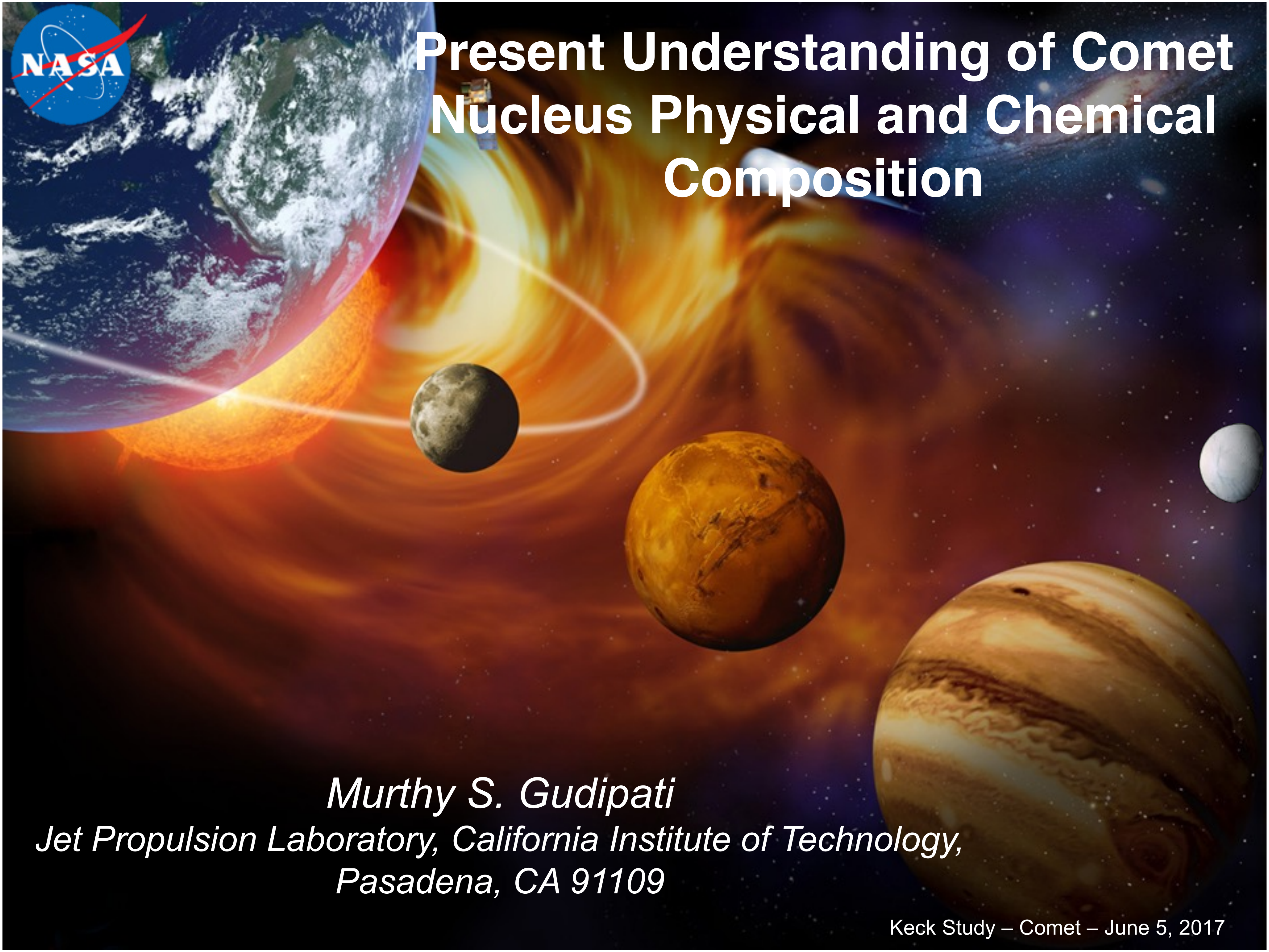
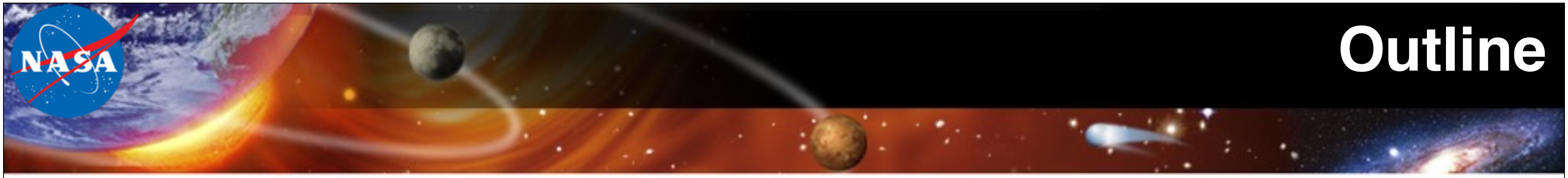


Present Understanding of Comet Nucleus Physical and Chemical Composition

Murthy S. Gudipati
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109

Keck Study – Comet – June 5, 2017



Outline

Comet – Physical Composition

Comet - Chemical Composition

Comet – History

Comet – Physical Composition

Physical Composition of Comets

Comet Physical Composition

Gas (Volatiles, now Super Volatiles)

Dust (Silicate Grains)

Water (in the form of Ice – major component)

The Elephant in the Room: How these three components are put together in a comet's nucleus?

Porosity

Science, 349, aab0639, 2015

COMETARY SCIENCE

Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar

Wlodek Kofman,[1] Alain Herique,[1] Yves Barbin,[2] Jean-Pierre Barriot,[3] Valérie Ciarletti,[4] Stephen Clifford,[5] Peter Edenhofer,[6] Charles Elachi,[7] Christelle Eyraud,[15] Jean-Pierre Goutail,[4] Essam Heggy,[7,17] Laurent Jorda,[12] Jérémie Lasue,[14] Anny-Chantal Levasseur-Regourd,[13] Erling Nielsen,[8] Pierre Pasquero,[1] Frank Preusker,[16] Pascal Puget,[1] Dirk Plettemeier,[9] Yves Rogez,[1] Holger Sierks,[8] Christoph Statz,[9] Hakan Svedhem,[10] Iwan Williams,[11] Sonia Zine,[1] Jakob Van Zyl[7]

The Philae lander provides a unique opportunity to investigate the internal structure of a comet nucleus, providing information about its formation and evolution in the early solar system. We present Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) measurements of the interior of Comet 67P/Churyumov-Gerasimenko. From the propagation time and form of the signals, the upper part of the "head" of 67P is fairly homogeneous on a spatial scale of tens of meters. CONSERT also reduced the size of the uncertainty of Philae's final landing site down to approximately 21 by 34 square meters. The average permittivity is about 1.27, suggesting that this region has a volumetric dust/ice ratio of 0.4 to 2.6 and a porosity of 75 to 85%. The dust component may be comparable to that of carbonaceous chondrites.

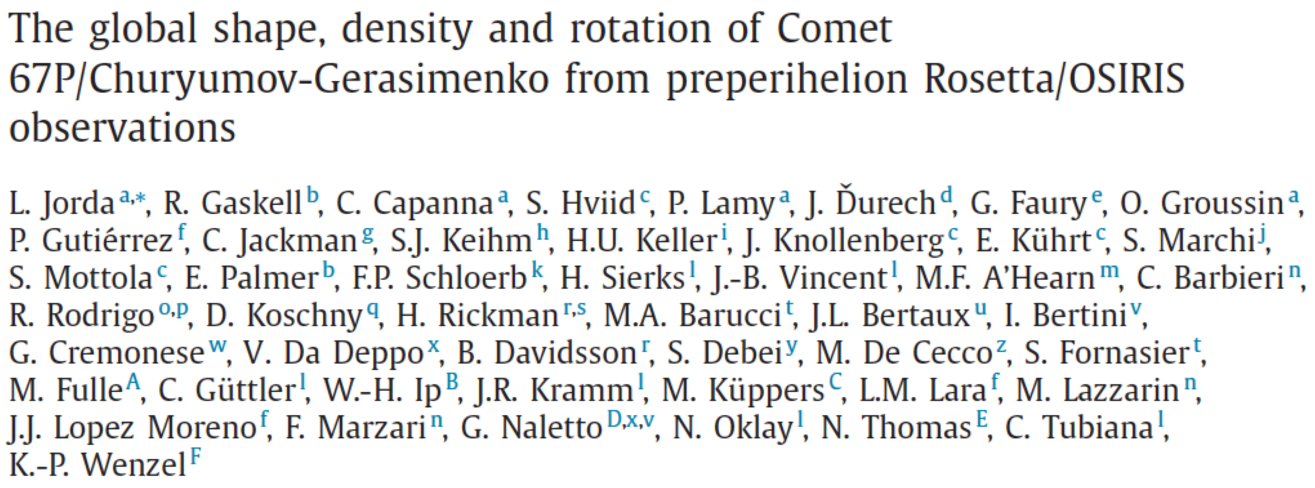
Dust/Ice = 0.4 – 2.6
Porosity = 75 -85%

Enrichment of Dust
Regions and vice versa?

Dust = Carbonaceous Chondrites
(high percentages of water & organics; silicates, oxides, sulfides, olivine, serpentine, etc.)

Density

Icarus 277 (2016) 257–278



The global shape, density and rotation of Comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations

L. Jorda[a,*], R. Gaskell[b], C. Capanna[a], S. Hviid[c], P. Lamy[a], J. Ďurech[d], G. Faury[e], O. Groussin[a], P. Gutiérrez[f], C. Jackman[g], S.J. Keihm[h], H.U. Keller[i], J. Knollenberg[c], E. Kührt[c], S. Marchi[j], S. Mottola[c], E. Palmer[b], F.P. Schloerb[k], H. Sierks[l], J.-B. Vincent[l], M.F. A'Hearn[m], C. Barbieri[n], R. Rodrigo[o,p], D. Koschny[q], H. Rickman[r,s], M.A. Barucci[t], J.L. Bertaux[u], I. Bertini[v], G. Cremonese[w], V. Da Deppo[x], B. Davidsson[r], S. Debei[y], M. De Cecco[z], S. Fornasier[t], M. Fulle[A], C. Güttler[l], W.-H. Ip[B], J.R. Kramm[l], M. Küppers[C], L.M. Lara[f], M. Lazzarin[n], J.J. Lopez Moreno[f], F. Marzari[n], G. Naletto[D,x,v], N. Oklay[l], N. Thomas[E], C. Tubiana[l], K.-P. Wenzel[F]

Density = 532 ± 7 kg m^{-3}

Crystalline water-ice = 920 kg m^{-3}
Amorphous water-ice = ~500 - 800 kg m^{-3}
Carbonaceous chondrites = ~3 to 3.7 kg m^{-3}

Thermal Inertia

Science, 349, aab0464, 2015

COMETARY SCIENCE

Thermal and mechanical properties of the near-surface layers of comet 67P/Churyumov-Gerasimenko

T. Spohn,[1*] J. Knollenberg,[1] A. J. Ball,[2] M. Banaszkiewicz,[3] J. Benkhoff,[2] M. Grott,[1] J. Grygorczuk,[3] C. Hüttig,[1] A. Hagermann,[4] G. Kargl,[5] E. Kaufmann,[4] N. Kömle,[5] E. Kührt,[1] K. J. Kossacki,[6] W. Marczewski,[3] I. Pelivan,[1] R. Schrödter,[1] K. Seiferlin[7]

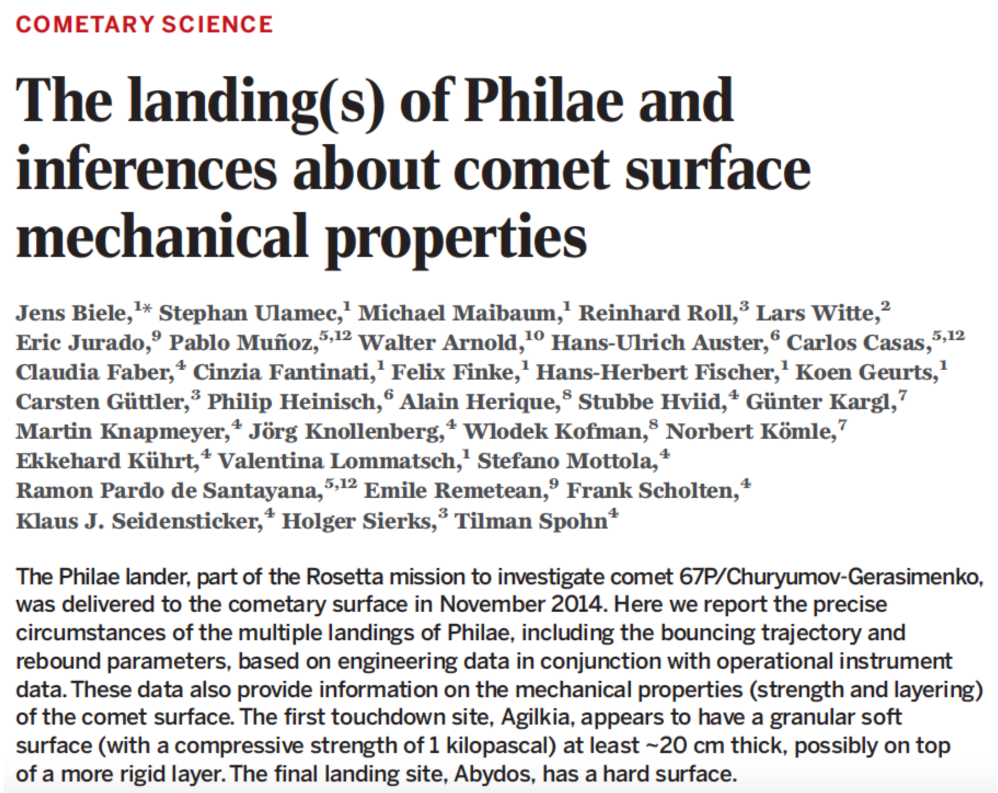
Thermal and mechanical material properties determine comet evolution and even solar system formation because comets are considered remnant volatile-rich planetesimals. Using data from the Multipurpose Sensors for Surface and Sub-Surface Science (MUPUS) instrument package gathered at the Philae landing site Abydos on comet 67P/Churyumov-Gerasimenko, we found the diurnal temperature to vary between 90 and 130 K. The surface emissivity was 0.97, and the local thermal inertia was 85 ± 35 J m^{-2} $K^{-1}$$s^{-1/2}$. The MUPUS thermal probe did not fully penetrate the near-surface layers, suggesting a local resistance of the ground to penetration of >4 megapascals, equivalent to >2 megapascal uniaxial compressive strength. A sintered near-surface microporous dust-ice layer with a porosity of 30 to 65% is consistent with the data.

