GOALS AND PRIORITIES FOR THE STUDY OF COMETS IN THE NEXT DECADE (2011-2020)

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Abstract:

Comets harbor the most primitive Solar System material, were the building blocks for the cores of the Giant Planets, transport water and organics (the seeds of life) throughout our planetary system, and possibly played a key role in terrestrial planet habitability. The study of comets is therefore critical to understanding the formation and evolution of the Solar System and will have important implications for understanding habitability in extrasolar planetary systems. We present the current status of cometary science, specify the major scientific questions resolvable by future NASA comet missions, and define a prioritized strategy for NASA's exploration of comets from 2011-2020.

Executive Summary

There is broad community support for the following *prioritized* (highest to lowest) recommendations for NASA's missions to comets during the next decade (2011-2020):

1. NASA's Discovery Program should support new missions every 18-24 months because these continue to provide outstanding opportunities for innovative and paradigm-shifting investigations of comets, and because the experience gained in executing Discovery missions will be critical to the success of future surface and interior sample return missions.
2. A Comet Surface Sample Return (CSSR) mission offers the best near-term potential to investigate the nature of cometary organics and is a high priority for NASA's New Frontiers Program during the next decade.
3. A Cryogenic Nucleus Sample Return (CNSR) mission, which would return the most primitive material available in the Solar System (a cryogenic sample extracted from a region deep below the surface of an active comet), remains the holy grail of cometary

science and should be a top candidate for NASA's Flagship Program. We recommend that NASA embark *this next decade* (2011-2020) on a *detailed feasibility study* of a CNSR mission that defines a technical development program to enable a CNSR mission in the following decade (2021-2030) and its likely cost.

In addition to the above priorities for future NASA comet missions, we also recommend:

- NASA should maintain a stable, well-funded Research & Data Analysis (R&DA) Program that enables the science return from its missions and provides the scientific insights that drive the prioritization and selection of future missions.
- NASA and NSF should continue to support a vigorous ground- and space-based comet observation program because this provides the vital link between NASA's in-situ exploration of individual objects and our understanding of the diverse population of comets. Remote observations also provide critical mission planning support.
- NASA should maintain a strong technology development program that enables the sampling from depth in the nucleus, improved in situ analysis, and the return of nucleus material to Earth. Low cost missions to comets would strongly benefit from advanced RPSs (Radioactive Power Systems) and improved solar array technology, more efficient SEP (solar electric propulsion) and chemical propulsion systems, and low power, lightweight instruments, including those that probe the interior structure of the nucleus (*e.g.,* penetrating radars and remotely deployable seismometers)**.**

I. Subdiscipline Overview

Comets represent the most unaltered (*i.e.,* primitive) samples of the early Solar System and, even though new results have shown that the surfaces of short period comets have undergone major evolutionary modifications, carefully selected samples can still be expected to provide key information on the processes of planetary formation during the first few hundred million years of Solar System history. This is perhaps even more true in the case of the less accessible "new" or Oort cloud comets. Recent space-based observations have revealed properties of cometary nuclei previously unimagined even a decade ago. In addition, synergistic telescopic observations from the Earth have enabled an improved assessment of their collective physical and chemical nature.

Spacecraft flybys of four comets (1P/Halley, 19P/Borrelly, 81P/Wild 2, and 9P/Tempel 1) have demonstrated an amazing diversity in the surface geology of cometary nuclei and have yielded new insights into the physical structure and density of cometary nuclei, the nature of cometary dust, the workings of the inner coma, and the processes involved in cometary activity.

- Data from the flyby spacecraft to 1P/Halley[1] demonstrated conclusively that: the nucleus is a single body rather than a swarm; the surface is incredibly dark (albedo ~4%); the surface temperature is unexpectedly hot (up to ~380 K at r=1AU) and not consistent with sublimating ice; only ~10% of the sunlit surface is active (*i.e.*, most of the surface is covered with a refractory mantle); H_2O is the dominant volatile accounting for ~80% of all the gases released into the coma; much of the CO is released from an extended source (perhaps polymerized formaldehyde); ~30% (by mass) of the dust grains are organic in composition (containing C, H, O, and N).

