VOLATILE-RICH ASTEROIDS IN THE INNER SOLAR SYSTEM. Joseph A. Nuth III[1], Daniel P. Glavin[1] [1]NASA's Goddard Space Flight Center, Solar System Exploration Division, Code 690, Greenbelt MD 20771 USA (joseph.a.nuth@nasa.gov)

Introduction: In the very early solar system, small bodies likely formed in a roughly continuous sequence from dry asteroids near the Sun, through increasingly water-rich bodies beyond the giant planet region [1]. Prior to spacecraft missions to small bodies it was generally assumed that meteorite parent bodies (asteroids) formed inside the orbit of Jupiter, while comets formed outside this orbit where very low temperatures promoted the condensation of a wide range of volatiles [2]. As a general rule, volatile-rich bodies are thought to be transient visitors to the inner solar system rather than long-term residents. We will argue below that there are two mechanisms that can place volatile-rich bodies, formed well beyond the Snow Line [3], into long-term residence in the inner solar system.

Giant Planet – Disk Interactions: There is evidence that any possible compositional order in the small body population of the early solar system was thoroughly scrambled due to tidal interactions between the growing giant planets and the nebular disk [3-8]. Jupiter may have migrated from ~3.5 au to ~1.5 au before reversing direction to end near its current orbit. The other giant planets migrated in a similar fashion. This large-scale migration threw dry bodies both into the outer nebula and out of the solar system, and drove water-rich bodies into the inner solar system and into the Sun. The numbers of bodies perturbed to any specific destination has not been quantitatively estimated.

Following the chaos caused by giant planet migration the small bodies that then remained in the inner solar system formed the terrestrial planets, the asteroid belt and the Jupiter Trojans. Volatile-rich small bodies that did not fall into the Sun or become incorporated into growing terrestrial planets therefore had a very wide range of environments in which to evolve, from perihelia near 2 au out to nearly 5 au Given the dust rich nature of the solar system during the formation of the terrestrial planets [9], even the closest planetesimals could have been shielded from direct sunlight for several thousand years, leading to slow metamorphism of their surfaces.

A volatile-rich body driven in to the main asteroid belt by gravitational interactions with a giant planet may evolve over several billion years, initially losing near-surface volatiles to form a coma and tail until such activity is shut down by natural processes such as by volatile depletion in the regolith or by the formation of a highly insulating crust [10]. Small impacts could disrupt an insulating crust leading to the vaporization of volatiles and the emission of dust until the breach is "healed" by the same triboelectric processes that formed the original insulating layer [10]. Larger impacts could lead to fragmentation, exposing the volatile-rich interior of the body and re-activating the previously dormant comet or cometary fragments to begin evolving all over again.

Because of the long evolutionary timescale and the warmer temperatures in the inner solar system it is possible that diffusion of water vapor through the regolith could result in monolayer to multilayer deposits on upper regolith layers that had previously lost volatiles via sublimation. The reactions of water with these grains could serve to cement such layers into coherent rocks, much like sandstones, though much less dense.

Modern Comets: Comets fall into the inner solar system from the Oort Cloud, the Hills Cloud and the Kuiper Belt via different orbital pathways. Once in the inner solar system their active phase is short (about 1000 perihelion passages) compared to their dynamic stability [11]. For typical Jupiter Family Comets (JFC) this leads to an active lifetime on the order of 10,000 years compared to their dynamic (orbital) lifetime near 500,000 years. Estimated active lifetimes for long period comets may range from 50 – 2000 perihelion passages [11] though uncertainties in their dynamic lifetime are much greater. At least for JFCs, the "comet" spends only a tiny fraction of its dynamic lifetime in the active phase and about 98% of its time as an asteroid. It is estimated that at least 6% of NEOs may be extinct comets [11].

Active asteroids or asteroid-comet continuum objects [12] have been discovered in the main asteroid belt in recent years. These may represent comets heading towards dormancy after losing most of their surface volatiles, but it is difficult to explain how such objects could transition from a cometary orbit to orbits in the main belt. An alternative is that they were emplaced in the asteroid belt during the giant planet migrations and have slowly evolved to the present day. Complementary to the active asteroids are Manx Comets [13] which have nuclei with the spectral properties of dry, rocky asteroids yet still display a coma such as found in comets. These could represent inner solar system (dry) asteroids flung into the Oort Cloud or Kuiper Belt by giant planet migration that condensed water onto their surfaces for several billion years prior to their deflection into the inner solar system.

Evidence from Meteorites: Based on eyewitness accounts of its fall, Gounelle et al. [14] reconstructed the orbit of the Orgueil parent body and estimated an atmospheric entry velocity > 17.8 m/sec, implying that the orbit aphelion was beyond Jupiter's orbit and therefore that Orgueil was a probable cometary meteorite. Scott et al. [15] have suggested that CR, CO, and ungrouped CCs may have formed beyond the orbit of Jupiter based on a number of significant isotopic differences between these meteorites and non-CCs. Unlike the case for Orgueil, however, there is no evidence that these primitive carbonaceous chondrites fell to earth from a cometary orbit. I therefore propose that such primitive chondrites were emplaced in the inner solar system during the giant planet migration period and evolved in place since that time.

Volatile-rich Asteroids/Dormant Comets?: If an asteroid type represents an evolutionary stage between an active comet and a small body devoid of volatiles, that asteroid type should have some members that fulfill the following criteria: some class members will be dual-classed and have both a cometary and an asteroid designation; some members will be "active asteroids" with the intensity of their activity correlated with solar distance; some class members will be parents of meteor streams; and some class members will occupy traditional "cometary" orbits. Not all class members will fulfill all criteria, and volatile-rich asteroids that evolve in non-traditional locations (*e.g*., main asteroid belt) might never display these properties. However, as they evolved from high water/rock ratio bodies towards dormancy by the same general processes as traditional comets, their regolith properties, spectra, internal structure and composition should be similar to those of dormant comets evolved in more "comet-like" orbits. B-type asteroids fulfill all of the criteria above to represent an evolutionary stage between active comets and volatile-poor asteroids. Some B-type asteroids are dual class, some are active asteroids, some are parents of meteor streams and some are Jupiter Family asteroids. B-type asteroids do not represent the only asteroid type derived from active comets. Similar (or better) cases can be made for both D- and C-type asteroids.

Spacecraft Observations: Hayabusa2 and OSIRIS-REx are the first missions to study C- and B-type asteroids, resp. and both targets show significant differences from the S-type asteroids (Eros & Itokawa) previously studied by orbital spacecraft. In particular, Bennu shows widespread hydration [16], porous (low thermal inertia) boulders [16] and particle emission [17] consistent with traits expected of evolved water-rich small bodies (comets?). Samples returned from these targets should therefore be more consistent with those expected from comets and less like primitive chondritic asteroids. For example, the organic composition of samples returned from Bennu should be intermediate between the organics found in primitive chondrites and the organics observed in active comets. (It is possible that the organics in Orgueil and Tagish Lake may come closest to those in Bennu, but even these might be more highly processed.) They should have enrichments in D/H and $^{15}N/^{14}N$, high C/Mg ratios (> ~7 wt%) and exhibit a greater range of compositions than found in meteorites, including an organic component poor in aromatics, and a more labile organic fraction. Bennu's organics should have a simple amino acid distribution dominated by glycine and β-alanine. Overall, Bennu's organics should represent a more primitive distribution of com-pounds than found in carbonaceous chondrites, but a more evolved suite of compounds than found in future samples returned from active comets.

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