Thermal Inertia:85±35 J $m^{-2}K^{-1}s^{-1/2}$

Thermal gradient?
How Deep to reach <30 K?

Surface

Science, 349, aaa9816, 2015

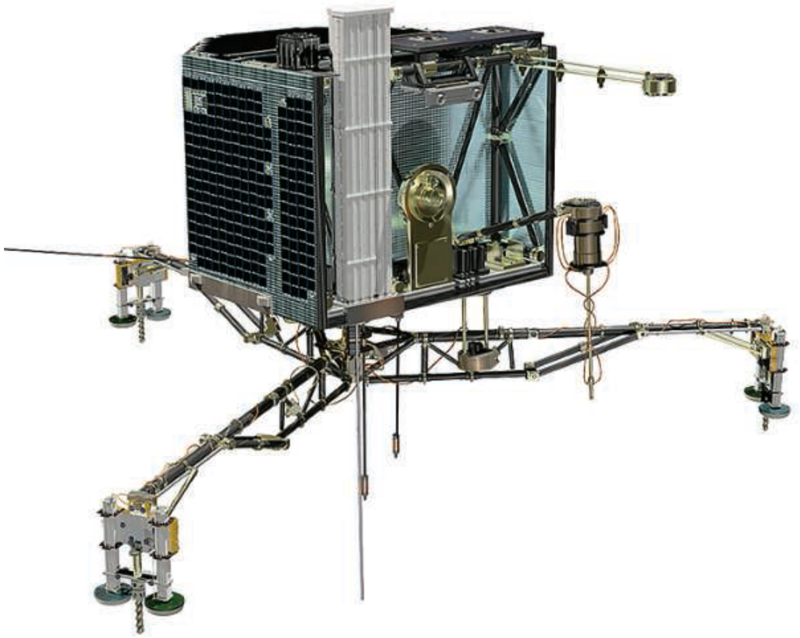


COMETARY SCIENCE

The landing(s) of Philae and inferences about comet surface mechanical properties

Jens Biele,[1*] Stephan Ulamec,[1] Michael Maibaum,[1] Reinhard Roll,[3] Lars Witte,[2] Eric Jurado,[9] Pablo Muñoz,[5,12] Walter Arnold,[10] Hans-Ulrich Auster,[6] Carlos Casas,[5,12] Claudia Faber,[4] Cinzia Fantinati,[1] Felix Finke,[1] Hans-Herbert Fischer,[1] Koen Geurts,[1] Carsten Güttler,[3] Philip Heinisch,[6] Alain Herique,[8] Stubbe Hviid,[4] Günter Kargl,[7] Martin Knapmeyer,[4] Jörg Knollenberg,[4] Wlodek Kofman,[8] Norbert Kömle,[7] Ekkehard Kührt,[4] Valentina Lommatsch,[1] Stefano Mottola,[4] Ramon Pardo de Santayana,[5,12] Emile Remetean,[9] Frank Scholten,[4] Klaus J. Seidensticker,[4] Holger Sierks,[3] Tilman Spohn[4]

The Philae lander, part of the Rosetta mission to investigate comet 67P/Churyumov-Gerasimenko, was delivered to the cometary surface in November 2014. Here we report the precise circumstances of the multiple landings of Philae, including the bouncing trajectory and rebound parameters, based on engineering data in conjunction with operational instrument data. These data also provide information on the mechanical properties (strength and layering) of the comet surface. The first touchdown site, Agilkia, appears to have a granular soft surface (with a compressive strength of 1 kilopascal) at least ~20 cm thick, possibly on top of a more rigid layer. The final landing site, Abydos, has a hard surface.

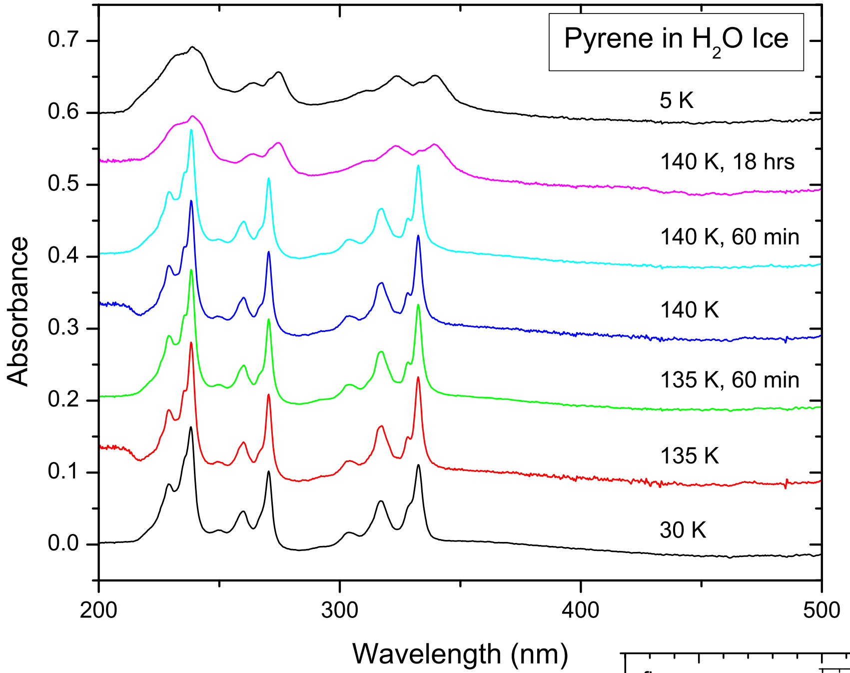


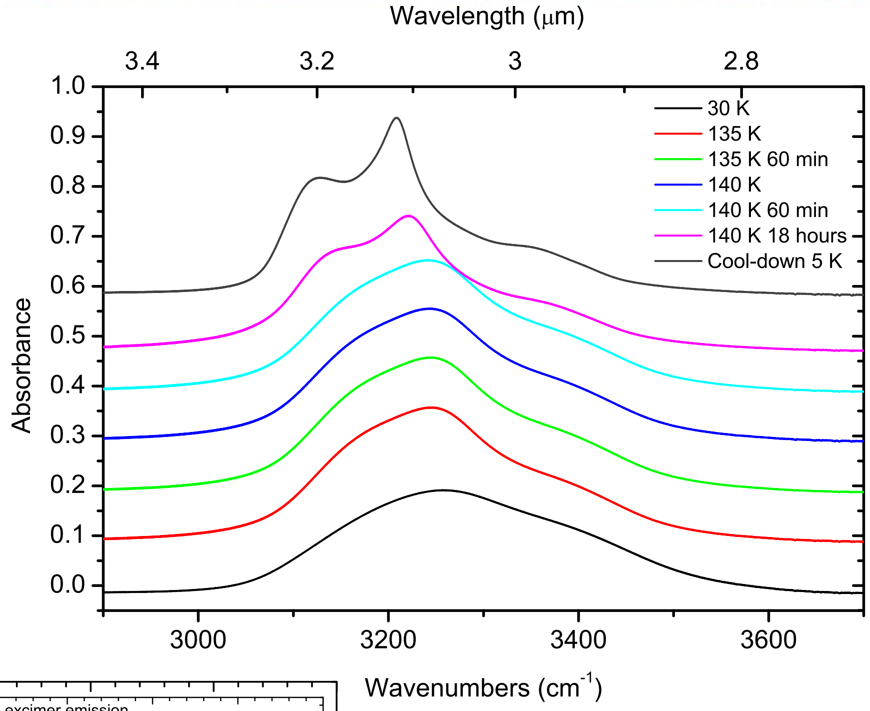
~20 cm granular (soft)
Below hard crust

How thick is the crust – cm range or m range?

Simultaneous UV & IR Absorption + Fluorescence

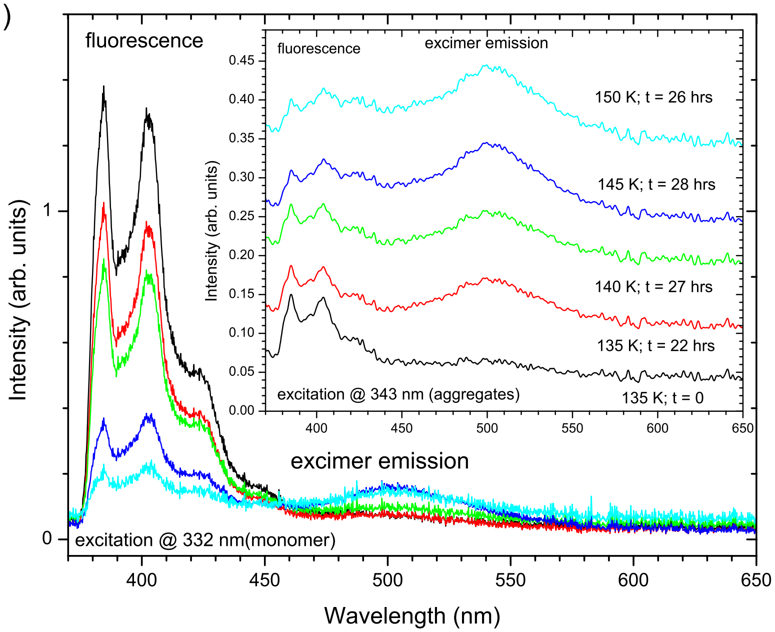
Pyrene in H2O Ice





UV - PAH

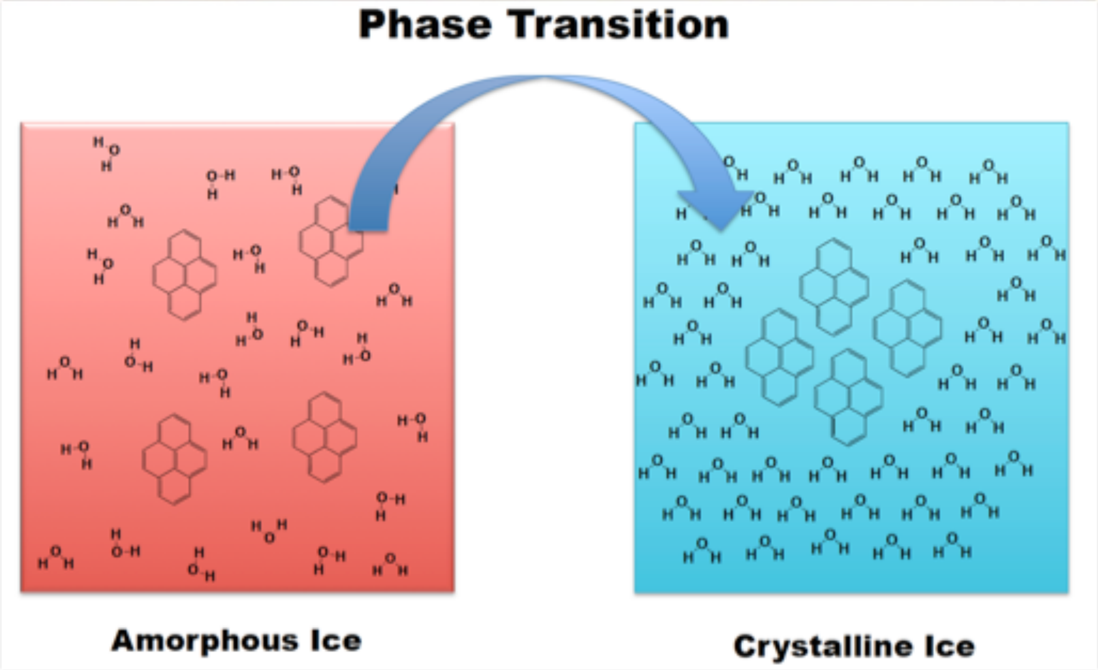
Flu - PAH



IR - Ice

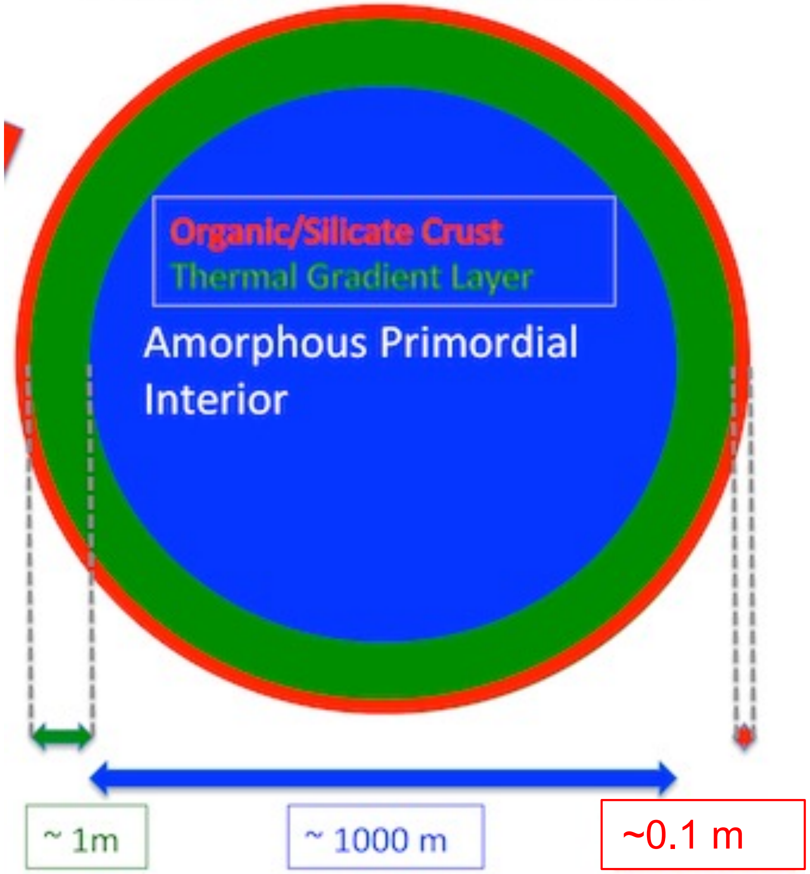
Lignell & Gudipati
J. Phys. Chem A.
119 (2015) 2607

Are Comets Like Deep Fried Ice Cream?



