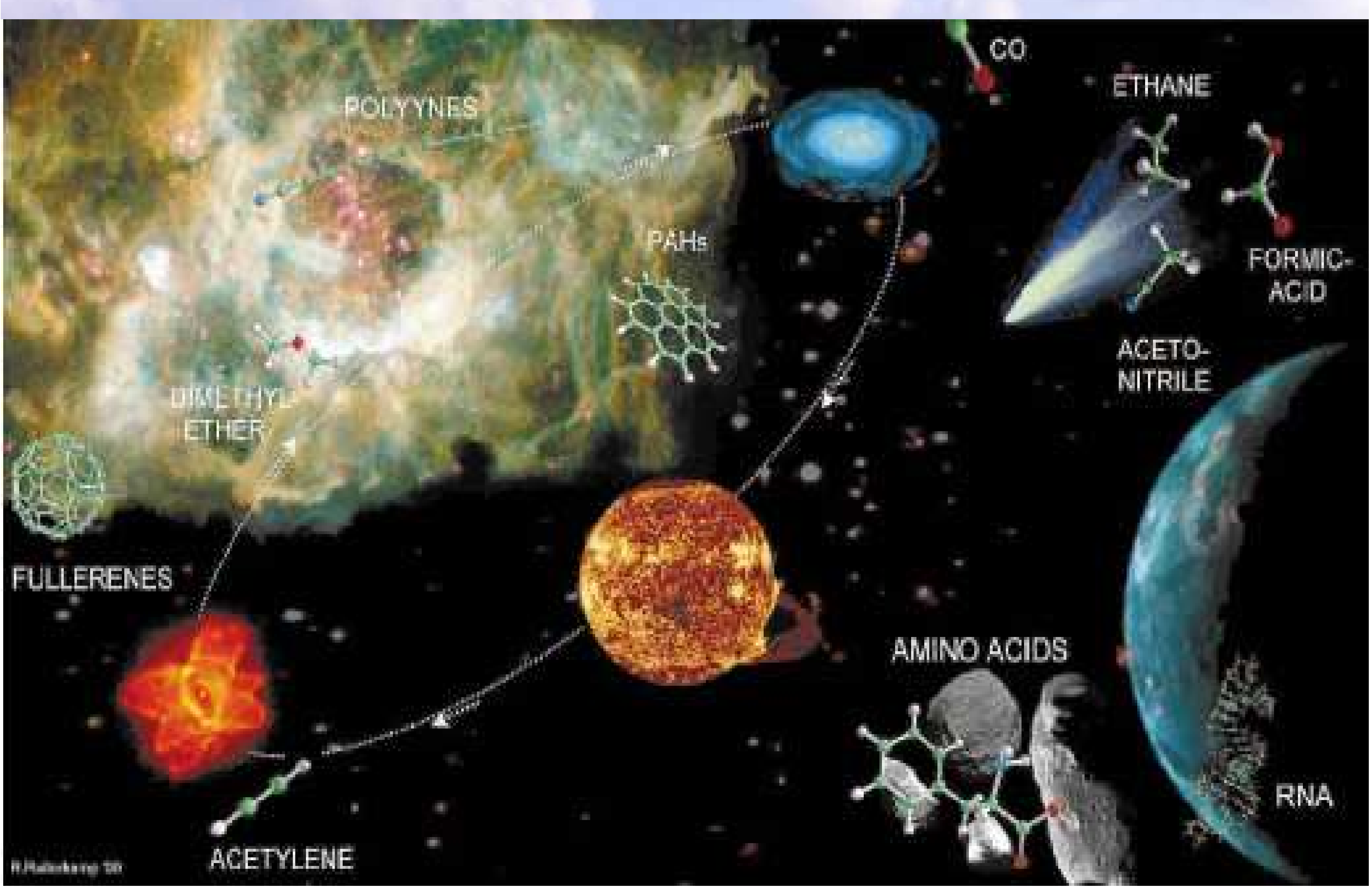
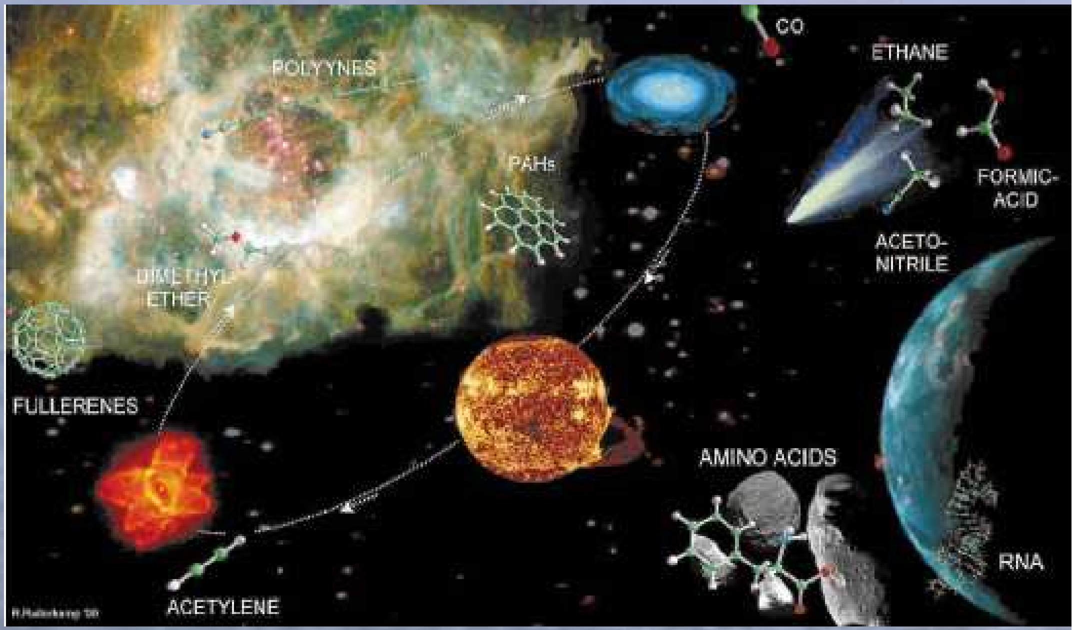
COMETS & METEORITES



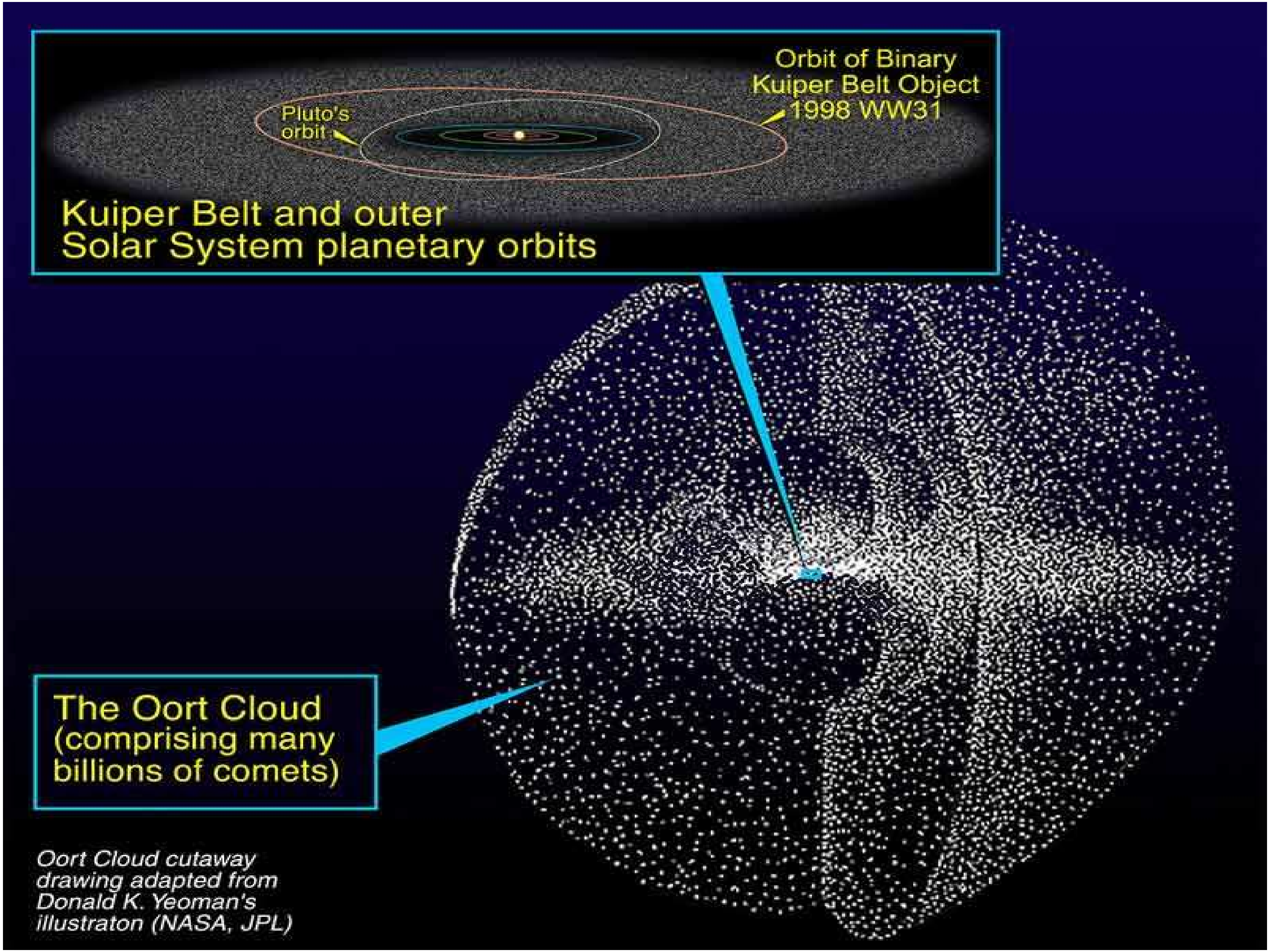
Outline

1. Origin and Structure of Comets
2. Cometary Composition & Coma Chemistry
3. Origin and Composition of Meteorites



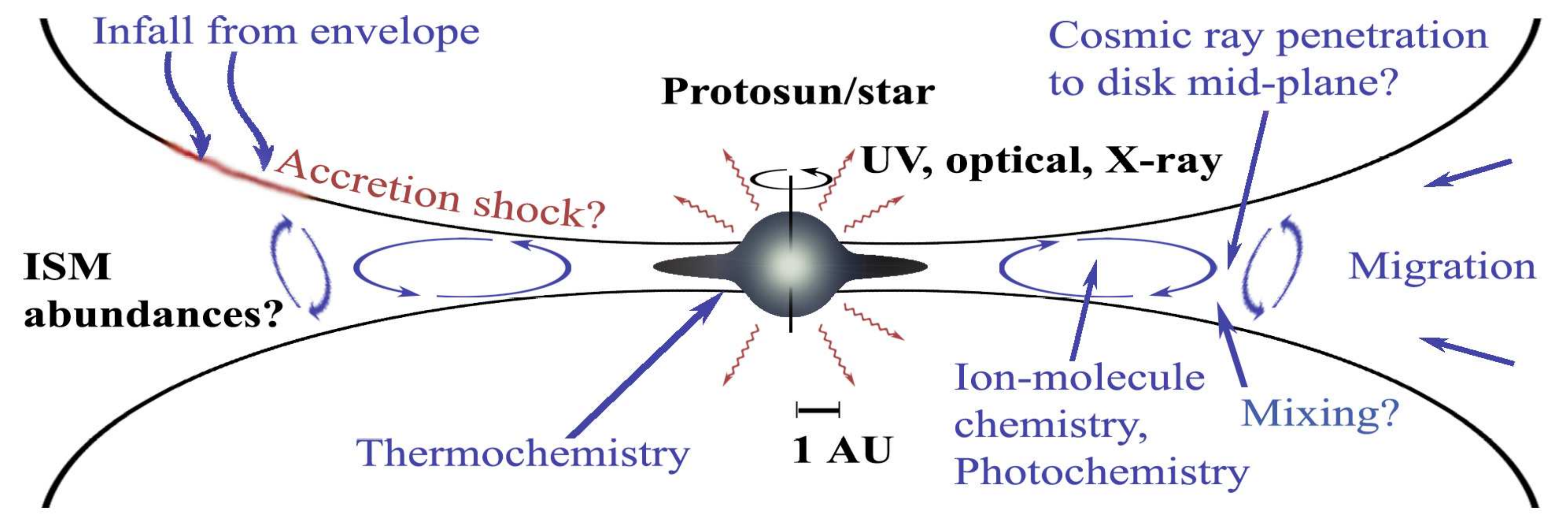
Comets, Astronomy & Astrobiology

- Comets are the key to understanding the Solar Nebula & its evolution.
- Comets could serve as probes of chemical processes occurring in the midplanes of astronomical disks
- Comets may have provided key organic nutrients required to jump start life on Earth.

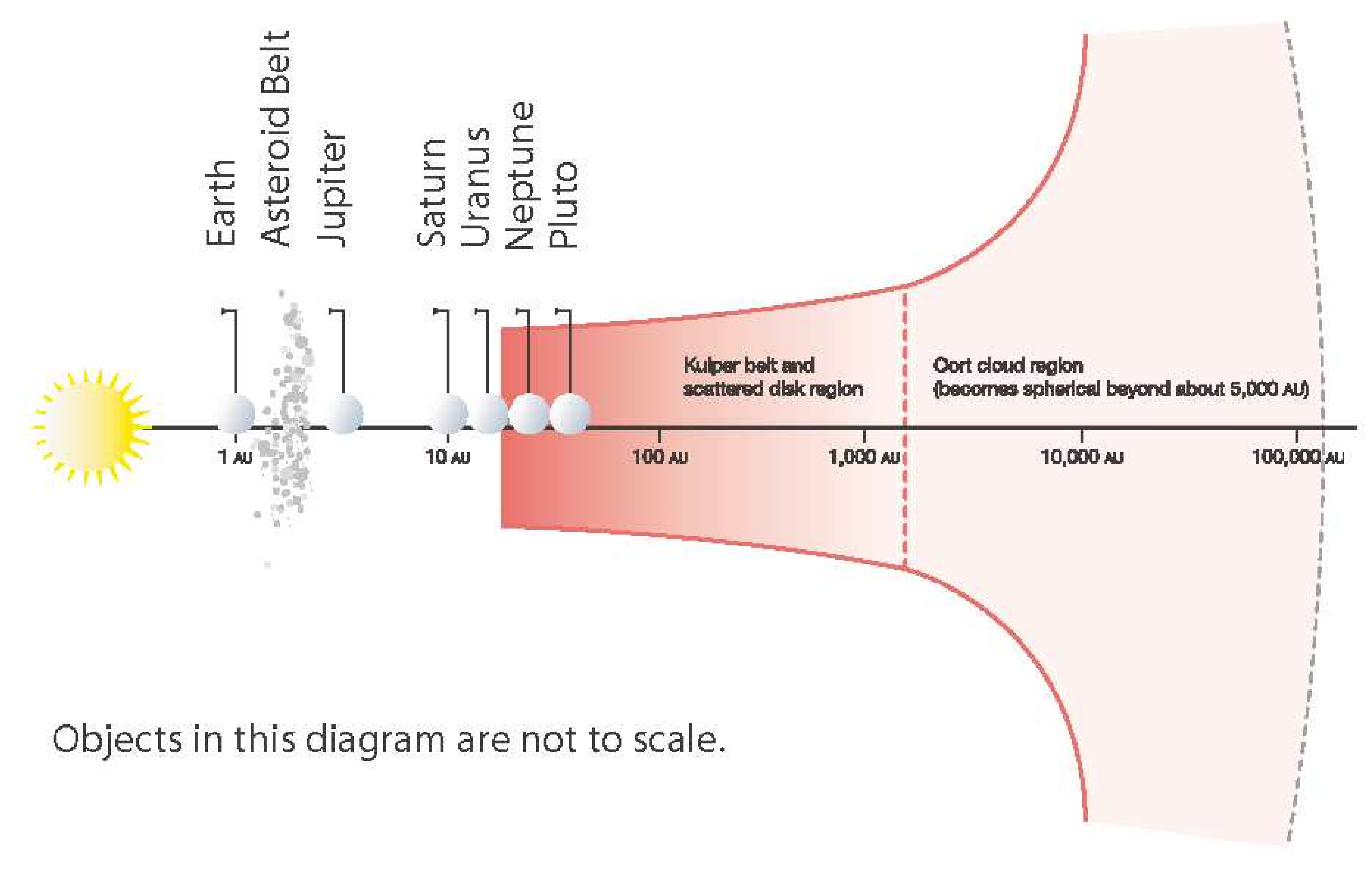


Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

Processes affecting ices and dust in Protoplanetary Disks.



