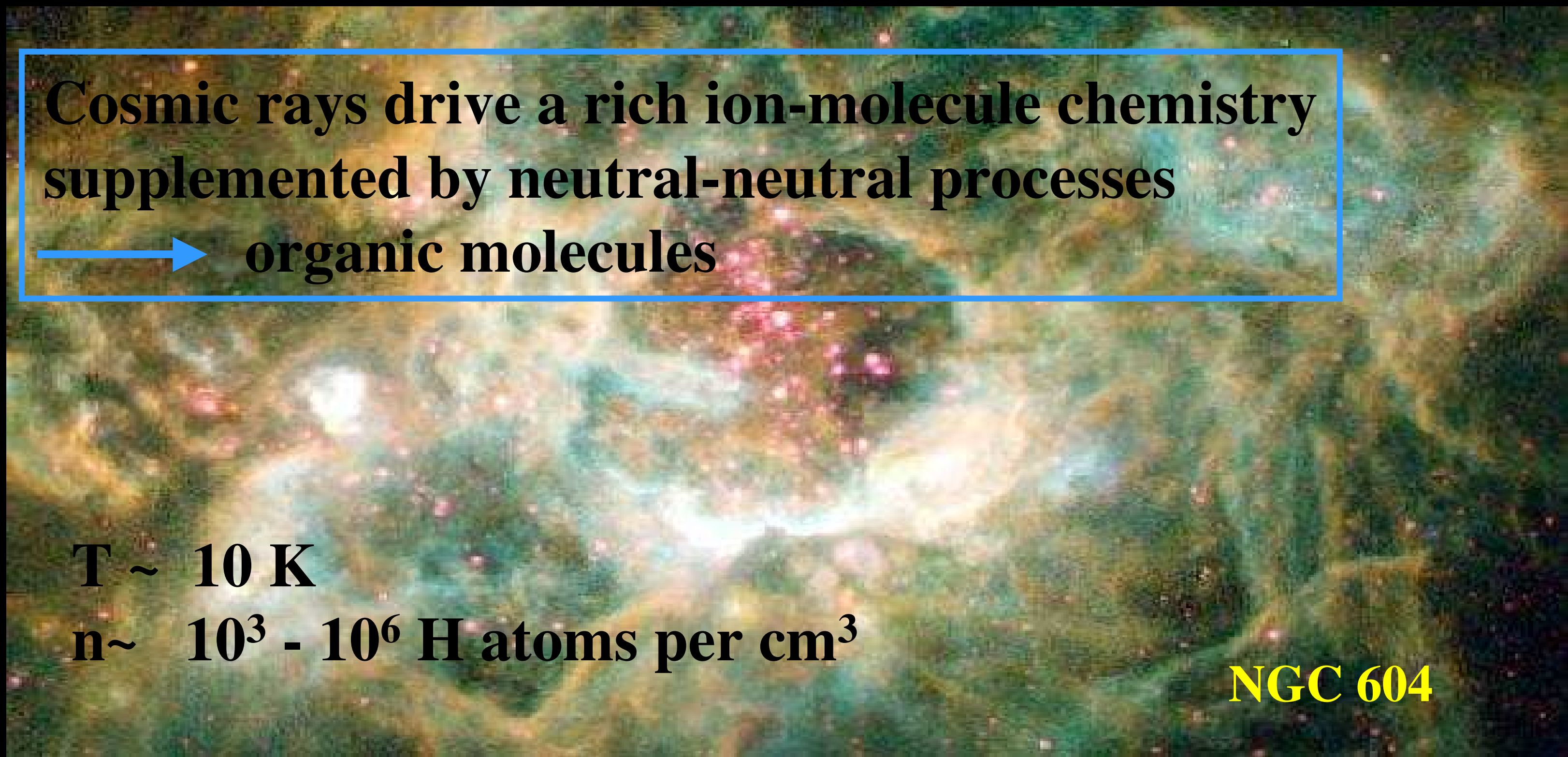
- **Injection of dust grains in SN ejecta and from atmospheres of late-type stars.**



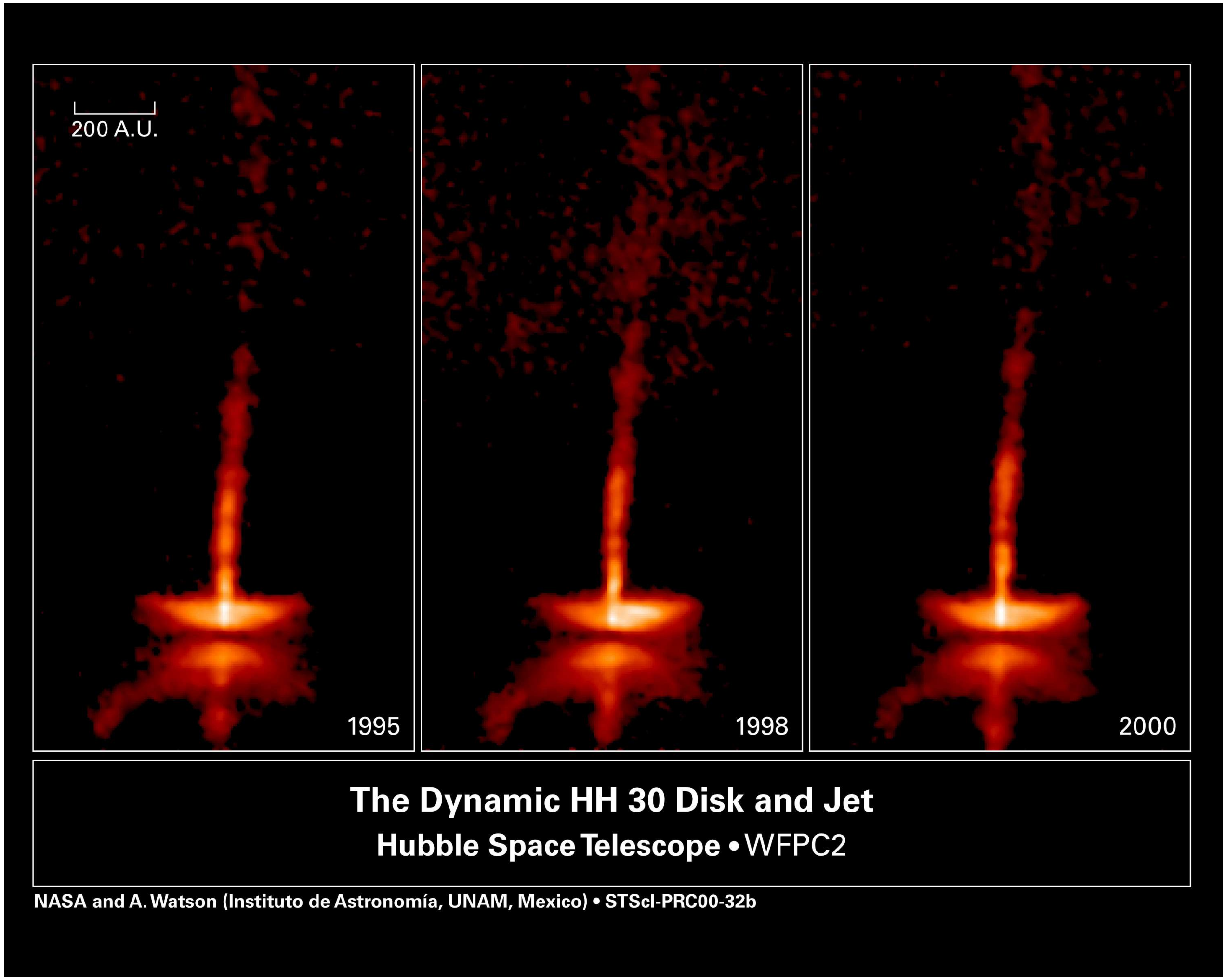


DENSE INTERSTELLAR CLOUDS

- Almost all molecular H_2
- Lifetime: 10^6 or $10^7 - 10^8$ years ?
- Site of star formation