Comet CG/67P

Processed ice ~ 1m
Unprocessed primordial ice >1m



Lignell & Gudipati J. Phys. Chem A. 119 (2015) 2607

Comet – Chemical Composition

Chemical Composition of Comets

Composition of Interstellar Medium

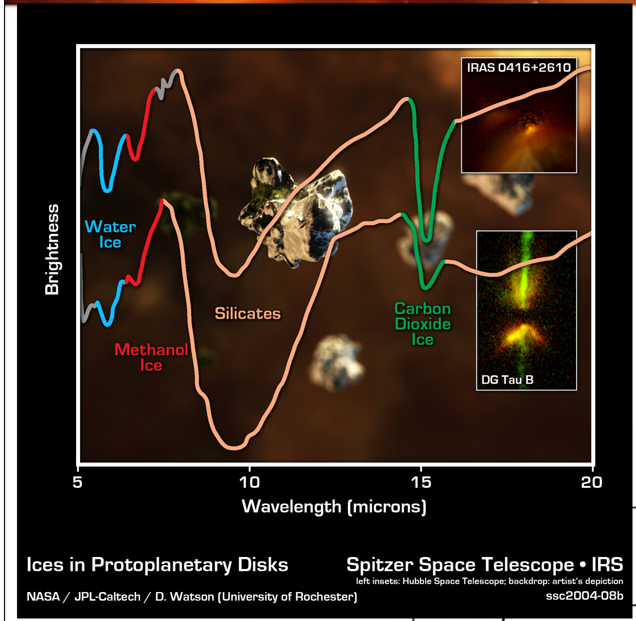
Characteristics of interstellar regions

Region	State of Hydrogen	Other Notable Constituents	Temperature T (K)	Density n (cm^{-3})
Coronal gas $\approx$ 50% of ISM by volume	H^+	O^{5+}	$10^5 - 10^6$	~ 0.01
Diffuse nebulae (H II regions)	H^+	other ions	$\sim 10^4$	$10^2 - 10^3$
Intercloud medium $\approx$ 40% of ISM by volume	H	C^+	$\sim 10^4$	~ 0.1
Diffuse clouds	H, H_2	C^+, CO	$50 - 100$	$10 - 10^2$
Dark clouds (molecular clouds)	H_2	many molecules	$10 - 50$	$10^3 - 10^7$
Giant molecular clouds $\sim 10^5$ solar masses	H_2	CO	~ 10	~ 600

At 1 atm. ~3 x 10^{19} molecules / cm^3

Interstellar Ice Grains: Loaded with Organics

Amorphous Interstellar Ices



Ices in Protoplanetary Disks

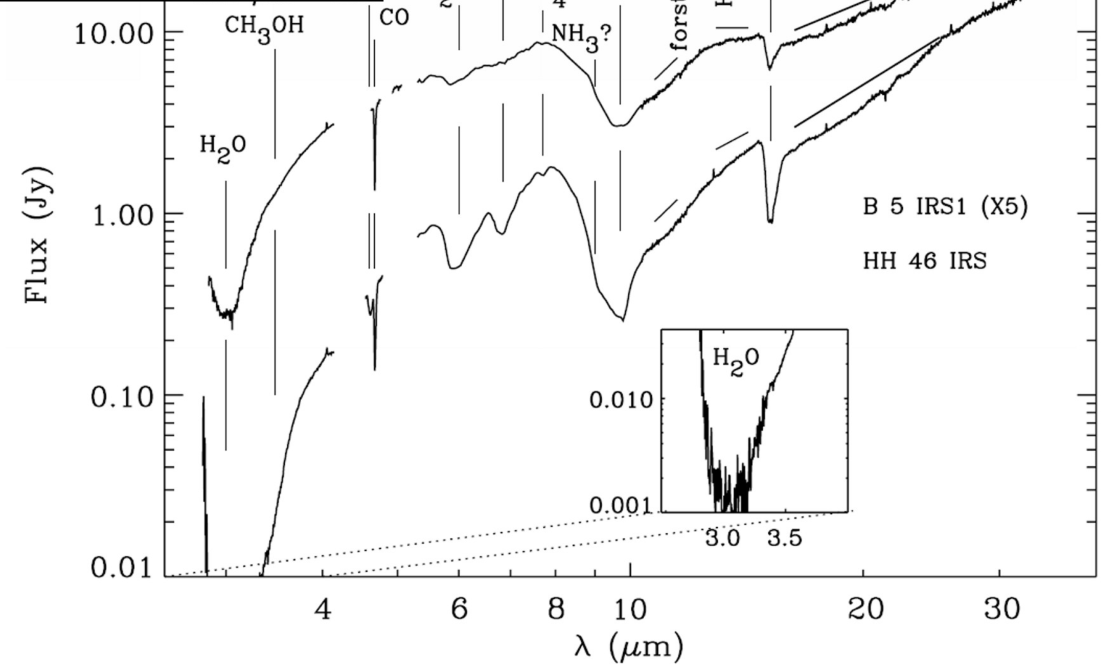
Spitzer Space Telescope • IRS

left insets: Hubble Space Telescope; backdrop: artist's depiction

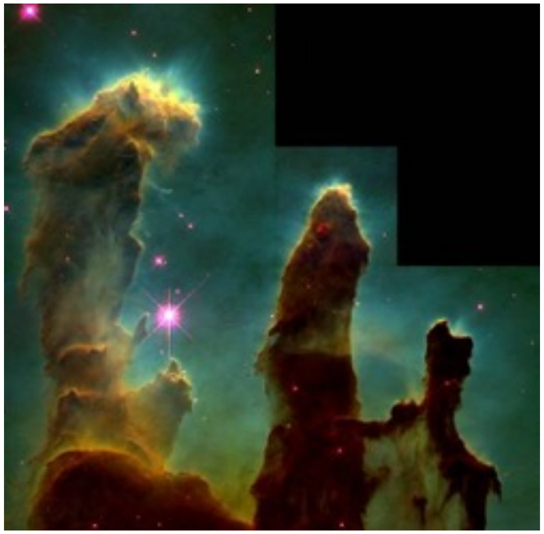
NASA / JPL-Caltech / D. Watson (University of Rochester)

ssc2004-08b

BOOGERT ET AL.

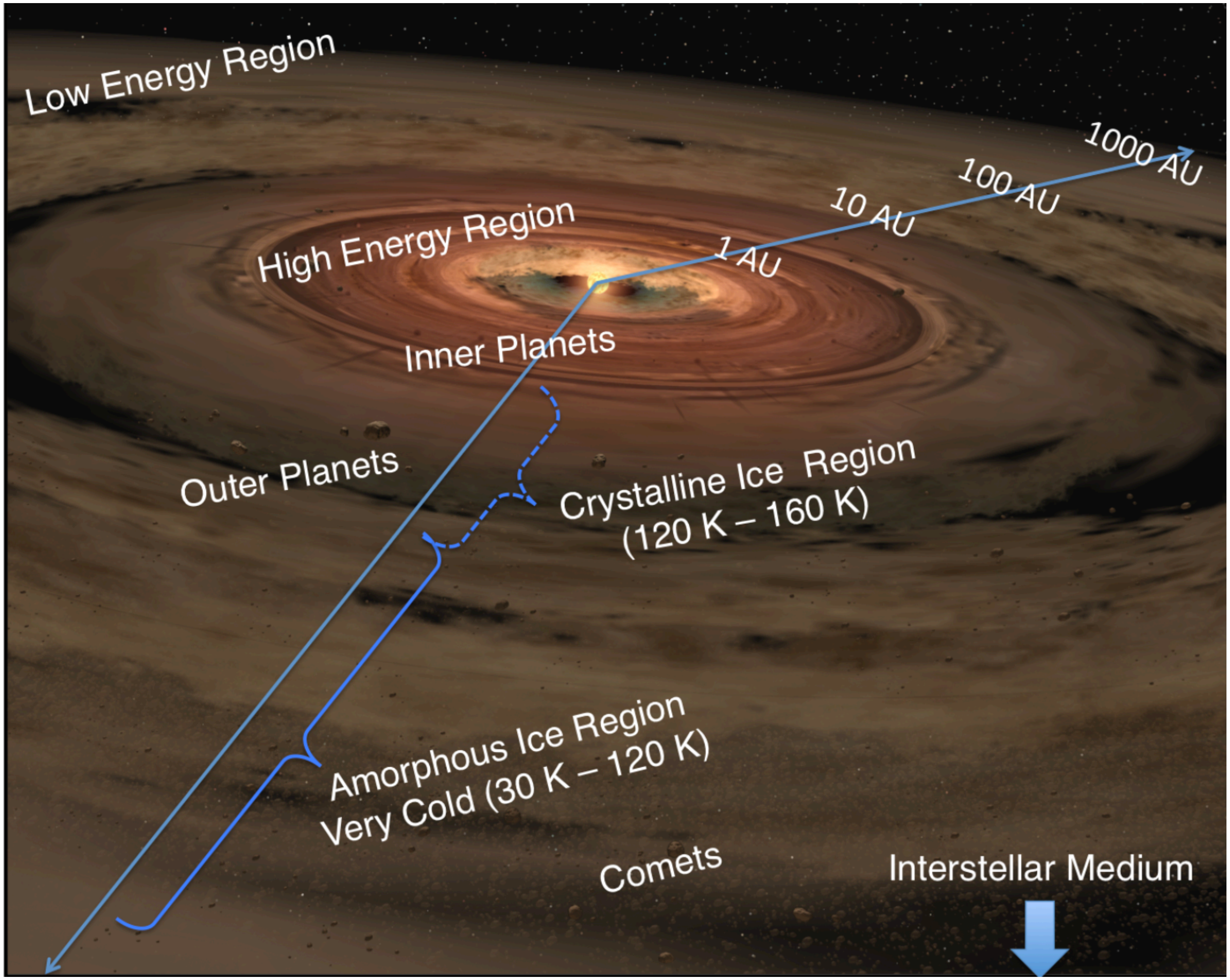


Star-forming Regions / Protostars



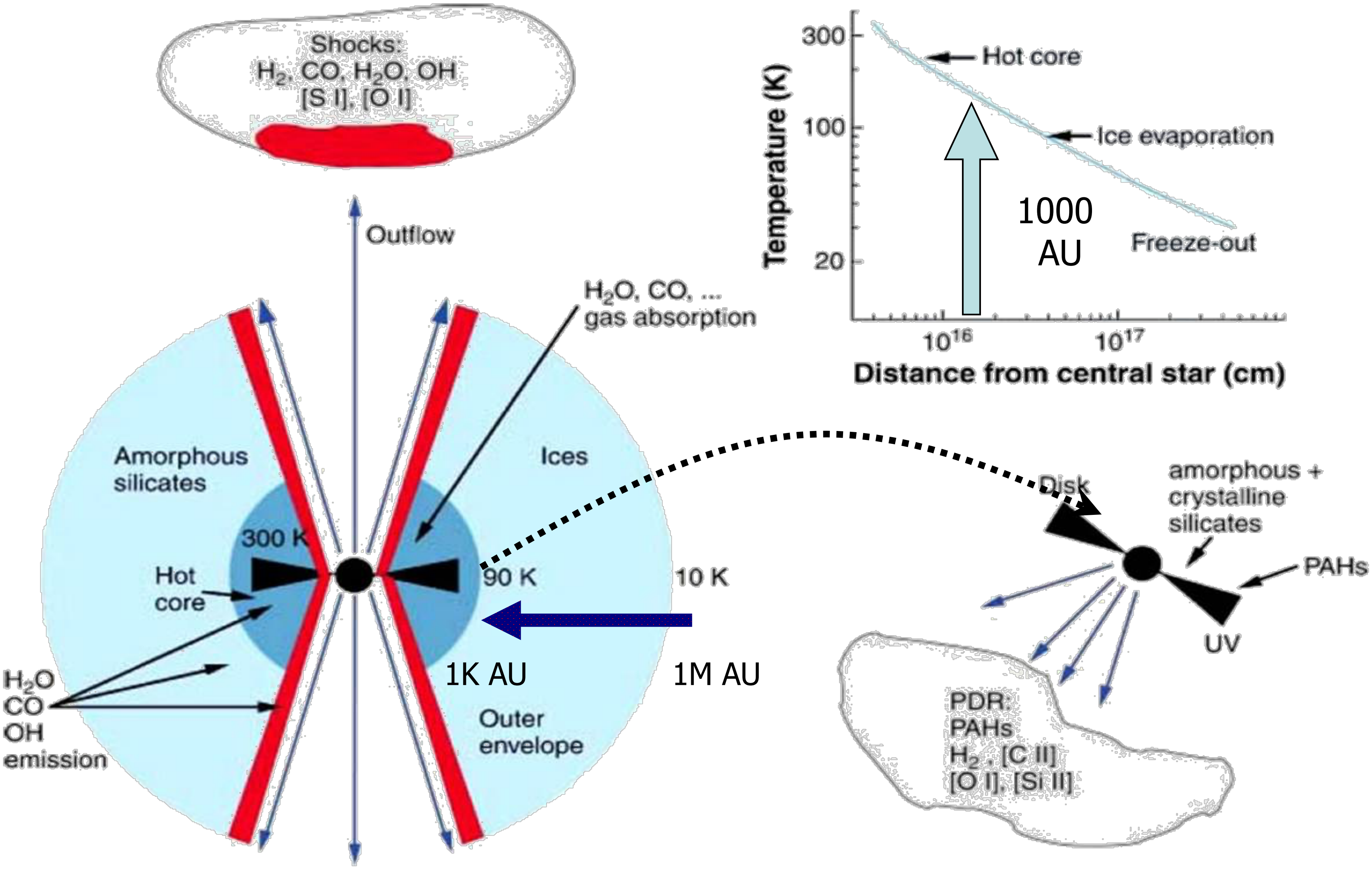
Dense Molecular Clouds (The Eagle Nebulae)

Connecting Solar System to Interstellar Matter



Interstellar Ices
are
Amorphous

Ices in the Star-forming Regions



Ewine van Dishoeck, Annu. Rev. Astron. Astrophys. 42, 119-167, 2004

How did our solar system come to be?

National Aeronautics and Space Administration

4.6 Billion Years Ago

It all began about 4.6 billion years ago in a wispy cloud of gas and dust.

This cloud was a small part of a much bigger cloud.

At some point, part of the cloud collapsed in on itself—possibly because the shockwave of a nearby supernova explosion caused it to compress.

The result: a flat spinning disk of dust and gas.

Nuclear fusion occurs when hydrogen atoms fuse into helium.