- Imaging of the nucleus of 19P/Borrelly by the Deep Space 1 mission revealed a diverse surface with smooth plains, low-lying areas filled with fine-grained materials, and multiple, 100m-high mesa-like structures bounded by scarps, which might be produced by sublimation-induced back-wasting[2].
- The mixture of high and low temperature minerals in the coma dust samples collected by the *Stardust* mission provides clear evidence of extensive mixing in the solar nebula prior to comet formation[3].
- Data from the *Deep Impact* mission to 9P/Tempel 1[4] revealed that: the porosity of the nucleus surface layer is >75%; the bulk density of the nucleus is ~0.4 g cm^{-3} (0.2-1.0) and its tensile strength is between 200 Pa (like talcum power) and < 12 kPa (like loosely packed snow); there is little bulk ice on the surface; CO_2 and H_2O are not uniformly mixed in the nucleus and their emission into the coma is not correlated with dust jets, and there is widespread evidence of global layering over the surface. Coma outflows were resolved into bundles of filaments, allowing us to connect activity to specific regions on the surface.
- Night-time activity was detected on two comets, which may indicate an interior source for the gases responsible.

Remote observations of comets from Earth-based facilities have also yielded exciting new insights into the nature of comets:

- Accurate size measurements have now been obtained for over 80 cometary nuclei, and their distribution suggests that comets are a collisionally evolved population, but probably deficient in sub-km objects[5].
- Space-based and ground-based measurements of three comets (1P/Halley[6-7], C/1996 B2 (Hyakutake)[8], and C/1995 O1 (Hale-Bopp)[9]) show that the deuterium abundance in cometary water is ~2x larger than the terrestrial value, but all of those comets likely came from the Oort cloud and there have been no similar measurements for the Jupiter family or Main Belt comets. The role of comets in supplying the Earth with water therefore remains unresolved.
- A ground-based measurement of a pronounced enhancement (relative to solar) in the DCN/HCN ratio in C/Hale-Bopp strongly suggests that this comet retained a signature of its interstellar heritage.
- Systematic optical surveys of many comets during the past several decades have shown abundance variations among the radicals CN, C_2, C_3, and NH, including the finding that roughly half of the Jupiter family comets, but very few Oort cloud comets, are significantly depleted of carbon-chain molecules[10-11] .
- Ultraviolet, infrared, and radio observations of CO emission in 16 comets over several decades demonstrate that this key molecule varies dramatically in abundance from comet-to-comet, with no clear correlation with dynamical class[12].
- Near-infrared and radio surveys of cometary parent molecules suggest a wide diversity in composition with no clear demarcation into groups, but with some intriguing compositional patterns[12].
- Optical[13], infrared[14], and radio[15] studies of split comet 73P/Schwassmann-Wachmann 3 showed a homogeneous chemistry for the fragments in contrast to the diverse chemistry seen within the comet population. These studies also suggest the chemistry of this Jupiter-family comet is primitive, not evolved
- Observations of activity in cometary nuclei at large heliocentric distances, and in the closely related Centaur population, suggest that exothermic phase transitions

between amorphous and crystalline H_2O ice in the interior of the nucleus, rather than sublimation of surface ice, may be responsible for cometary activity[16]. However, amorphous ice has not yet been detected in comets, and determining the phase of the ice in the nucleus remains a critical challenge.

- A new class of icy bodies has been discovered resident in the asteroid belt (the "Main Belt Comets"). The ices in these objects likely formed in-situ and represent a previously unexplored icy Solar System reservoir[17].

In addition to the above observational results, recent models of Solar System formation show that small icy planetesimals have had a rich dynamical history, suggesting that the chemical fingerprints of formation within the solar nebula cannot be fully interpreted without coupled dynamical models. Thus, by being selective in our choice of targets for NASA's missions to comets, we could potentially map the changing chemistry of the condensable fraction of the nebula with relatively few missions (*e.g.,* one mission to a comet formed primarily from interstellar materials with high CO, N_2, and amorphous dust, one mission to a comet formed near the end of nebular accretion with high C_2H_6 and other hydrocarbons plus NH_3 and highly crystalline dust, and another mission to a comet whose composition appears to be intermediate relative to the previous two).