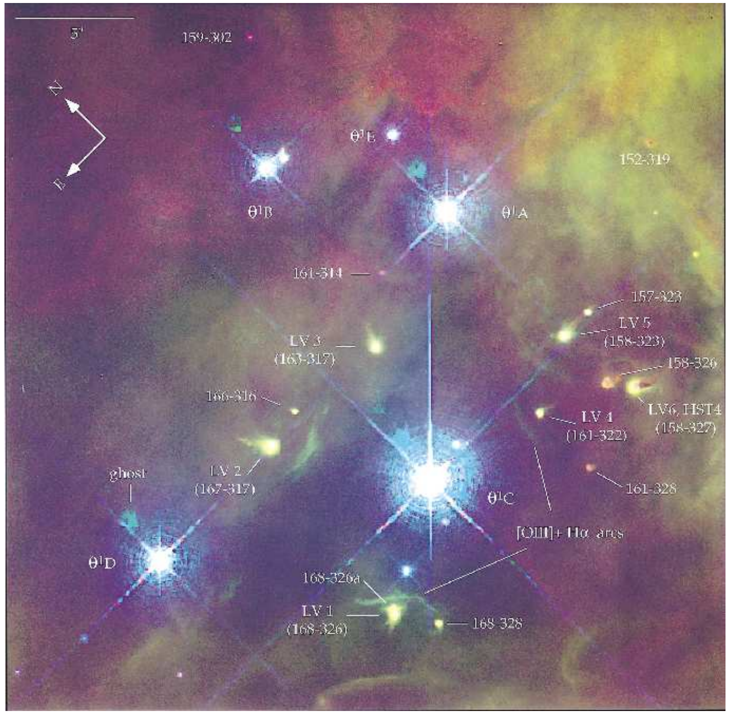


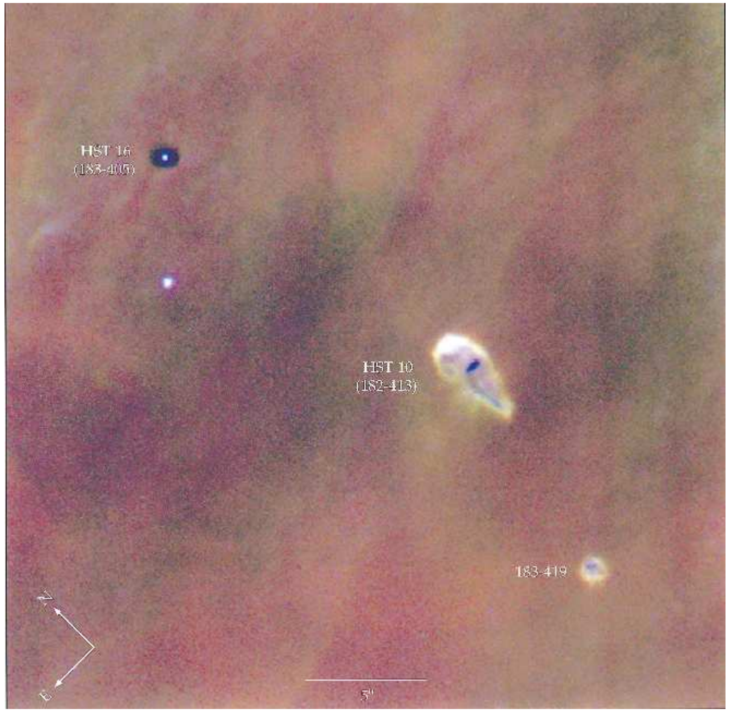
Flared Proto-planetary Disk in HH-30



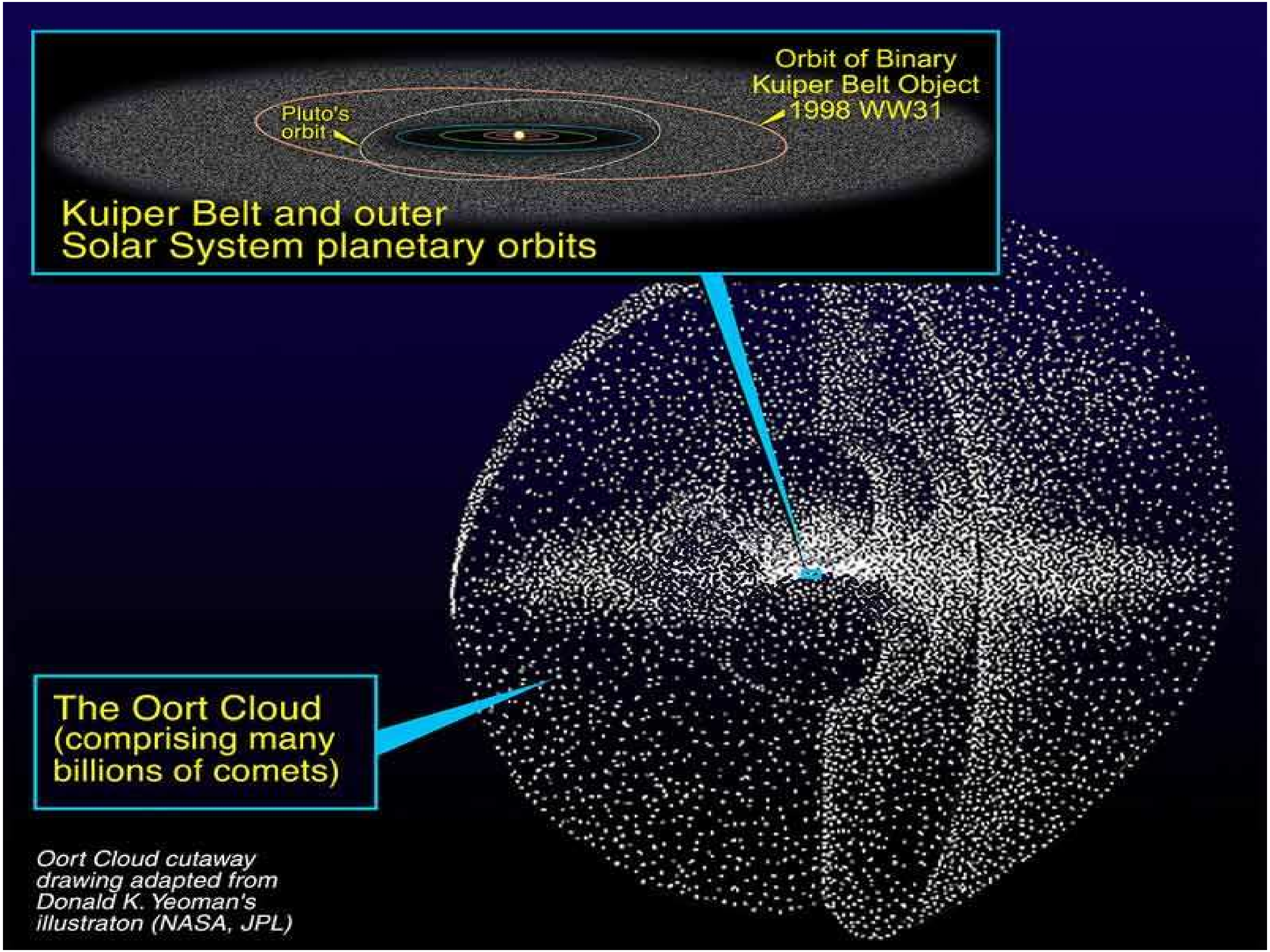
HH-30 is about 140 parsecs from Earth; 200 AU = 1.4 arc-sec on the sky

Proplyds in Orion





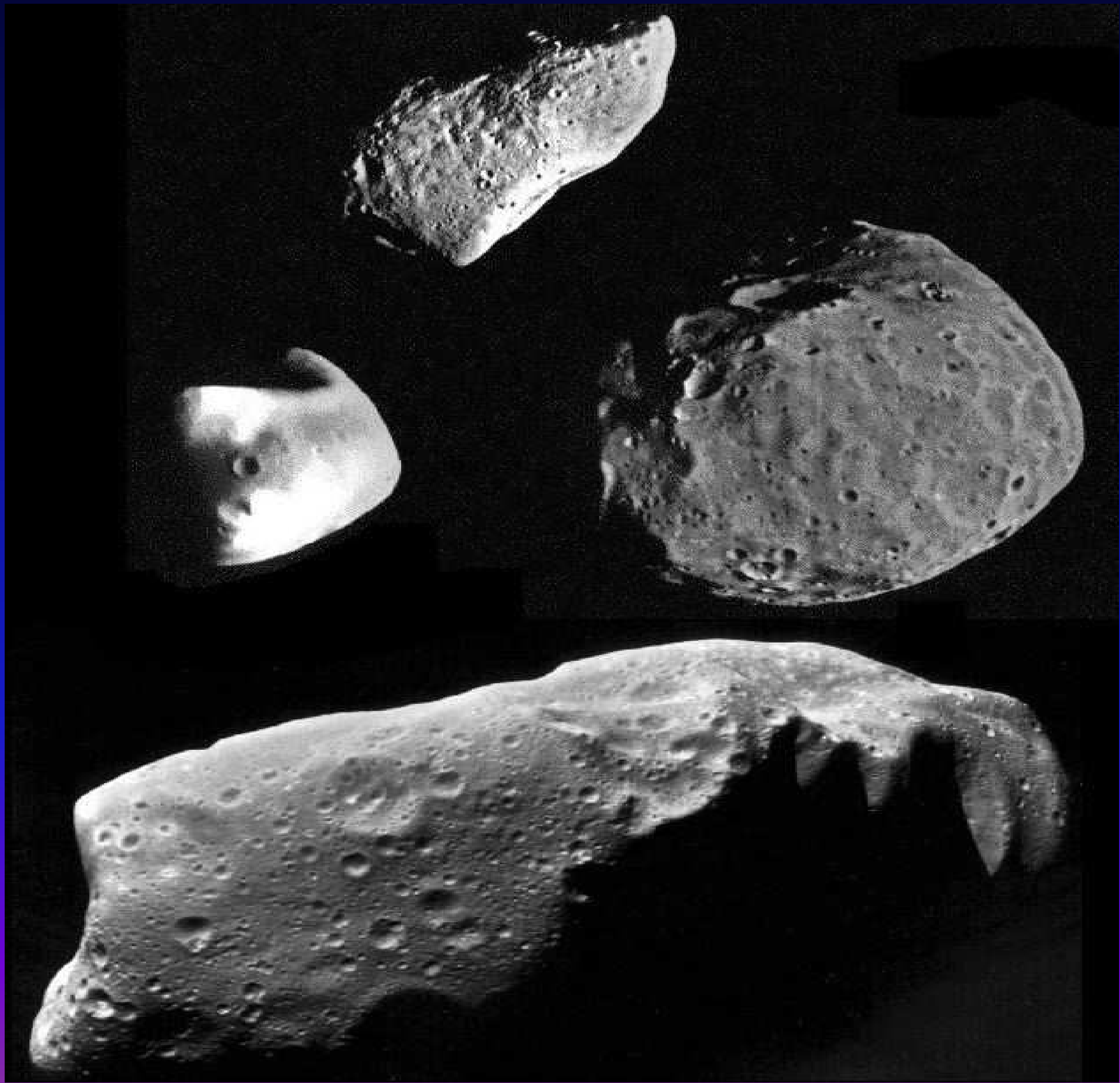
After Bally et al. AJ 116:293 (1998)



Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)