When enough material collected at this disk's center, nuclear fusion began. Our sun was born. It gobbled up 99.8% of all the material.

The material left behind by the sun clumped together into bigger and bigger pieces.

These clumps became planets, dwarf planets, asteroids, comets, and moons.

Late Heavy Bombardment (LHB)

Present

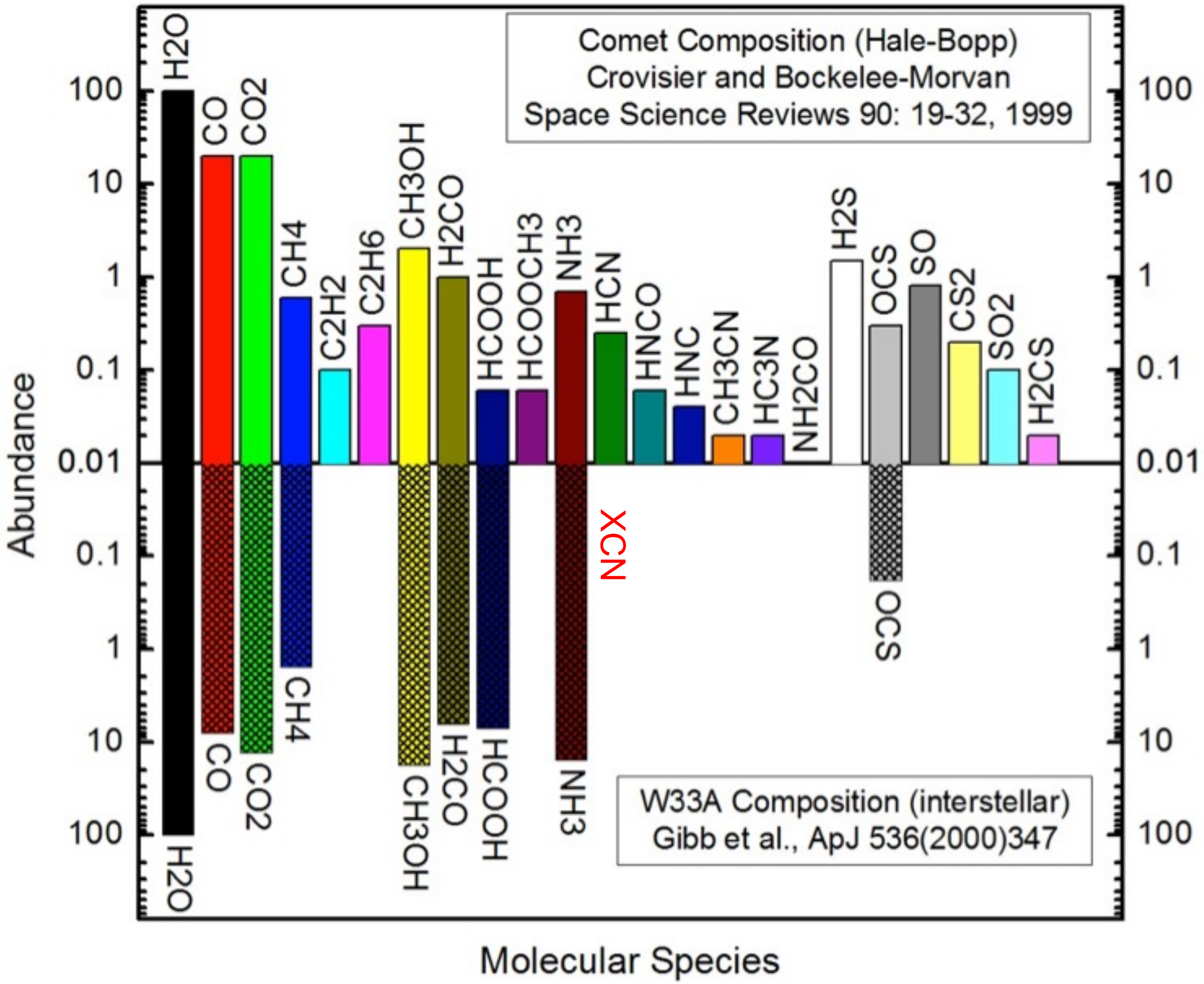
0.5 – 1 BY

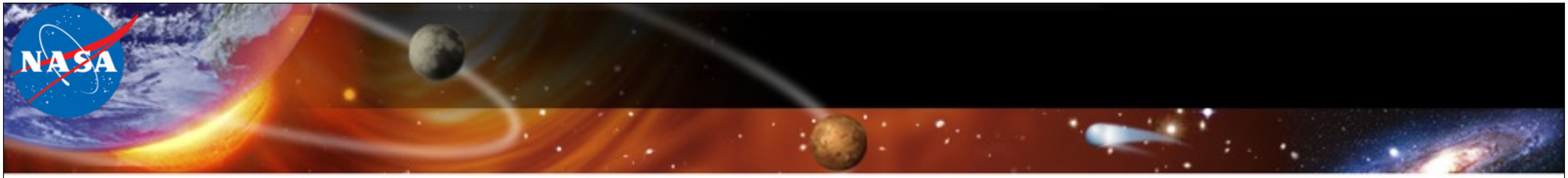
Only rocky things could survive close to the sun, so gaseous and icy material collected further away. That's how our solar system came to be the place it is today!

Comets and asteroids are the left over remains of the solar system's formation.

Space Place in a Snap!

Similar Composition: Comets and Interstellar Ice Grains



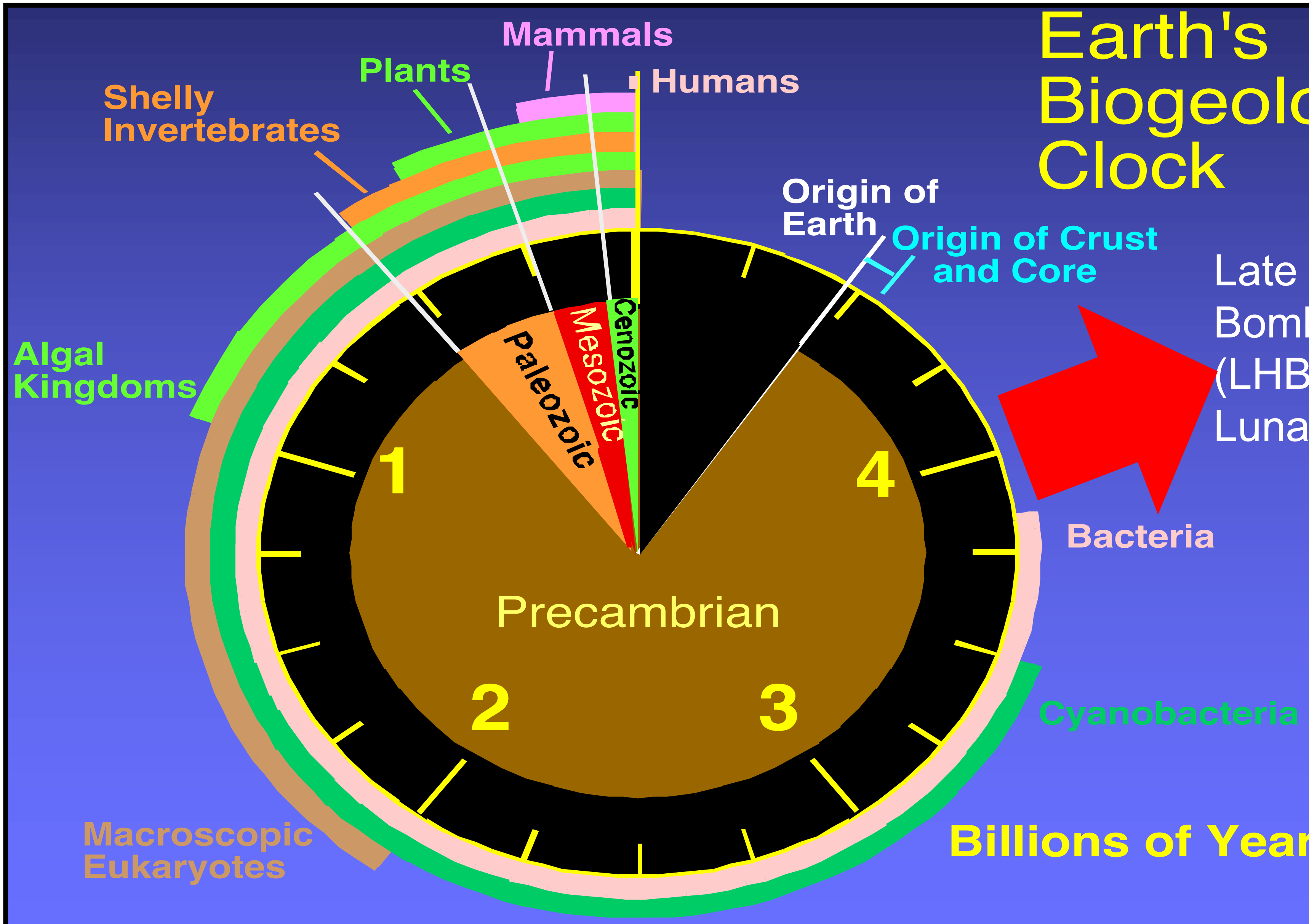


Comets and Origin of Life

Earth, Comets & Asteroids, and Life

Water & Organic Matter delivered to Earth by Comets/Asteroids ~4 Billion Years Ago

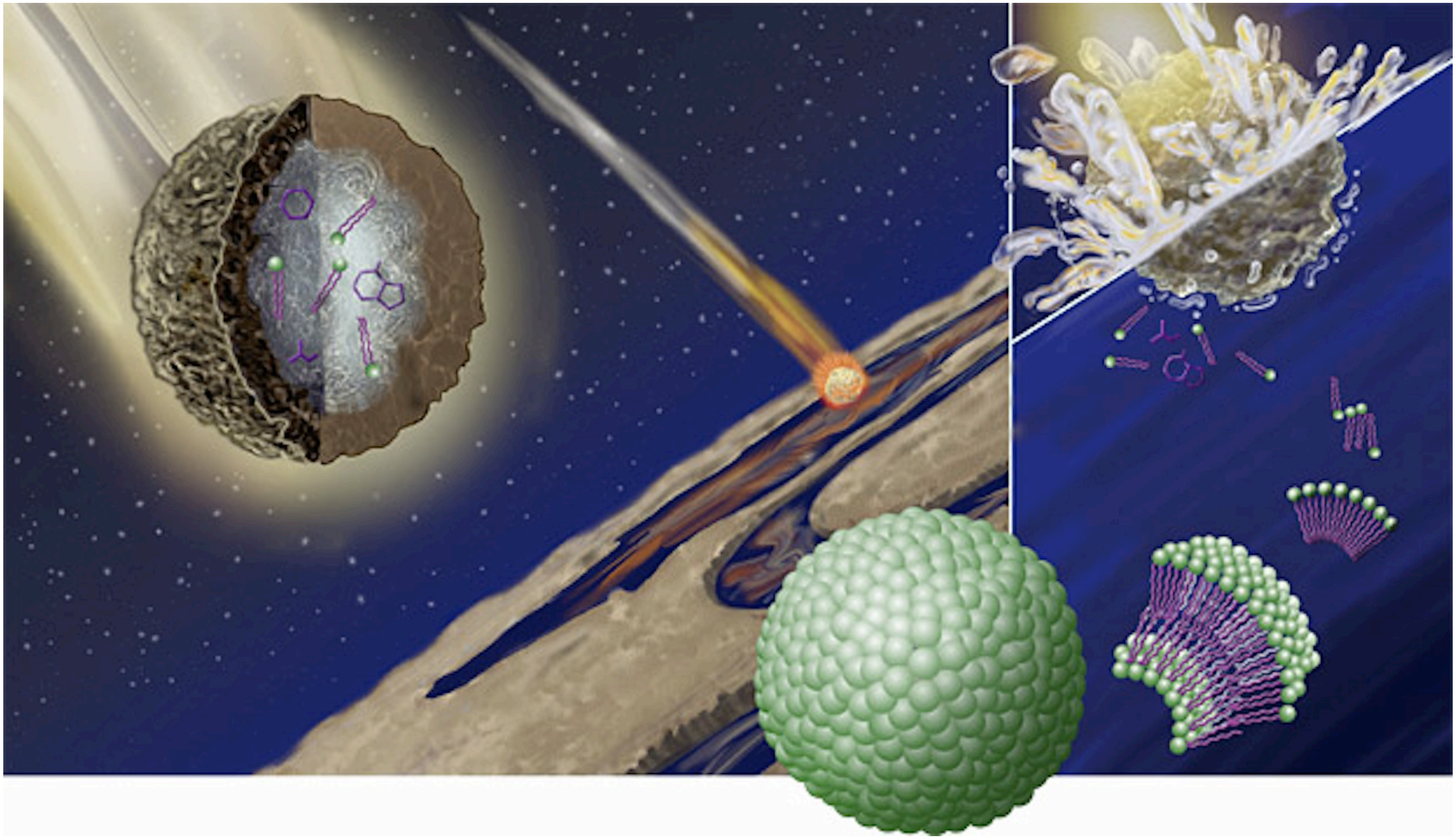
Earth's Biogeologic Clock



Late Heavy Bombardment (LHB) Lunar Cataclysm

D. Des Marais
NASA, Ames Research Ctr.

The Origin(s) of Life – Role of Comets



Did Organics Survive Comet Entry and Impacts on Earth?
Do we fully understand Comets? (Deep Impact, Epoxi, Rosetta)

