Comet Science Goals II

{questions for goals}

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Did the events postulated by the Nice Hypothesis really happen? Were there wide-spread solar system wide impact events that were coeval with the Moon's Late Heavy Bombardment? Were the impactors, ice-rich bodies with primitive chondritic elemental compositions? Did the impactors form beyond Jupiter?

What is the diversity among comets? Why are some JFC's depleted in C2, C3 & CN relative to OCC's? Is the diversity related to formation or the result of evolution? Are comets less diverse than asteroids?

Did all comet rocks & minerals form in the inner solar system? How did inner SS materials like chondrules and CAIs get to the comet accretion regions? What solids formed in the comet accretion regions and why? Are all non-volatile components of comets also found in primitive asteroids.

What was the formation temperature of cometary ices? How do the ice compositions of "warm ice"comets such as main-belt comets compare with JFC and OCC comets? Do D/H ratios of warm ice comets match meteorites & SMOW?

Do comets significantly contribute volatiles and critical pre-biotic molecules to habitable planets? Do comets carry noble gas or isotopic tracers that can be used to determine the cometary contribution to planetary volatiles?

How did the major rock, organic and ice components of comets form?
Were the ice and organic components formed in the same locale?
Do comets show significant fractionation between these components?

Were comet interiors ever subjected to hydrothermal alteration processes?
Were they significantly heated by ^{26}Al or major impacts?

Do the structures of comet interiors retain information on their mode of accretion?
Are they layered? Are they rubble piles? Are they aggregates of smaller bodies?
Are km-sized comets typically fragments of larger bodies?
Were comets homogenized by their formation?

What was the initial size distribution of ice-rich planetesimals that formed beyond Neptune? What fraction of the initial mass was in dwarf planets?
How did the KBO dynamical groups form?

What are the lowest temperature condensates preserved in comets? How do ices evolve over time?

Did comets accrete solids from the entire nebular disk and over its full lifetime? Are comets the best collection of nebular solids? Can ^{26}Al ages of cometary chondrules provide a formational history of nebular igneous solids?

How do comets maintain cometary activity? How do sub-surface volatile reservoirs recharge near-surface deposits and keep comes active. How Are do dormant comets compare to active ones?

Why do comets fragment? Is this this their major form of mass loss?

Why do comets eject so much mass as large particles?

Are the materials in SS comets a reasonable proxy for the materials that commonly makeup the debris disks around other stars. Are SS cometary materials closely similar to material in disks around other stars?

When and where did JFC's and OCC's accrete?

Did all comet rocky materials form in the inner solar system or did some form beyond Jupiter?

Input from Comet White Paper

II. Top-Level Scientific Questions

The most important scientific questions that can be addressed by NASA's missions to comets in priority order are:

How did the Solar System form from the protoplanetary cloud – what were the physical and chemical conditions in the nebula, what was the nature of the solid materials in the nebula, and what role did mixing of material within the nebula play (*e.g.*, transport of material from small to large heliocentric distances and vice-versa)?

- Were cometary nuclei formed as an agglomeration of amorphous H_2O ice and dust? Does such ice still exist in the interior of comet nuclei as they enter the inner Solar System? Does it drive cometary activity?
- Are the layers seen on comets 9P and 81P signs of a primitive formation process or massive internal activity in their later evolution?
- What roles have fragmentation and collisional processes played in the formation of cometary nuclei?

What is the history of Solar System volatile and organic compounds? Did amorphous H_2O ice play a role in trapping super-volatiles in cometary ices?

What was the role of comets in the delivery of water to planets, particularly in the habitable zone and what does the distribution of primordial icy volatile material tell us about the evolution of habitable planets in extrasolar planetary systems?

How can measured comet chemistry be related to formation location or evolutionary processing history? What roles do evolutionary processes (collisional, photon and particle irradiation, solar heating, mass loss, radioactivity) play?

What is the detailed physical structure of comets, and how does this relate to the mechanisms for cometary activity?

A significant shortcoming in current research and our ability to link comets to early Solar System processes is the role of amorphous H_2O ice in cometary evolution. Another stems from the lack of measurements of the isotopic tracers of the volatile distribution, specifically D/H, $^{14}N/^{15}N$, $^{13}C/^{12}C$, and $^{18}O/^{17}O/^{16}O$ in various species, and the abundances of noble gas isotopes (particularly for Ar, Kr, and Xe). A further shortcoming is our inability to measure the diversity and complexity of cometary organics. How complex is cometary matter? Do comets harbor the precursors of biological molecules? Did comets supply a significant fraction of the terrestrial organics? How are cometary organics distributed versus depth in the nucleus? What is the detailed composition and mineralogy of cometary dust? None of these questions can be answered yet, and they likely can only be answered by future NASA missions to comets.

Comets - points from the last decadal study

Fundamental Issues
The fundamental questions concerning primitive bodies as building blocks of the solar system can be summarized as follows:

• Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
• What processes led to the formation of these objects?