© by Calvin J. Hamilton

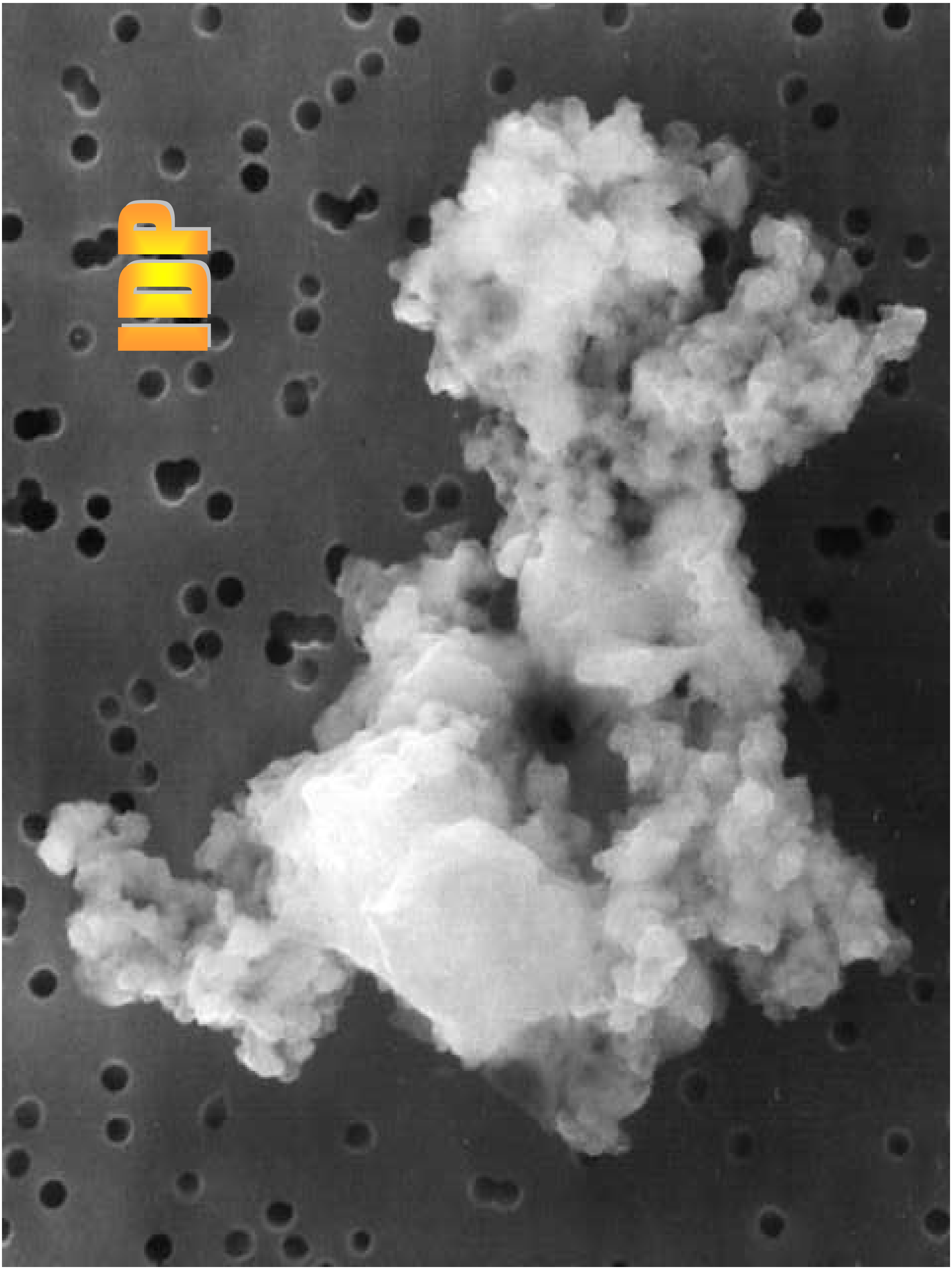
Asteroids



Carbonaceous meteorites

Murchison

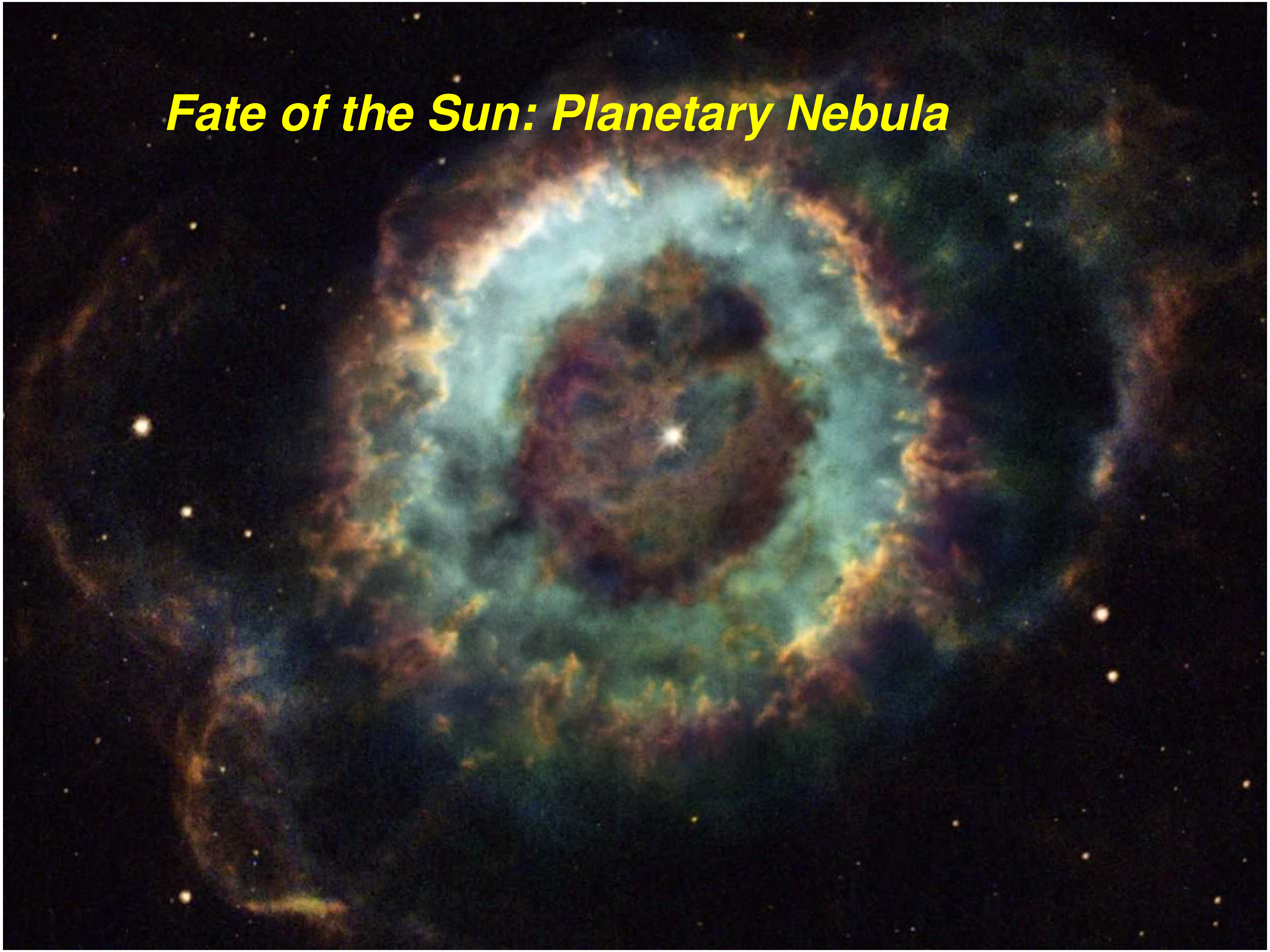
Comet Hale-Bopp and M31

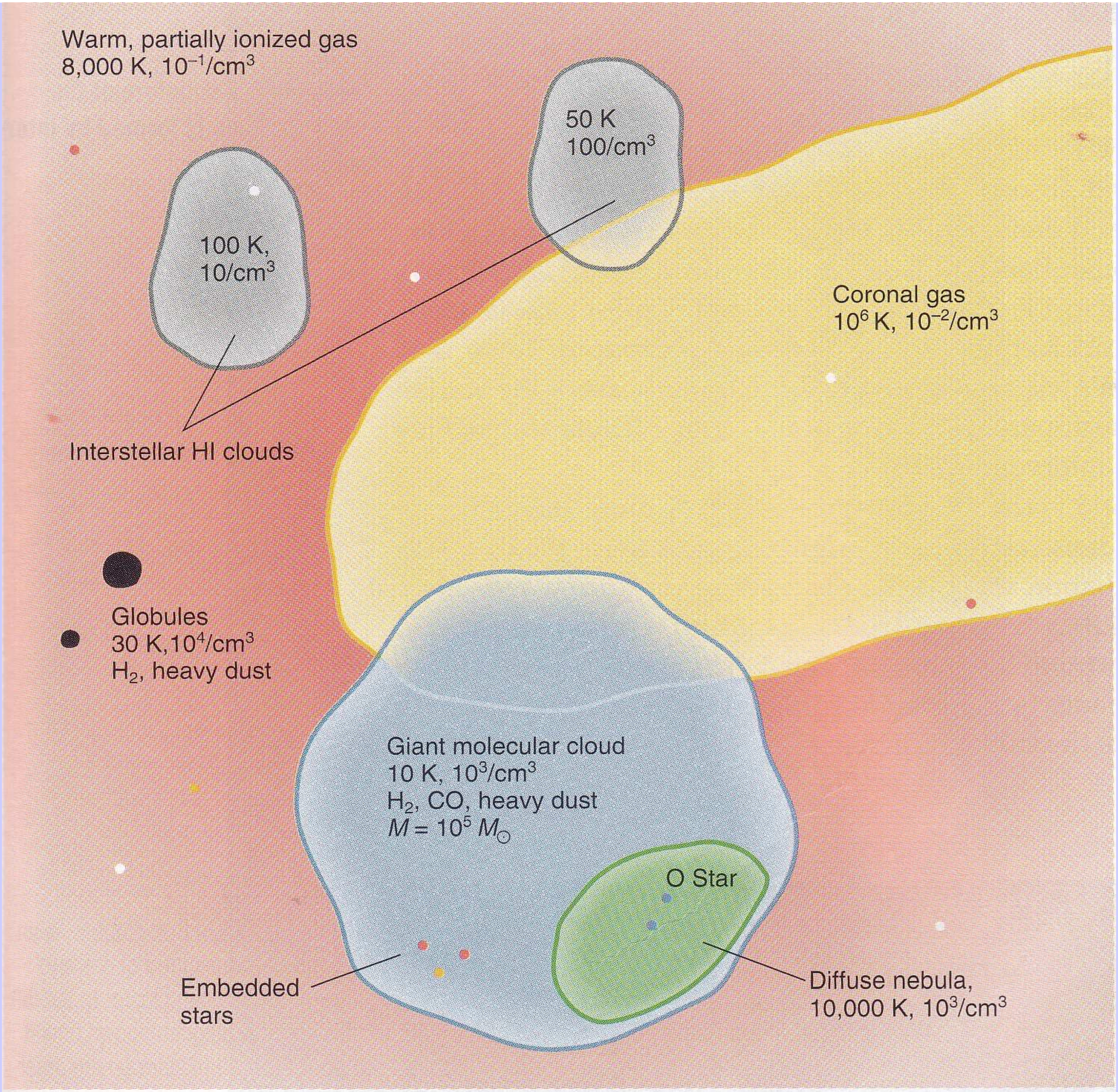

IDP

EARLY EARTH

- Heavy bombardment by comets over 700 mill. years
- Strong geological activity
- First evidence for Life: ~ 3.6 billion years ago

Fate of the Sun: Planetary Nebula




Warm, partially ionized gas
8,000 K, $10^{-1}/cm^3$
50 K
$100/cm^3$
100 K,
$10/cm^3$
Coronal gas
10^6 K, $10^{-2}/cm^3$
Interstellar HI clouds
Globules
30 K, $10^4/cm^3$
H_2, heavy dust
Giant molecular cloud
10 K, $10^3/cm^3$
H_2, CO, heavy dust
$M = 10^5 M_\odot$
O Star
Embedded
stars
Diffuse nebula,
10,000 K, $10^3/cm^3$

Molecules in the Galactic ISM

- **Only in cold dense phases:**

  - contain the bulk of the interstellar gas mass

  - composed of atomic and molecular gas

  diffuse HI clouds $n_H \sim 30\ cm^{-3}$, T=100 K

  molecular clouds $n_H > 300\ cm^{-3}$, T=20 K

- **Dust grains**

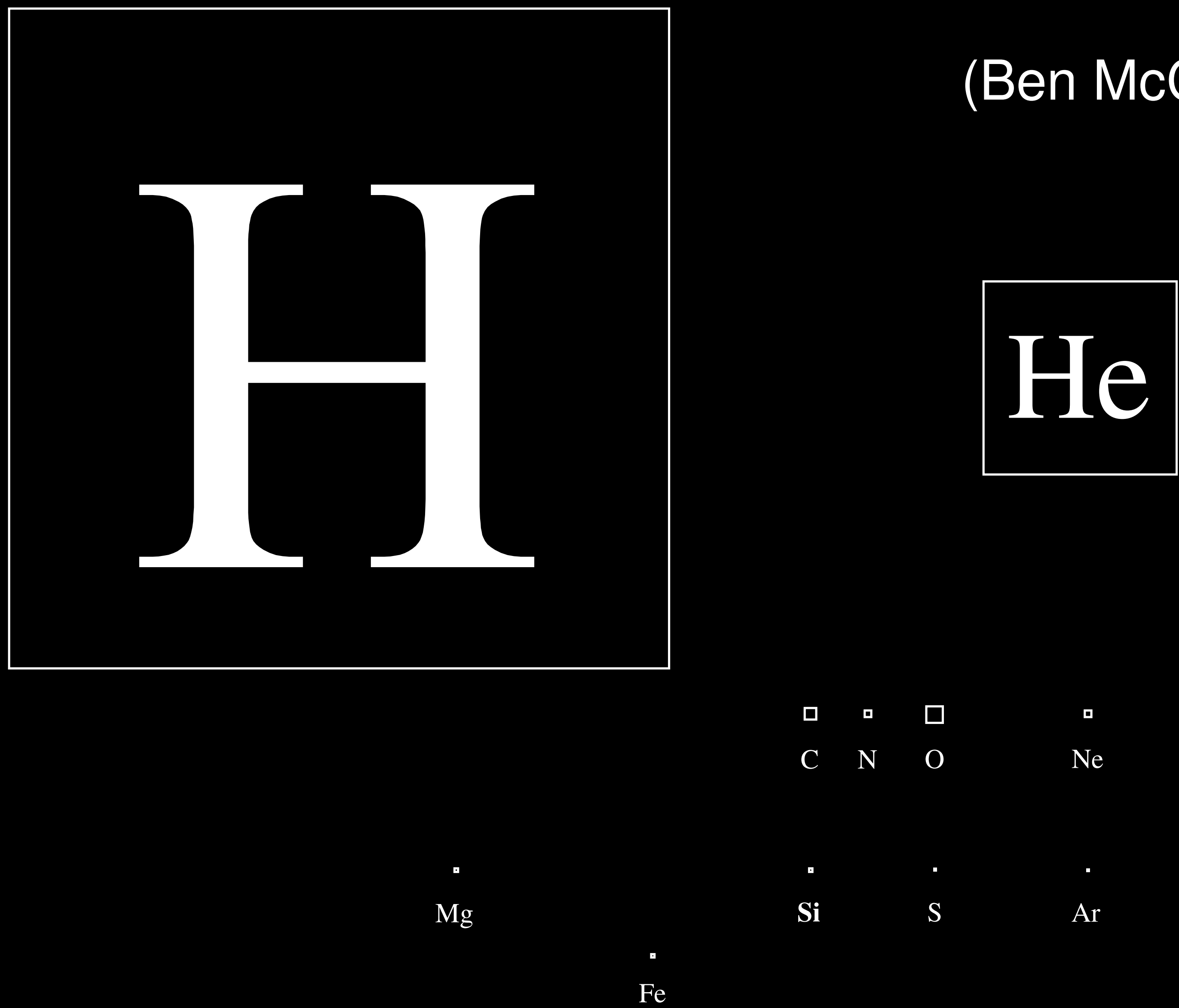
  carbonaceous and silicate particles provide extinction

- **Astrochemistry of heavy elements**

  unimolecular and bimolecular gas reactions driven by cosmic rays and UV photons.

The Astronomer's Periodic Table

(Ben McCall)

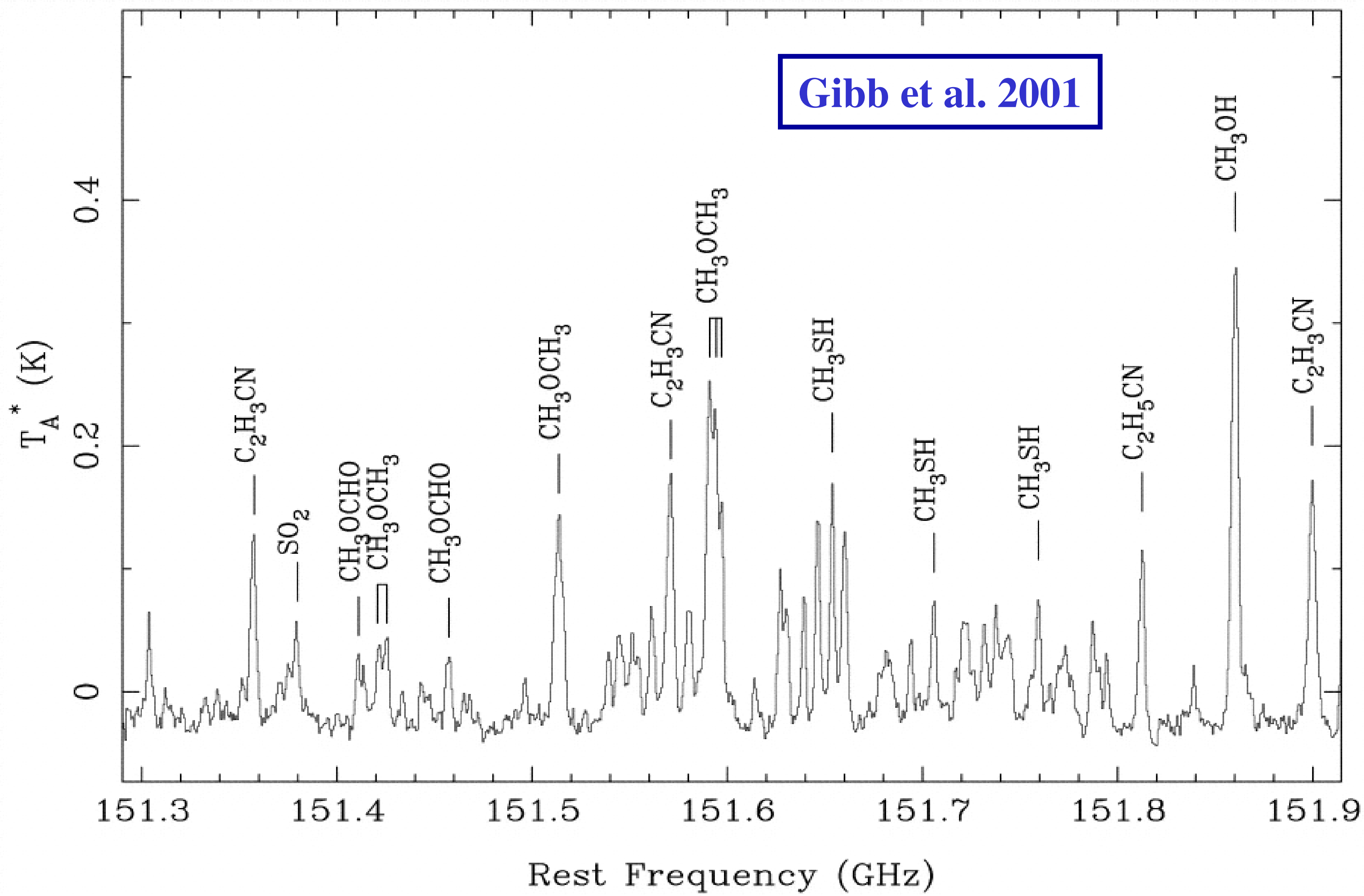


Courtesy Ben Mc Call

Brief History of Astrochemistry

- **1937-1941: optical detection of CH, CN, CH^+**
- **1951: Bates & Spitzer theory**
- **1968-73: ammonia, formaldehyde, water, CO**
- **1970-1980's mm-wave telescopes led to discovery of many species**
- **Herbst & Klemperer (1973) : ion-molecule chemistry**
- **1987: Blake et al. line survey of Orion-KL**

