Are B-type Asteroids Dormant Comets?

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We know that comets originate in the Kuiper Belt and in the Oort Cloud, but where do comets go when volatile emissions decrease and are no longer sufficient to produce a coma, or a plasma/dust tail?

Introduction: It has become increasingly clear that comets and asteroids may not be distinct object classes established at the beginning of the solar system, but may in fact be a continuum of objects ranging from dry planetesimals formed close to the Sun to water-rich bodies formed well beyond Jupiter's orbit [1]. In addition, since the dynamical lifetime of a comet in the inner solar system is on the order of 200,000 – 500,000 years while the mean active lifetime of such a comet is only about 20,000 years [2] (or ~1000 perihelion passages), there should be more than an order of magnitude more "dead" or dormant comets than active ones. Dual-classified comet/asteroid 107P/Comet Wilson-Harrington/Asteroid 4015 (1979VA) [3,4] and 2060 Chiron (95P/Chiron) are B-type asteroids, as is the asteroid Phaethon (1983TB) that has been observed to be a source of orbital debris from a comet-like tail. Other dual-class objects include Comet 133P/Elst– Pizarro (7968 Elst–Pizarro) [5,6] a C-type asteroid, 60558 Echeclus (174P/Echeclus), a Centaur of unknown spectral type, and asteroid 118401 LINEAR (176P /LINEAR) [7,8], a "main-belt comet" of unknown spectral type. While some of these objects may (or may not) be rubble piles, turned inside out repeatedly by close passages near the earth or other large bodies, there is still the possibility that some of these objects retain an icy component under an insulating regolith or in their deep interiors.

Comets could become dormant by being covered with a highly insulating and very porous mineral layer formed via sublimation of mineral bearing ices [9] well before all of their volatiles are exhausted. It is also possible that comets stop producing a coma once their near-surface volatile content (H_2O, CO, CO_2, etc.) reaches a threshold value where the pressure of the subliming volatiles is too low to drive vapor through lightly filled regolith voids. As the H_2O residence time in the regolith increases, the potential for reaction with primitive amorphous silicates and with cosmic-ray-induced, defect-laden silicate minerals increases. Therefore, while the silicate dust emitted by active comets like Wild2 may contain mostly anhydrous minerals, the fraction of hydrous silicates on (or within) the surfaces of dormant comets should increase as active comets evolve into inactivity. However, volatiles could still be activated by exposure to the Sun if small impacts remove insulating regolith prior to perihelion.

Inactive comets no longer shed tens of meters of material at every perihelion passage, thus allowing cosmic ray damage to both silicates and ices to increase to levels not possible in active comets with shorter periods. Potentially higher concentrations of radicals such as OH, CH, NH, O, C or H trapped in the ice can be activated by a thermal wave propagating into the surface near perihelion passage that increases the diffusion of these species. As these radicals react and release energy into the ice, the diffusion and reaction rates increase, potentially resulting in a thermal runaway, that can power outbursts, much as has been proposed to occur on ice-coated grains in the interstellar medium [e.g., 10].

Here we are asking the question, **If comets become asteroids, which asteroid spectral type is likely to have once been a comet?** As comets evolve into asteroids, the spectral signature of the surface will also evolve from a volatile-rich regolith plus anhydrous minerals to a desiccated phyllosilicate. As cometary activity winds down, particle emission events will become less frequent and meteor streams associated with that body will become less dense. The presence of meteor streams implies the potential that there may be meteorites in our collections that originated on the surface of a comet (dormant or active). This raises a related question, **Are there some meteorite types that are likely to have originated on a comet?**

Meteorites from Comets: Although many meteorites contain some water, there are others such as the CI chondrite Orgueil that show extreme levels of hydration. Some meteorites contain significant levels of volatile hydrocarbons as well as water of hydration and salts, such as ungrouped carbonaceous chondrite (CC) Tagish Lake [11–15]. Gounelle et al. [16] have suggested that these volatile-rich CCs originate from the outer solar system or even from comets. Scott et al. [17] have also 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. Chondrules and CAIs formed in the innermost solar nebula, yet samples from Wild2 also contain small shards of such materials, probably transported from the inner nebula to the comet forming region [18, 19] early in the history of the solar system. Because their formation and transport might require considerable time, early-formed comets might only contain primitive silicates (Evolution of these bodies would produce meteorites without either chondrules or CAIs.) while later-forming objects would be richer in more crystalline materials [19].