The above discoveries and new insights bring cometary science to a new level of maturity, one that is moving towards closer contact with the geological and geophysical disciplines. A new paradigm is being formulated and will certainly be affected by future results expected from the EPOXI mission to 103P/Hartley 2 (2010), the Stardust-NExT mission back to 9P/Tempel 1 (2011), and the Rosetta rendezous and lander mission to 67P/Churyumov-Gerasimenko (2014). The space exploration of comets is an endeavor of great discoveries and challenging science. Nevertheless, even with the advances discussed above, we are still far from being able to use comets to map out the physical and chemical processes in the solar nebula at the time of planet formation. Nor have we obtained an accurate assessment of their contribution to the distribution of volatiles and organic chemicals throughout the Solar System. This requires further exploration of comet diversity, comet interiors through tomographic radar or seismology, the return of organic samples and, eventually, primitive cryogenic samples to terrestrial laboratories.

II. Top-Level Scientific Questions

The previous Decadal Survey identified four cross-cutting themes as the basis of the next decade's exploration strategy: the first billion years of Solar System history; volatiles and organics; the origin and evolution of habitable worlds; and understanding Solar System processes. Comets, as accessible primordial samples of early Solar System material, are key to answering compelling questions about our origins. 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.

III. Required Research and Research Facilities

- Comet nucleus sample returns are expected to become increasingly important for future NASA comet missions. NASA should be looking ahead to ensure it will have the facilities to support sample analysis and archiving and analysis of cometary samples, eventually including cryogenic samples.
- Population studies of comets are best accomplished from remote-observing facilities (ground-based, airborne, suborbital, and Earth-orbiting observatories). High spectral resolution near-IR and radio investigations of parent volatiles in multiple comets are particularly important, and NASA should recognize that such investigations are worthy of support because these studies provide the essential context for interpreting spacecraft observations that are necessarily limited to small numbers of objects.

Maintaining access to medium- to large-aperture ground-based telescope facilities is key to both the interpretation of mission data and for providing target characterization necessary for successful mission execution. Ground-based data can provide information at wavelengths and timescales not available from mission instrument suites, which is especially important for the Discovery class missions. An excellent example of the synergy between ground-, space- , and in-situ science investigations was the extensive world-wide observing campaign executed in support of the Deep Impact mission[18].

IV. Technology Needs

NASA must maintain a strong technology development program that enables low cost comet flyby and rendezvous missions, and the return to Earth of material from cometary comae, from cometary surfaces (for complex organics), and from deep within nuclei (for the most primitive matter). Specific technology needs include:

- Power systems: More efficient solar arrays, including flexible ones, will allow savings in mass and size, which could enable operations in close proximity to the nucleus. Nuclear power is the key to exploring the outer Solar System, but NASA currently faces a crisis in the supply of ^{238}Pu, the essential ingredient of RPSs. The use of RPS-powered spacecraft more easily enables landing on and sampling cometary nuclei, and we strongly recommend that NASA pursue a strategy to increase and preserve its supply of nuclear fuel, including the development of more efficient RPSs (*e.g.,* the Advanced Stirling Radioisotope Generator, or ASRG).
- Propulsion technologies: Comet rendezvous missions and multiple target flybys typically require low-thrust propulsion for success at reasonable mass and cost. Although recent small body missions have employed ion engines (DS1 and Dawn), additional investments in this technology are needed for reliable, routine future use.
- Telecommunications and data compression: Maintaining and improving NASA's Deep Space Network, and creating better onboard data compression techniques, will maximize the data returned from missions.
- Navigation: The development of better navigation and guidance and control systems, including the incorporation of autonomous navigation capabilities with LIDARs providing feedback, will enable nucleus close-proximity operations and landing.
- Sensor technologies: Lightweight, low power imagers, spectral imagers, and mass spectrometers (the latter including high mass resolution and coverage over large mass ranges) need to be developed, and techniques must be found to protect them in hazardous dust environments. Better techniques should also be developed to measure the mechanical properties (strength, porosity) of cometary nuclei, possibly employing seismometry and radar/radio tomography.
- Sampling mechanisms: A wide range of sampling mechanisms are possible, and each will likely require technology development.
- Sample return technology: Technology development is needed to produce sample return canisters that protect and preserve cometary material during entry into Earth's atmosphere and subsequent transfer to Earth-based laboratories.