Survey of organic molecules in G327

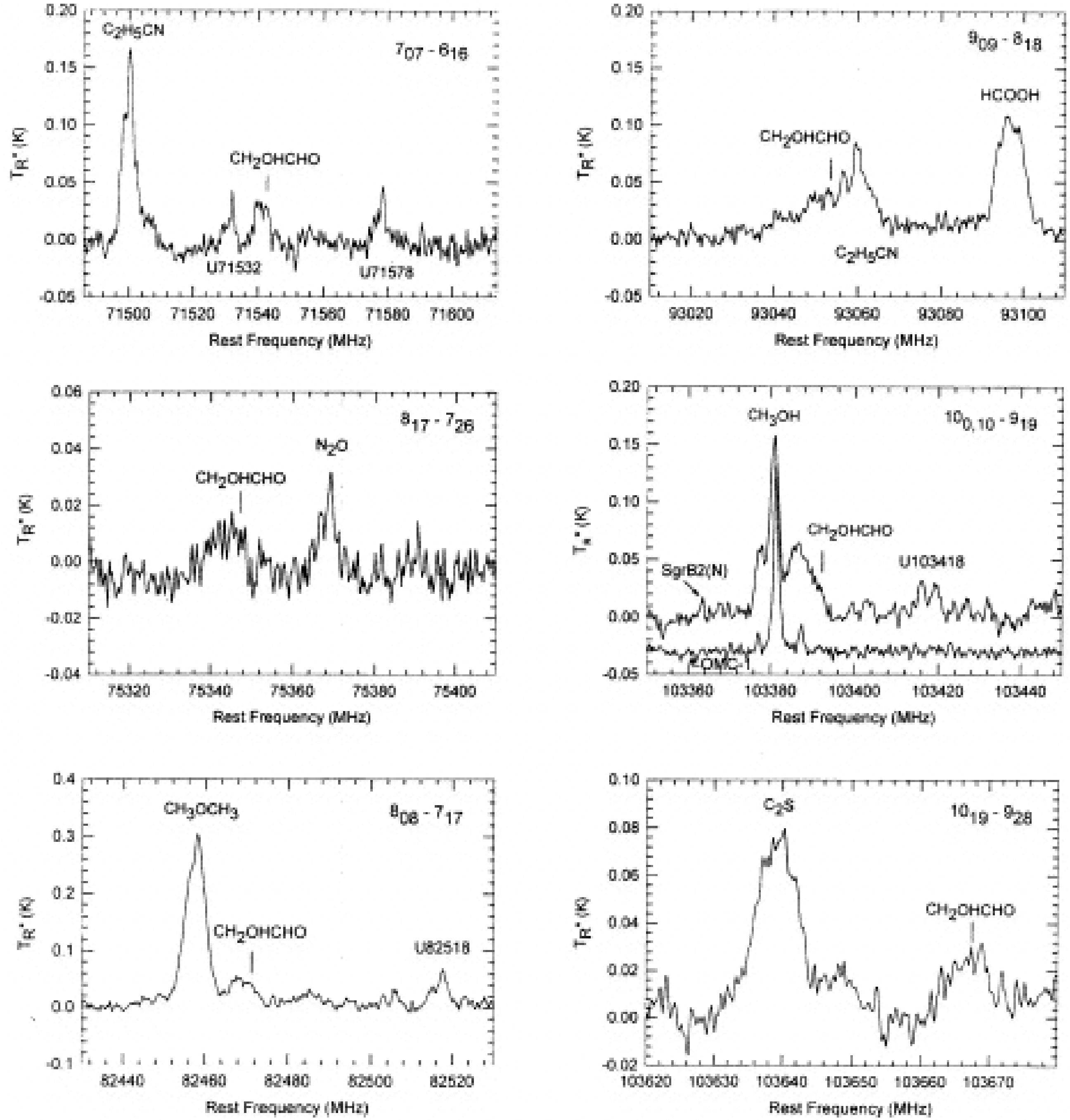


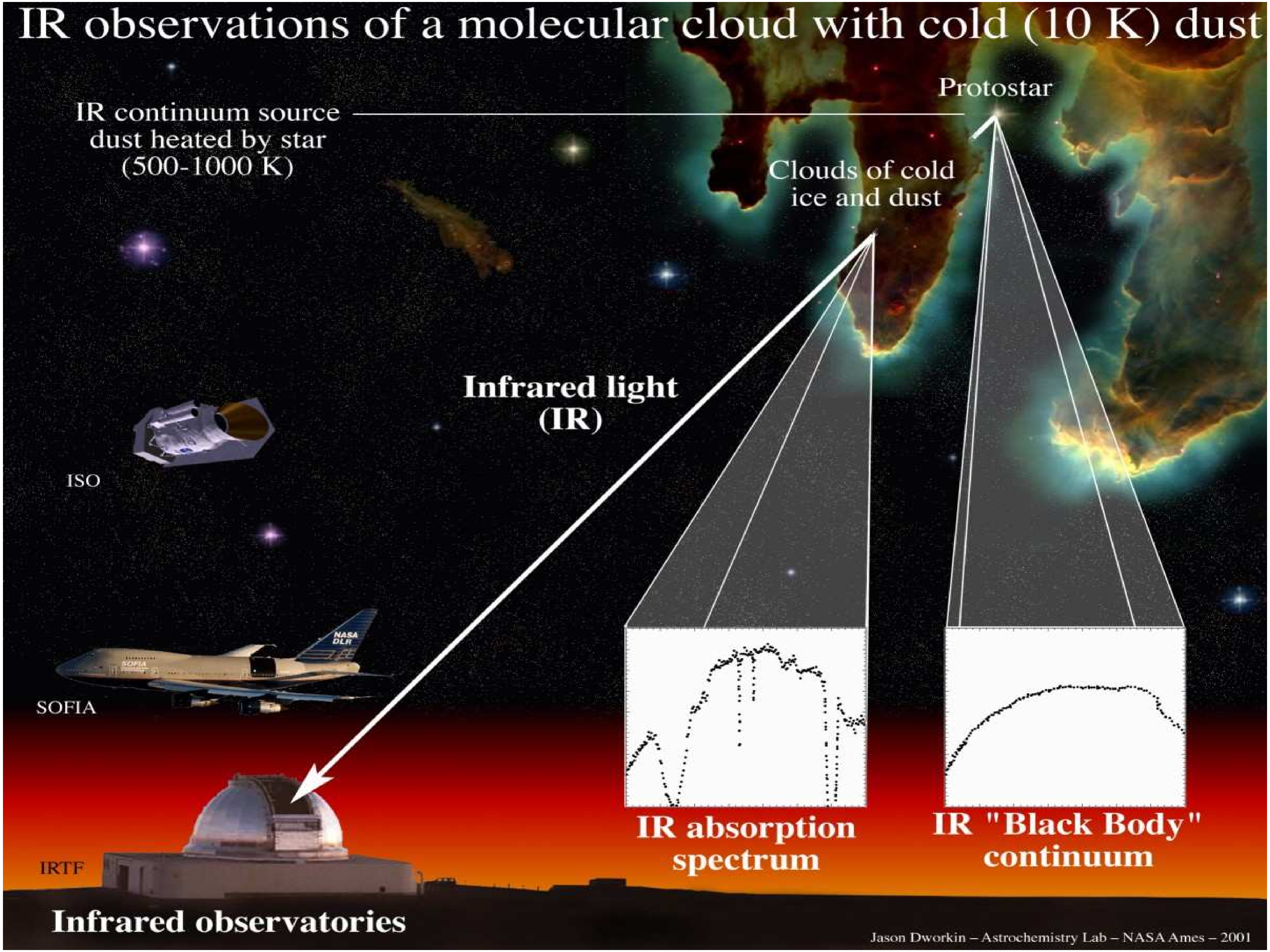
Glycol-aldehyde

the simplest Sugar

CH_2CHCHO

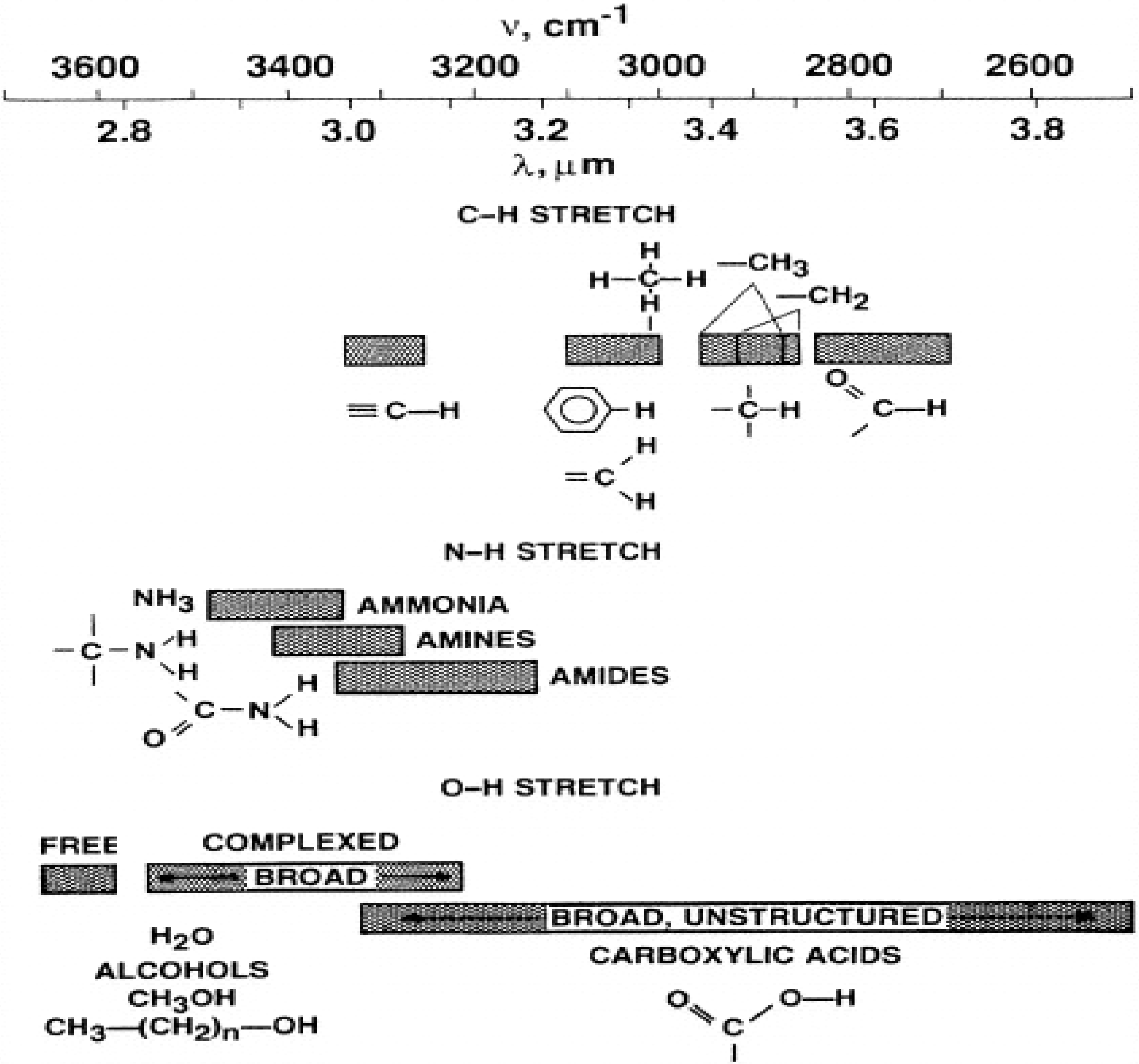
detected in 2000 toward SgrB2(N)