Comet Reservoirs in our planetary system.



After Stern, Nature 424:639-642 (2003).

When comets are near the Sun and active, comets have several distinct parts:

- **nucleus:** relatively solid and stable, mostly ice and gas with a small amount of dust and other solids

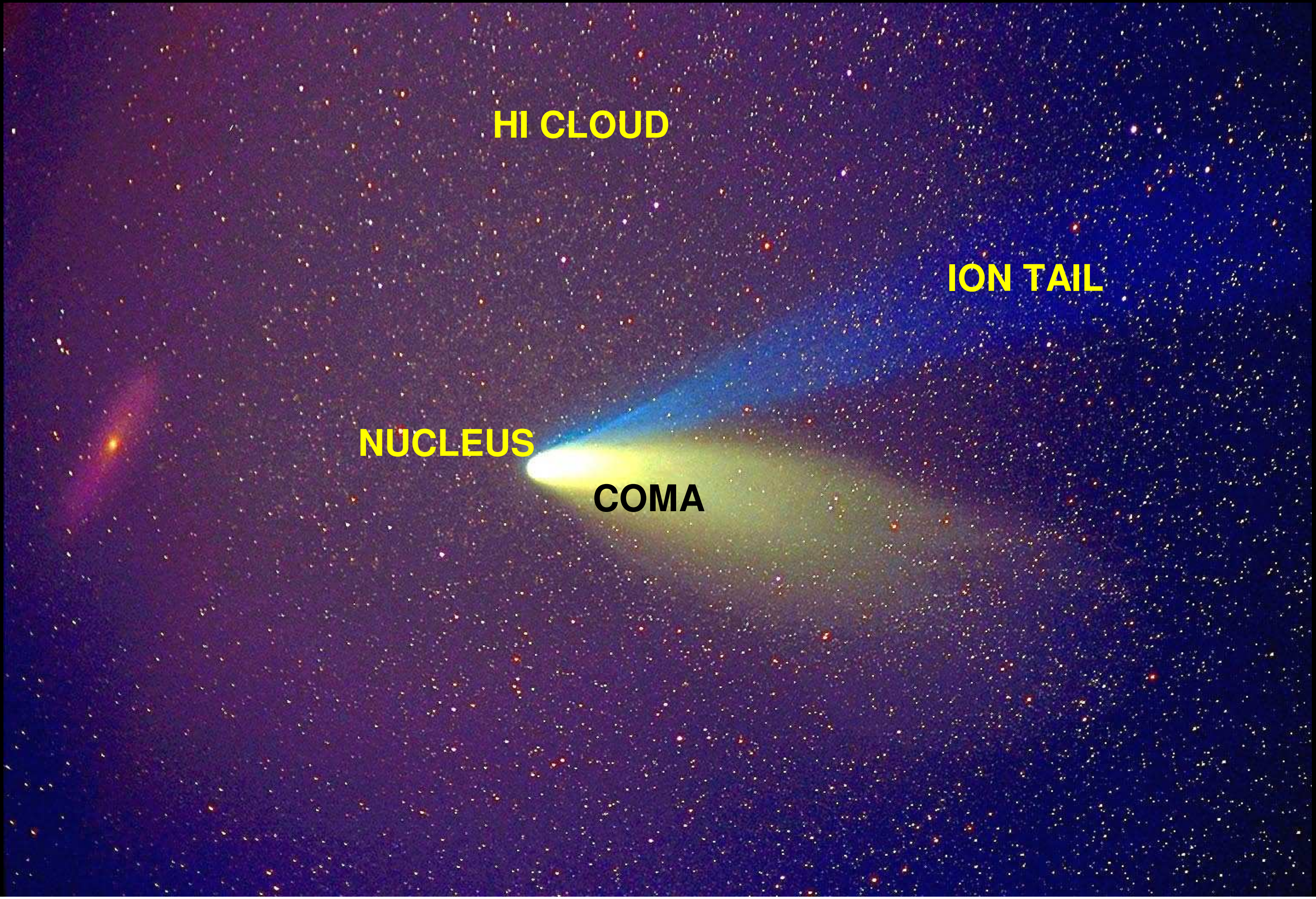
- **coma:** dense cloud of water, carbon dioxide and other neutral gases sublimed from the nucleus

- **hydrogen cloud:** huge (millions of km in diameter) but very sparse envelope of neutral hydrogen

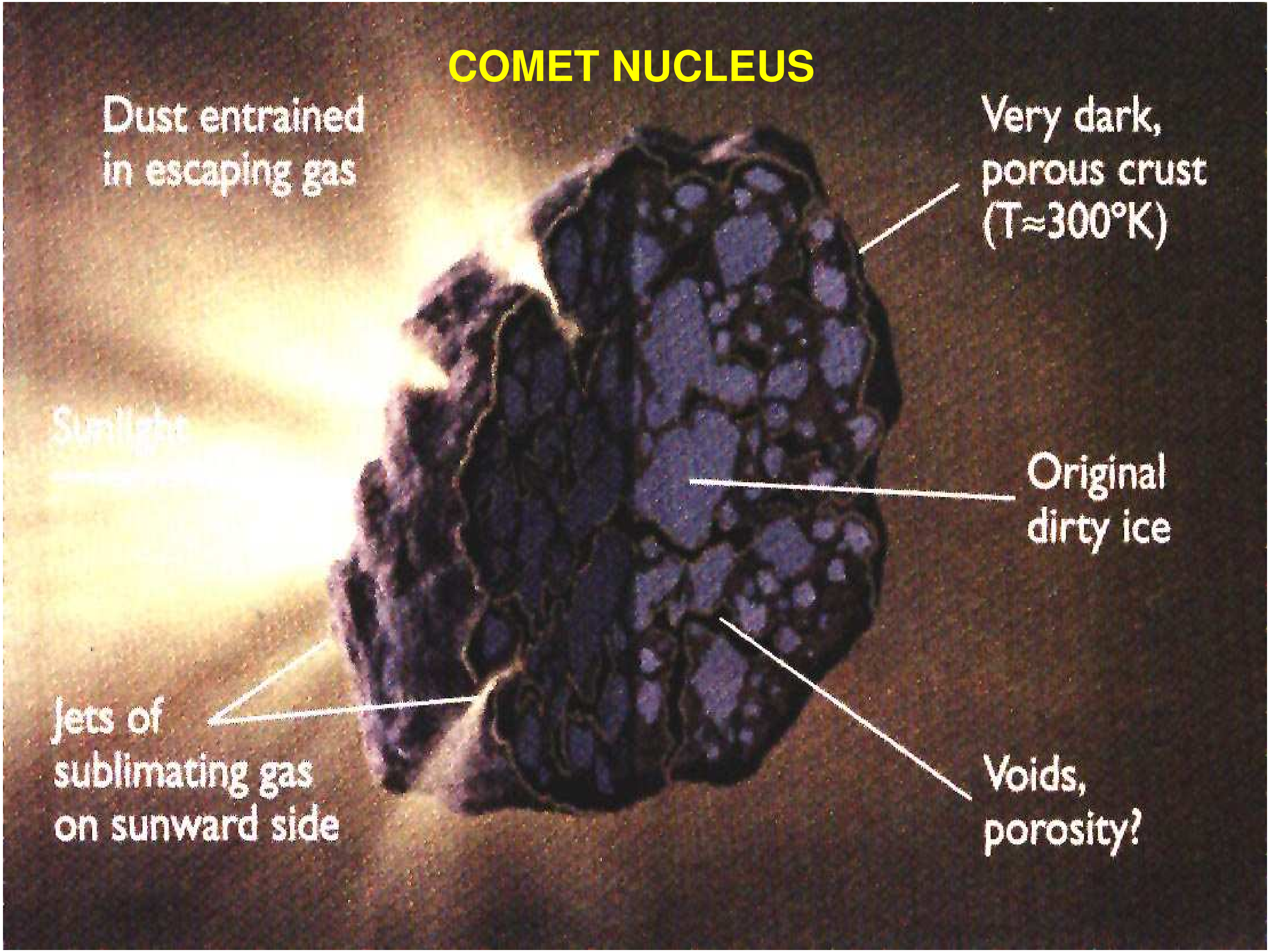
- **dust tail:** up to 10 million km long composed of smoke-sized dust particles driven off the nucleus by escaping gases; this is the most prominent part of a comet to the unaided eye

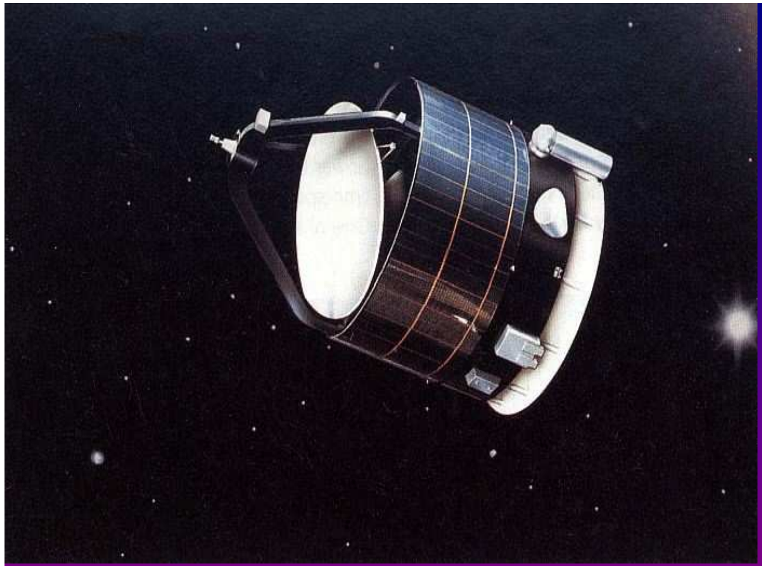
- **ion tail:** as much as several hundred million km long composed of plasma ⟶ interactions with the solar wind

Major Comet Structures



COMET NUCLEUS





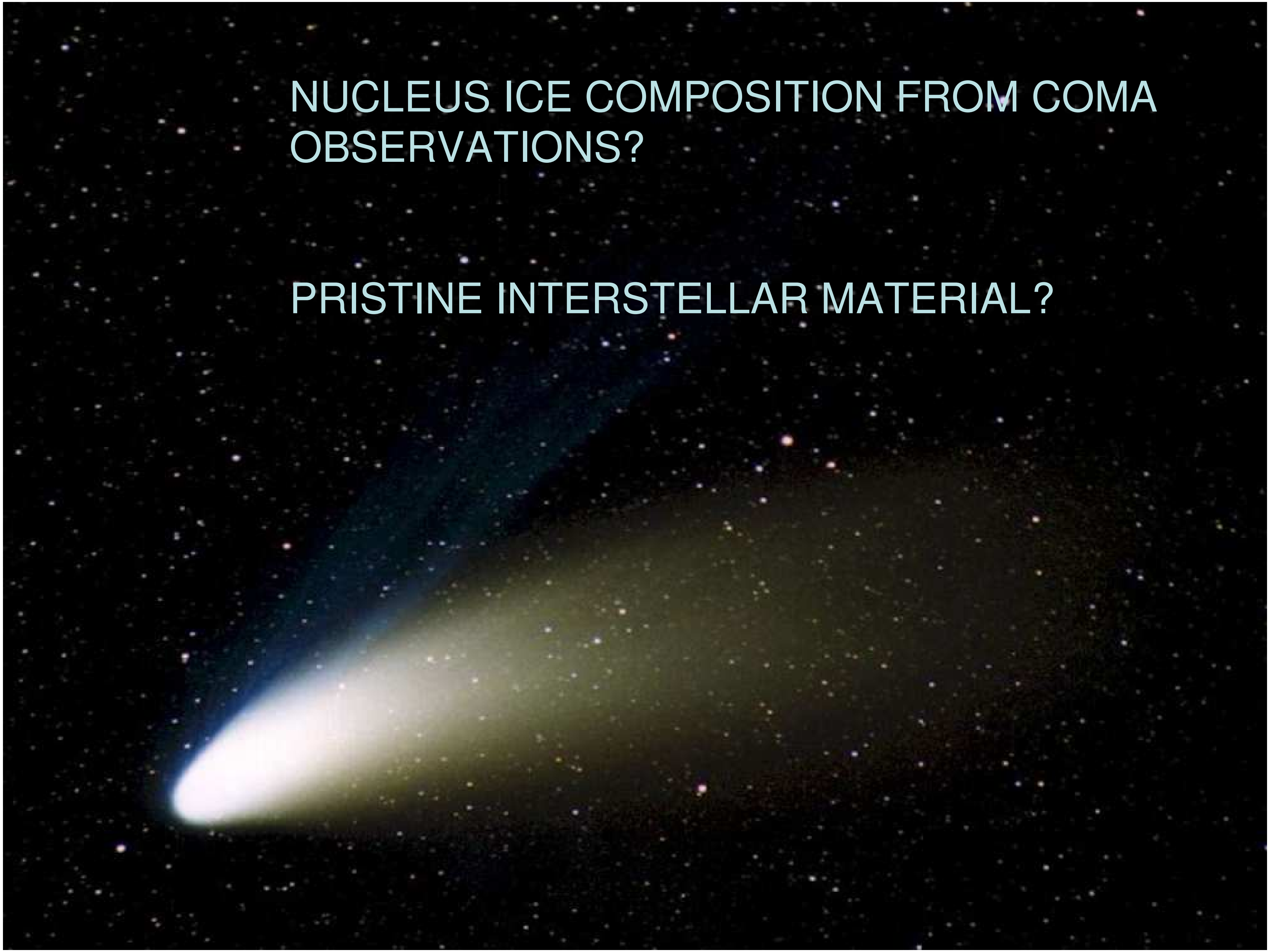
GIOTTO PIA
VEGA-1 PUMA-1
VEGA-2 PUMA-2

Time-of-flight mass spectra were recorded during impact of dust

Comets: Porous aggregates of ices and refractories

- 70 % of the dust grains comprise: mixed phase of organics and silicates
- 30 % of the dust grains do not contain organics
- CHON particles and silicate components are interspersed on sub-micron scales

Kissel & Krueger 1987
Jessberger et al. 1988



NUCLEUS ICE COMPOSITION FROM COMA OBSERVATIONS?