Laboratory Simulations

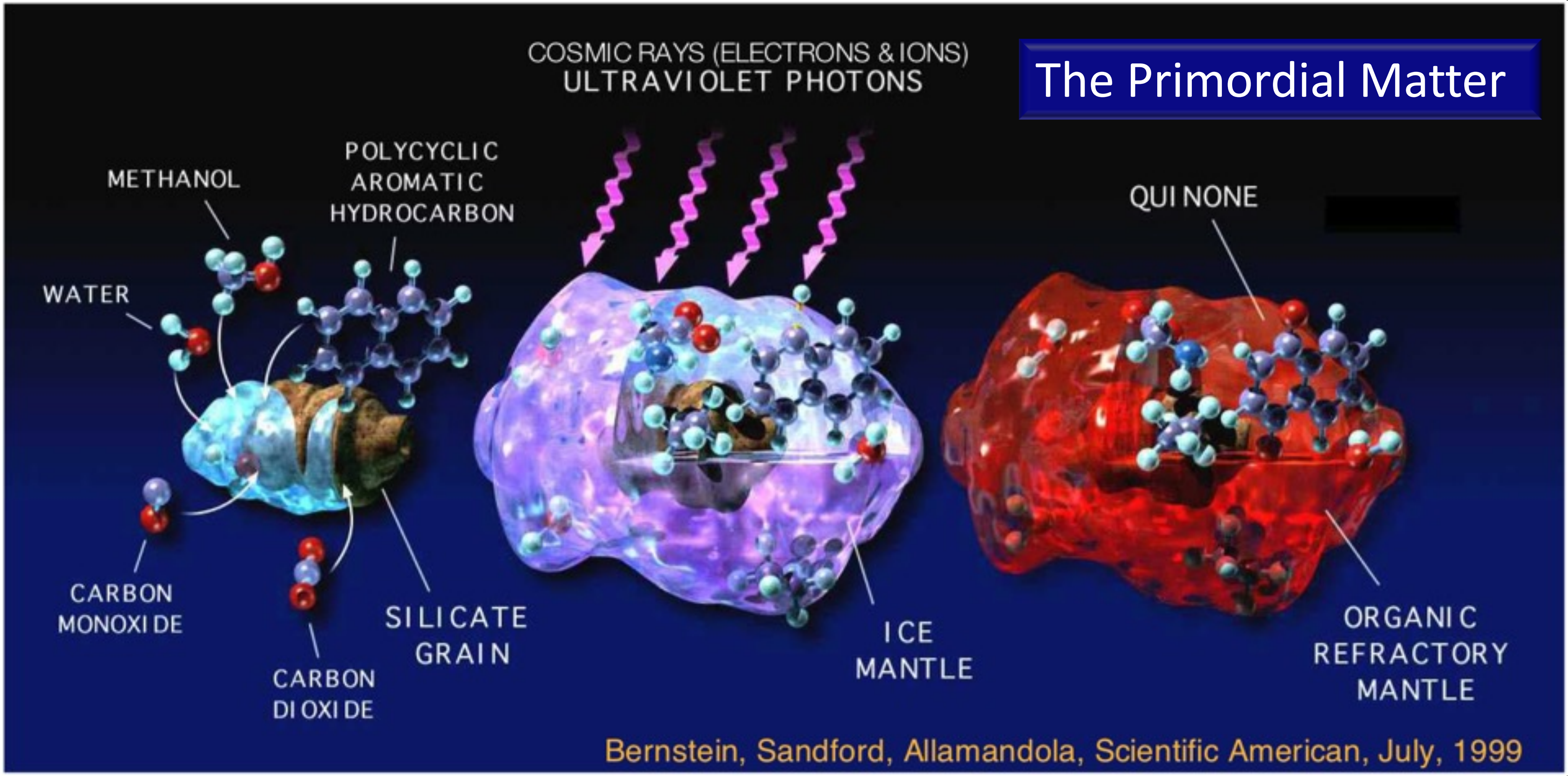
Complex Organic Molecules are made in very cold Interstellar Ices.

The Interstellar Ices evolve into large icy chunks in the Kuiper Belt and Oort Cloud – The Birthplaces of Comets.

Thanks to Laboratory Experimental Research

Interstellar Ice Grains:

Interstellar ice grains (a few microns size) are made of sand coated with ice containing organic matter. The building blocks of life such as amino aids and quinones are made and stored in these grains that later form comets.

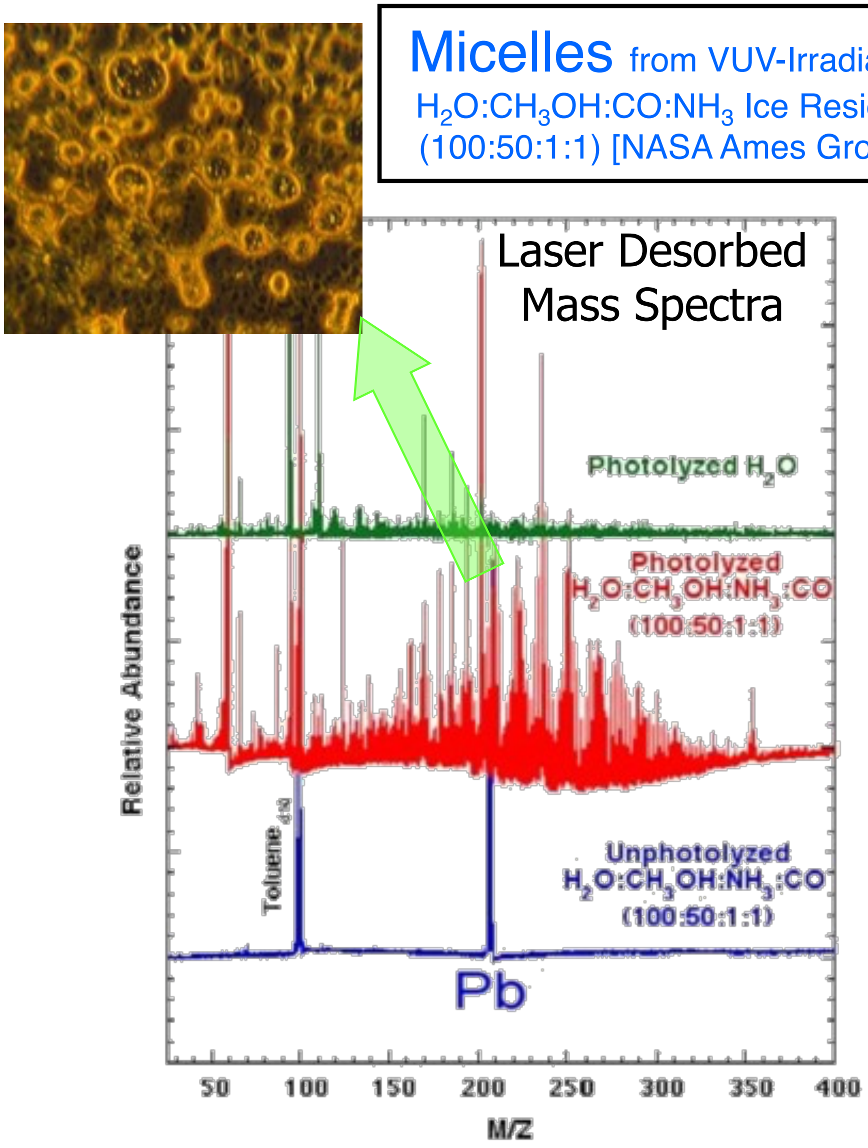


The Primordial Matter

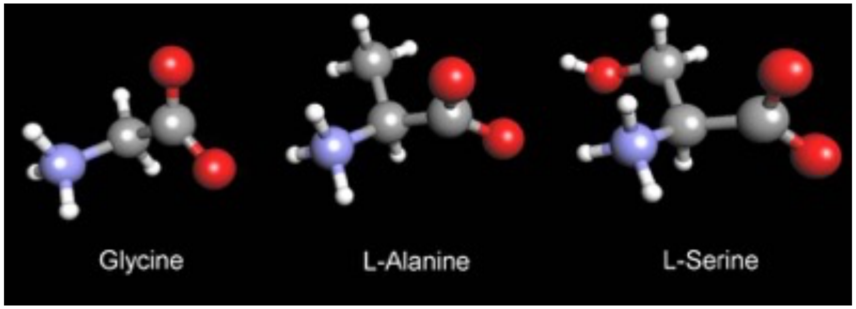
Bernstein, Sandford, Allamandola, Scientific American, July, 1999

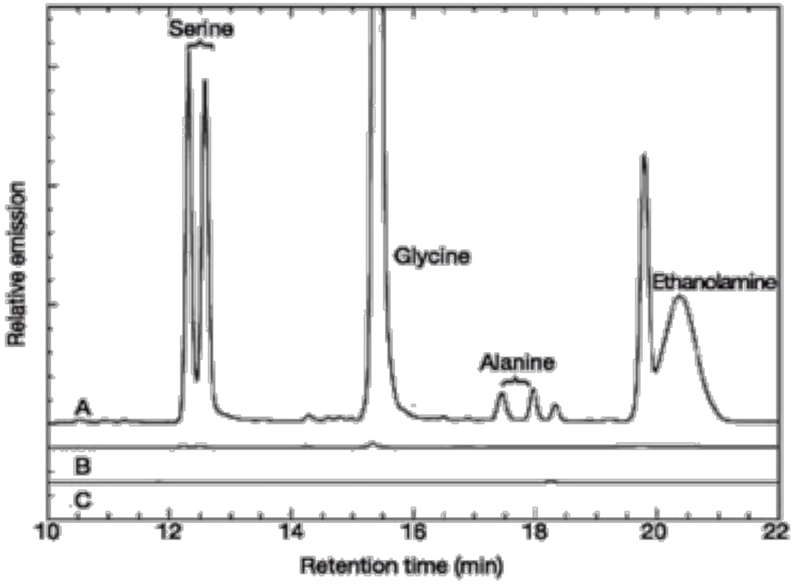
Prebiotic Chemistry in Interstellar Ice Analogs

Micelles from VUV-Irradiated
$H_2O:CH_3OH:CO:NH_3$ Ice Residue
(100:50:1:1) [NASA Ames Group]


Laser Desorbed
Mass Spectra

Amino Acids from VUV-Irradiated
NASA Ames Group ($H_2O:CH_3OH:NH_3:HCN$ = 20:2:1:1)
Leiden Group ($H_2O:CH_3OH:NH_3:CO:CO_2$ = 2:1:1:1:1)

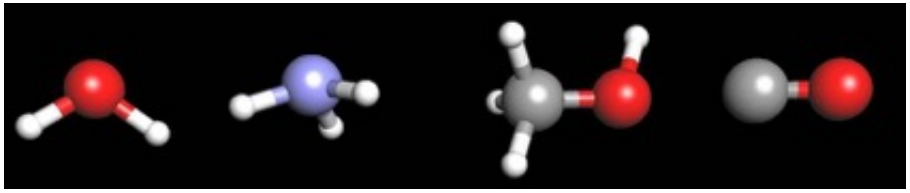




Dworkin et al. *Proc. Nat. Acad. Sci.* **98**, 815 (2001); Bernstein et al. *Nature* **416,** 401 (2002); Muñoz-Caro et al. *Nature* **416**, 403 (2002)

The Missing Link

Cryogenic
Cosmic Ices

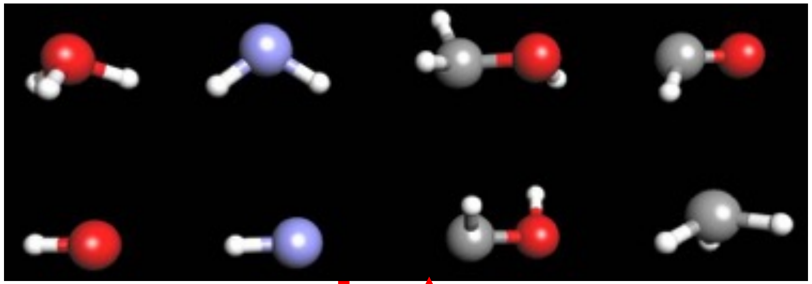


Raw Material
H_2O, NH_3, CH_3OH, CO

Photons/Electrons
Cosmic Rays
Debris/Collisions

Temperature

Radicals,
Ions,
Electrons, &
Molecules

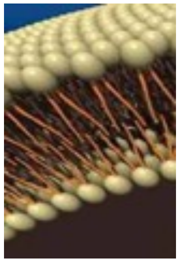


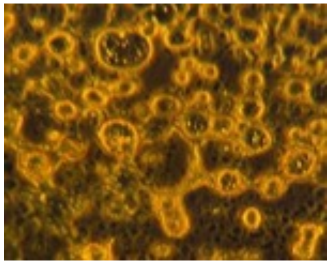
Building Blocks
Atoms, Radicals & Ions

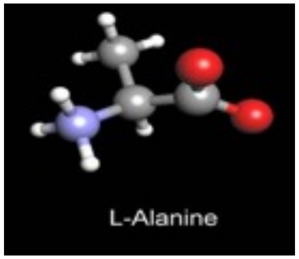
Temperature

Photons/Electrons
Cosmic Rays
Debris/Collisions

Amino Acids,
Micelles, etc.



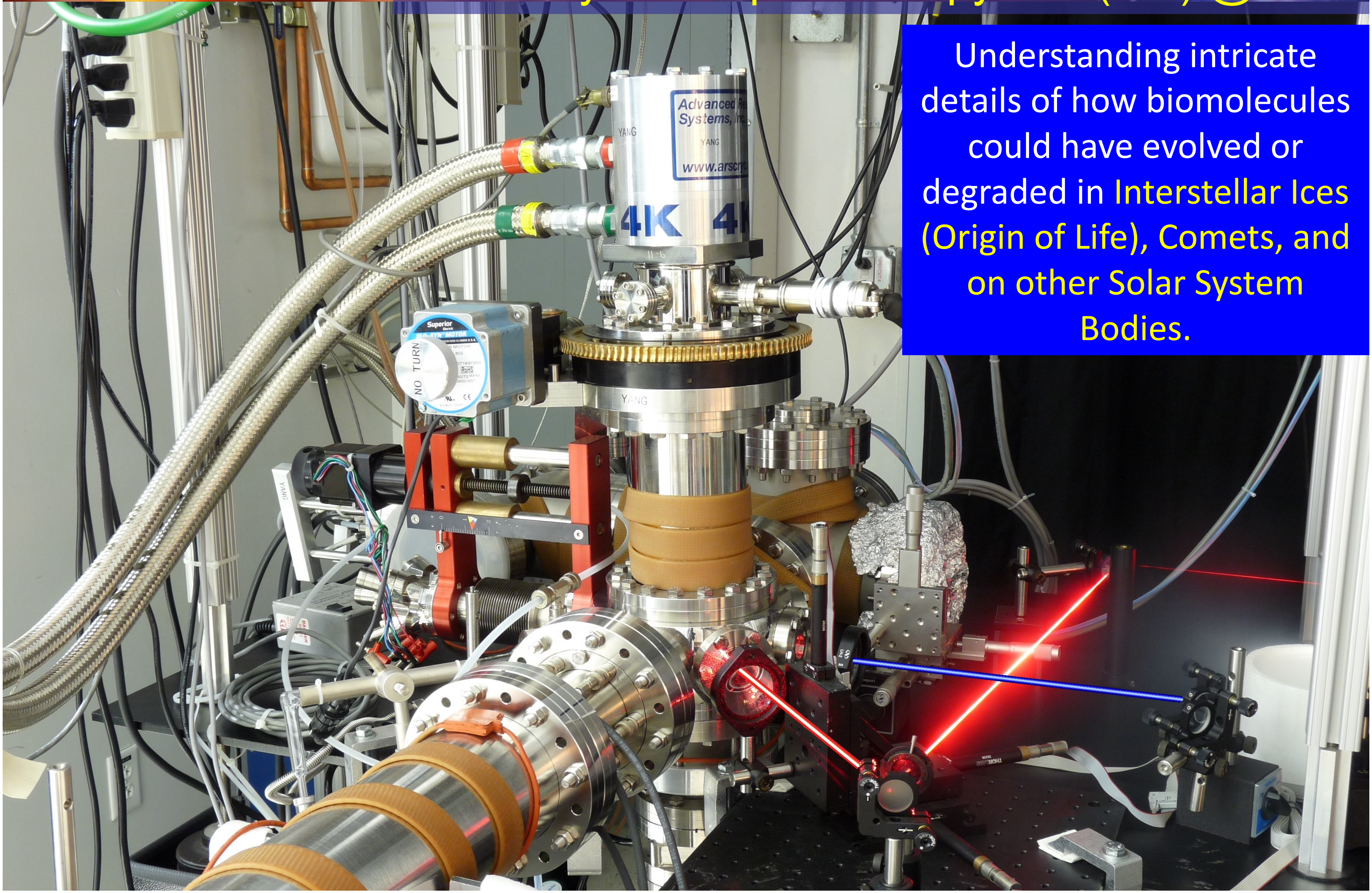




Biomolecules
Amino Acids etc.