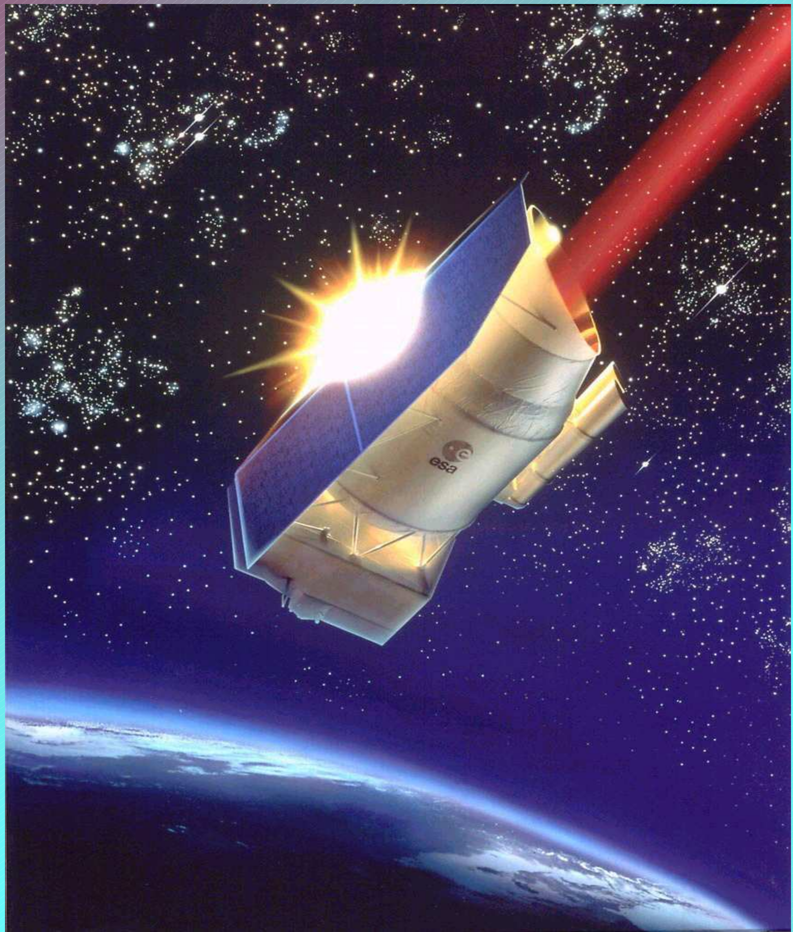


IR observations of a molecular cloud with cold (10 K) dust
Protostar
IR continuum source
dust heated by star
(500-1000 K)
Clouds of cold
ice and dust
Infrared light
(IR)
ISO
NASA
DLR
SOFIA
IR absorption
spectrum
IR "Black Body"
continuum
IRTF
Infrared observatories
Jason Dworkin – Astrochemistry Lab – NASA Ames – 2001

H-X STRETCHING FREQUENCIES



THE INFRARED SPACE OBSERVATORY

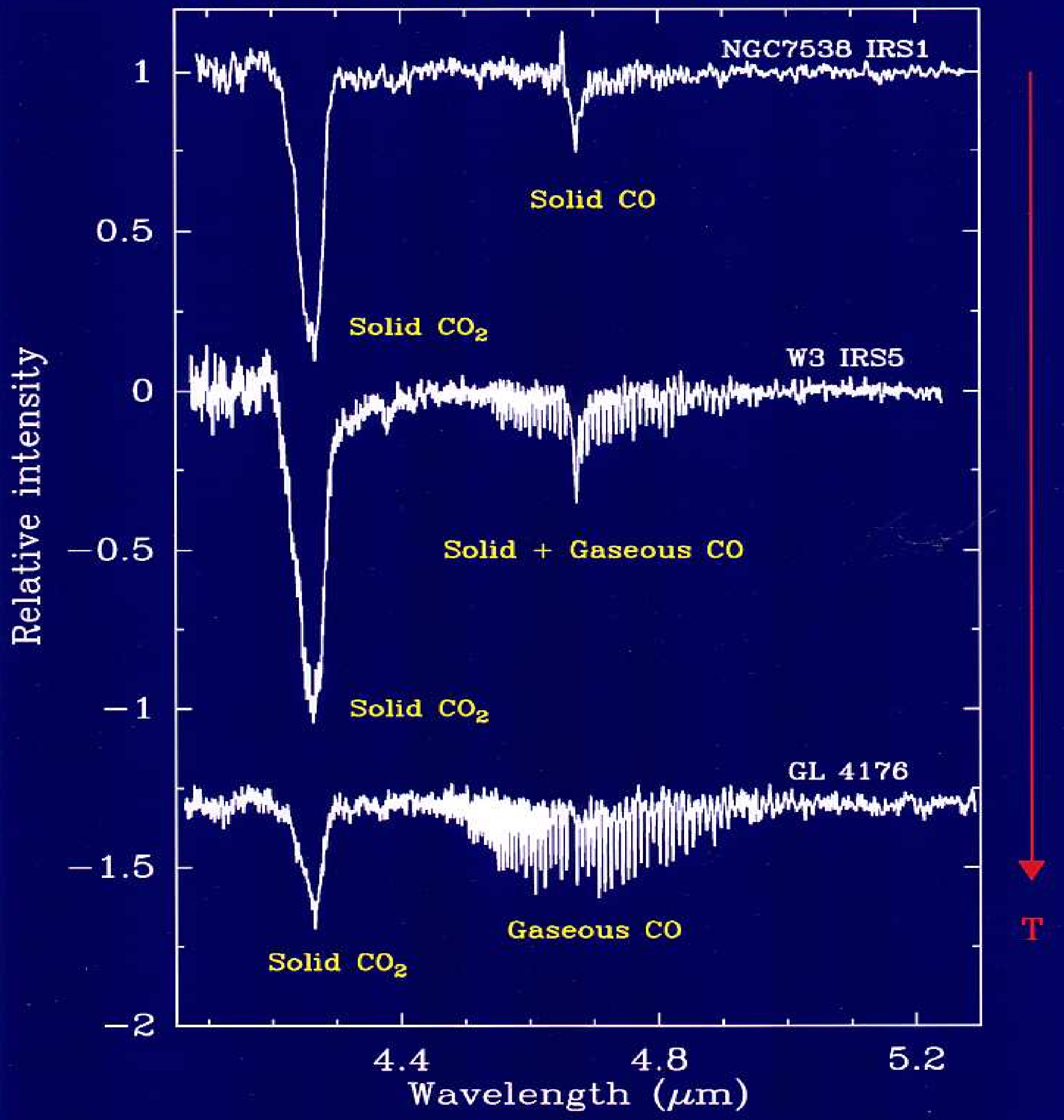


ISO allowed the first complete inventory of cosmic dust between 2.5-200 micron

- Discovery of new molecules
- Accurate abundances
- Gas-grain interactions
- Irradiation and temperature conditions in proto-stellar environments

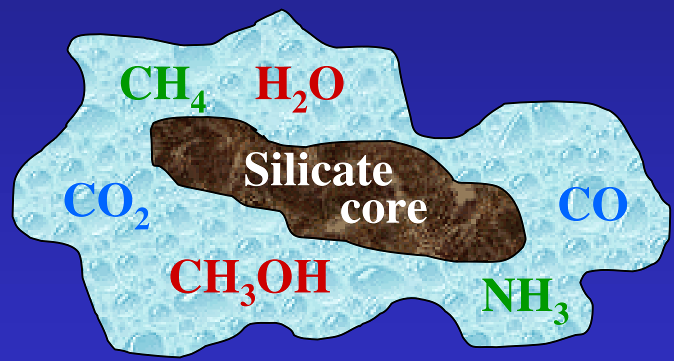
ISO 1995-1998 ….

Evolution of Solid and Gaseous CO_2 and CO

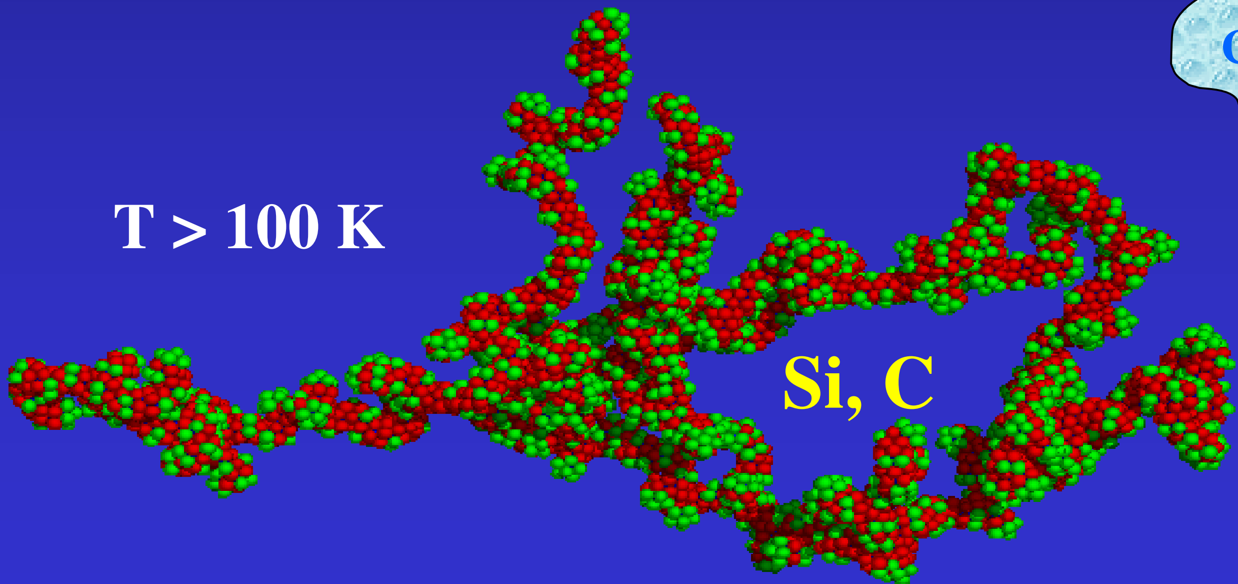


van Dishoeck et al. 1998

Dust and molecules in space



T > 100 K



T < 100 K

Molecular inventory

2	3	4	5	6	7	8	9	10	11	12	13
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N?	HC_9N	C_6H_6	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$			
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$HOCH_2CH_2OH$			
C_2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	NH_2CH_2COOH			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	$HCOCH_3$	H_2C_6	HC_7N				
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	NH_2CH_3	CH_2OHCHO	C_8H				
CN	HCO	CH_2D^+?	CH_4	CH_3SH	c-C_2H_4O	C_2H_6					
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	CH_2CHOH						
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO							
CP	HOC^+	HNCO	HCOOH	NH_2CHO							
CSi	H_2O	HNCS	H_2CHN	C_5N							
HCl	H_2S	$HOCO^+$	H_2C_2O								
KCl	HNC	H_2CO	H_2NCN								
NH	HNO	H_2CN	HNC_3								
NO	MgCN	H_2CS	SiH_4								
NS	MgNC	H_3O^+	H_2COH^+								
NaCl	N_2H^+	NH_3									
OH	N_2O	SiC_3									
PN	NaCN	CH_3									
SO	OCS										
SO^+	SO_2										
SiN	c-SiC_2										
SiO	CO_2										
SiS	NH_2										
CS	H_3^+										
HF	SiCN										
SH	AlNC										
FeO?	H_2O^+										
SiH											

Physics World, Charnley et al. 2003

Astronomers have made a list of 131 molecules that have been discovered in interstellar space, which range from simple two-atom species (left) to complex molecules that contain up to 13 atoms. Many of these play important roles in terrestrial biochemistry, and several organic classes are represented: acids, aldehydes, ketones, alcohols, ethers, esters and pre-sugars. Some of these molecules, which include structural isomers such as HCN and HNC, are also present in meteorites and in comets. Many of the hydrocarbons that contain multiple carbon atoms exist as long carbon chains. The smallest member of the cyanopolyyne series – cyanoacetylene (HC_3N) – is ubiquitous in molecular clouds, and another member – cyanodecapentayne ($HC_{11}N$) – is the largest molecule that has been unambiguously identified in the interstellar medium. A few small ring molecules are present in the list but many larger organic compounds await detection in space. The present authors, for example, are currently using the Arizona Radio Observatory 12 m and Green Bank telescopes to search for ring compounds (PAHs) containing nitrogen. Table courtesy of Al Wootten and updated from www.astrochemistry.net.