PRISTINE INTERSTELLAR MATERIAL?

THE COMA

Molecules are liberated from the nucleus by solar heating and sublimation

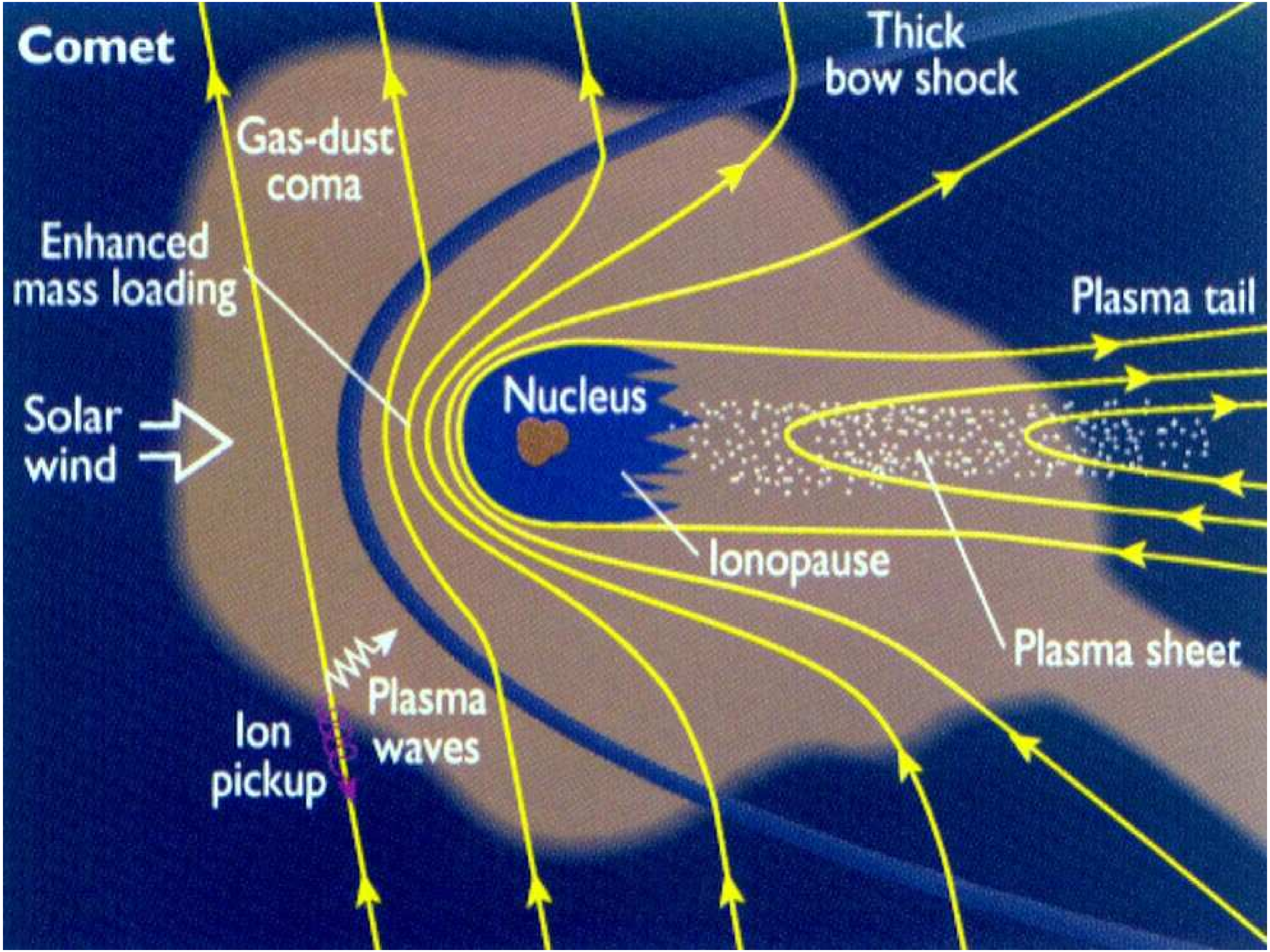
Molecules are destroyed by photodissociation & photoionization

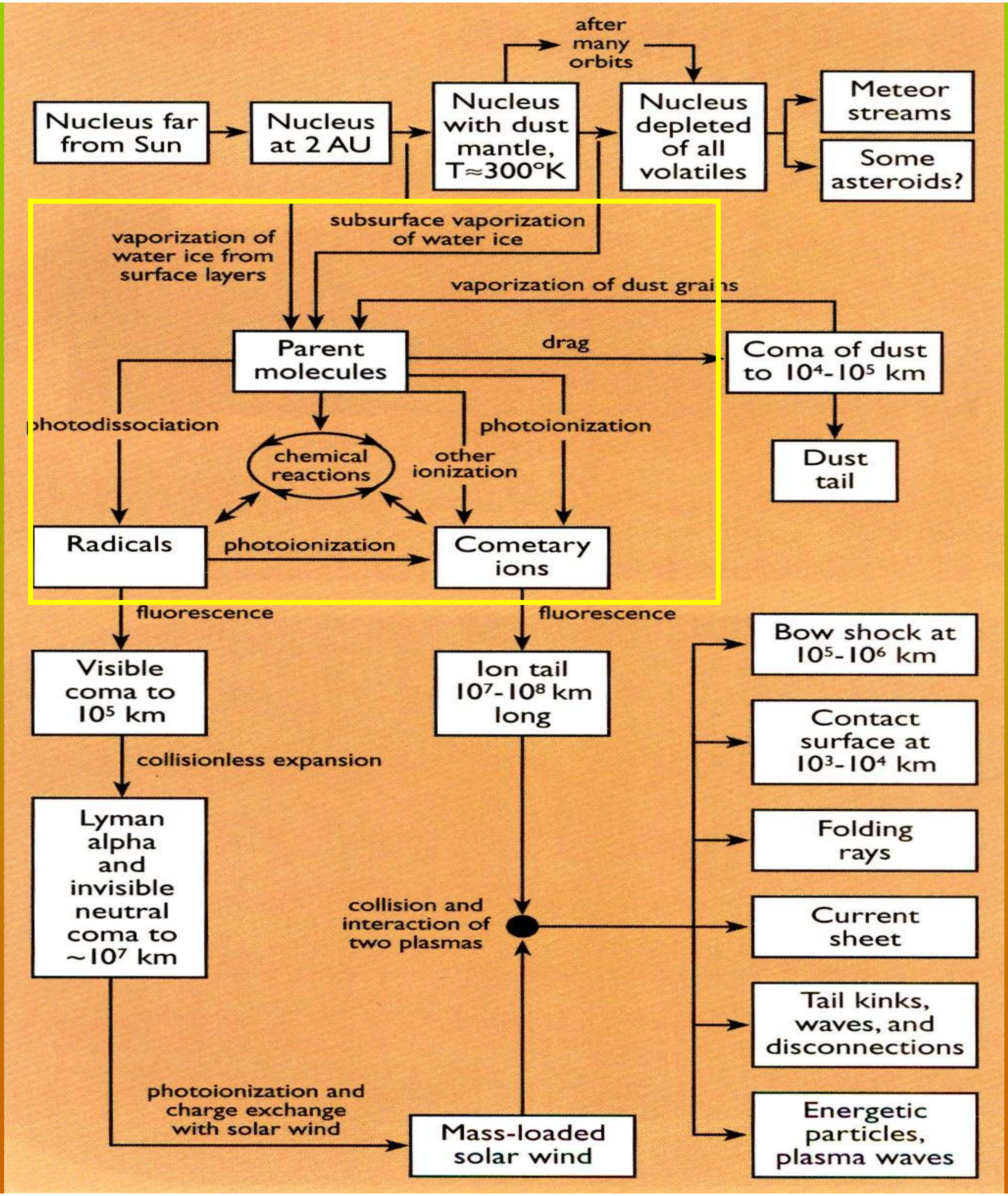
$$H_2O + h\nu \longrightarrow H + OH$$
$$OH + h\nu \longrightarrow H + O$$

$$H_2O + h\nu \longrightarrow H_2O^+ + e^-$$

Nucleus molecules are referred to as the "parent molecules"

The fragments produced by the absorption of a photon are called "daughters"


Comet
Gas-dust coma
Thick bow shock
Enhanced mass loading
Plasma tail
Nucleus
Solar wind
Ionopause
Plasma sheet
Plasma waves
Ion pickup



Nucleus far from Sun

Nucleus at 2 AU

Nucleus with dust mantle, T≈300°K

after many orbits

Nucleus depleted of all volatiles

Meteor streams

Some asteroids?

vaporization of water ice from surface layers

subsurface vaporization of water ice

vaporization of dust grains

Parent molecules

drag

Coma of dust to 10^4-10^5 km

Dust tail

photodissociation

chemical reactions

other ionization

photoionization

Radicals

photoionization

Cometary ions

fluorescence

fluorescence

Visible coma to 10^5 km

Ion tail 10^7-10^8 km long

collisionless expansion

Lyman alpha and invisible neutral coma to ~10^7 km

collision and interaction of two plasmas

photoionization and charge exchange with solar wind

Mass-loaded solar wind

Bow shock at 10^5-10^6 km

Contact surface at 10^3-10^4 km

Folding rays

Current sheet

Tail kinks, waves, and disconnections

Energetic particles, plasma waves

CHEMICAL REACTION PROCESSES

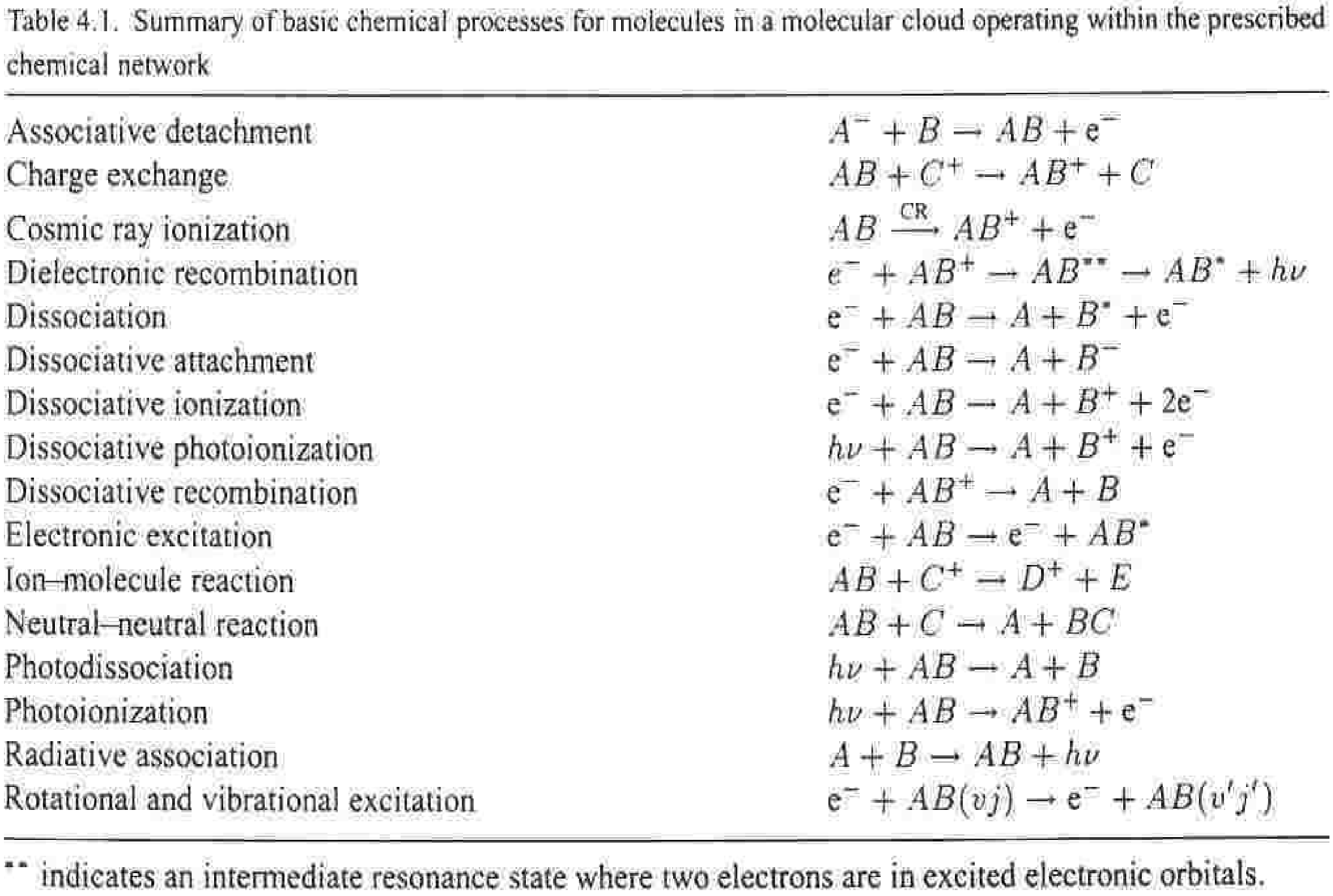
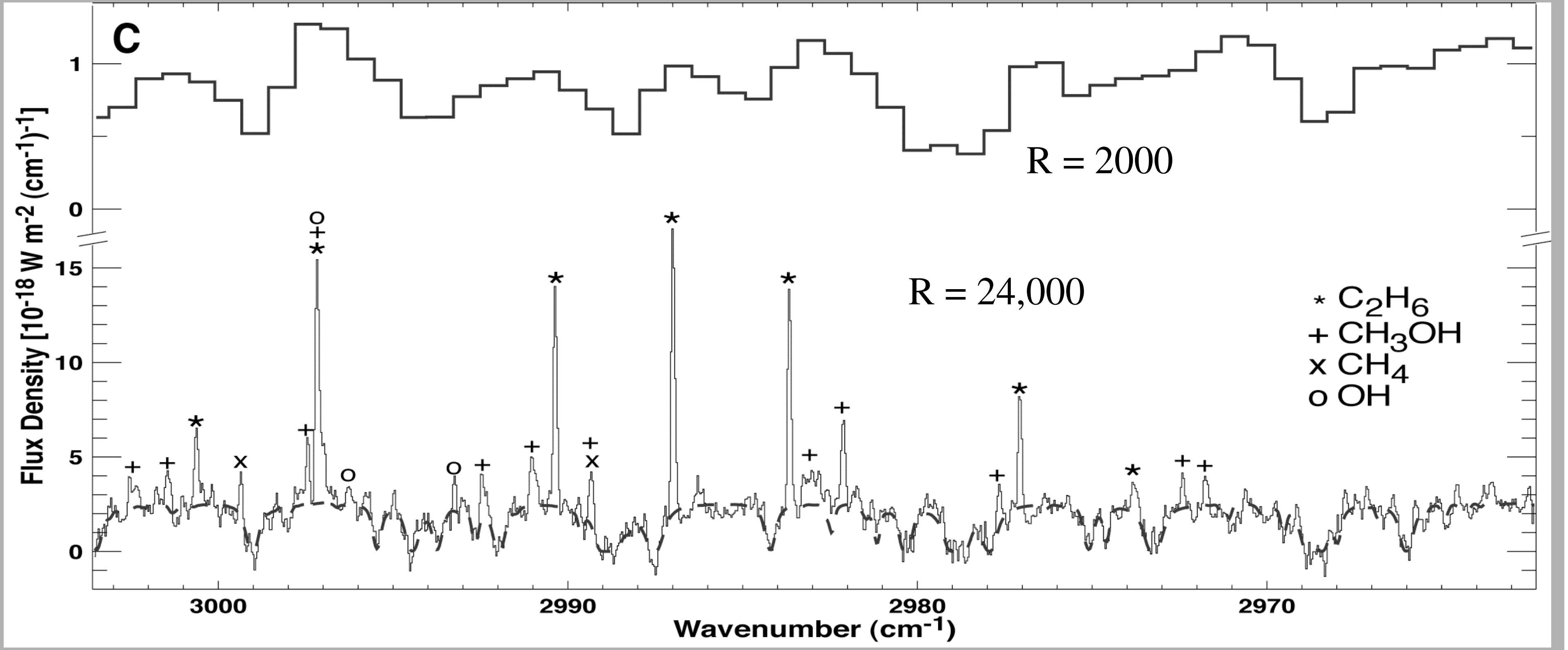