Understanding Prebiotic Chemistry in Comets

At Murthy's Ice Spectroscopy Lab (ISL) @ JPL



Understanding intricate details of how biomolecules could have evolved or degraded in Interstellar Ices (Origin of Life), Comets, and on other Solar System Bodies.

Snapshots of Prebiotic Chemistry in Comets

Identification of atoms and molecules produced at various ice temperatures and radiation does

Interstellar & cometary ice chemistry

Evolution of prebiotic molecules

TOF-MS

3856 M+

Mass Selection

QMS

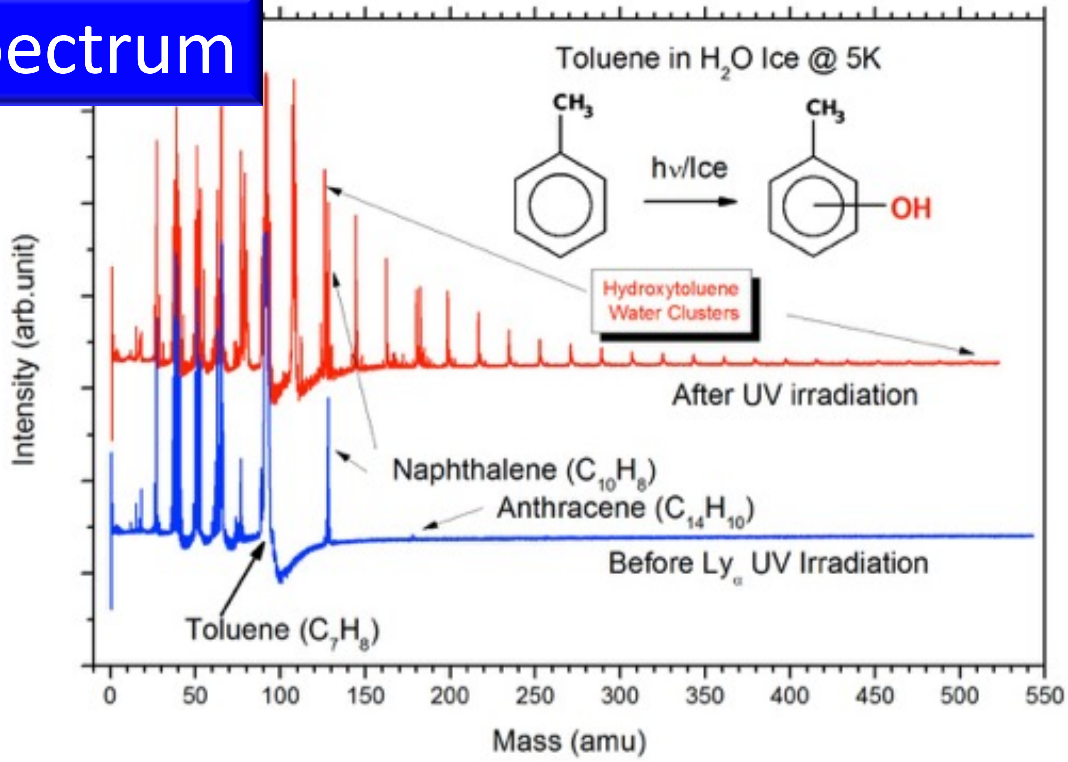
Snapshot

Isolation
&
Analysis

Controlled Temperature 5 K – 200 K (relevant for various Solar System Ices)

Oxygenation of Organics in Ices under Radiation

2S-LAIMS Spectrum



Even under coldest interstellar conditions

Gudipati & Yang ApJL 756, L24, 2012

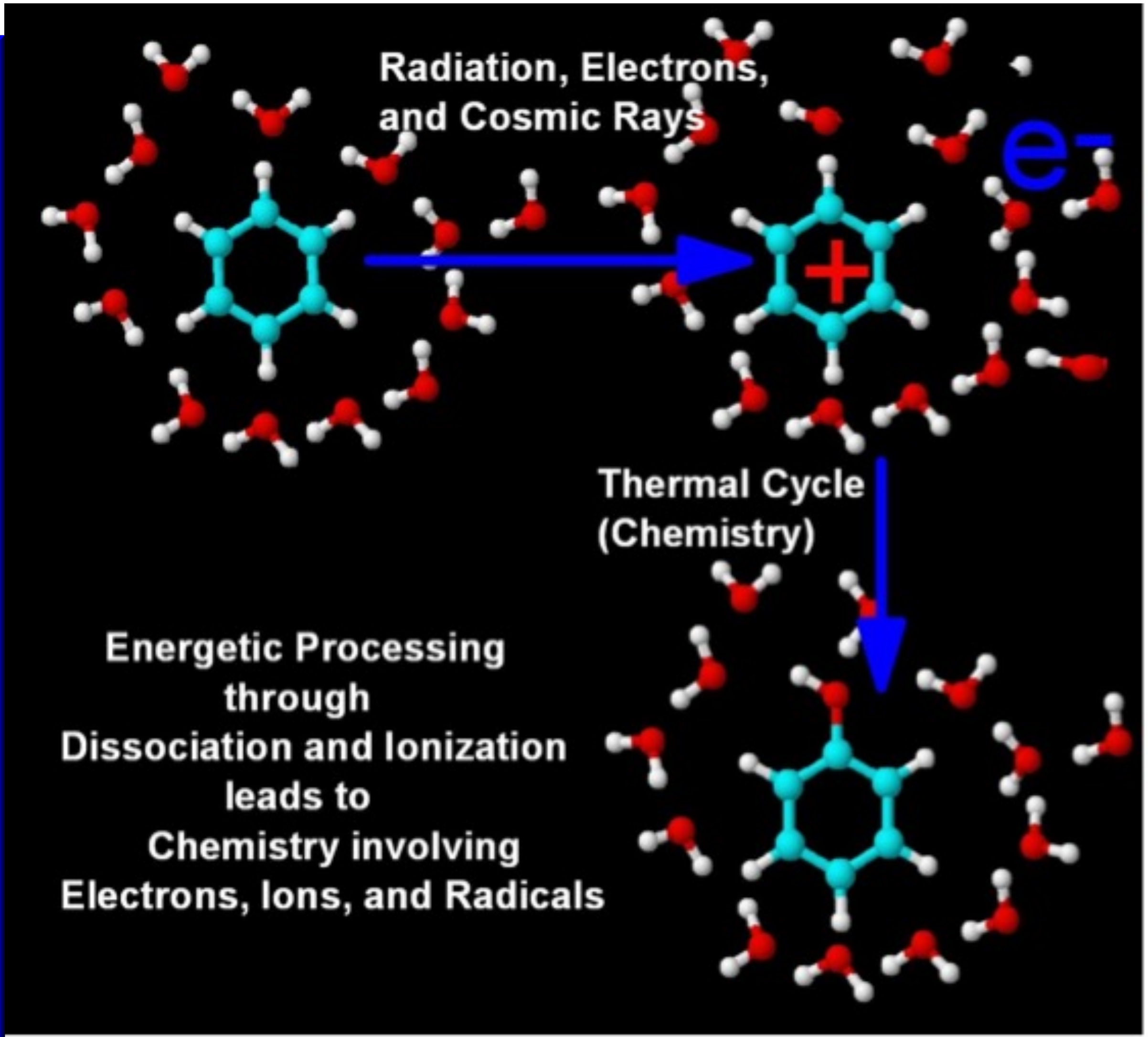
New Chemical Pathways (Brewing) in Ice

Solar Radiation (Light, electrons, and ions) and Galactic Cosmic Rays (electrons and ions) carry sufficient energy to cause physical and chemical changes

in ices even at

10 K.

Individual particle (photon) energy and the flux determine the equilibrium state of these ices.



Radiation, Electrons, and Cosmic Rays

Thermal Cycle (Chemistry)

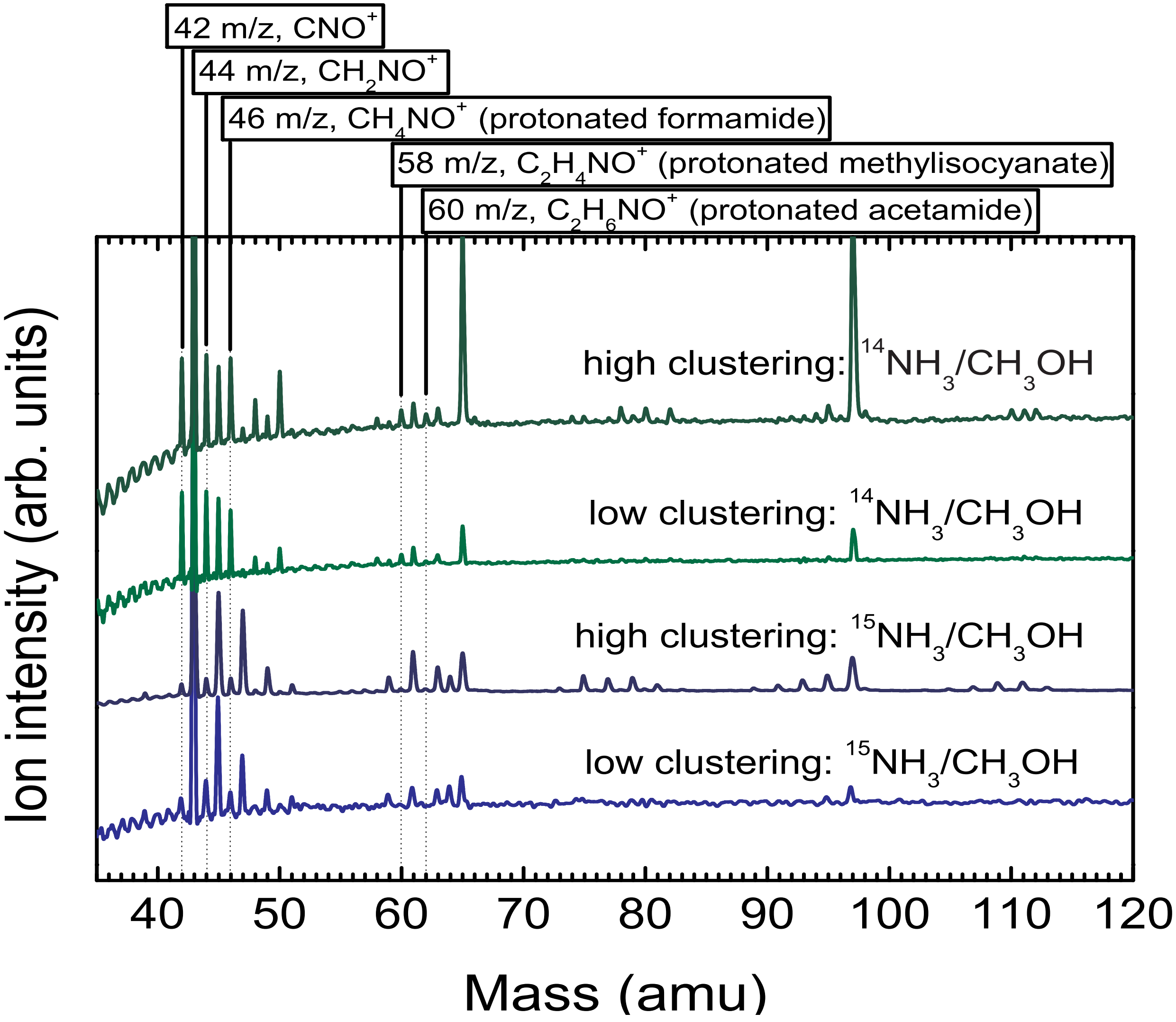
Energetic Processing through Dissociation and Ionization leads to Chemistry involving Electrons, Ions, and Radicals

Realistic Cometary/Interstellar Ice Analogs

Snapshots/Scooping the Evolution of Astrophysical Ice Analogs

Cometary Ice
Analogs
Produce Key
Building Blocks
Of Life upon
Radiation
Processing