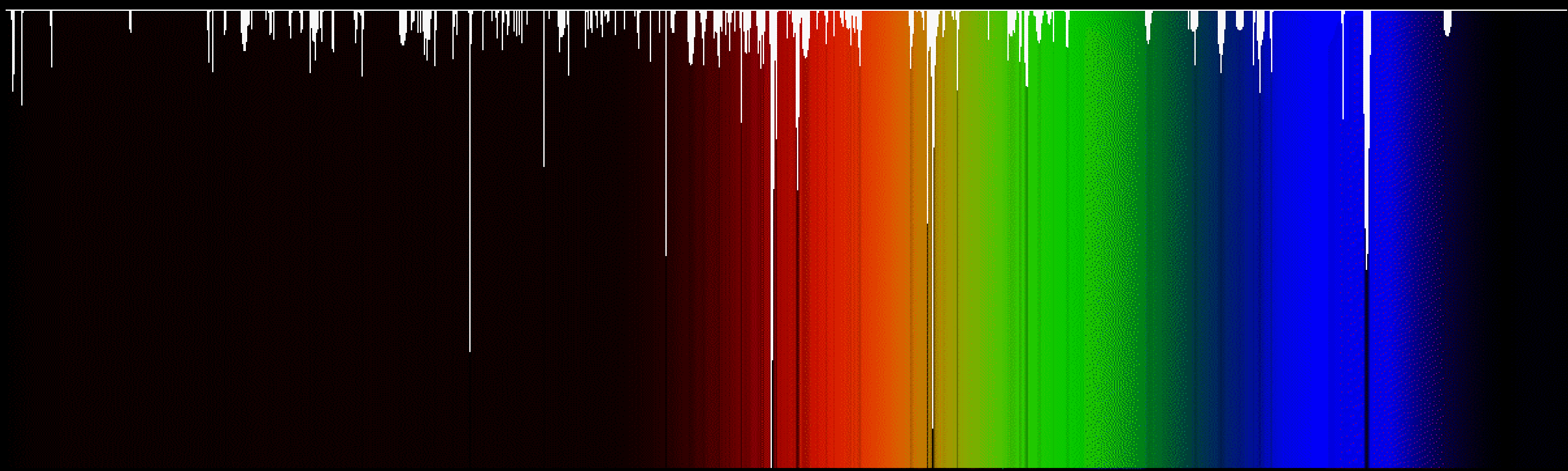
Clouds: Compositional Differences

- **Diffuse clouds:** atomic ions (C^+, S^+), simple molecules (OH, CH, CN), some unexpected polyatomics (C_3H_2, C_3H), plus large unidentifed structures
- **Dark Clouds:** H_3^+, CO, long unsaturated carbon chains (e.g. HC_nN), high D/H
- **Cold Prestellar Cores:** very high D/H, evidence for selective depletion onto dust
- **Hot Protostellar Cores:** very high D/H, many complex organics (ethanol, dimethyl ether), evidence for grain chemistry

Astrochemistry or MolecularAstrophysics?

- **Chemical diagnostics:** gas density (HCO^+, CS, NH_3, HCN), molecular hydrogen mass (CO isotopes), temperature (NH_3, CH_3OH), infall (H_2CO), ionization (HCO^+, DCO^+), magnetic field (CCS).
- **Chemical controls:** temperature (CO, H_2, CII, CI, H_2O cooling), ambipolar diffusion rate (electron fraction)
- **The known molecules have great utility !**

The Diffuse Interstellar Bands



Courtesy: P. Jenniskens, F.-X. Desert

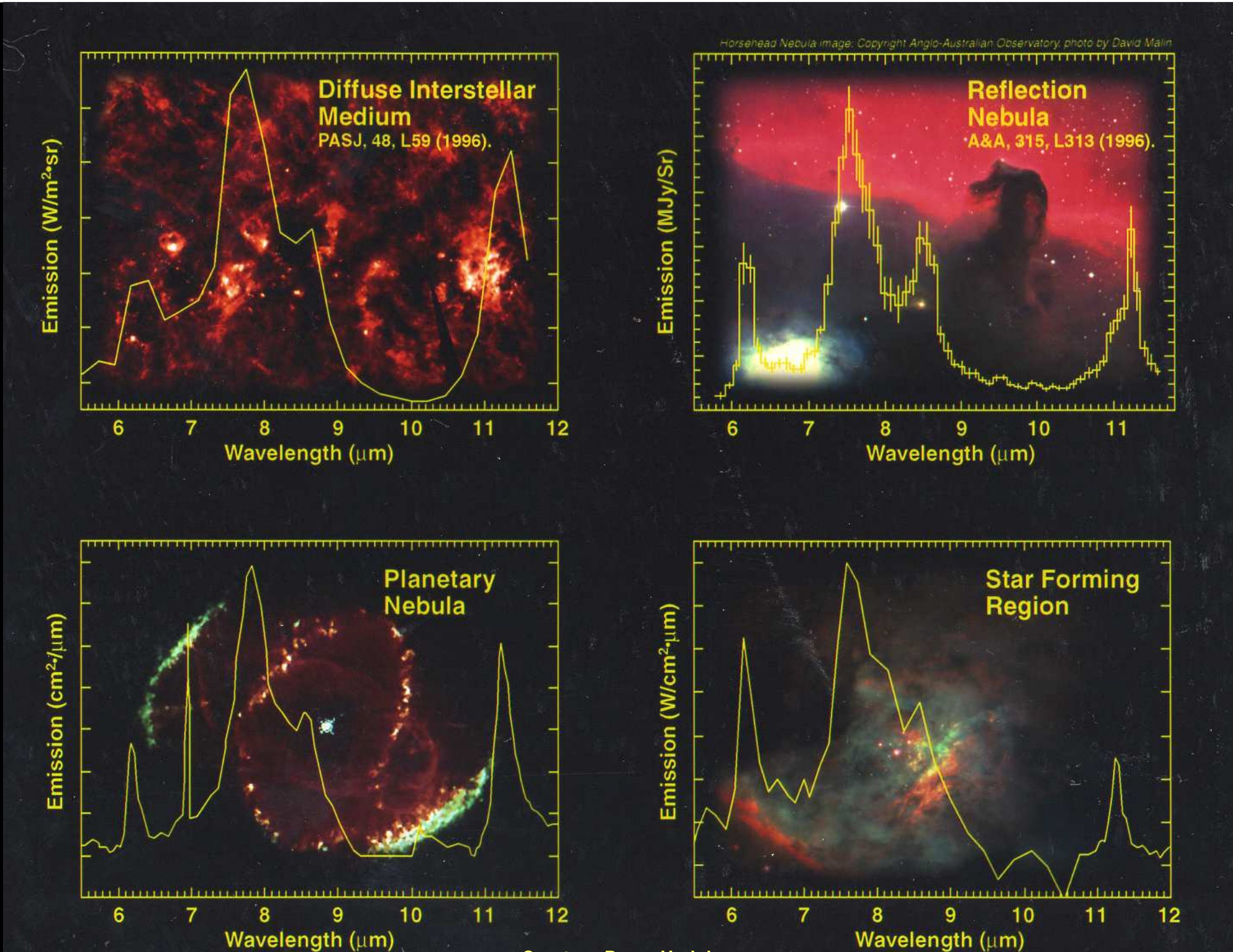
DIBs - Absorption bands which are observed ubiquitously in diffuse clouds

→ **Astronomical observations revealed up to ~ 300 DIBs**

The carrier seems to be → **chemically stable**

→ **in the gas phase**

→ **carbonaceous in nature**

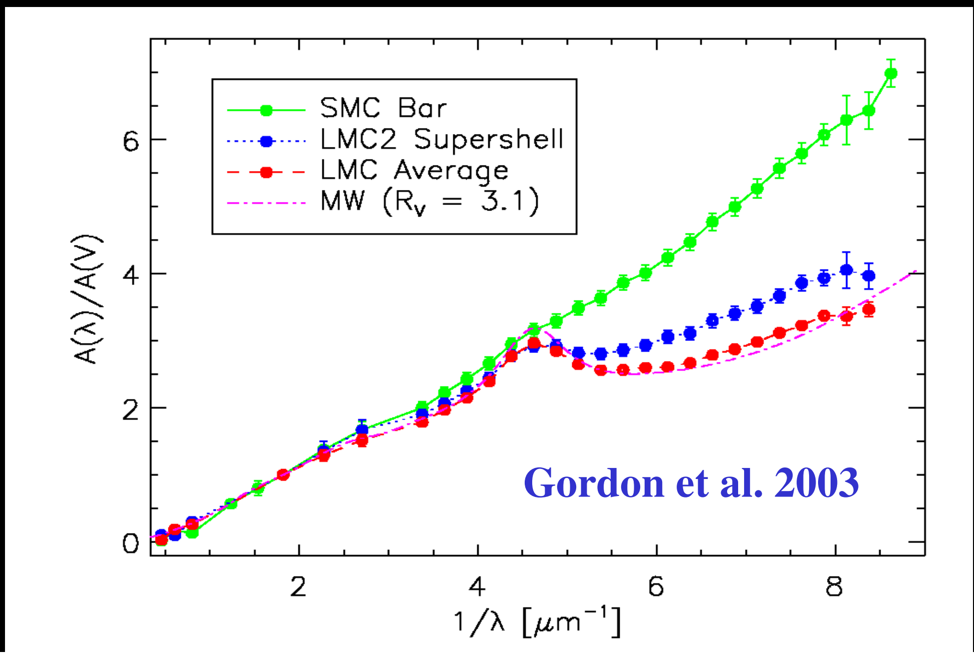


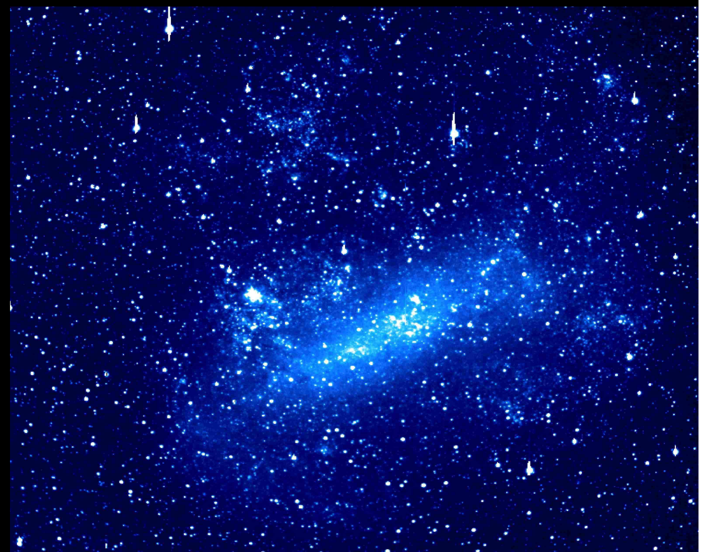
Courtesy Doug Hudgins

CARBON CHEMISTRY IN SPACE

➢ **The carbon chemistry seems to follow common pathways throughout the Universe**

- ✓ **Aromatic hydrocarbons (mid-IR)**
- ✓ **Diffuse interstellar bands (Optical)**
- ✓ **Aliphatic hydrocarbons (near-IR)**
- ✓ **Ices in star-forming regions (near and mid-IR)**