Table 4.1. Summary of basic chemical processes for molecules in a molecular cloud operating within the prescribed chemical network

Associative detachment	$A^- + B \to AB + e^-$
Charge exchange	$AB + C^+ \to AB^+ + C$
Cosmic ray ionization	$AB \xrightarrow{\text{CR}} AB^+ + e^-$
Dielectronic recombination	$e^- + AB^+ \to AB^{**} \to AB^* + h\nu$
Dissociation	$e^- + AB \to A + B^* + e^-$
Dissociative attachment	$e^- + AB \to A + B^-$
Dissociative ionization	$e^- + AB \to A + B^+ + 2e^-$
Dissociative photoionization	$h\nu + AB \to A + B^+ + e^-$
Dissociative recombination	$e^- + AB^+ \to A + B$
Electronic excitation	$e^- + AB \to e^- + AB^*$
Ion–molecule reaction	$AB + C^+ \to D^+ + E$
Neutral–neutral reaction	$AB + C \to A + BC$
Photodissociation	$h\nu + AB \to A + B$
Photoionization	$h\nu + AB \to AB^+ + e^-$
Radiative association	$A + B \to AB + h\nu$
Rotational and vibrational excitation	$e^- + AB(vj) \to e^- + AB(v'j')$

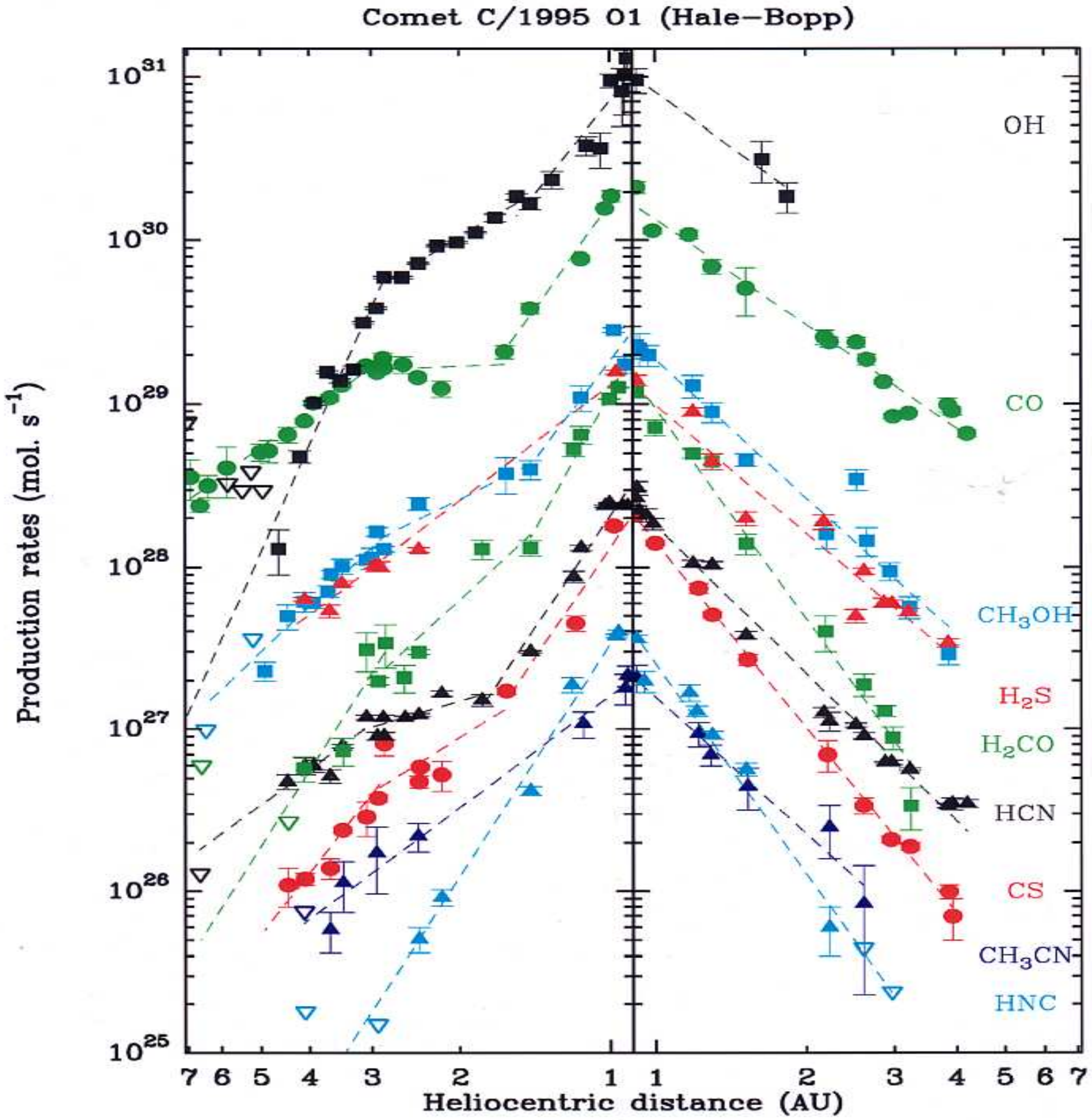
** indicates an intermediate resonance state where two electrons are in excited electronic orbitals.

Remote Sensing of Cometary Comae



Mumma et al. (2003)

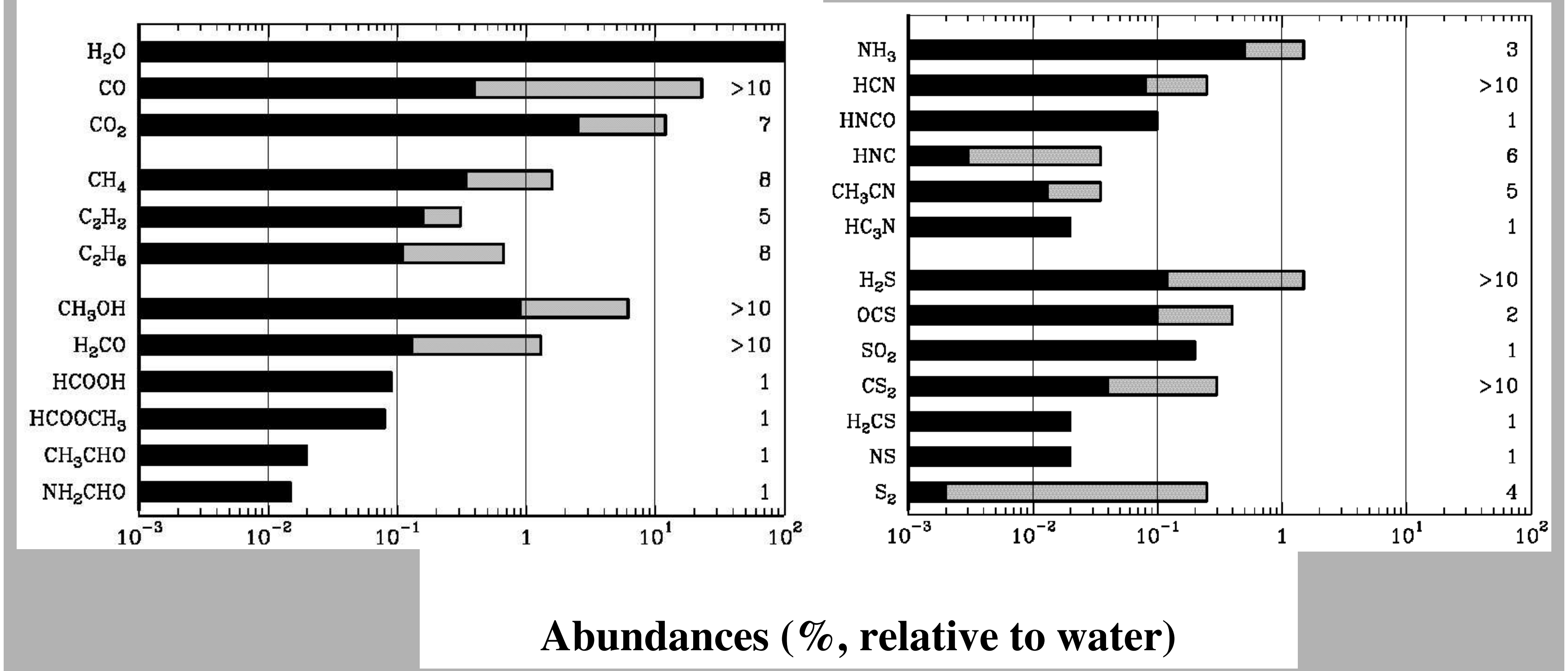
OUTGASSING CURVES OF VOLATILES



Biver et al. 1998

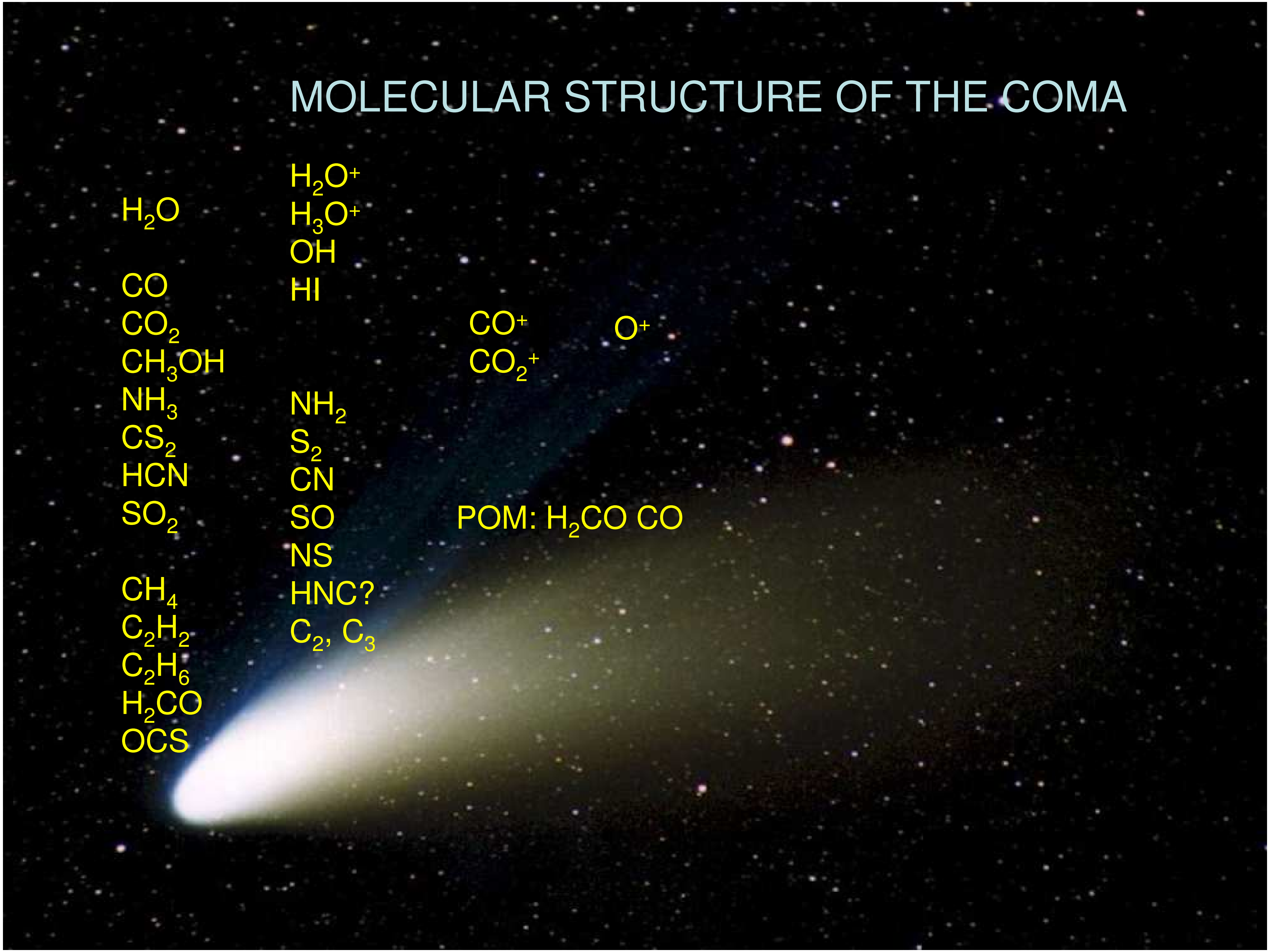
Chemical Composition of Comets

(The grey bar indicates the range measured to date)



Bockelee-Morvan, Crovisier, Mumma, and Weaver (Comets II, 2003)

MOLECULAR STRUCTURE OF THE COMA



H_2O

CO
CO_2
CH_3OH
NH_3
CS_2
HCN
SO_2

CH_4
C_2H_2
C_2H_6
H_2CO
OCS

H_2O^+
H_3O^+
OH
HI

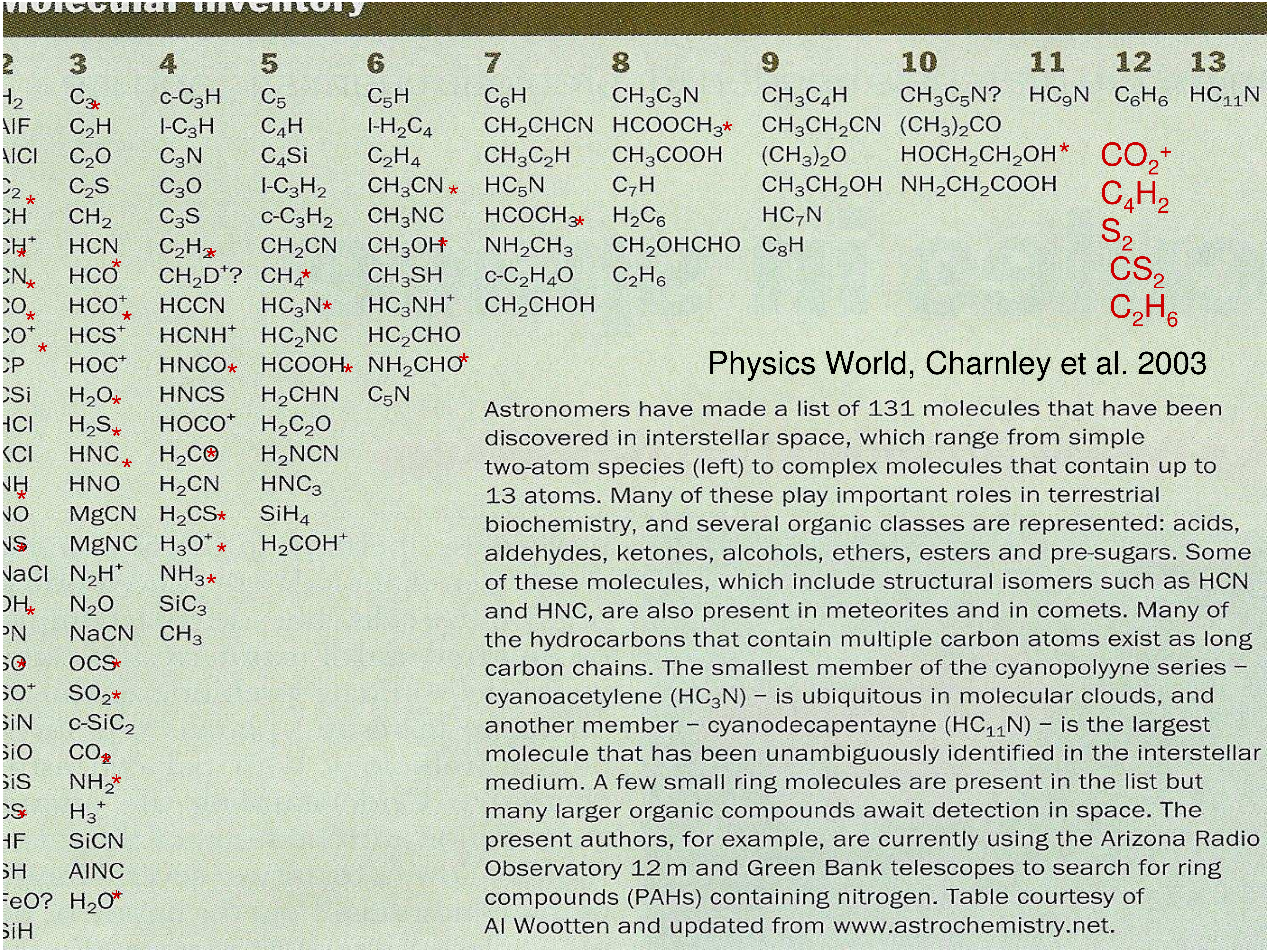
NH_2
S_2
CN
SO
NS
HNC?
C_2, C_3

CO^+
CO_2^+

POM: H_2CO CO

O^+

SPECIES	HM PROTOSTARS	LM PROTOSTARS	COMETS
H_2O	100	100	100
CO	1-20	1-60	5-20
CO_2	~20	15-40	2-10
CH_4	1-4	-	0.2-1.2
CH_3OH	1-35	1-20	0.3-2
H_2CO	3	-	0.2-1
OCS	0.05-0.18	< 0.08	0.5
NH_3	< 5	-	0.6-1.8
C_2H_6	< 0.4	-	0-4-1.2
HCOOH	3	-	0.05
O_2	< 20	-	0.5 ul
N_2	?	?	?
XCN	0.3-2.9	-	-
HCN	< 3	-	0.2



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											

CO_2^+
C_4H_2
S_2
CS_2
C_2H_6

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.
]

COMA CHEMISTRY PROBLEMS

- **Molecule formation in the collisional inner coma ?**

HNC, S_2, NS, C_2, C_3 … role of `exotic' reactions (electrons and H_f) ?

- **Origin of extended coma sources ?**

Polyoxymethylene (POM) --> H_2CO, CO

other complex organic polymers --> HNC, CN, OCS ?

- **Cosmogonic information ?**

conditions in the 5-40AU region of the early Solar System; D/H (HDO/H_2O), ortho-para ratios, $^{14}N/^{15}N$

Fast H Atoms in the Coma

- H_f atoms created in photodissociation of water:

$$H_2O \;+\; \nu \;\text{-->}\; OH^* \;+\; H_f$$

- Thermalisation of H_f atoms is the principal heat source in the inner coma.

- Possible role in driving ‘suprathermal’ chemistry (reactions with barriers or which are endoergic) ?

Destruction of Methanol

1) Photodissociation:

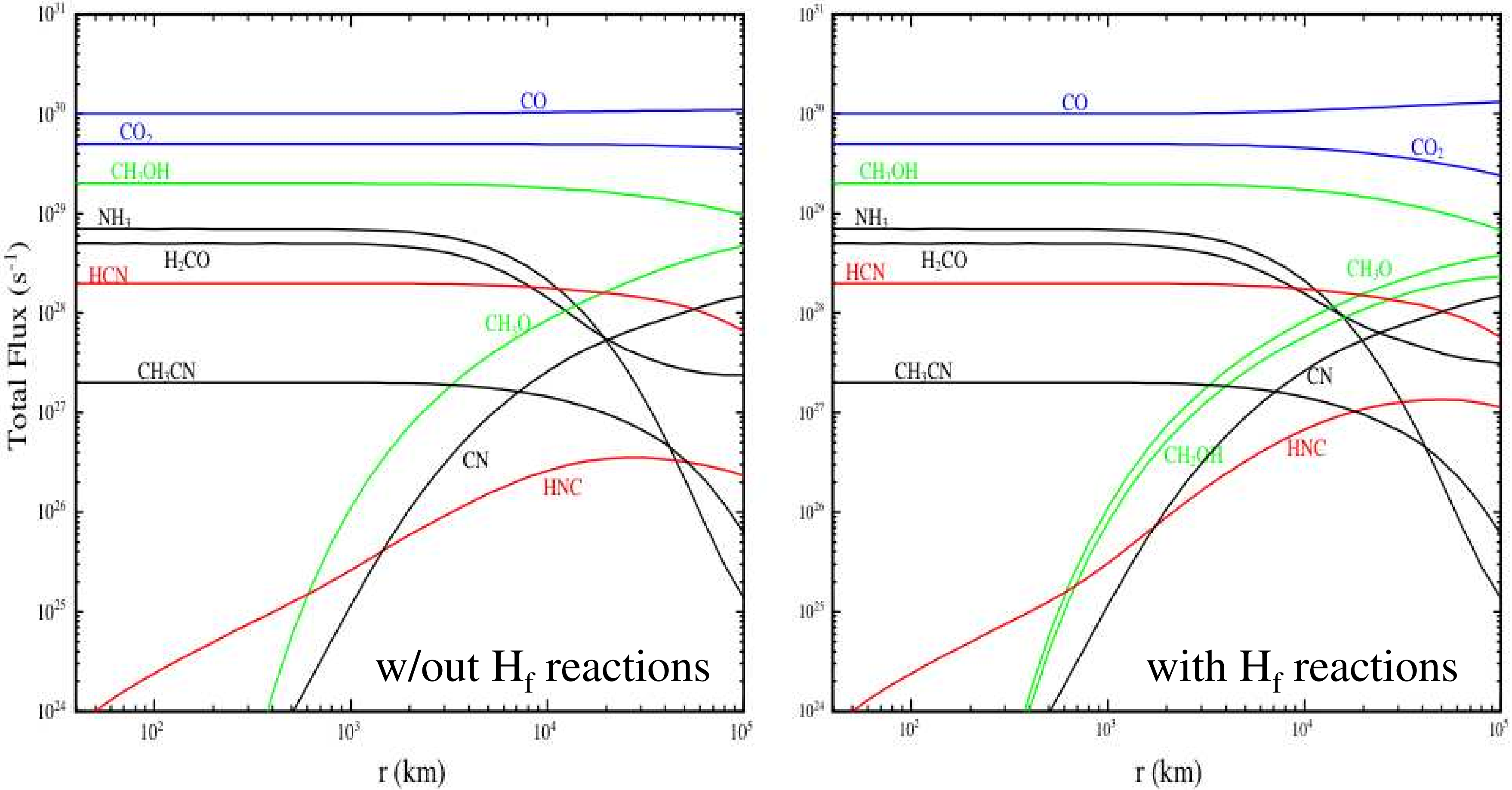
$CH_3OH + \nu$ --> $CH_3O + H$ (~60%)

$CH_3OH + \nu$ --> $H_2CO + 2H$ (~40%)

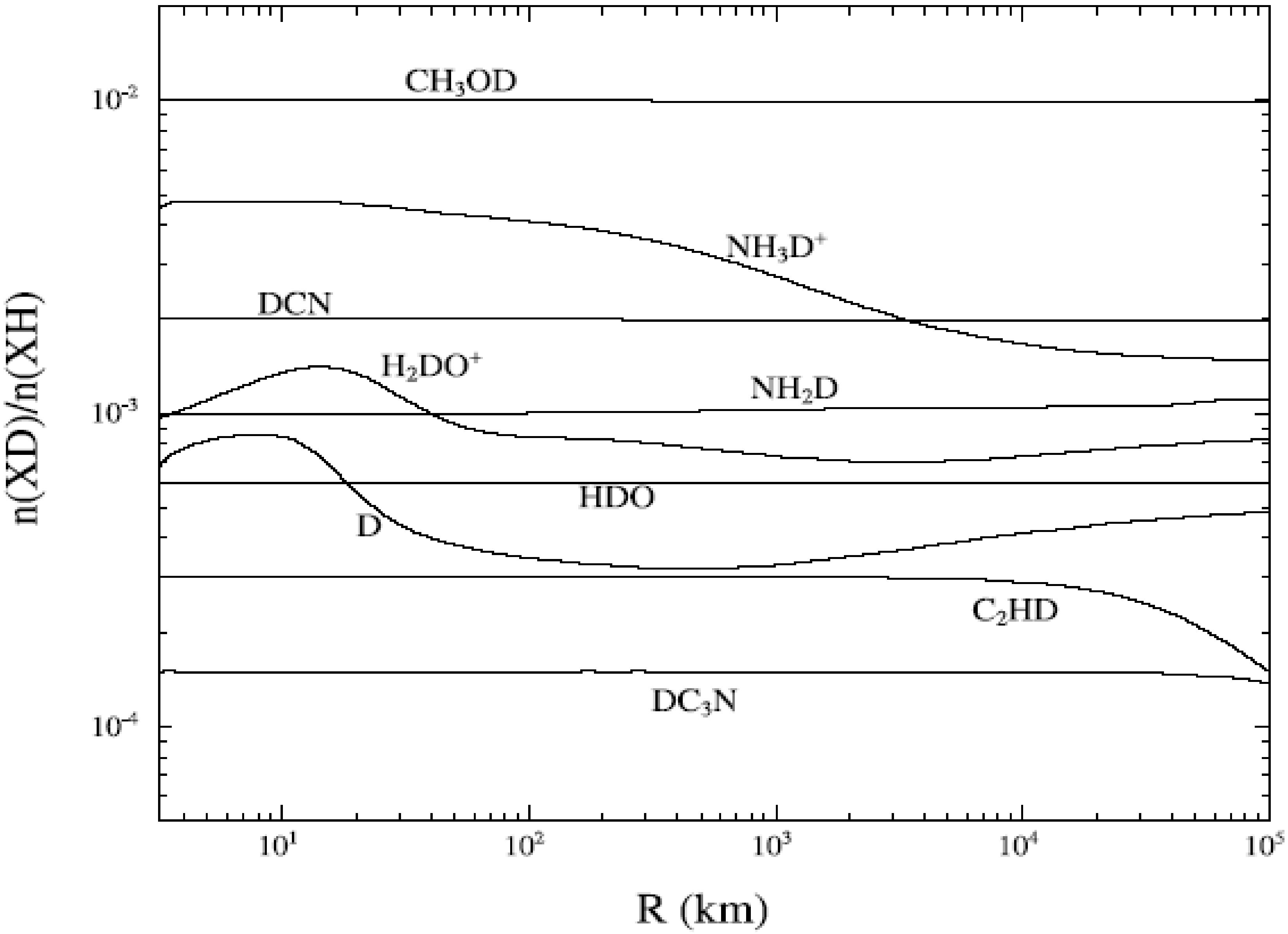
2) H_f Reactions:

$CH_3OH + H_f$ --> $CH_2OH + H_2$

Coma Chemistry in Hale-Bopp



Deuterium Chemistry in Hale-Bopp



Chemical differences between two dynamical comet families

New, LP, & Halley-type (HTCs)
5 - 40 AU
Oort cloud

Jupiter-family (JFCs)
> 40 AU
Kuiper belt

1P/Halley

OH, C_2, C_3, CN, NH

ENRICHED IN C_2H_6 & CH_3CCH?

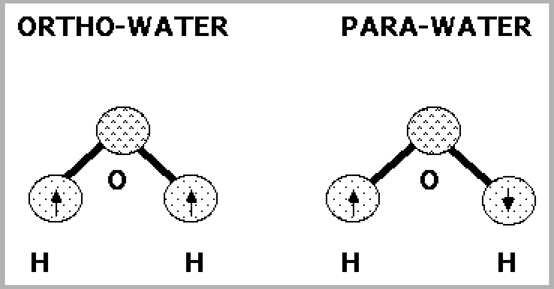
Giotto.HMC.MPAE

19P/Borrelly

CARBON-DEPLETED?

DS-1.JPL.NASA

Nuclear Spin Temperatures in Oort Cloud Comets.