Primitive bodies
• Since their formation, what processes have altered the primitive bodies?
• How did primitive bodies make planets?
• How have they affected the planets since the epoch of formation?

Important questions
• What processes in the solar nebula acted to alter presolar material?
• Are comets differentiated, and do they contain presolar material?
and how have these processes varied over time?
• What is the time-history of collisional events and their consequences at various distances from the Sun?
• What are the thermal histories of all classes of comets; do they become extinct or dormant?
• Do Kuiper Belt objects exhibit evidence of transient atmospheres or epochs of internal activity?
• What roles did tidal activity, atmospheric escape, and internal activity play in generating the strongly dichotomous appearance of Pluto-Charon?
• Are Jupiter-family comets fragments of much larger Kuiper Belt objects, or are they still near their original size?

• How did primitive bodies contribute to the volatile inventories of the terrestrial planets?
• Did organic matter delivered to early Earth (and other planets) by primitive bodies trigger the formation of life or provide the materials?
• When did Pluto and the Kuiper Belt objects form?
• How does accretion work, where do the materials come from, and what is the time scale?
• How much radial mixing of primitive material took place?
• How large are the accreted bodies in the outermost solar system?
• What was the role of gas drag in the early solar system?

• Do impacts lead to discrete and long-lasting changes in the surface-atmosphere regime?
• What volatiles and organics were delivered to the terrestrial planets?
• What fraction of impactors are comets vs. asteroids?

• What is the composition, origin, and primordial distribution of solid organic matter in the solar system?
• What is its present-day distribution?
• What processes can be identified that create, destroy, and modify solid organic matter in the solar nebula, in the epoch of the faint early Sun, and in the current solar system?
• How did organic matter influence the origin of life on Earth and other planets?
• Is organic matter similarly distributed among primitive bodies in other planetary systems?

• What is the composition and structure of primitive organic matter in the solar system?
• Where and under what conditions did organic matter originate?
• What are the relative fractions of organic matter in meteorites and comets that are interstellar and solar nebula in origin?
• Was primitive organic matter racemic?

Questions that emerge regarding the present-day distribution of organic matter include the following:

• Which asteroids (or comets or Kuiper Belt objects) are the sources of the carbonaceous meteorites of various types, including the micrometeorites?
• What are the compositions of organic matter that color some icy bodies, including Pluto and the Kuiper Belt objects?
• What are the sources of IDPs?

• Are there unidentified processes that create and destroy organic matter?
• Do natural processes result in racemic mixtures of complex OM?
• What are the chemical details of the formation of macromolecular organic solids under different conditions and with different starting mixtures?
• What is the temporal history of organic formation in various environments in the solar syst
• What is the balance in the creation and destruction of OM in impacts and radiation environments?

• How does refractory OM vary among the comets, asteroids, planetary satellites, and other solar system bodies, and what does this tell us about the chemical environments in which it formed?
• What kind and quantities of OM delivered to early Earth and other terrestrial planets survived the impact
and the planetary environments at that time?
• Did extraterrestrial organic matter trigger or provide the feedstock for early life on Earth?
• Where else in the solar system does life exist or has it existed?
• Could the terrestrial L-enantiomer preference result from the chirality of extraterrestrial OM?

• Are there planets in the habitable zones around other stars?
• What are the characteristic signatures of primitive body reservoirs around other stars?
• Is our assemblage of primitive bodies typical?

• What is the population structure of the solar system?
• What is the nature of Kuiper Belt objects?
• What is the formation history of the trans-Neptunian region?
• Where in the solar system did building blocks form; which were transported and which were not?

Questions of pivotal importance include the following:
• How do compositional differences between the Oort cloud and the Kuiper Belt bodies relate to their sites
of origin?
• Are small, distant bodies such as Kuiper Belt objects, Pluto, and Charon geologically active today?
• What is the nature of binary objects in the solar system, and what do they tell us about formation history?
• What processes modify the surfaces of all categories of building blocks?
Foundation-building questions are as follows:
• How do colors and albedos of small bodies relate to their compositions and histories of alteration by
various processes since their origin?
• What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the
solar system, and what were the time scales?
• What are the orbital distributions of long-period and new comets, and how have these distributions evolved over the age of the solar system?

Primitive Bodies As Reservoirs of Organic Matter
Potentially paradigm-altering questions about primitive bodies as reservoirs of organic matter include the
following:
• What are the compositions and origins of the organic and volatile materials in primitive bodies?
• How is organic matter distributed throughout the solar system?
• What is the chemical and isotopic composition of cometary surface materials?
• What are the physical and chemical/isotopic properties of comet nuclei, and do they vary with depth?
Questions of pivotal importance include the following:
• Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?
• What are the parent bodies of the carbonaceous meteorites, interplanetary dust particles, and micrometeorites?
Foundation-building questions are as follows:
• What are the processes by which organic material forms on the surfaces of icy and other primitive bodies
in the current epoch?
• What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?