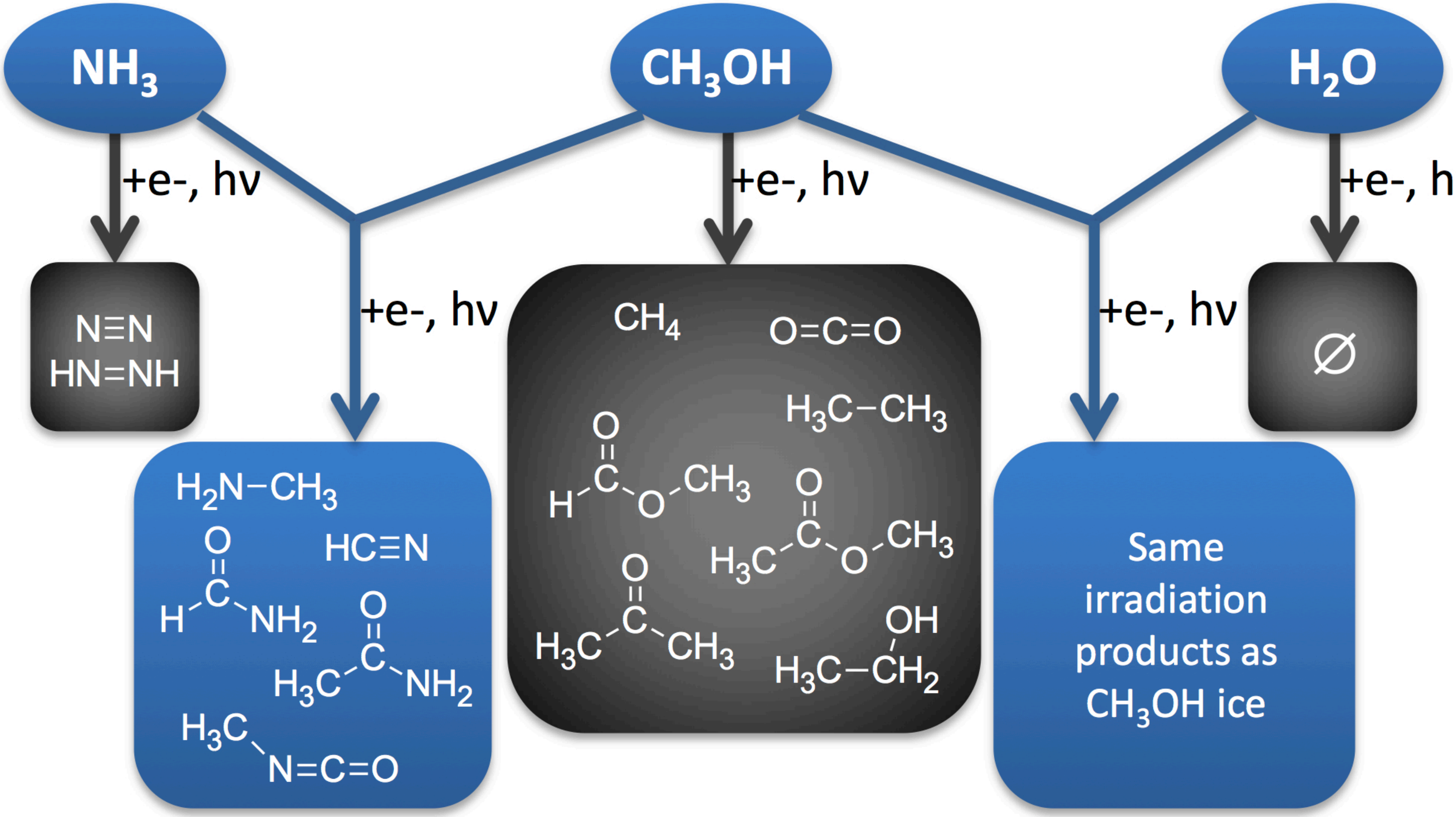
Abundant Products
m/z 43: H3CCO?
m/z 29: HCO



Henderson and Gudipati ApJ - 800:66 (17pp), 2015

Molecules found in interstellar ice analogs

Irradiation Products of Single and Dual-Component Ices, 5 K



NH_3

CH_3OH

H_2O

+e-, hν

$N\equiv N$

$HN=NH$

+e-, hν

H_2N-CH_3

$HC\equiv N$

+e-, hν

CH_4

$O=C=O$

H_3C-CH_3

+e-, hν

Same irradiation products as CH_3OH ice

+e-, hν

∅

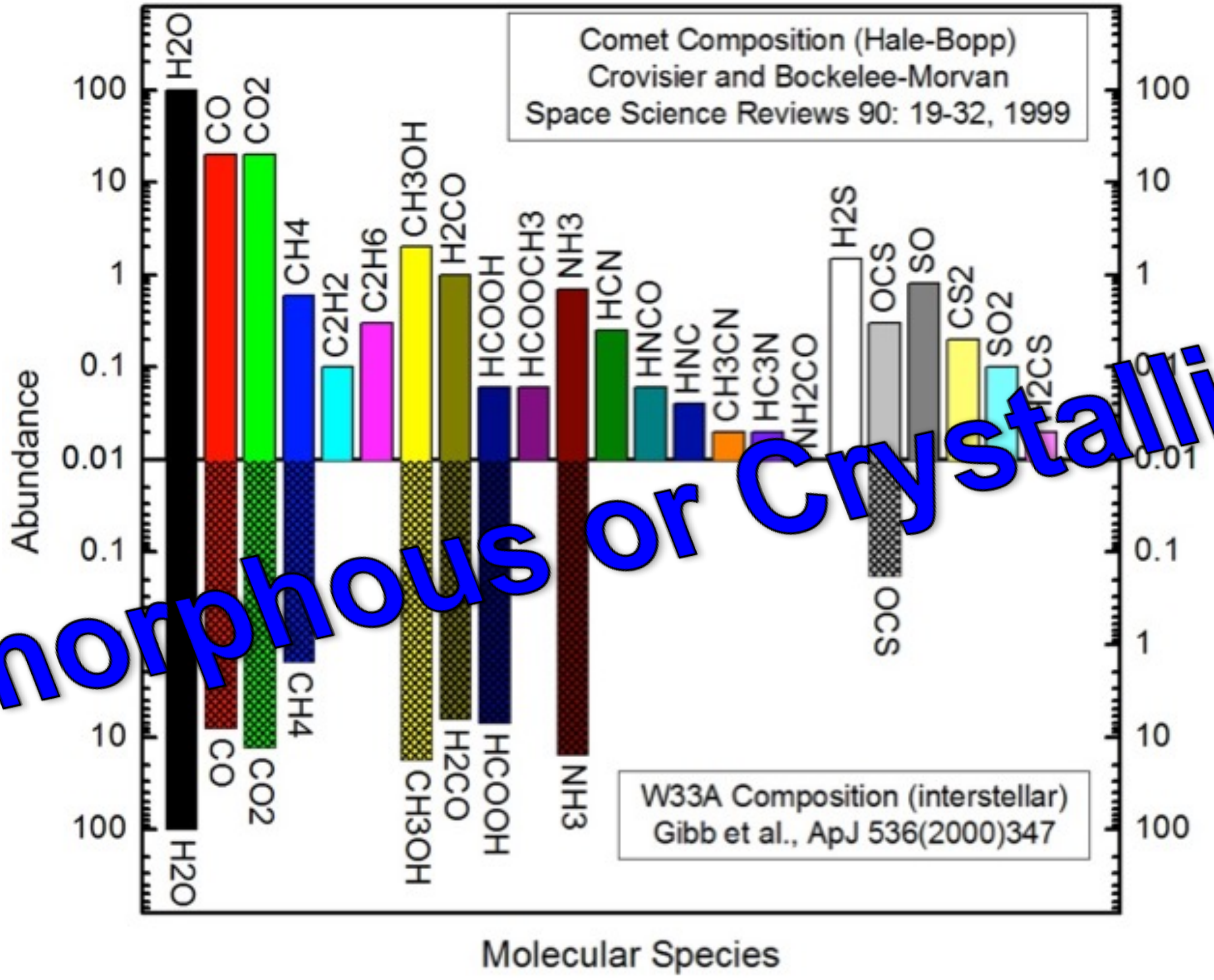
Many of these molecules are detected by Rosetta-ROSINA

NH_3 less reactive than CH_3OH under radiation

A Comet’s Nucleus – What is it? Amorphous, Crystalline, or Crystalline with Clathrates?

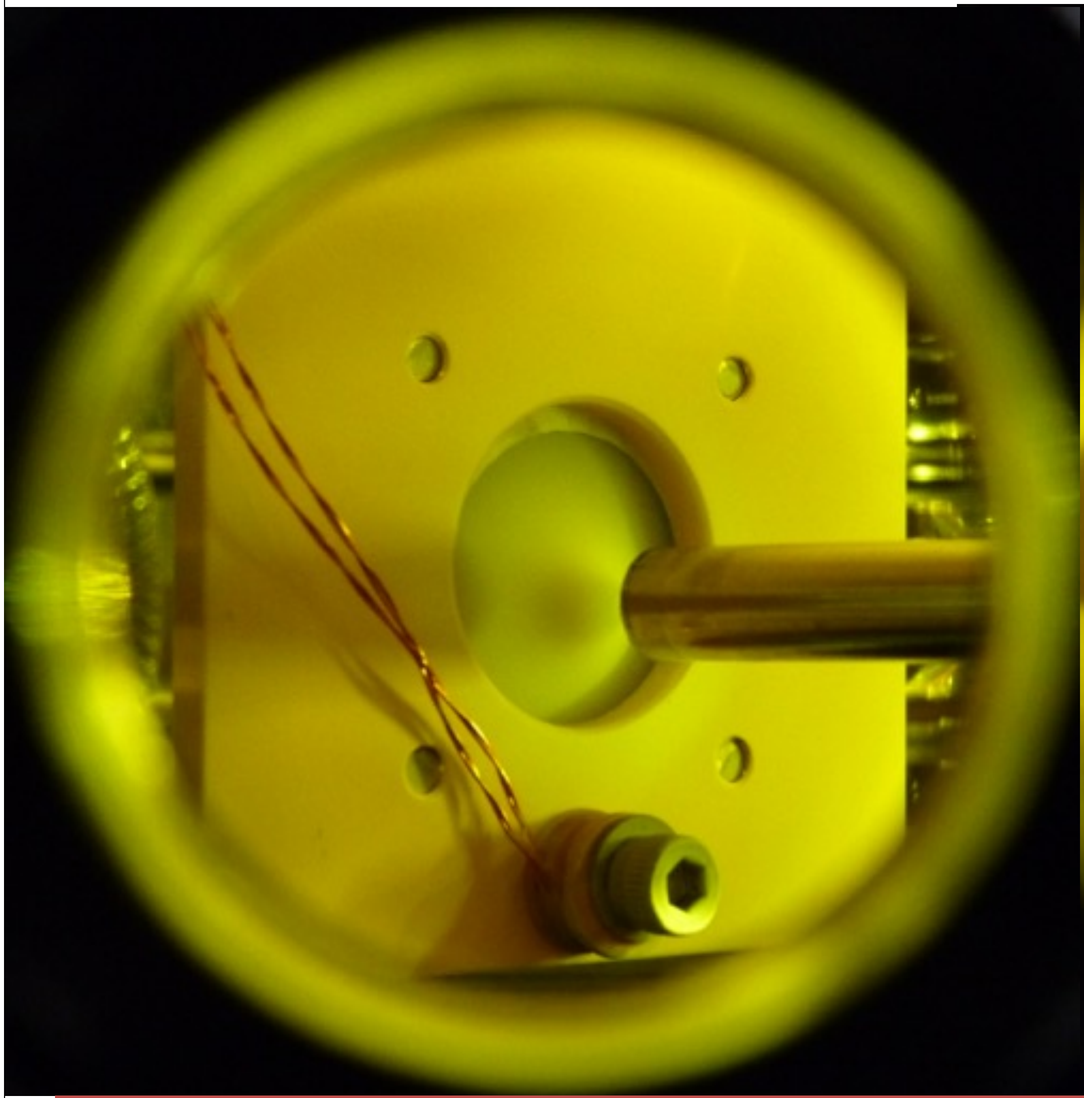
Cometary and Interstellar Ices: Composition

Helen Fraser's neutron diffraction studies: amorphous ices are porous indeed!

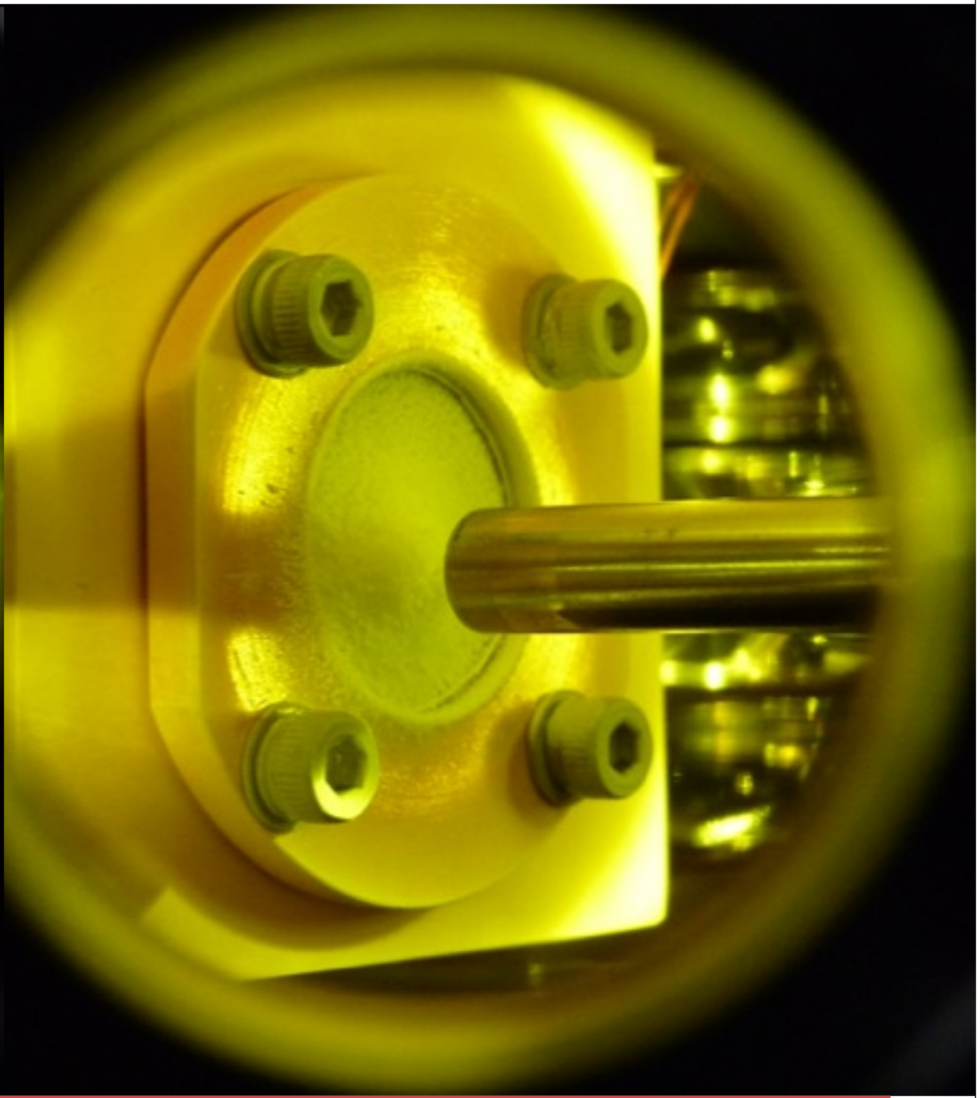


Amorphous or Crystalline?