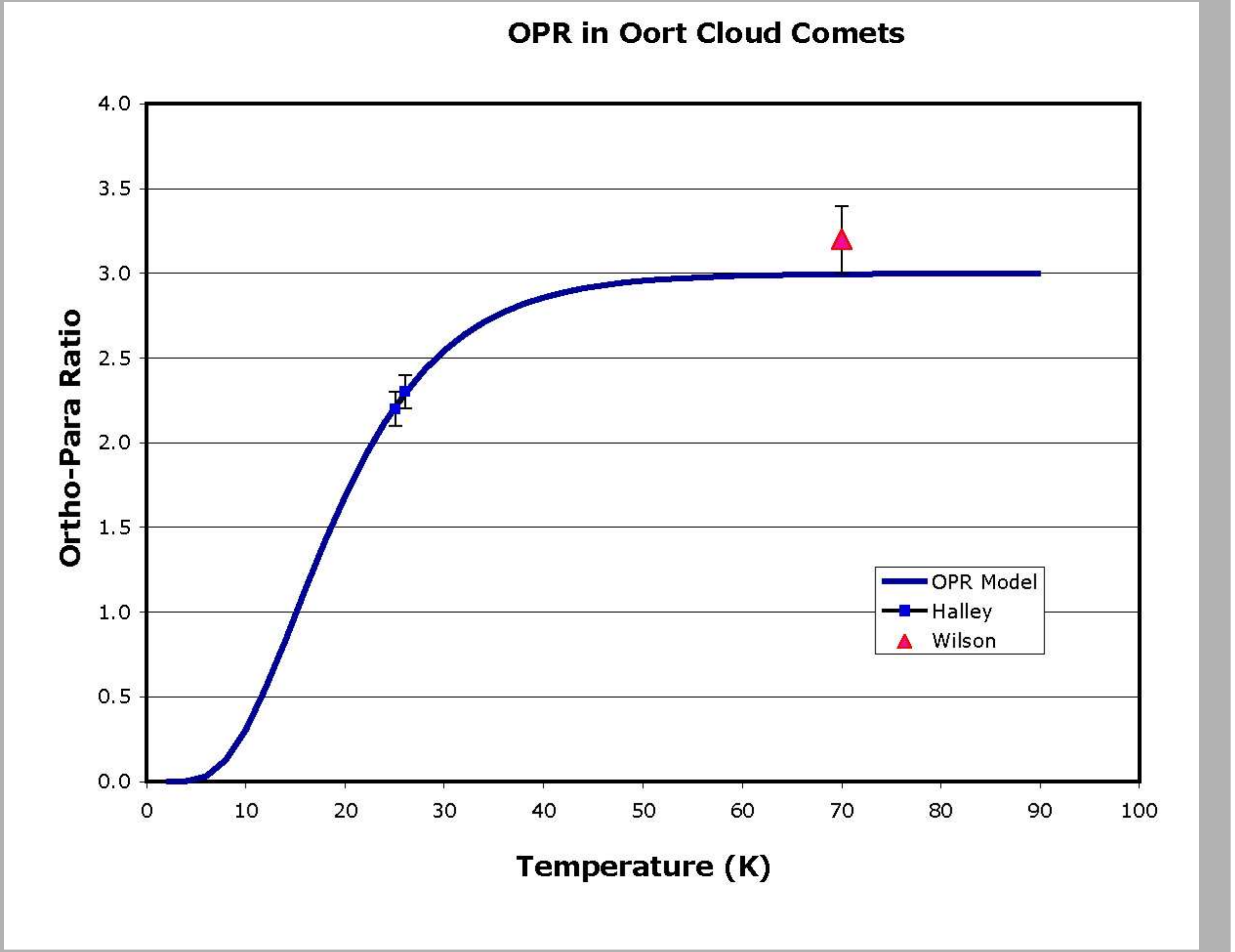


I = 1 I = 0

2I +1 = 3, ortho
= 1, para

$$\mathrm{OPR} = 3\, e^{-\Delta E/kT}$$

$$\Delta E = 24\ \mathrm{cm}^{-1}$$



Mumma et al. 1987; 1989; 1993

Nuclear Spin Temperatures in Oort Cloud Comets.

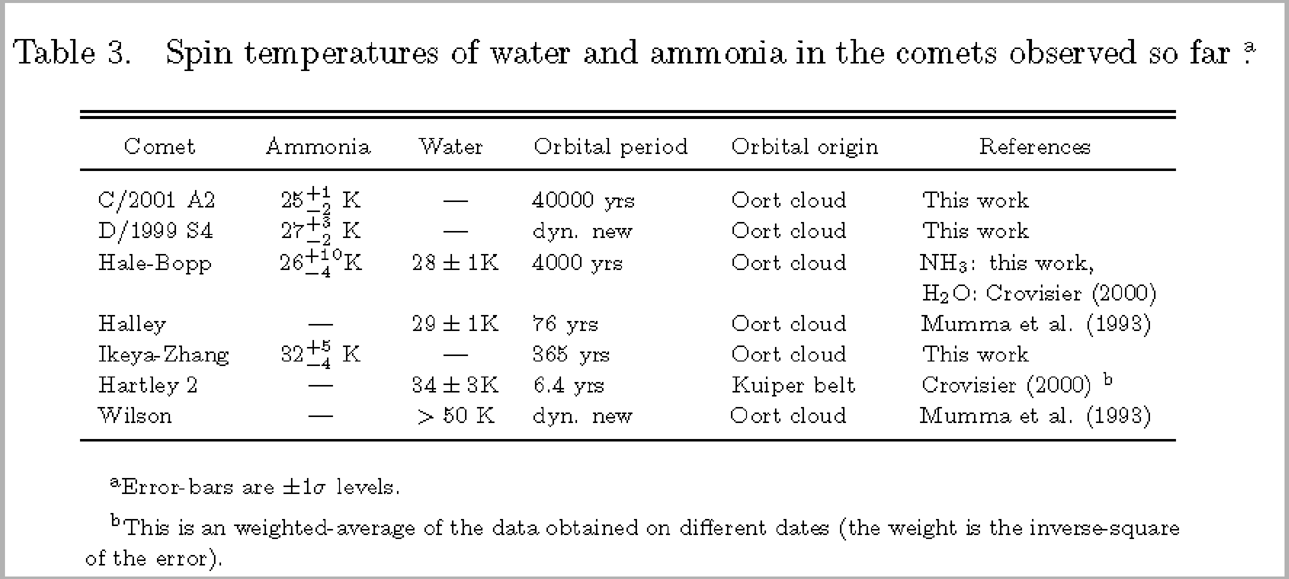
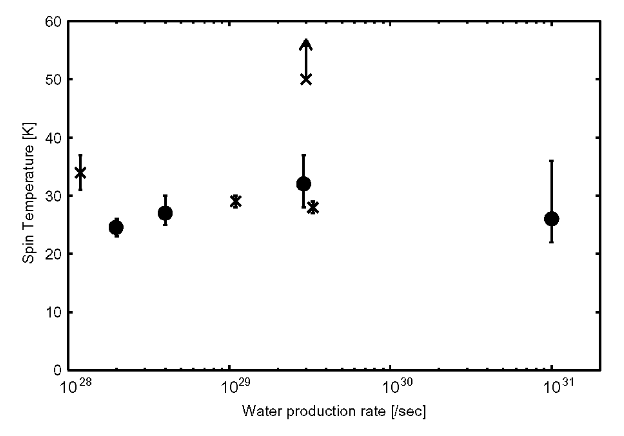


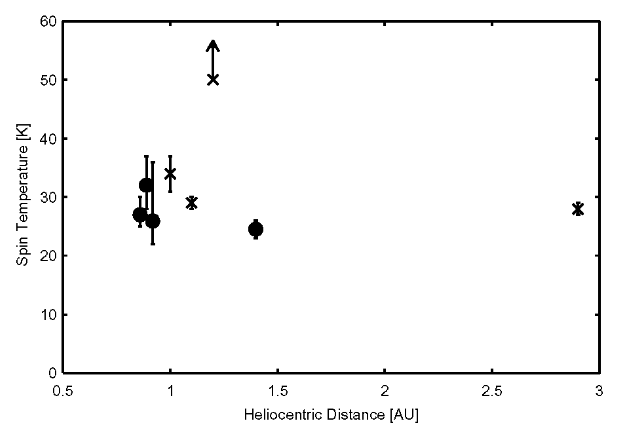
Table 3. Spin temperatures of water and ammonia in the comets observed so far [a]

Comet	Ammonia	Water	Orbital period	Orbital origin	References
C/2001 A2	25^{+1}_{-2} K	—	40000 yrs	Oort cloud	This work
D/1999 S4	27^{+3}_{-2} K	—	dyn. new	Oort cloud	This work
Hale-Bopp	26^{+10}_{-4}K	28 ± 1K	4000 yrs	Oort cloud	NH_3: this work, H_2O: Crovisier (2000)
Halley	—	29 ± 1K	76 yrs	Oort cloud	Mumma et al. (1993)
Ikeya-Zhang	32^{+5}_{-4} K	—	365 yrs	Oort cloud	This work
Hartley 2	—	34 ± 3K	6.4 yrs	Kuiper belt	Crovisier (2000) [b]
Wilson	—	> 50 K	dyn. new	Oort cloud	Mumma et al. (1993)

[a] Error-bars are $\pm 1\sigma$ levels.

[b] This is an weighted-average of the data obtained on different dates (the weight is the inverse-square of the error).

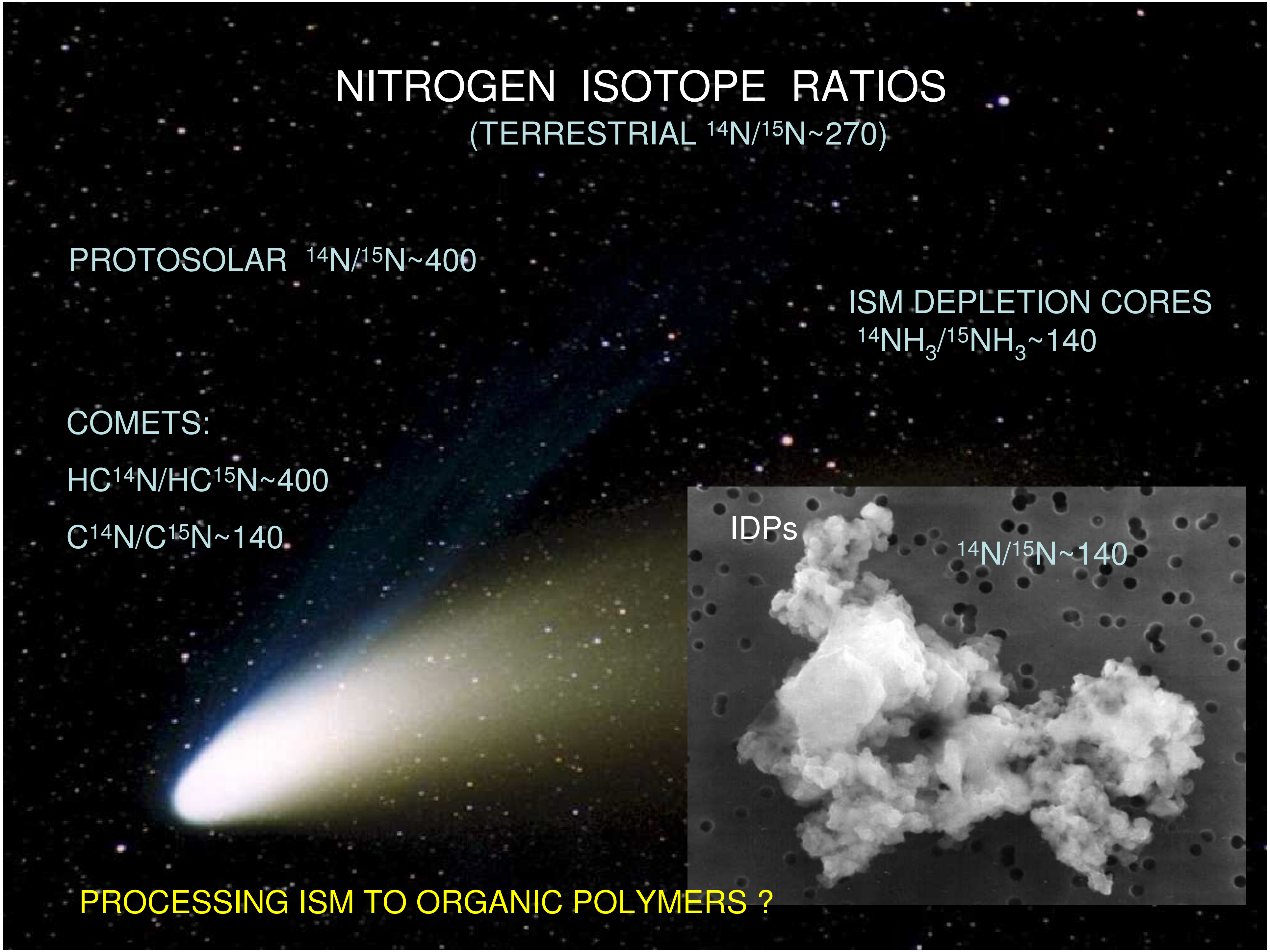




After Kawakita et al. Ap. J. (in press, 2003)

NITROGEN ISOTOPE RATIOS

(TERRESTRIAL $^{14}N/^{15}N\sim270$)



PROTOSOLAR $^{14}N/^{15}N\sim400$

ISM DEPLETION CORES

$^{14}NH_3/^{15}NH_3\sim140$

COMETS:

$HC^{14}N/HC^{15}N\sim400$

$C^{14}N/C^{15}N\sim140$

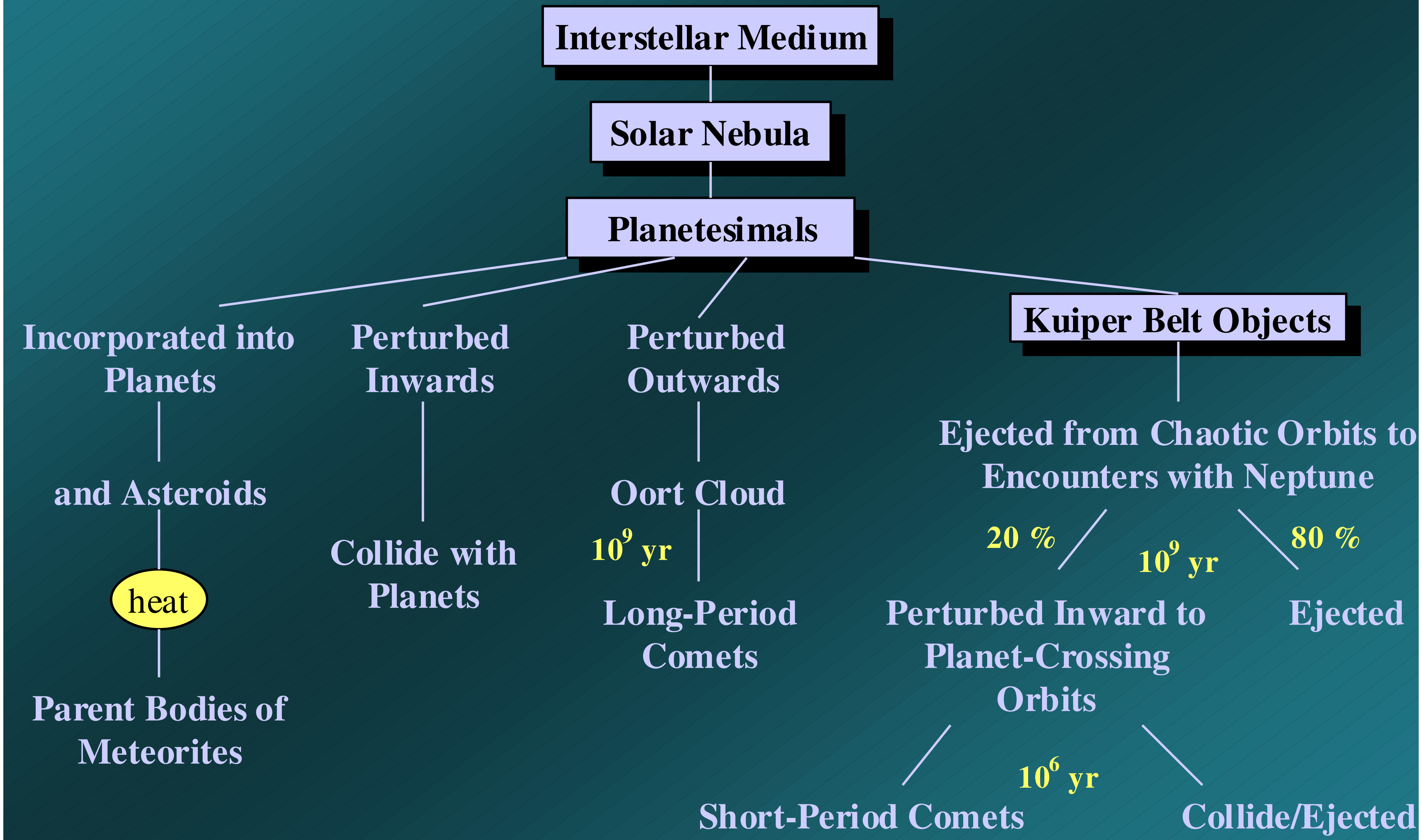
IDPs

$^{14}N/^{15}N\sim140$

PROCESSING ISM TO ORGANIC POLYMERS ?

Parent Body Evolution

D. Cruikshank, in
From Stardust to Planetesimals,
ASP Conference Series 122, 315 (1997



Interstellar Medium

Solar Nebula

Planetesimals

Incorporated into Planets

and Asteroids

heat

Parent Bodies of Meteorites

Perturbed Inwards

Collide with Planets

Perturbed Outwards

Oort Cloud

10^9 yr

Long-Period Comets

Kuiper Belt Objects

Ejected from Chaotic Orbits to Encounters with Neptune

20 %

10^9 yr

80 %

Perturbed Inward to Planet-Crossing Orbits

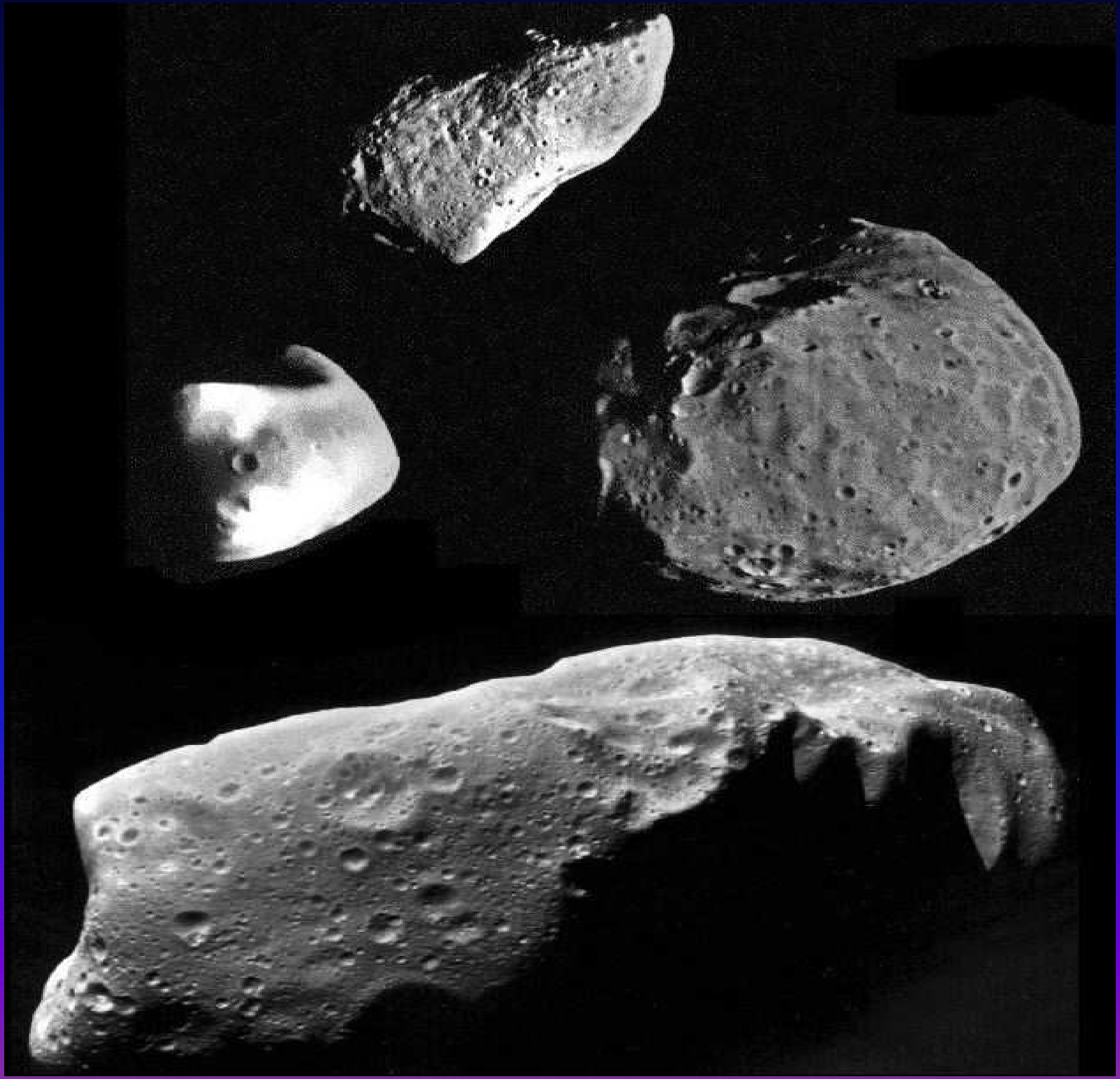
Ejected

10^6 yr

Short-Period Comets

Collide/Ejected

Asteroids



Asteroids **are classified into a number of types according to their spectra (and hence their chemical composition) and albedo:**

C-type, includes more than 75% of known asteroids: extremely dark (albedo 0.03); similar to carbonaceous chondrite meteorites; approximately the same chemical composition as the Sun minus hydrogen, helium and other volatiles

S-type, 17%: relatively bright (albedo .10-.22); metallic nickel-iron mixed with iron- and magnesium-silicates

M-type, most of the rest: bright (albedo .10-.18); pure nickel-iron

There are also a dozen or so other rare types

Asteroids are also categorized by their position in the solar system:

Main Belt: located between Mars and Jupiter roughly 2 - 4 AU from the Sun; further divided into subgroups:
Hungarias, Floras, Phocaea, Koronis, Eos, Themis, Cybeles and Hildas

Near-Earth Asteroids (NEAs): ones that closely approach the Earth

Atens: semimajor axes less than 1.0 AU and aphelion distances greater than 0.983 AU;

Apollos: semimajor axes greater than 1.0 AU and perihelion distances less than 1.017 AU

Meteorites

Murchison

Five Meteorite Types

Iron	primarily iron and nickel; similar to type M asteroids	
Stony Iron	mixtures of iron and stony material like type S asteroids	
Chondrite	by far the largest number of meteorites fall into this class; similar in composition to the mantles and crusts of the terrestrial planets	

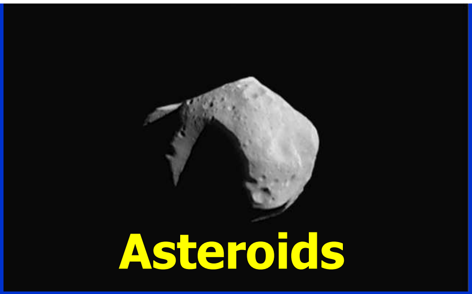
Meteorite Types

Carbonaceous Chondrite	**very similar in composition to the Sun less volatiles; similar to type C asteroids**	
Achondrite	**similar to terrestrial basalts; the meteorites believed to have originated on the Moon and Mars are achondrites**	

TYPES OF METEORITES

TYPE	SUBTYPE	FREQUENCY	COMPOSITION	FORMATION
Stones	Carbonaceous Chondrites	5 %	Water, carbon silicates, metals	Primitive
	Chondrites	81 %	Silicates	Heated under pressure
	Achondrites	8 %	Silicates	Heated
Stony irons		1 %	50 % silicates, 50 % free metal	Differentiated
Irons		5 %	90 % iron 10 % nickel	Differentiated

Parent Bodies



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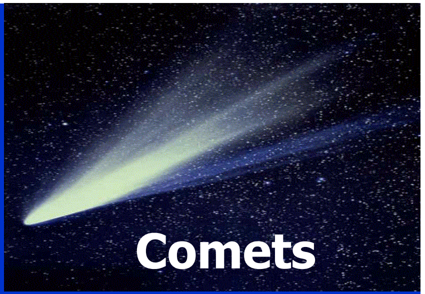


Parent Body Processing:

Energy sources:

- Radiocactive decay processes
- Low-energy impacts
- Irradiation processes

Heat
Liquid water

Organic compounds are converted into secondary products

→ e.g. amino acids

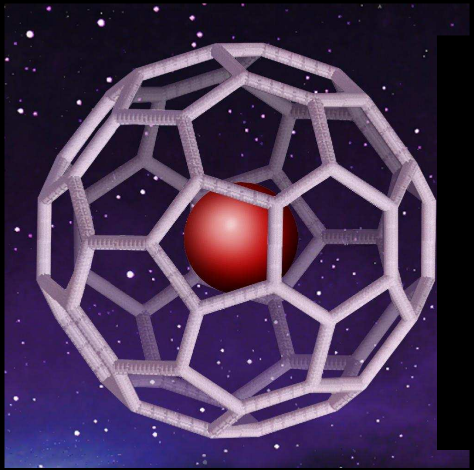
Carbonaceous Chondrites (CC)

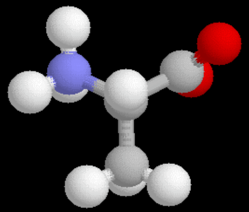
- Stony meteorites; classified into CM, CI, CV and CO, based on chemical dissimilarities.
- are the most primitive meteorites in terms of their elemental composition.
- have experienced different degrees of aqueous alteration of their original anhydrous silicate matrix.
- are rich in organic matter (C content of > 3%).
- Most important CC's: Murchison, Murray, Orgueil.

Meteorites represent the only extraterrestrial material which can be studied on Earth.

Murchison

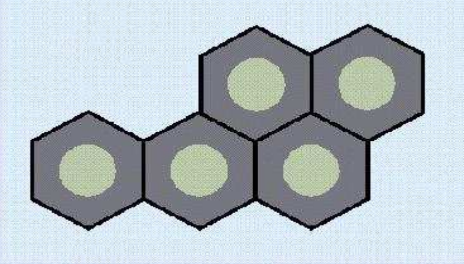
Volatile fraction:



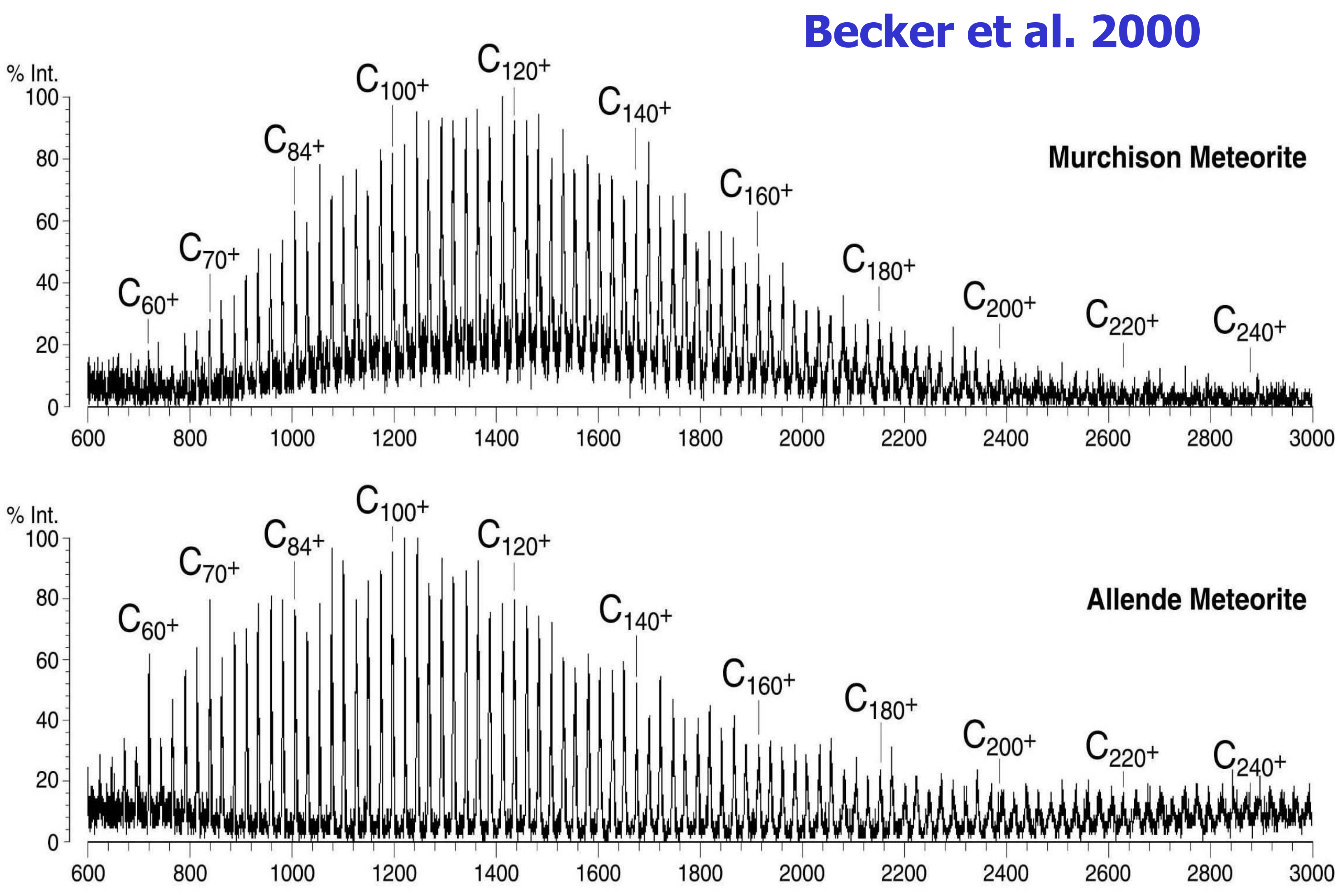


Insoluble C-fraction:

60-80 % aromatic carbon highly substituted small aromatic moieties branched by aliphatic chains



Fullerenes in Carbonaceous Chondrites



Organics Found in Meteorites

Total Carbon Content: > 3% (by weight); Soluble Fraction: < 30% of total C

COMPONENTS:

ACIDS:

Amino acids
Carboxylic acids
Hydroxycarboxylic acids
Dicarboxylic acids
Hydroxydicarboxylic acids
Sulfonic acids
Phosphonic acids

HYDROCARBONS:

non-volatile: aliphatic
aromatic (PAH)
polar
volatile

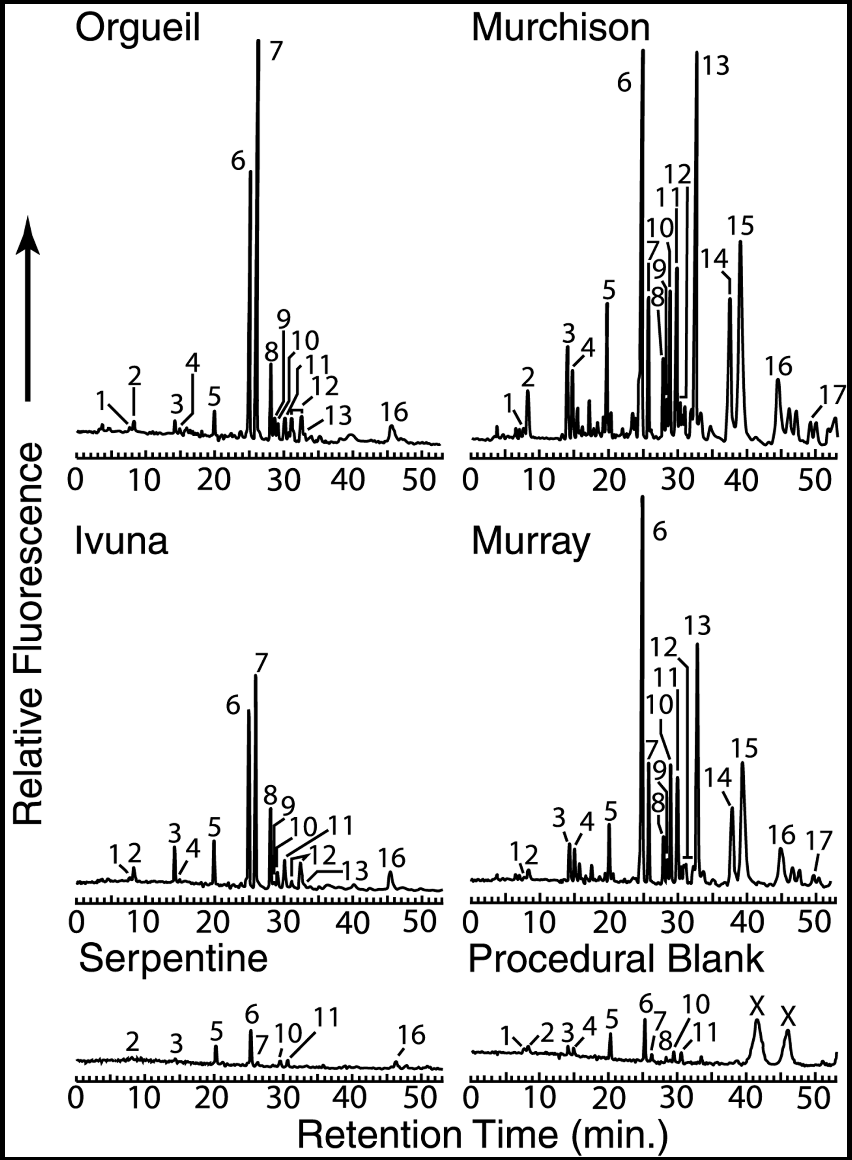
FULLERENES:

C_{60}, C_{70}
$He@C_{60}$
Higher Fullerenes

OTHERS:

N-Heterocycles
Amides
Amines
Alcohols
Carbonyl compounds

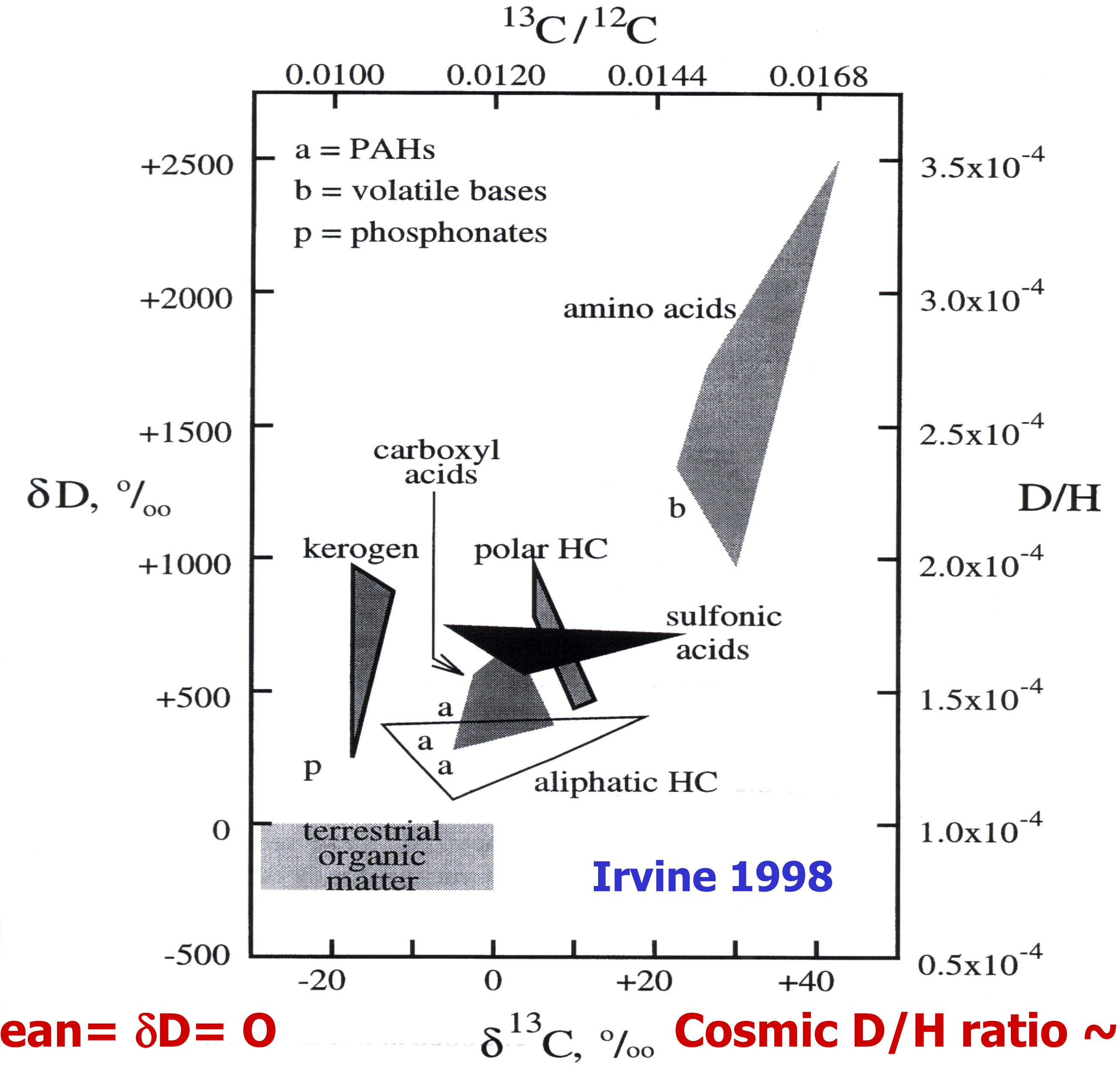
Chromatograms of Meteorite Extracts



1 D-Aspartic Acid
2 L-Aspartic Acid
3 L-Glutamic Acid
4 D-Glutamic Acid
5 D,L-Serine
6 Glycine
7 β-Alanine
8 γ-Amino-*n*-butyric Acid (g-ABA)
9 D,L-b-Aminoisobutyric Acid (b-AIB)
10 D-Alanine
11 L-Alanine
12 D,L-β-Amino-n-butyric Acid (b-ABA)
13 α-Aminoisobutyric Acid (AIB)
14 D,L-α-Amino-n-butyric Acid (a-ABA)
15 D,L-Isovaline
16 L-Valine
17 D-Valine
X: unknown

Ehrenfreund *et al.*, 2001

ISOTOPIC RATIOS FOR “C” AND “H”



Irvine 1998

Terr.ocean= δD= O

Cosmic D/H ratio ~ 0.8-2x10^{-5}

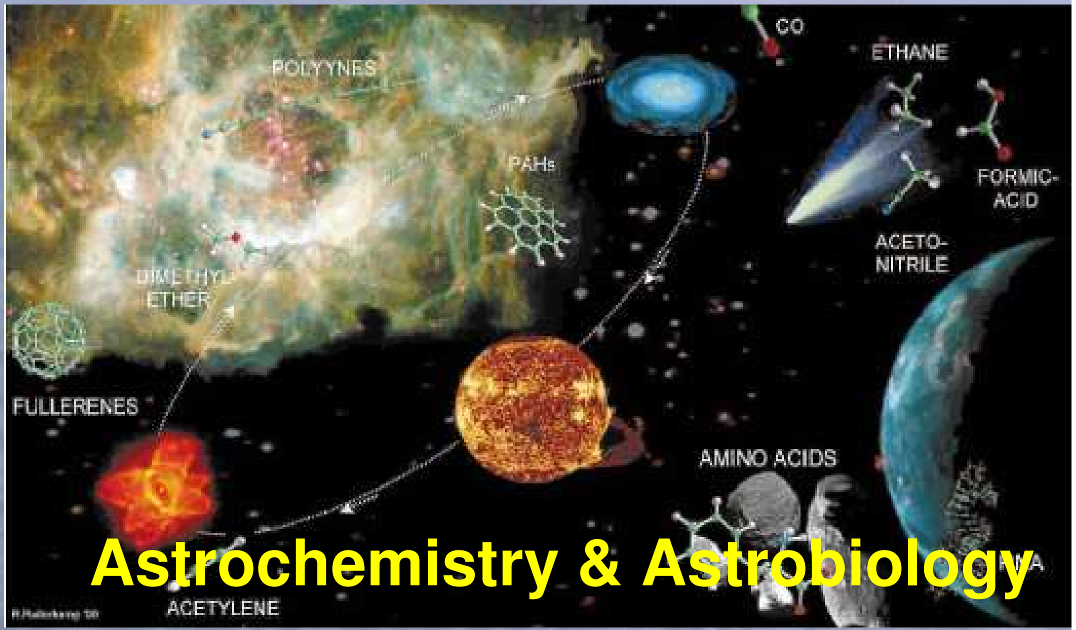
Amino Acids in Carbonaceous Chondrites

- Amino acids are readily synthesized under a variety of plausible prebiotic conditions (e.g. in the Miller-Urey Experiment).
- Amino acids are the building blocks of proteins and enzymes in life on Earth.
- Chirality (handedness) can be used to distinguish biotic vs. abiotic origins.
- Most of the amino acids found in meteorites are very rare on Earth (AIB, isovaline).

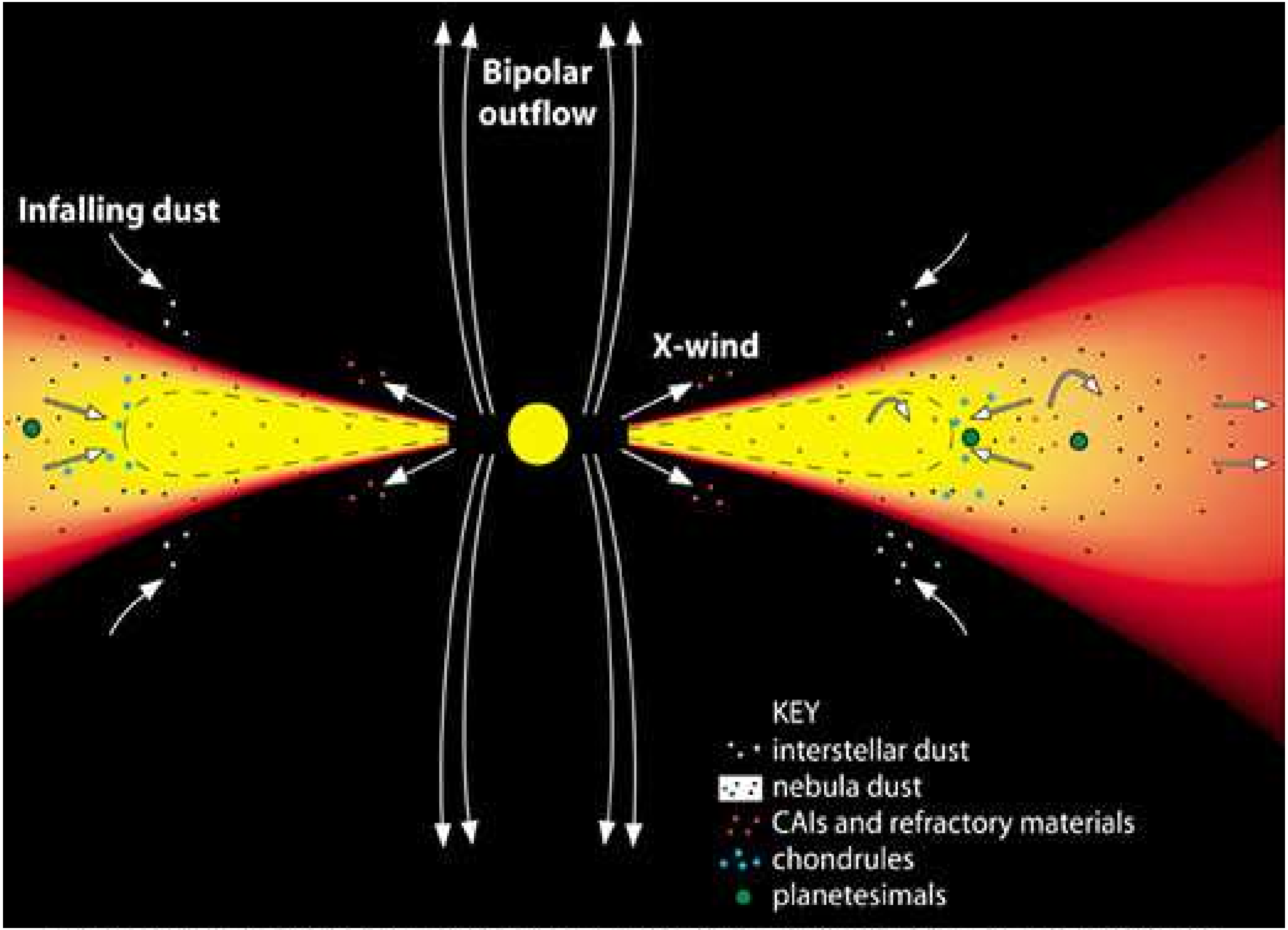
Summary

- Comets preserve record of the early Solar System
- Coma chemistry constrains nucleus composition
- Comets are a mixture of pristine ISM & nebular materials
- Meteorites are highly processed nebular material
- Meteorites are very rich in organics

Tomorrow:



Astrochemistry & Astrobiology



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

Interstellar Molecules in the Galaxy