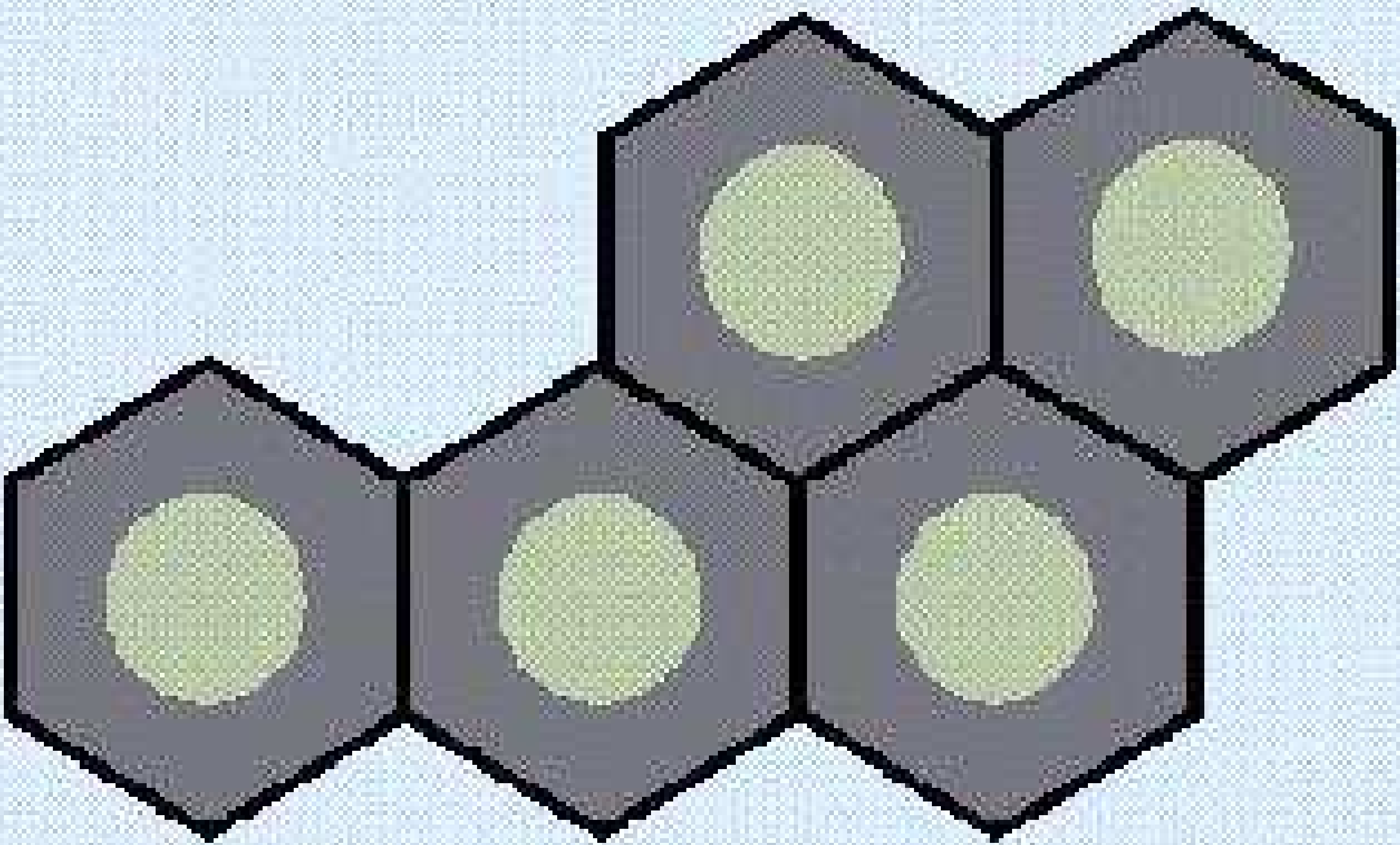


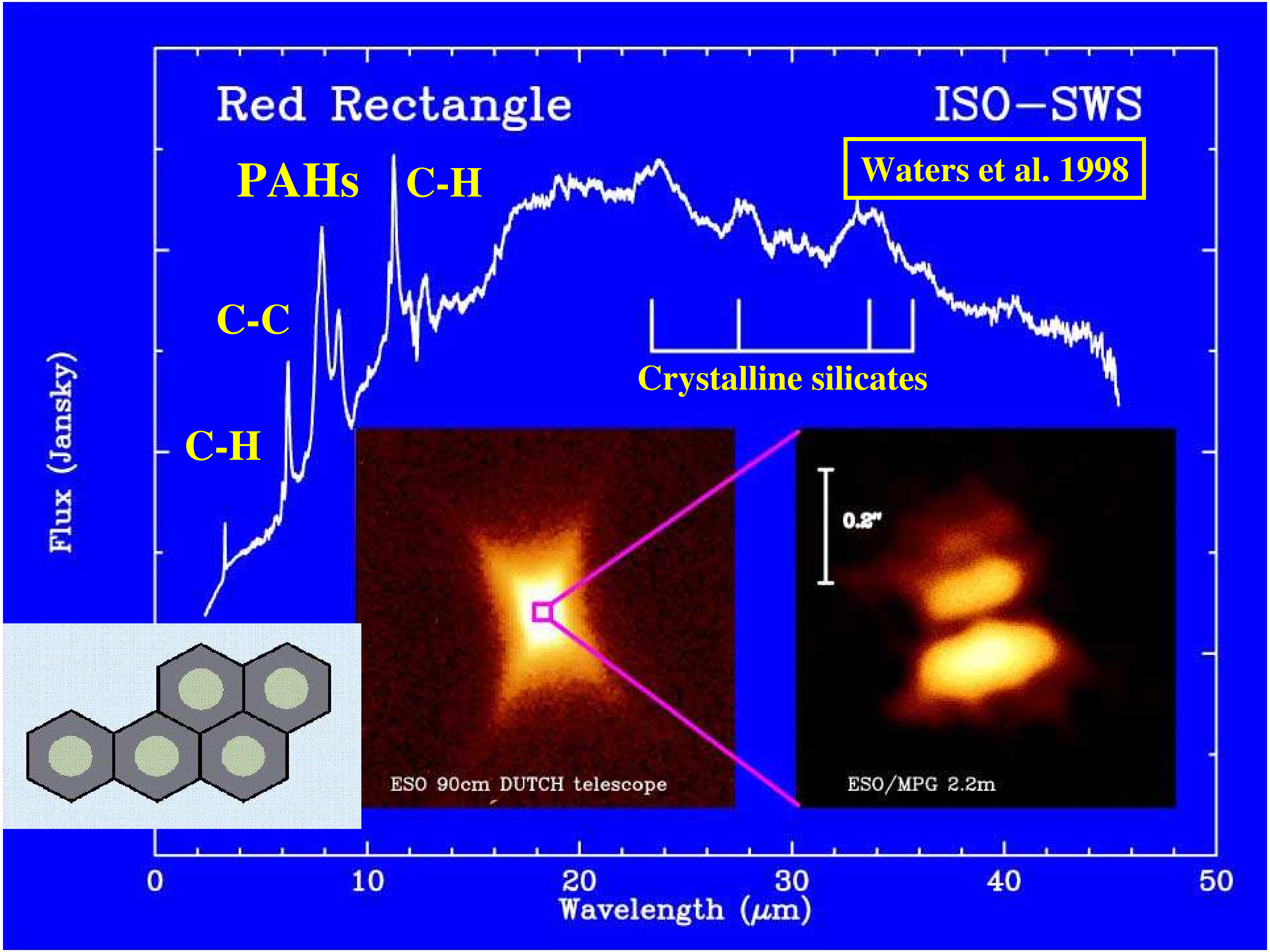


Interstellar extinction curve

⟶ **UV bump ~ 220 nm**

Polycyclic Aromatic Hydrocarbons (PAHs): the most abundant organic molecules in space

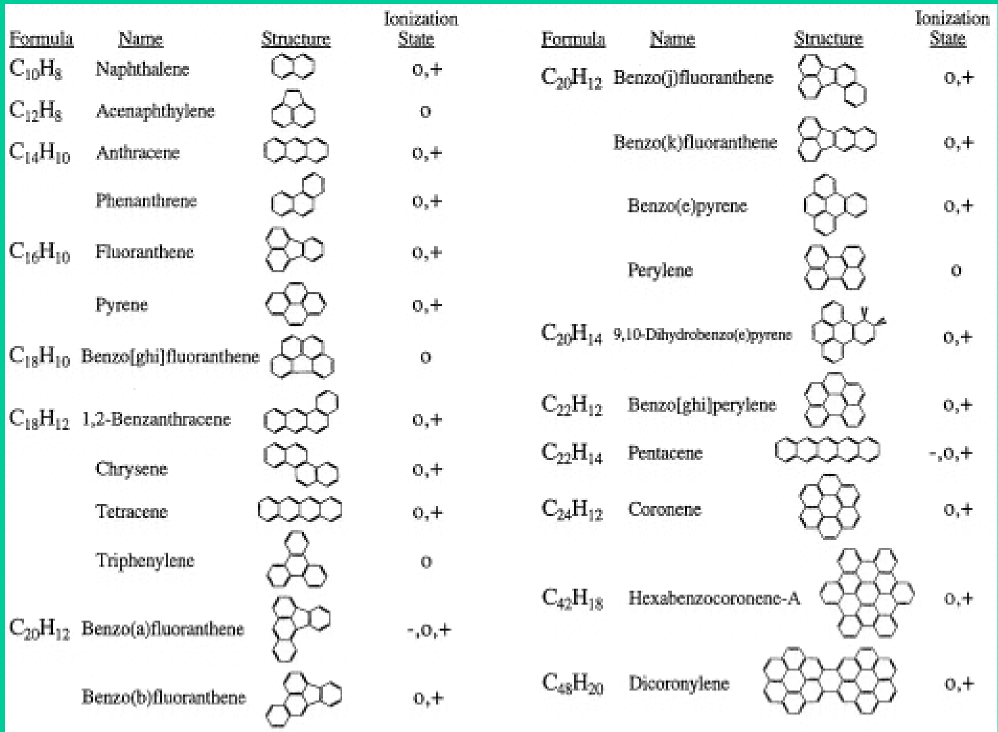




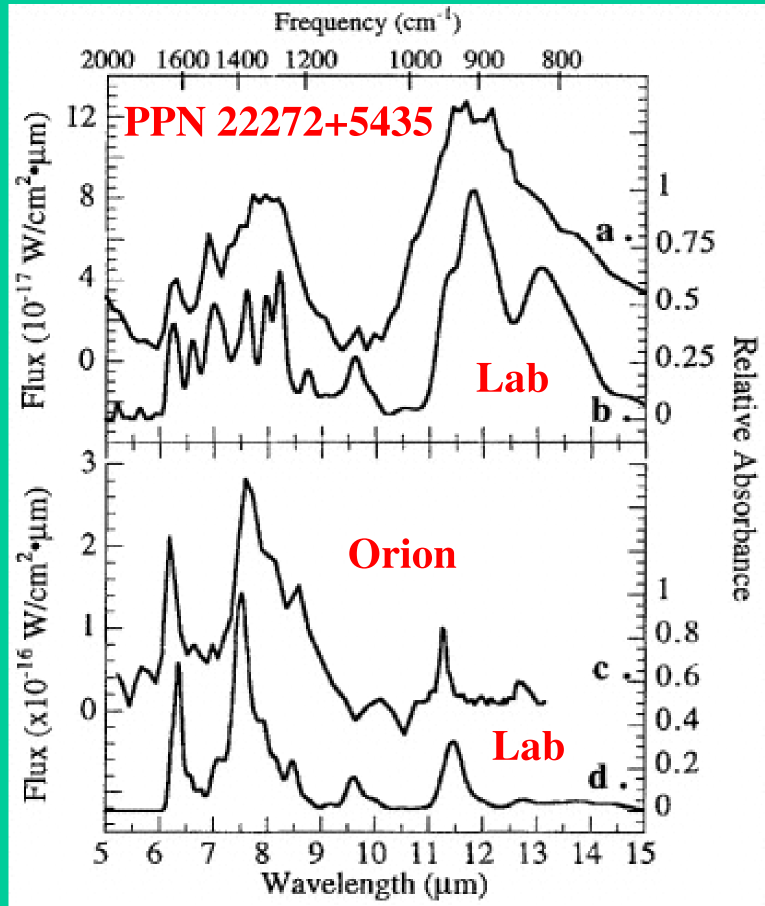
Red Rectangle
ISO–SWS
PAHs
C-H
Waters et al. 1998
C-C
C-H
Crystalline silicates
ESO 90cm DUTCH telescope
0.2"
ESO/MPG 2.2m
Flux (Jansky)
0
10
20
30
40
50
Wavelength (μm)

Polycyclic aromatic hydrocarbons - PAHs

Combined laboratory spectra of neutral and positively charged PAHs



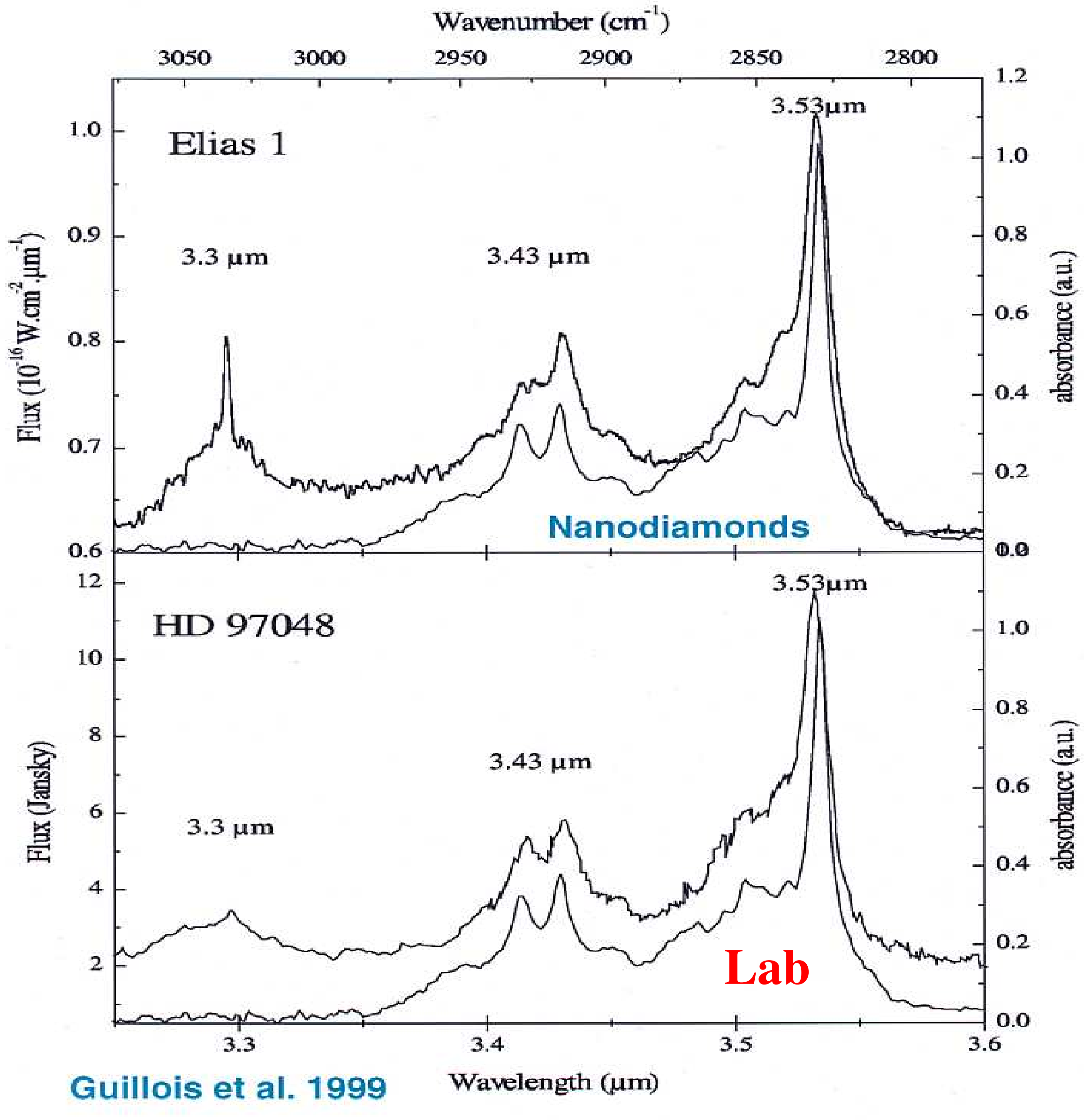
Formula	Name	Ionization State
$C_{10}H_8$	Naphthalene	o,+
$C_{12}H_8$	Acenaphthylene	o
$C_{14}H_{10}$	Anthracene	o,+
	Phenanthrene	o,+
$C_{16}H_{10}$	Fluoranthene	o,+
	Pyrene	o,+
$C_{18}H_{10}$	Benzo[ghi]fluoranthene	o
$C_{18}H_{12}$	1,2-Benzanthracene	o,+
	Chrysene	o,+
	Tetracene	o,+
	Triphenylene	o
$C_{20}H_{12}$	Benzo(a)fluoranthene	-,o,+
	Benzo(b)fluoranthene	o,+
$C_{20}H_{12}$	Benzo(j)fluoranthene	o,+
	Benzo(k)fluoranthene	o,+
	Benzo(e)pyrene	o,+
	Perylene	o
$C_{20}H_{14}$	9,10-Dihydrobenzo(e)pyrene	o,+
$C_{22}H_{12}$	Benzo[ghi]perylene	o,+
$C_{22}H_{14}$	Pentacene	-,o,+
$C_{24}H_{12}$	Coronene	o,+
$C_{42}H_{18}$	Hexabenzocoronene-A	o,+
$C_{48}H_{20}$	Dicoronylene	o,+