Macroscopic Amorphous Ices in the Lab: Simulating Interstellar & Comet Ices

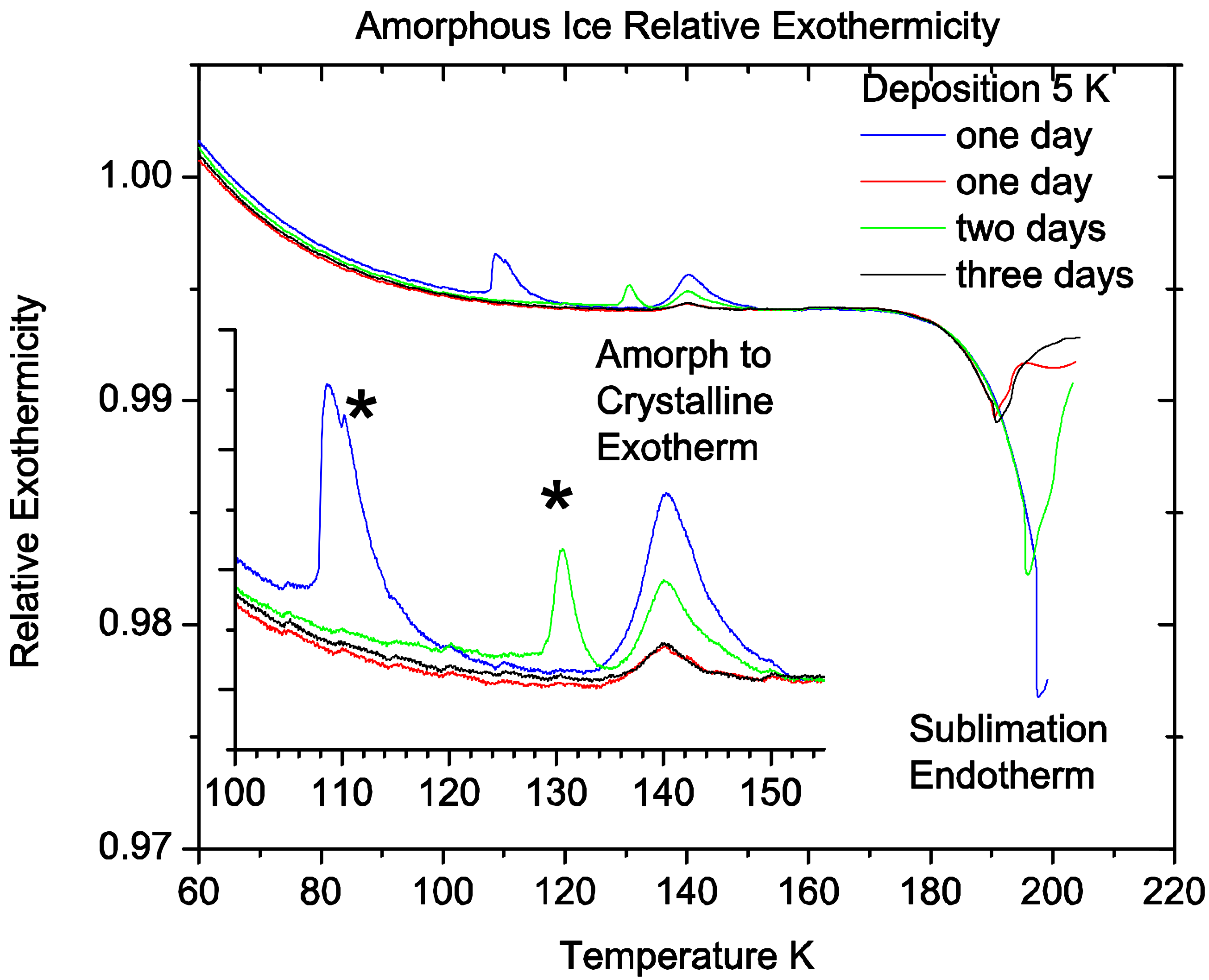


150 K Deposition
(Crystalline)



5 K Deposition
(Amorphous)

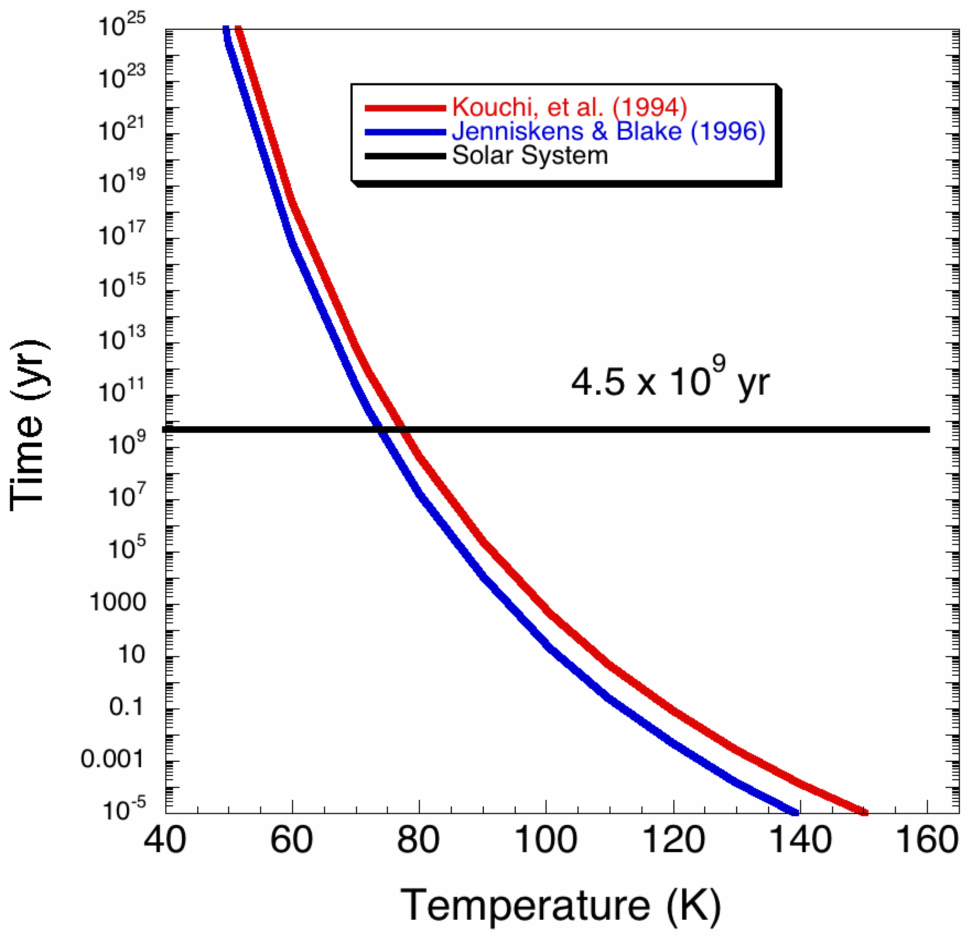
Amorphous to Crystalline – Exothermic?

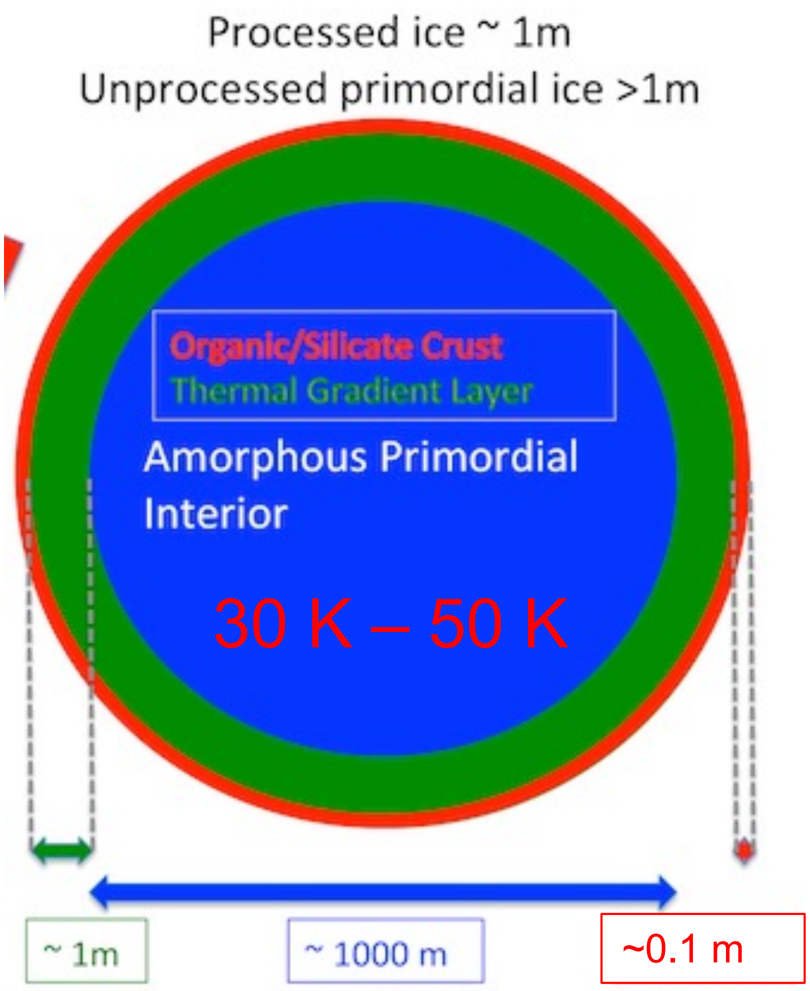


Impurities may change exothermic to endothermic (amorphous to crystalline) transition

Robert Wagner and Murthy Gudipti (2013) to be published

How Primitive is a Comet's Interior?



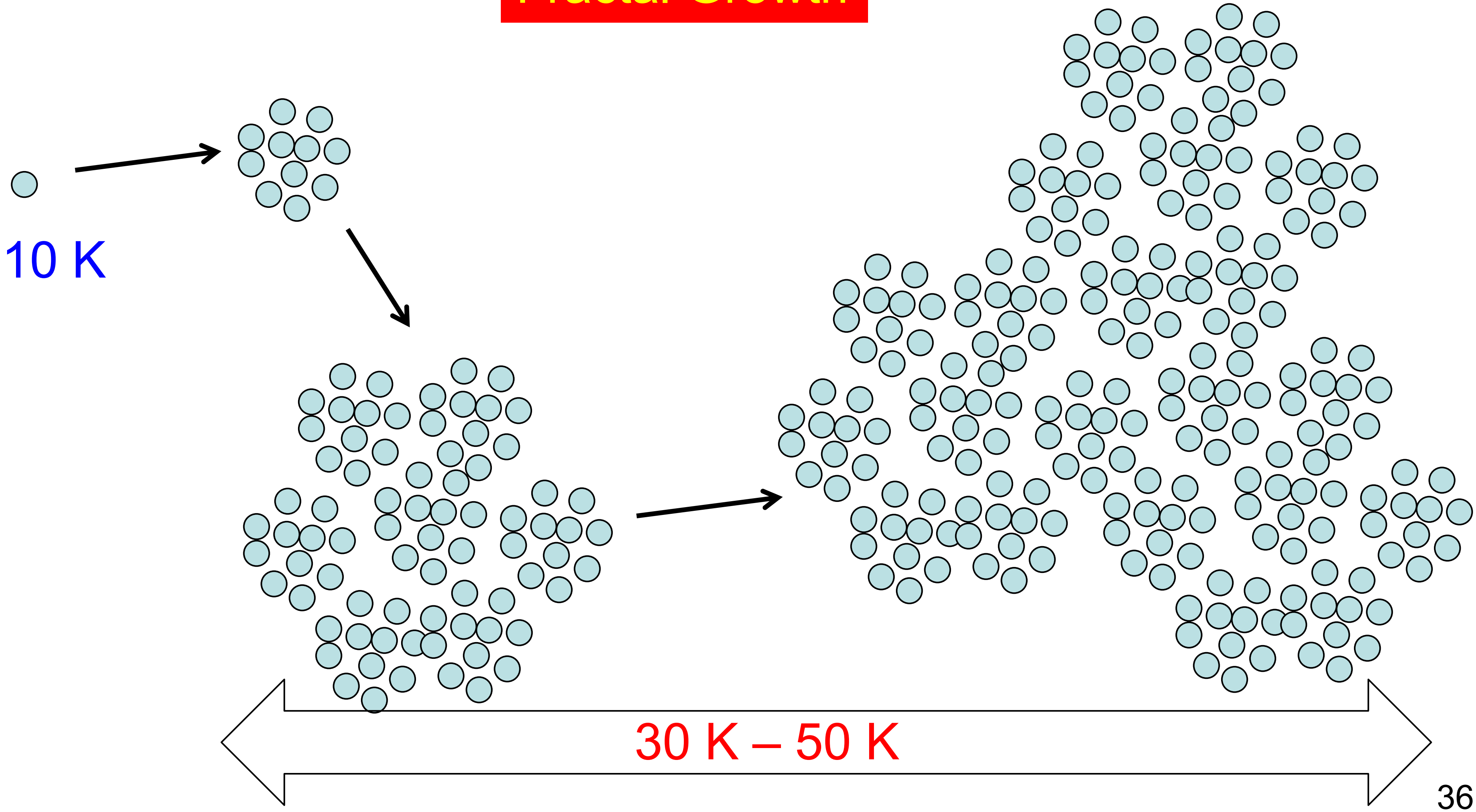


Mastrapa, Grundy, Gudipati (Solar System Ices 2013)

My Hypothesis

Everything is done in interstellar ices and preserved in a comet's nucleus – yes – a comet's nucleus is primitive.

Fractal Growth



Outstanding Questions

Surface: Hard Shell – how thick?
Interior: When do we hit the coldest temp?
Interior: Separated gas/dust/ice aggregation?
Interior: Interstellar ice grain retained?
Protoplanetary: Disassemble/Reassemble?
Protoplanetary: Amorphous/Crystalline/Clathrates?
Protoplanetary: How the material is exchanged?
Protoplanetary: Ice grains to Cometesimals – how?