Both comets and CCs (particularly CIs, CMs, and CRs) contain organic material in a variety of forms, both soluble and insoluble, as well as aromatic and nonaromatic [20]. In CI and CM chondrites, insoluble organic material (IOM) comprises ~2 wt% of the matrix [21, 22]. This IOM in chondrites shares a number of similarities with refractory organic material in Chondritic Porous IDPs, which are probably of cometary origin, and organics analyzed as emanating directly from comets. Alexander [22] notes that the bulk composition of the IOM normalized to 100 carbon atoms is $C_{100}H_{70-79}N_{3-4}\ O_{11-21}S_{1-5}$, which is similar to the average composition of Comet Halley CHON particles measured by the PUMA mass spectrometer on Vega 1 [23] of $C_{100}H_{80}N_{4}O_{20}S_{2}$. Furthermore, both share similar enrichments in D/H and $^{15}N/^{14}N$.

Although Sandford et al. [24] suggested an interstellar or protostellar origin based on these isotopic enrichments, Alexander [22] notes that these isotopic enrichments are indicative of formation at very cold temperatures and, although favoring a protostellar or interstellar origin, cannot rule out formation in the outer solar system. This carbonaceous material is also much more abundant in comets. Based on Mg/C ratios, solar C is ~7 wt% in CC IOM but ~30% in comet Halley CHON particles. Sandford et al. [25] found that Wild2 particles exhibit a greater range of composition, include an organic component poor in aromatics, and contain a more labile fraction. In this sense, cometary organics from active comets seem to be more "primitive" compared with those in meteorites: evolution of this component may include considerable volatile loss, as well as polymerization of the original, cometary organics.

Comet Hale-Bopp, a long period (2533 year orbit) and very active comet may have first passed through the inner solar system in 2215 BC.

Orbital evolution of material into the Near Earth Object population: The mechanisms for delivery of material to the Near Earth Object (NEO) population have been studied for some time. It has been shown that collisional activity in the Main Belt followed by resonant interactions is capable of delivering a steady supply of fresh material to the NEO population [26-28] though the size distribution of such material is not consistent with observations. This might suggest that Yarkovsky thermal drag could play a dominant role in delivery of fresh material. Studies of the evolution of comets into asteroids [29, 30] has shown that potentially 6 (+/- 4) % of the NEO population could be derived from Jupiter Family Comets (JFC) and has identified a number of candidate asteroids that might have originated as JFCs based on their Tisserand parameter [31], a measure of the strength of the orbital interaction of the body with Jupiter. (Many of the asteroids identified are primitive Type-B or Type-C asteroids.) The contribution of Long Period Comets to the NEO population is currently unknown [30].

Summary: Where are the dormant comets?

As noted above, the spectrum of a comet likely changes significantly as it evolves from having a volatile-rich surface containing anhydrous minerals, such as Comet Hale-Bopp, to a less active, older body, to a sporadic source of particle emission (Comet Wilson-Harrington?). Depending upon its evolutionary stage, an evolving comet may show several different spectral signatures. We can, however, turn the question around to ask which asteroid spectral type is most likely to be derived from comets.

Observable characteristics of an asteroid type that are former comets should include:

1) Some class members should be independently identified as both comets and asteroids;
2) Some class members should show volatile-driven particle outbursts;
3) Some class members will be known sources of meteor streams;
4) Some class members will have a Jupiter Tisserand parameter near 3 (like JFCs);
5) Surfaces of some members should contain a high fraction of phyllosilicate minerals;

Not all members of the type need display these characteristics. If cometary activity dies out slowly, only the youngest objects will meet (1) while the intensity of (2) will continuously decrease and become subject to observational limits. As particle emissions decrease, any stream (3) associated with an object will become more diffuse, making detection more difficult. Not all comets are JFCs (4). Finally, detailed surface mineralogy (5) is very difficult to characterize using remote observations and can be obscured by space weathering effects. Given the caveats above we conclude that Type-B asteroids are likely to be one stage in the progressive evolution from a comet to an asteroid:

Type-B Asteroids Satisfy All Five Criteria to be Dormant Comets.

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