V. Major Mission Priorities

A. Flagship class mission(s)

The holy grail of cometary spacecraft missions is the return to Earth of a cryogenic sample extracted from deep (> 1 m; the deeper, the better) within a nucleus, which is referred to generically as the Cryogenic Nucleus Sample Return (CNSR) mission. Owing to the complexity and technical challenges associated with CNSR, it is commonly assumed that such a mission will fall into the NASA Flagship class. Undoubtedly a

CNSR mission will be challenging, but probably less so than many of the other Flagship missions being proposed. The fact that comets pass relatively close to the Earth (allowing frequent access dynamically), their nuclei are highly porous (making the drilling to depth relatively manageable), and they don't have significant gravitational potential wells (allowing easy escape back to the Earth), suggest that a CNSR mission is technically within our reach over the next couple of decades. A recently disrupted comet may be a good target for CNSR, providing access to recently exposed interior materials. We strongly recommend that NASA invest in a detailed study of the technical feasibility and cost of a CNSR mission during the next decade (2011-2020), with a goal of enabling such a mission in the following decade (2021-2030). The promise of CNSR, the analysis of the most primitive material ever returned to Earth, justifies this path.

B. New Frontiers Class mission(s)

We reiterate the finding of the previous Decadal Survey that the return to Earth for analysis of a sample from the surface of a comet's nucleus remains a critical component of NASA's systematic investigation of comets. The complexity of such a mission pushes it into the New Frontiers class, but the potential scientific return justifies this larger investment. In particular, a Comet Surface Sample Return (CSSR) mission will reveal the complexity of cometary organics, and whether comets could have provided pre-biological material to the Earth and other planets.

VI. Discovery Science Goals

Discovery class missions are a vital component of any strategy to understand the nature of comets, as they can address the diversity of comets and their activity mechanisms through flybys of multiple targets and low-cost rendezvous investigations of specific targets, including the characterization and reconnaissance of the best CNSR targets.

VII. Balancing Priorities

Regarding future NASA missions, the highest priority is to support the Discovery program because these missions continue to provide outstanding opportunities for innovative and paradigm-shifting investigations of comets. Discovery missions can address the diversity and the physical evolution of cometary nuclei, the processes by which activity is manifested, the diversity of Jupiter family comets, and their distinction from Oort cloud comets. They can provide the technical and scientific stepping-stones to the more ambitious New Frontiers and Flagship missions. We recommend that NASA initiate a new Discovery program every 18-24 months during the next decade (2011-2020) as the best strategy for advancing our understanding of comets.

A Comet Surface Sample Return (CSSR) mission offers the best near-term potential for investigating the nature of cometary organics, and this is our second highest priority for NASA missions during the next decade (2011-2020).

A Cryogenic Nucleus Sample Return (CNSR) mission, which would return the most primitive material available in the Solar System (a cryogenic sample extracted from a region deep below the surface of an active comet), should be a top candidate for NASA's

Flagship Program. We recommend that NASA embark *this next decade* (2011-2020) on a *detailed feasibility study* that defines a technical development program and cost for a CNSR mission (including, possibly, a low-cost reconnaissance mission). It is our expectation that these precursor studies will enable the implementation of a CNSR mission sometime during the following two decades (2021-2040).

In addition to supporting the analysis of mission data, NASA should also support facility access and ground- and space-based remote observations of comets because those efforts are critical for putting the mission results in their proper perspective.

The R&DA program provides the backbone of scientific advancement and the fertile soil for the genesis of new mission concepts. NASA should therefore maintain a vigorous, financially stable R&DA program.

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