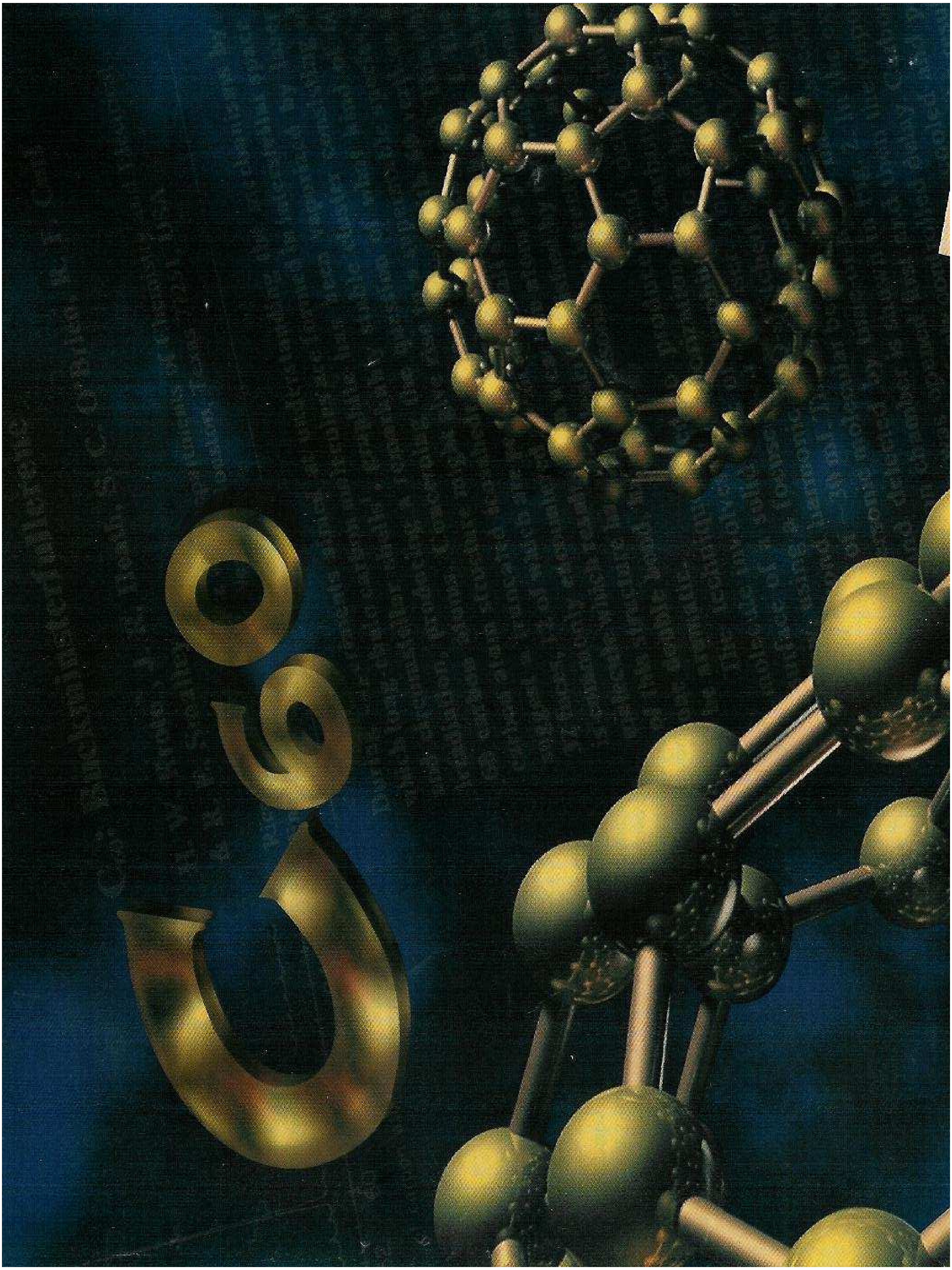
IR Database - NASA AMES

Allamandola et al. 1999

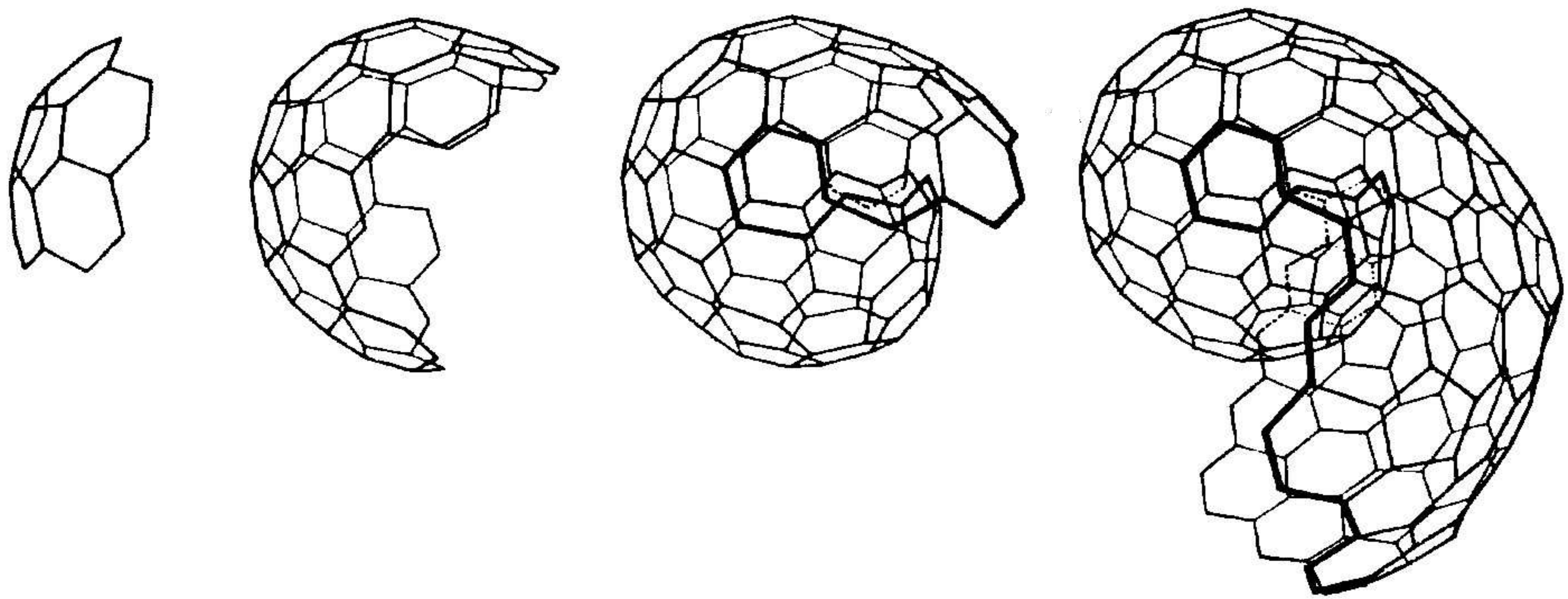
DIAMONDS IN THE SKY



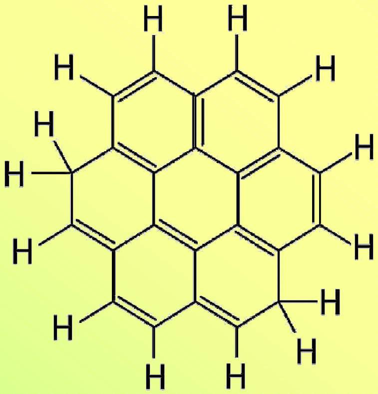
Guillois et al. 1999


C60

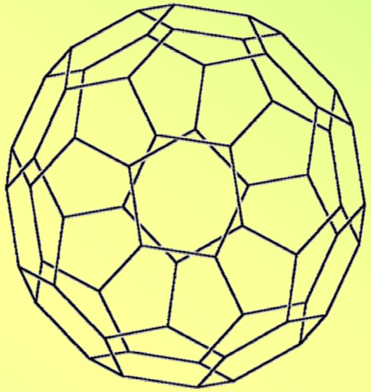
Nucleation scheme for the formation of fullerene carbon particles in the gas phase



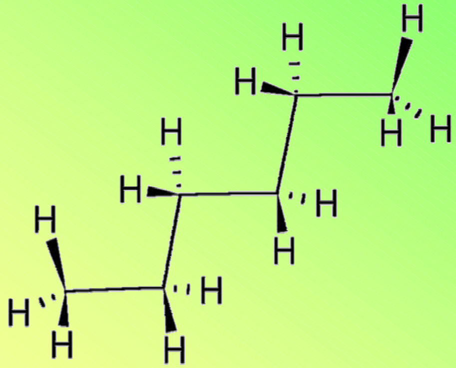
Large carbonaceous molecules in space (EC2000)



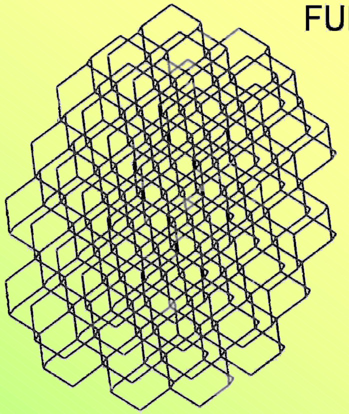
PAHs



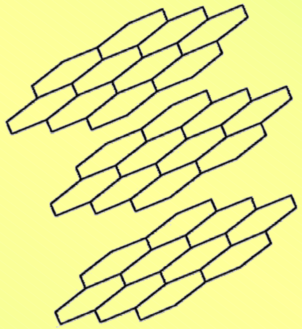
FULLERENES



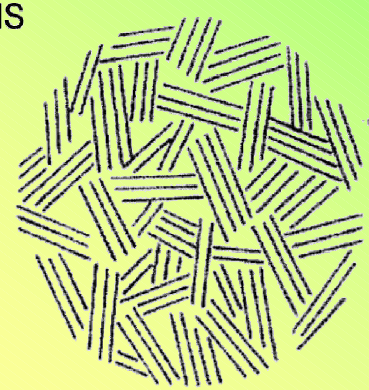
SHORT CHAINS



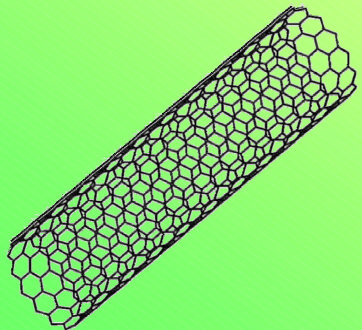
DIAMONDS



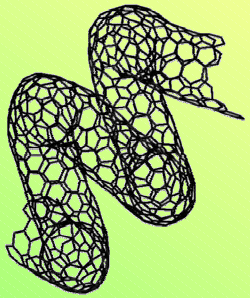
GRAPHITE



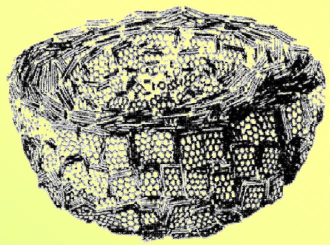
SOOT



BUCKY TUBES



COMPLEX BUCKY TUBES



ONION TYPE C PARTICLES

Summary

- Over 120 molecules detected; most are organic
- Many more await detection
- Laboratory data is key
- Possible to trace interstellar material as far as comets

Tomorrow: