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Meteorites from the Outer Solar System?

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We investigate the possibility that a small fraction of meteorites originate from the outer solar system, i.e., from the Kuiper belt, the Oort cloud, or from the Jupiter-family comet reservoir. Dynamical studies and meteor observations show that it is possible for cometary solid fragments to reach Earth with a velocity not unlike that of asteroidal meteorites. Cosmochemical data and orbital studies identify CI1 chondrites as the best candidates for being cometary meteorites. CI1 chondrites experienced hydrothermal alteration in the interior of their parent body. We explore the physical conditions leading to the presence of liquid water in comet interiors, and show that there are a range of plausible conditions for which comets could have had temperatures high enough to permit liquid water to interact with anhydrous minerals for a significant amount of time. Differences between CI1 chondrites and cometary nuclei can be ascribed to the diversity of cometary bodies revealed by recent space missions. If CI1 chondrites do indeed come from comets, it means that there is a continuum between dark asteroids and comets. We give some indications for the existence of such a continuum and conclude that there should be a small fraction of the ~30,000 meteorites that originate from comets.

1. INTRODUCTION

When Ernst Chladni first proposed that meteorites originated from outside the terrestrial atmosphere, he did not speculate much further on their origin. At that time, asteroids had not been discovered, and the only possible candidates for meteorite parent bodies were planets, satellites, and comets. At the time of the L'Aigle fall, when meteorites were recognized as extraterrestrial objects (*Gounelle,* 2006), Poisson quantitatively examined Laplace's hypothesis that meteorites originated from lunar volcanos (*Poisson,* 1803). With the discovery of Ceres in 1801, soon followed by the detection of several other small planets, asteroids became an additional possible source of meteorites, although they were not explicitly considered until the 1850s (*Marvin,* 2006).

Because most meteorites are primitive chondrites that originate from bodies too small to have differentiated, modern meteoriticists recognized asteroids and comets as the most likely source for meteorites. For some time, the two possibilities were considered as equally probable, mainly because of the difficulty in delivering meteorites onto Earth from the asteroid belt (e.g., *Wetherill,* 1971). The dynamics of meteorite delivery from the asteroid belt to Earth are now well understood (e.g., *Morbidelli and Gladman,* 1998; *Vokrouhlický and Farinella,* 2000). All meteorites for which a precise orbit has been calculated originate from the asteroid belt (e.g., *Gounelle et al.,* 2006, and references therein). There is at present a large consensus that asteroids are the source of all meteorites present in museum collections, except for a few tens of lunar or martian meteorites. It is still possible, however, that a *minor fraction* of

meteorites originate from the outer solar system, i.e., from Jupiter-family comets (JFCs), long-period comets (LPCs), Halley-type comets (HTCs), or Kuiper belt objects (KBOs). As KBOs are the source for JFCs (*Levison and Duncan,* 1997), we will often use the generic term "cometary meteorites" when referring to meteorites coming from any outer solar system object.

The scope of this review is to examine critically the possibility that some of the meteorites present in museum collections originate from outer solar system objects. We will limit ourselves to objects larger than 1 mm, and will not discuss, except incidentally, the case of interplanetary dust particles (IDPs) and Antarctic micrometeorites. Thoughts about the origin of this submillimeter fraction of the extraterrestrial flux can be found in a diversity of recent reviews (e.g., *Engrand and Maurette,* 1998; *Rietmeijer,* 1998). On the topic of possible cometary meteorites, an excellent review was offered by *Campins and Swindle* (1998) some 10 years ago. Important developments both in our astronomical knowledge of the outer solar system (this volume) and in meteorite analyses (e.g., *Krot et al.,* 2005; *Lauretta and McSween,* 2005) were so numerous in the last 10 years that a reexamination of the question is both timely and necessary.

The importance of the question "Can meteorites originate from the outer solar system?" arises not only because asteroids and outer solar system small bodies, generally called comets, are perceived as radically different celestial objects both by laymen and astronomers, but because they sample different regions of the solar system. If we were certain that some meteorites originate from the outer solar system, this would give us the possibility of studying in the laboratory objects that spent most of their lifetime beyond the reach of modern analytical techniques. At present, only the dust brought back by the Stardust spacecraft from the JFC 81P/Wild 2 gives us the opportunity to study, with an unprecedented range of laboratory techniques, solid matter derived with certainty from an outer solar system body (*Brownlee et al.,* 2006).

Before entering detailed consideration of the possible cometary origin of some meteorites, it is important to realize that there are more than 30,000 meteorites present in the world's collections. If one takes into account the numerous desert meteorites not officially declared to the *Meteoritical Bulletin* because of their lack of scientific or commercial value, this number might be as high as 40,000. If there are no cometary meteorites, it means there are extremely powerful mechanisms that prevent them either being delivered to Earth, or surviving the effects of atmospheric entry. In other words, given the number of meteorites we have at hand, it would be surprising if *none* of them originated from comets.

Among the ~135 different meteorite groups (*Meibom and Clark,* 1999), what are the best candidates for representing cometary meteorites? It is unlikely that differentiated meteorites or metamorphosed chondrites originate from comets given the primitive nature of the latter. Volatile-rich, primitive carbonaceous chondrites are good candidates since they are chemically unfractionated relative to the Sun's composition (*Lodders,* 2003). Among these, the low-petrographic-type carbonaceous chondrites (types 1 and 2, representing respectively ~0.5% and ~1.3% of the meteorite falls) are the most likely candidates for being cometary meteorites because they are dark, rare, friable, and rich in organic matter, as expected for cometary meteorites (e.g., *McSween and Weissman,* 1989).

Because of the intricate nature of the subject addressed here, we will tackle the question raised in the title of this chapter in a diverse number of ways, sometimes apparently disconnected. All these approaches will be wrapped together into our conclusions. The paper is divided as follows. In section 2, we examine the possible dynamical routes between the outer solar system and Earth, and estimate the expected number of cometary meteorites relative to asteroidal meteorites. In section 3, we review the fireball evidence for hard, dense matter reaching Earth from cometary orbits. In section 4, we examine the similarities and differences between carbonaceous chondrites — our best bet for outer solar system meteorites — and comets. Section 5 is devoted to identifying the conditions under which hydrothermal alteration is possible within cometary interiors. Hydrothermal alteration in comets is a necessary, although not sufficient, condition for low petrographic carbonaceous chondrites being cometary. Section 6 discusses the diversity of comets revealed by recent space missions and emphasizes on the possible continuum between comets and asteroids. Its scope is to critically examine the implicit assumption stating that there is a clear distinction between comets and asteroids. In section 7, we summarize our main conclusions and give a tentative answer to the question enounced in the title.

2. DYNAMICAL PATHWAYS

It is well known that the Kuiper belt and scattered disk subpopulation (see chapter by Gladman et al.) is the source of JFCs (*Levison and Duncan,* 1997). The debiased orbital distribution of JFCs from the Kuiper belt has been computed through numerical simulations in *Levison and Duncan* (1997). These simulations followed the evolution of thousands of test particles, from their source region up to their ultimate dynamical elimination. The dynamical model included only the perturbations exerted by the giant planets, and neglected the effects of the inner planets and the effect of nongravitational forces. Consequently, the resulting JFCs had almost exclusively orbits with Tisserand parameter relative to Jupiter

$$T_J = \frac{a_J}{a} + 2\cos(i)\sqrt{(1-e^2)\frac{a}{a_J}}$$

smaller than 3. Actually, most of the simulated comets had $2 < T_J < 3$, in good agreement with the observed distribution. A follow-up of the Levison and Duncan work has been done by *Levison et al.* (2006), which included also the perturbations from the terrestrial planets. These perturbations allow some comets to acquire orbits with $T_J > 3$, although

not much larger than this value. This is consistent with the existence of one active comet (P/Encke) with $T_J > 3$, and of a few other objects with sporadic activity (4015 Wilson-Harrington). Nevertheless, the ratio comets/asteroids should drop to a negligible value for $T_J > 3$ [see Fig. 5 of *Levison et al.* (2006)].

Bottke et al. (2002) developed a model of the orbital and absolute magnitude distributions of near-Earth objects (NEOs) that accounts for asteroids escaping from the main belt through various channels, as well as for active and dormant JFCs from *Levison and Duncan* (1997) simulations. Using the *Bottke et al.* (2002) model, and the albedo distribution model of *Morbidelli et al.* (2002) to convert absolute magnitudes to diameters, in addition to the orbit-dependent impact probabilities with Earth computed in the same work, we estimate that the impact rate of a JFC with our planet is only ~7% of that for an asteroid of the same size. Interestingly, even among objects with $T_J < 3$, comets account only for ~60% of the impacts, the rest being of asteroidal origin. This is important to keep in mind, when analyzing fireball data, as in section 3. The mean impact velocity of JFCs, weighted by collision probability, is ~21 km/s, similar to that of asteroids (20 km/s) (*Morbidelli and Gladman,* 1998), due to the predominance of low-inclination JFCs among cometary impact events. When considering these impact probability ratios, however, one should not forget that the *Bottke et al.* (2002) NEO model is calibrated for objects of about 1 km in size and it is not valid, *a priori*, for NEOs of size comparable to meteorite precursor bodies (typically a few meters). In fact, there is evidence that the size distribution of JFCs is shallower than that of asteroidal NEOs in the size range from a few thousand meters to a few kilometers (*Whitman et al.,* 2006). This is believed to be the consequence of the short physical lifetime of small comets. If this shallow size distribution can be extrapolated to meteorite sizes, the fraction of cometary vs. asteroidal meteoritic impacts would be much smaller than the 7% value quoted above. Taken to some extreme, one might speculate that meteorite-sized "comets" have such a short physical lifetime (a few days, consistent with observations of boulders released from comets) that they can be considered to be inexistent, in practice (*Boehnhardt,* 2004). On the other hand, active comets might continuously release a large number of meteorite-sized bodies into space, in particular close to perihelion. Thus, even if these fragments have a short physical lifetime, their population might be continuously regenerated in the inner solar system. Consequently, the JFC size distribution might become even steeper at small sizes than that estimated by *Whitman et al.* (2006) at intermediate sizes, increasing the fraction of meteorite-sized bodies of cometary origin relative to those of asteroidal origin. So, despite the intense modeling effort quoted above, the real ratio of cometary/asteroidal meteoritic impacts is still not well constrained. Impacts of HTCs and LPCs from the Oort cloud, conversely, should be negligible relative to JFC impacts (*Levison et al.,* 2002), and the much larger impact velocities should be prohibitive for allowing meteorites to reach the ground.

However, there is another dynamical path by which cometary bodies might impact Earth at the present time. Several cometary bodies, either from the Jupiter-Saturn region or from the transneptunian region, might have been trapped in the asteroid belt. Some of them might escape from the asteroid belt, along with normal asteroids, and contribute to the NEO population with $T_J > 3$, which, as we have seen, dominates the impact rate relative to the genuine JFC population.

There are three phases in solar system history when cometary objects might have been implanted in the main belt. The first phase occurs very early, prior to the formation of the giant planets. Icy bodies, accreted at the snow line, might have migrated inward due to gas drag (*Cyr et al.,* 1998). Because gas drag is important only for bodies smaller than a few kilometers in size, most of these icy bodies should not have survived to modern times. In fact, the collisional lifetime of bodies of this size in the main belt is smaller than the solar system lifetime (*Bottke et al.,* 2005). However, they or their fragments might have been incorporated into bigger bodies forming *in situ* (namely within the snow line, in the asteroid belt), delivering a significant amount of water to these objects (*Cyr et al.,* 1998). These water-enriched bodies could be transition objects between asteroids and comets (D-type asteroids?), and the meteorites released by them could be proxies for real cometary meteorites.

The second phase of implantation of comets in the asteroid belt occurred as soon as Jupiter formed. The scattering action of Jupiter dislodged the comets from their formation region in Jupiter's vicinity, making them evolve into JFCs. However, due to gas drag, the smallest members of this group could have had their orbital eccentricity reduced, reaching stable orbits in the asteroid belt. Again, due to the small sizes of these objects, only a tiny fraction of them should survive in the present-day asteroid belt. However, some bigger cometary objects might have been decoupled from Jupiter and inserted onto stable orbits by interaction with the numerous planetary embryos that should have existed at the time in the asteroid belt. Actually, the model postulating the existence of planetary embryos is the best one to explain the current properties of the main asteroid belt (*Petit et al.,* 2000). The possibility of capture of comets by embryos has never been explored in detail. This dynamical path has not been investigated yet, but should be analogous to that recently developed by *Bottke et al.* (2006) for the implantation of iron meteorite parent bodies from the terrestrial planet region into the asteroid belt. The cometary bodies implanted in the asteroid belt by this mechanism are not necessarily small, and therefore some might have survived up to the present time. These bodies would be genetically related with some of the Oort cloud objects (and therefore with some LPCs and HTCs), as a fraction of the Oort cloud was built from planetesimals originally in the Jupiter-Saturn zone (*Dones et al.,* 2004).

The third phase of implantation of comets should have occurred during the late heavy bombardment (LHB) of the inner solar system. Recent work by *Gomes et al.* (2005)

showed that the LHB may have been caused by a phase of dynamical instability of the giant planets, which destabilized the transneptunian planetesimal disk (see chapter by Morbidelli et al. for a detailed description of that model). *Morbidelli et al.* (2005) showed that during this phase of instability some of the originally transneptunian bodies should have been captured as permanent Trojans of Jupiter (see chapter by Dotto et al. for more details). In a similar way, transneptunian objects (TNOs) could also be captured in the outer main belt and in the 3:2 resonance with Jupiter (where the Hilda asteroids reside now). Figure 1 compares the semimajor axis and eccentricity distribution of the trapped bodies (Fig. 1b) with that of all known asteroids (Fig. 1a). The bodies trapped during the LHB should be genetically related to Kuiper belt/scattered disk bodies, and therefore with JFCs and Trojans.

D-type asteroids are the best candidates to be implanted cometary bodies, due to their spectral similarities with dormant cometary nuclei (see section 4.2). The objects captured during the LHB should have semimajor axes larger than 2.8 AU (Fig. 1). Those captured during an earlier phase might have, in principle, smaller semimajor axes. With the exception of one object with a ~ 2.25 AU, the currently known D-type asteroids in the main belt reside beyond 2.5 AU (see Fig. 1a). Five of them have a semimajor axis between 2.6 and 2.8 AU; the remainder (on the order of 20 objects) are beyond this threshold. According to the NEO model of *Bottke et al.* (2006), the outer main-belt asteroids (defined as objects with a > 2.8 AU) should contribute only ~10% of the asteroidal impacts on Earth. Because D-type asteroids are less than 50% of the outer belt population, even assuming that all D-type objects have a cometary origin, we should conclude that the putative cometary population trapped in the outer belt does not account for more than 5% of the total meteorite impacts.

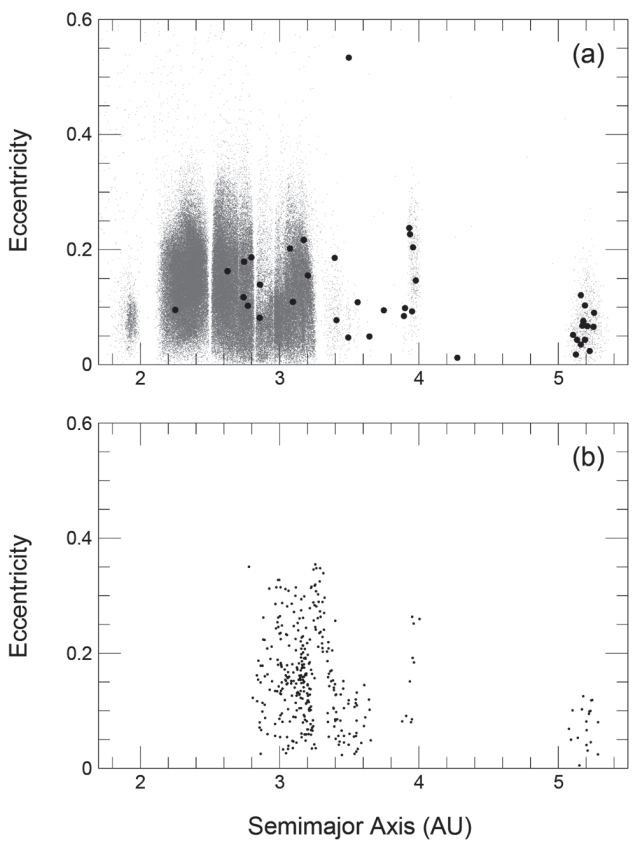

Fig. 1. **(a)** Semimajor axis vs. eccentricity distribution of main-belt asteroids (small gray dots) and of known D-type objects (large black dots). **(b)** Distribution of the particles of transneptunian origin captured in the asteroid belt during the late heavy bombardment (courtesy of H. F. Levison).

In conclusion, the indirect dynamical pathway that allows cometary bodies to impact Earth after a long period trapped in the main belt should not account for more than a few percent of objects striking the upper atmosphere. Therefore, from a dynamical point of view, it is not out of the question to have cometary samples in the current meteorite collections, but these samples should be rare.

3. EVIDENCE FROM METEORS AND FIREBALLS

In this section, we explore the possibility of cometary meteorites (i.e., objects larger than a millimeter) surviving atmospheric entry and reaching the ground. Meteor and fireball data help addressing that question in evaluating the fraction of solid materials originating from objects with a putative cometary orbit that reach Earth's surface.

Considering the meteor dataset, *Swindle and Campins* (2004) review the evidence for dense material in lightcurve data recorded from Leonid meteors whose cometary origin is secure. *Murray et al.* (1999) present several lightcurves that have a double-humped appearance, suggesting the presence of a harder portion that ablates later. Less than 10% of the lightcurves show this feature. Given that roughly half the mass of the double-humped meteor appears to be a high density solid, this would suggest that less than 5% of the total mass of cometary meteors is present as hard material. *Borovička and Jenniskens* (1998) also discuss a cometary fireball that had a hard portion continuing after the terminal burst. This harder component corresponds to 1 mg of a 1 kg meteor, approximately the size of a chondrule. This result clearly does not mean that chondrules are contained in comets, but it does suggest the presence of harder particles within them.

Fireball camera networks have the advantage that they record the entry of objects that survive the passage through the atmosphere and might be collected as meteorites. Camera network studies have hugely expanded our knowledge of meteoroid composition. The associated orbital information allows us to discriminate between cometary and asteroidal sources. Given the large dataset of camera network fireballs recorded over the last five decades, do we see evidence for the survival of cometary materials? In an early analysis of fireballs thought to be of cometary origin (based on orbital considerations), *Ceplecha and McCrosky* (1976) and *Wetherill and ReVelle* (1982) suggested that a small fraction of cometary material may survive atmospheric

entry. *Wetherill and ReVelle* (1982) went so far as to suggest that the proportion may be high enough to account for all carbonaceous meteorites. Subsequent work does not support this level of cometary meteoroid survival, but suggests that a smaller portion could survive (see below).

In the Canadian network study, fireball events were categorized based on initial velocity into groups thought to contain (mostly) asteroidal and cometary material (*Halliday et al.,* 1996). There was no suggestion that the groups were exclusive — cometary events were included in the asteroidal group, and vice versa — but it was considered that the groups might have been dominated by one type of material. Although material in the cometary group had generally lower densities than material in the asteroidal group, 25% of the samples in the cometary category, for which a density was estimated, had densities >2 g cm^{-3} (*Halliday et al.,* 1996), raising the possibility that dense material may be contained within the set of cometary meteoroids.

It is important to note that high-density material can survive atmospheric entry even at large entry velocities. An interesting case involves fireball 892 from the MORP network dataset (*Halliday et al.,* 1996). This fireball had an initial velocity of 28.9 km/s, but produced a terminal mass of 62 g. Similarly, *Spurný* (1997) discussed a number of cases from the European Fireball Network. EN251095A "Tizsa" had an initial velocity of 29.2 km/s, and a probable terminal mass of 2.6 kg. Other (less spectacular) cases within this category include EN220405 "Kourim" (an entry velocity of 27.5 km/s, and terminal mass < 0.1 kg), and EN160196 "Ozd" (entry velocity of 25.6 km/s, and terminal mass <0.2 kg). Finally, *Wetherill and ReVelle* (1982) observed this type of event in the Prairie Network fireballs: PN39409 had a high initial velocity (31.7 km/s) and produced a terminal mass, as did PN40460B. All these fireballs are type I events, which represent (by definition) the densest, strongest part of the meteoroid complex. From the events described above it is clear that middle- to high-velocity material may survive to Earth's surface. But it is necessary to stress that entry velocity alone does not provide a robust discriminant between asteroidal and cometary material. As we have seen in section 2, the Tisserand parameter is a more robust criterion for distinguishing cometary and asteroidal bodies. All the events described above have $T_J > 3$, so they are likely to be asteroidal events despite their high entry velocity.

In the context of our current study, possibly the most interesting case comes from the European Fireball Network, discussed by *Spurný and Borovička* (1999). On June 1, 1997, three Czech camera stations recorded a fireball (EN 010697 "Karlštejn") that began its luminous trajectory at 93 km, with a very high initial velocity of 65 km/s. The object had an aphelion beyond the orbit of Jupiter, and was on a retrograde orbit. It has a Tisserand parameter of 0.22. This orbit is typical of HTCs. What makes the object unique is that it penetrated down to an altitude of 65 km above Earth's surface — about 25 km deeper than cometary meteoroids of similar velocity and mass (the European Network has observed ~500 cometary meteoroids on the basis of their Tisserand parameter). The atmospheric behavior of the Karlštejn object is consistent with it being a hard, strong, stony meteoroid. In addition, a spectral record taken at Ondřejov Observatory showed no trace of the sodium line in the Karlštejn fireball — a feature that is prominent in all other meteor spectra. It appears that the Karlštejn meteoroid had an approximately chondritic composition in terms of refractory elements (this does not imply that the object was a CI1 chondrite — many other meteorite groups also have approximately chondritic levels of refractory elements). What is curious, especially for an object on a cometary orbit, is that it was strongly depleted in volatile elements, to a degree not seen in other chondritic meteorites (*Spurný and Borovička,* 1999).

The Karlštejn event currently appears to be unique — we have not found any similar case among all other fireballs from photographic networks (>1000 events). In addition, there is no single event that shows a meteoroid on a clearly cometary orbit surviving atmospheric entry. Based on the meteor data, it therefore appears likely that the proportion of cometary meteorites is less than 1 in 1000. But the Karlštejn event suggests that dense, strong material is contained within comets. Therefore, at least a small portion of cometary material is capable of reaching the surface of Earth intact.

4. A BEST BET: CARBONACEOUS CHONDRITES

Among the meteorites present in our collections, hydrated or low petrographic type carbonaceous chondrites (petrographic type ≤2) are the best candidates for being cometary meteorites (e.g., *Campins and Swindle,* 1998). They indeed conform to the simplest criteria established for recognizing cometary meteorites: They should be dark, weak, porous, have nearly solar abundances of most elements, and have elevated contents of C, N, and H (*Mason,* 1963). C1 chondrites are mainly made of secondary minerals such as phyllosilicates, carbonates, and magnetite. Pyroxene and olivine are extremely rare among these meteorites. C2 chondrites are made of olivine and pyroxene coexisting with secondary minerals such as phyllosilicates and carbonates. Both C1 and C2 chondrites endured extensive hydrothermal alteration on their parent bodies, with the C1s being more altered than the C2s. Below, we develop the most important similarities and differences between carbonaceous chondrites and comets, emphasizing new data. Other relevant aspects of that discussion can be found in *Campins and Swindle* (1998).

4.1. Orbit of the Orgueil CI1 Chondrite

Nine precise meteorite orbits have been determined over the years using camera networks, satellite data, multiple video recordings, and visual observations (e.g., *Brown et al.,* 2004). Except for Tagish Lake (*Brown et al.,* 2000), all these meteorites are high petrographic type ordinary and enstatite chondrites. All originate from the asteroid belt.

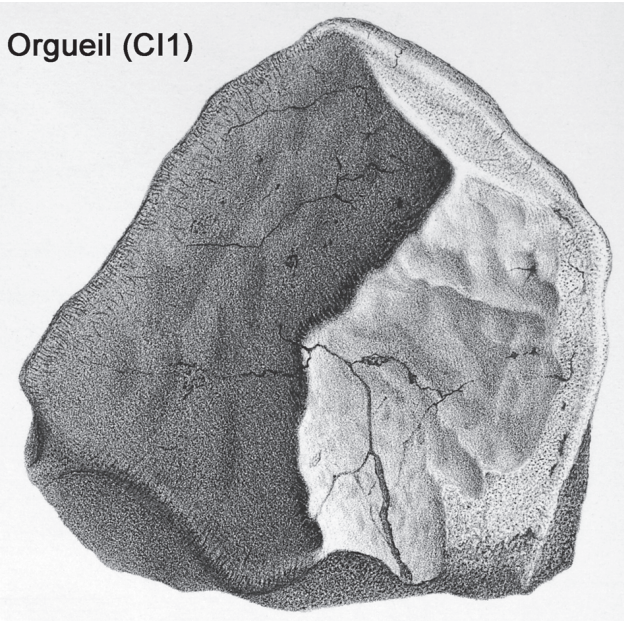

Fig. 2. Hand drawing of the Orgueil meteorite made by Daubrée at the time of the meteorite fall (1864). The orbit of the Orgueil meteorite was demonstrated to be compatible with that of a JFC (*Gounelle et al.,* 2006). If there are any cometary meteorites among our meteorites collections, CI1 chondrites such as Orgueil are the best candidates (see section 4).

Recently, the orbit of the Orgueil (CI1) meteorite was calculated using numerous visual observations communicated shortly after its fall (May 14, 1864) to the main mineralogist of the time, Auguste Daubrée (Fig. 2). Taking into consideration 13 visual observations, *Gounelle et al.* (2006) suggested that the orbit of the Orgueil meteorite was more compatible with that of a JFC than with that of an asteroid (aphelion Q > 5.2 AU and inclination i ~ 0°). Clearly, given the nature of the input data (150-year-old visual observations), this conclusion is more a best informed guess rather than a certainty. *Gounelle et al.* (2006) argue that if Orgueil has a cometary origin, it might also be the case for related carbonaceous chondrites such as other CI1 chondrites, Tagish Lake (ungrouped C2), or even CM2 chondrites. We note, however, that the orbit of Tagish Lake is asteroidal (*Brown et al.,* 2000), and that its cometary origin is possible only if it represents a comet that was trapped in the main asteroid belt (see section 2). This possibility is strengthened by the fact that Tagish Lake is similar to D-type asteroids that might be trapped outer solar system objects (see section 2).

4.2. Spectroscopy and Photometry Evidence

The direct comparison of carbonaceous chondrites' near-infrared spectra with that of KBOs or cometary nuclei might be meaningless for several reasons. First, cometary and KBO surfaces are subject to space weathering, i.e., modification of the surface optical properties due to micrometeorite impact or irradiation by the solar wind and galactic cosmic rays, that compromises a relevant comparison with the laboratory spectra of chondrites (e.g., *Jedicke et al.,* 2004). Second, it is possible that carbonaceous chondrites originate from the interior of a comet or a KBO, and therefore are different from their surfaces sampled by visible and infrared spectrometers. Third, it should not be forgotten that there is growing evidence that comets have a variety of compositions (see section 6.1.), suggesting that the limited number of near-infrared cometary nuclei spectra may not allow any definitive conclusion. Finally, it is now accepted that CI1 (and possibly other) chondrites widely interacted with the terrestrial atmosphere, resulting in a severe modification of their mineralogy (*Gounelle and Zolensky,* 2001), and consequently of their infrared spectrum. The prominent 3-μm feature seen in Orgueil and other hydrated carbonaceous chondrites (*Calvin and King,* 1997) might be enhanced by the ability of Orgueil and other carbonaceous chondrites to adsorb as much as 10 wt% of terrestrial water (e.g., *Gounelle and Zolensky,* 2001, and references therein).

Given the limitations exposed above, we will limit ourselves to mention a few explicit comparisons made in the literature. Tagish Lake near-infrared spectrum is similar to that of D asteroids (*Hiroi et al.,* 2001). Based on dynamical studies (*Morbidelli et al.,* 2005) and on the comparison of their spectra (*Licandro et al.,* 2003), there is a growing consensus that D asteroids and comets might have a common origin (see section 2). The Tagish Lake spectrum is also similar to the Oort cloud Comet C/2001 OG_{108} (*Abell et al.,* 2005). There is therefore a potential link between cometary nuclei and the Tagish Lake ungrouped C2 chondrite. On the other hand, the near-infrared spectrum of Tagish Lake is unlike that of Comet 19P/Borrelly (*Soderblom et al.,* 2004). We note that a relatively good match exists between the spectrum of Comet 162P/Siding Spring and that of the CI1 chondrite Alais (*Campins et al.,* 2006).

Carbonaceous chondrite mineralogy can be compared to the mineralogy of cometary dust as observed spectroscopically, bearing in mind the caveats discussed in the previous paragraph. Crystalline as well as amorphous olivine and pyroxene grains were detected in a variety of Oort cloud comets (*Wooden et al.,* 2005). Most of them are magnesium-rich, as are olivine and pyroxene grains in low petrographic type carbonaceous chondrites. Olivine and pyroxene are present but quite rare in CI1 chondrites (*Bland et al.,* 2004), and more abundant in type 2 chondrites such as Tagish Lake or CM2 chondrites (*Zolensky et al.,* 2002). While phyllosilicates are one of the main constituents of hydrated carbonaceous chondrites (*Bland et al.,* 2004), an upper limit of 1% has been proposed for the abundance of phyllosilicates in the Hale-Bopp dust, based on the montmorillonite 9.3-μm spectral feature (*Wooden et al.,* 1999). Recently, however, the analysis of the dust ejecta of the JFC 9P/Tempel 1 produced by the Deep Impact mission revealed the presence of phyllosilicates (*Lisse et al.,* 2006) (see section 4.5). The 0.7-μm spectral feature, attributed to the Fe^{2+}

to Fe^{3+} transition in phyllosilicates (*Rivkin et al.,* 2002), has also been tentatively identified in the TNO 2003 AZ_{84} (*Fornasier et al.,* 2004).

Comparing the albedo of carbonaceous chondrites to that of cometary nuclei or KBO objects is problematic because data are gathered under radically different experimental conditions (viewing geometries). The albedo of CI1 and CM2 chondrites ranges from 0.03 to 0.05 (*Johnson and Fanale,* 1973). Tagish Lake has an albedo of ~0.03 (*Hiroi et al.,* 2001). This compares well to the range of cometary nuclei geometric albedos, between 0.02 and 0.06 (*Campins and Fernández,* 2002). Centaur and Trojan asteroids have albedos varying from 0.04 to 0.17 (*Barucci et al.,* 2002) and 0.03 to 0.06 (e.g., *Emery et al.,* 2006) respectively. Small KBOs also have low albedos, while larger objects have higher albedos due to the presence of ices (see chapter from Barucci et al.). The hydrated carbonaceous chondrite albedos match those of comets, Trojan asteroids, and small KBOs.

4.3. Isotopic Data

The H-isotopic composition of comets, measured by radio spectroscopy, has often been considered as a key tool for identifying cometary components among meteorites. It is usually admitted that comets are enriched in D relative to the primitive solar system value, Earth, and chondritic meteorites (e.g., *Robert,* 2002). This led several authors to argue that IDPs, rather than carbonaceous chondrites, had a cometary origin based on large D excesses observed at the micrometer scale with secondary ion mass spectrometry (e.g., *Messenger et al.,* 2006).

This view relies on two misconceptions. First, when 2σ error bars (Fig. 3) and most recent measurement of comets are taken into account (*Bockelée-Morvan et al.,* 1998; *Crovisier et al.,* 2005; *Eberhardt et al.,* 1995; *Meier et al.,* 1998), only Comet 1P/Halley is clearly enriched in D relative to CI1 chondrites. We note also that only Oort cloud comets have known D/H ratios, while the D/H ratio of JFCs is unknown. To summarize, although *one* comet is clearly enriched in D relative to chondrites (1P/Halley), it is premature to conclude, as it is often the case, that *all* comets are enriched in D relative to chondrites. Second, it is now clear that the enrichment in D is not limited to IDPs. Recent carbonaceous chondrite studies revealed D enrichments larger than the ones found in IDPs (*Busemann et al.,* 2006; *Mostefaoui et al.,* 2006). This means either that D enrichments in extraterrestrial matter cannot be taken as a proof for a cometary origin, or that these carbonaceous chondrites originate from comets as well. The moderate enrichment in D of *bona fide* cometary samples from Comet 81P/Wild 2 supports the idea that D enrichments are not a definitive proof for a cometary origin (see section 4.5) (*McKeegan et al.,* 2006).

Besides H, the C- and N-isotopic composition of comets is also known (*Hutsemékers et al.,* 2005). The C-isotopic composition of Oort cloud comets and JFCs is identical within error bars to that of Earth (*Hutsemékers et al.,* 2005). This is compatible with bulk measurements of carbonaceous chondrites (e.g., *Robert,* 2002) and IDPs (*Floss et al.,* 2006). Thus, the C-isotopic composition of comets cannot be taken as a reliable indicator of an outer solar system origin. The N-isotopic composition of comets is terrestrial for HCN molecules and enriched in ^{15}N by a factor of 2 relative to Earth for CN radicals (*Hutsemékers et al.,* 2005). Most hydrous carbonaceous chondrites have bulk N-isotopic compositions similar to that of Earth (*Robert and Epstein,* 1982). Some IDPs as well as the anomalous CM2 chondrite Bells have bulk enrichment in ^{15}N relative to terrestrial as large as a few hundred permil (*Floss et al.,* 2006; *Kallemeyn et al.,* 1994). "Hotspots" with enrichments in ^{15}N as large as a factor of 2 (*Floss et al.,* 2006) and 3 were found in IDPs and in the anomalous CM2 chondrite Bells (*Busemann et al.,* 2006) respectively.

To summarize, the isotopic composition of comets is of no help at present to identify cometary meteorites for three fundamental reasons. First, the isotopic composition of comets is not well constrained because of the rarity of precise measurements (D/H ratios) and because it is unknown just how representative are its components (HCN molecules vs. CN radicals for the $^{15}N/^{14}N$ ratio). Second, within error bars, there is a variety of primitive materials (low petrographic type carbonaceous chondrites and IDPs) that have an isotopic composition compatible with that of comets. Third, it should be kept in mind that the spectroscopically measured isotopic composition of H, C, N in comets is that of the gas phase (i.e., ice), while that of putative cometary

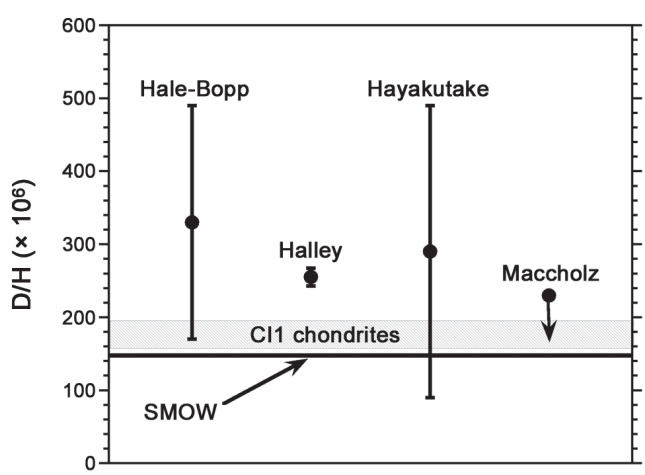

Fig. 3. Hydrogen-isotopic composition of Oort cloud comets (*Bockelée-Morvan et al.,* 1998; *Eberhardt et al.,* 1995; *Meier et al.,* 1998; *Crovisier et al.,* 2005) and CI1 chondrites (*Eiler and Kitchen,* 2004). Error bars are 2σ. Note that the D abundance measured in CI1 chondrites is probably a lower limit as these meteorites are notorious for having adsorbed terrestrial water whose D/H ratio is lower than that of the average value of CI1 chondrites (*Gounelle and Zolensky,* 2001).

samples is that of the solid phase (i.e., dust). Although little fractionation is expected between these phases, were they in equilibrium, these two components might, however, have formed in different loci.

4.4. Organics Record

The organics content of comets is poorly known. Carbon-rich grains that might contain pure C particles, polycyclic aromatic hydrocarbons (PAHs), branched aliphatic hydrocarbons, and more complex organic molecules were detected in the coma of Comet 1P/Halley (*Fomenkova,* 1997). Spectroscopic evidence indicates that amorphous carbon is an important component of cometary comae (*Ehrenfreund et al.,* 2004, and references therein). Indications of the presence of PAHs were seen in a diversity of comets (*Ehrenfreund et al.,* 2004, and references therein). These organic compounds are present in carbonaceous chondrites (e.g., *Gardinier et al.,* 2000; *Remusat et al.,* 2005). *Ehrenfreund et al.* (2001) suggested, on the basis of their amino acid peculiar abundances, that CI1 chondrites originate from comets. We show instead below that the distinctive amino acid population of CI1 chondrites as well as other important organic properties are the result of important parent-body processes unrelated to its asteroidal or cometary nature.

4.4.1. Amino acids. Amino acid compositions in CM2 meteorites display a wider variety in total abundance than in CI1s. However, the relative compositions (with respect to the glycine abundance) are similar. In contrast, the amino acid composition of the CI1 chondrites Orgueil and Ivuna is notably different from the CM2s, and very similar to each other (*Ehrenfreund et al.,* 2001). Glycine and β-alanine are the two most abundant amino acids in these meteorites, with much lower abundances of more complex amino acids. It was shown that relative amino acid abundances are a useful tool to investigate parent body processes (*Botta and Bada,* 2002). The observed differences between CM2s and CI1s prompted the suggestion that these meteorites originate from two completely different types of parent bodies, e.g., extinct comets could be the parent bodies of CI1s. However, it is interesting to note that the Nogoya meteorite, which is the most intensively altered CM2, displays a relative amino acid distribution that may show a trend from that of less-altered CM2s (*Cronin and Moore,* 1976), such as Murchison and Murray, toward that seen for the CI1s. This may indicate that progressive transformation of CM2 amino acids by aqueous alteration could generate the distributions observed in Nogoya and ultimately the CI1s.

4.4.2. Carboxylic acids. Aromatic acids detected in the CM2 Murchison include benzoic and methylbenzoic acids, phthalic and methylphthalic acids, as well as hydroxybenzoic acids (*Martins et al.,* 2006). The CI1 Orgueil, by contrast, displays a more simple distribution of carboxylic acids with abundant benzoic acid but few dicarboxylic acids, phthalic acids, or hydroxybenzoic acids. The distributions of carboxylic acids in the two meteorites can be attributed to the different levels of parent-body aqueous alteration affecting a common starting material. For instance, oxidation reactions occurring during the aqueous process could have selectively removed aliphatic carboxylic acids from the more extensively altered CI1 Orgueil (*Sephton et al.,* 2004), and a similar process may have removed the methyl and methoxy substituents of benzoic and phthalic acid units to leave behind the simple benzoic-acid-dominated distribution (*Martins et al.,* 2006).

4.4.3. Macromolecular materials. Macromolecular materials are relatively intractable organic entities and, as such, should provide a more robust record of aqueous transformations than is provided by free compounds. Hydrous pyrolysis of macromolecular material from Orgueil (CI1), Cold Bokkeveld (CM2), and Murchison (CM2) all contain volatile aromatic compounds with aliphatic side chains, hydroxyl groups, and thiophene rings attached (*Sephton et al.,* 2000). The macromolecular materials in these meteorites appear qualitatively similar. However, the pyrolysates show significant quantitative differences, with the pyrolysis products of ether linkages and condensed aromatic networks being less abundant in the more aqueously altered meteorites. In addition, the methylnaphthalene maturity parameter negatively correlates with aqueous alteration (*Sephton et al.,* 2000). These features are interpreted as the result of chemical reactions involving different amounts of water. Hence, the molecular architecture of the macromolecular materials can be explained by varying extents of aqueous alteration on a common organic progenitor.

4.4.4. Stable isotopes. Carbon- and N-isotopic variability within macromolecular materials was exploited by *Sephton et al.* (2003, 2004) to gain an insight into the parent-body alteration history of chondritic organic matter. The stable-isotopic data suggests that all carbonaceous chondrites accreted a common organic progenitor, which may have predated the formation of the solar system (*Alexander et al.,* 1998) or was formed in the presolar nebula (*Remusat et al.,* 2006). It is proposed that the organic starting material exhibited enrichments in the heavy isotopes of C and N and that these were progressively lost during increasing aqueous and thermal processing on the parent asteroid (*Sephton et al.,* 2003, 2004). If this hypothesis is correct, then the level of alteration endured by a carbonaceous chondrite can be assessed by establishing the preservation state of its stable-isotopic enrichments. Laboratory aqueous alteration experiments, performed on isolated macromolecular material from the Murchison CM2 meteorite, support the proposal that isotopic enrichments may be removed during parent-body alteration (*Sephton et al.,* 1998). Parent-body aqueous alteration, it seems, produces predictable and reproducible isotopic features consistent with the alteration of a common organic starting material for CM2 and CI1 meteorites.

With such compelling evidence of an alteration sequence of a common organic progenitor between the CI1 and CM2 chondrites, it follows that the organic content of low petro-

graphic types is not diagnostic of its cometary or asteroidal origin.

4.5. Recent Insights from Space Missions

Stardust is a particularly important mission as it is the only solid sample return mission from a specific astronomical body other than the Moon (*Brownlee et al.,* 2006). Phyllosilicates typical of type 1 and type 2 carbonaceous chondrites were not found among the 25 well-characterized Stardust samples (*Zolensky et al.,* 2006). Magnetite, a typical mineral of CI1 chondrites, was also not identified. Although it is possible that phyllosilicates were destroyed during impact, it is more likely they were not present within the dust expelled by the 81P/Wild 2 cometary nucleus and harvested by the Stardust spacecraft (*Brownlee et al.,* 2006). The most common minerals found in Stardust samples are olivine, pyroxene, and iron sulfides. The wide composition range of olivine and the enrichment in some minor elements such as Mn are compatible with observations of IDPs, micrometeorites, and carbonaceous chondrites (*Zolensky et al.,* 2006). The mineralogy of abundant Ni-poor, Fe sulfides is, however, more compatible with anhydrous IDPs than with any other primitive material [with the exception of two pentlandite grains (*Zolensky et al.,* 2006)]. Some enrichments in D, ^{15}N, and ^{13}C, similar to those found in anhydrous IDPs (*Messenger et al.,* 2006) and in carbonaceous chondrites (*Busemann et al.,* 2006), were also found in 81P/Wild 2 dust (*McKeegan et al.,* 2006). Although we have only preliminary data, the organics record of Comet 81P/Wild 2 show similarities and differences with carbonaceous chondrites (*Sandford et al.,* 2006).

Results from the Deep Impact mission contrast with those of Stardust. On July 4, 2005, a 370-kg copper projectile impacted onto the Comet 9P/Tempel 1 nucleus surface (*A'Hearn et al.,* 2005). Near- and mid-IR observations made onboard the Spitzer Space Telescope revealed a large diversity of minerals (*Lisse et al.,* 2006). The signature of phyllosilicates and carbonates, in addition to the more classical cometary minerals, olivine and pyroxene, has been tentatively identified in the 9P/Tempel 1 dust from a high signal/noise ratio spectrum (*Lisse et al.,* 2006). Before we discuss the presence of phyllosilicates and carbonates in the 9P/Tempel 1 spectrum, we note that their identification does not rely on a search for individual spectral features as is usually the case (e.g., *Crovisier et al.,* 1996), but from the decrease of the residual χ^2 after a fit of the observed spectrum by a modeled spectrum. The weighted surface area of phyllosilicates and carbonates is estimated to be ~14% and 8% respectively. The mineralogy of Comet 9P/Tempel 1 dust (olivine, pyroxene, phyllosilicates, carbonates, sulfides) is not unlike that of CM2 chondrites or Tagish Lake (*Zolensky et al.,* 2002). It is, however, important to note that the magnetite signature was not detected in the dust ejecta of 9P/Tempel 1, and that the identified sulfide, niningerite, is not the typical Fe-Ni sulfide found in hydrated carbonaceous chondrites (e.g., *Bullock et al.,* 2005).Were the detection of phyllosilicates and carbonates confirmed in 9P/Tempel 1, this would provide a strong link between the nucleus of Comet 9P/Tempel 1 and hydrated carbonaceous chondrites.

The differences between the Stardust and Deep Impact results may be due to the sampling of different size fractions, to the different location of the dust within each comet, and to a strong diversity between cometary nuclei (see section 6.1). The difference between the dust gently released by the sublimation process (coming from the most outer layers of the comet) and the dust coming from the interior is demonstrated by the fact that the pre-impact spectrum of 9P/Tempel 1 dust is different from the post-impact spectrum (*Lisse et al.,* 2006). Only the post-impact spectrum revealed carbonates and phyllosilicates that might have formed in the comet interior.

5. HYDROTHERMAL ALTERATION IN COMETS

The possible cometary origin of CI1 chondrites raises the question of hydrothermal alteration in comets. It is not trivial that water-rich bodies formed in the outer solar system can have been hot enough to permit the circulation of liquid or vapor water. There have been numerous theoretical studies of the thermal history of comets (e.g., *Prialnik,* 1992, 2002; *Prialnik and Podolak,* 1999). The central issue in the context of a possible cometary origin of CI1 chondrites is the likelihood that comet interiors sustained liquid water for times sufficient to generate aqueous alteration of the type seen in CI meteorites (thousands to perhaps millions of years at ~273 K). Answering this specific question is complimentary to the chapter by Coradini et al., which addresses more generally the structure of Kuiper belt objects, and to that of de Bergh et al., who describe alteration minerals present in KBOs. We tackle this problem using a time-dependent energy balance equation for comets.

5.1. Model for the Thermal Evolution of a Comet

Here we will summarize the salient features of the thermal history of comets in the early stages of solar system evolution using a simple heat conduction model. Our basic state is a spherical body composed of rock/dust and water in all its various phases. In such a body there are two principle sources of heat: (1) radioactive decay of short-lived nuclides in the rock and dust and (2) exothermic crystallization of amorphous water ice to crystalline ice. As we are concerned primarily with the temperatures triggering the alteration, we will not include heat sources from reactions associated with alteration itself (reactions that form clay minerals, for example, are strongly exothermic). These two sources of heat are balanced by radiative cooling at the surface of the body and by endothermic phase changes in water such as sublimation and melting of water ice. Note that for

the sake of simplicity, we do not take into account the cratering heat source, which might, however, play a significant role.

With these processes in mind, the temperature variations with time in the comet can be obtained using an energy conservation equation of the form

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + (1-\phi)\frac{Q}{c} \tag{1}$$

where T is temperature; t is time; κ is the bulk thermal diffusivity (m^2/s) at r; r is radial distance from the center of the spherical body (m); ϕ is the volume fraction of all H_2O phases (solid, liquid, gas) combined (a nominal value of 0.7 was adopted for the calculations here); Q is heat production due to decay of the radiogenic heat sources, primarily ^{26}Al and ^{60}Fe (W/kg); and c is the specific heat for rock modified to include the enthalpies of reaction. Equation (1) incorporates latent heats associated with phase changes into a variable specific heat (*Carslaw and Jaeger,* 1959). It is a suitable treatment of the problem where enthalpies of reaction are released over a finite temperature interval ΔT. Accordingly, values for c are specified by the relation

$$\begin{aligned} c = c_{rock} &+ \left(\frac{\Delta H_{xstl}}{\Delta T_{xstl}}\right)\left(\frac{\phi}{1-\phi}\right)\frac{\rho_{ice}}{\rho_{rock}}\xi_{xstl} + \\ X_{sub}&\left(\frac{\Delta H_{sub}}{\Delta T_{sub}}\right)\left(\frac{\phi}{1-\phi}\right)\frac{\rho_{ice}}{\rho_{rock}}\xi_{sub} + \\ &\left(\frac{\Delta H_{melt}}{\Delta T_{melt}}\right)\left(\frac{\phi}{1-\phi}\right)\frac{\rho_{w}}{\rho_{rock}}\xi_{melt} \end{aligned} \tag{2}$$

where ΔH_{xstl} and ΔT_{xstl} are the heat of reaction and temperature interval for crystallization from amorphous to crystalline water ice, respectively; ΔH_{sub} and ΔT_{sub} are the analog values for sublimation of ice; ΔH_{melt} and ΔT_{melt} apply to melting to form liquid water; and ρ_w, ρ_{rock}, and ρ_{ice} are the mass densities of liquid water, rock, and ice. The ϕ and mass densities in equation (2) scale heats of reaction to a per kilogram rock basis and X_{sub} is the fraction of ice subjected to sublimation (see below). The ξ terms are reaction progress variables for each indicated phase change with a range of 0 to 1. For convenience in numerical calculation, these variables can be defined to provide a smooth transition over temperature ΔT using an error function formulation for process i

$$\xi_i = \mathrm{erf}\left(2\frac{T - T_{low}}{\Delta T_i}\right) \tag{3}$$

where T_{low} refers to the lower bound for the temperature interval for the phase transition.

Values for κ are obtained by combining the thermal diffusivities of the individual phases such that

$$\kappa = \phi\kappa_{H_2O} + (1-\phi)\kappa_{rock} \tag{4}$$

$$\begin{aligned} \kappa_{H2O} = \xi_{melt}\kappa_w + (1-\xi_{melt})\kappa_{ice} + \\ X_{sub}(\xi_{sub}\kappa_{vap} + (1-\xi_{sub})\kappa_{ice})) \end{aligned} \tag{5}$$

$$\kappa_{ice} = \xi_{xstl}\kappa_{xstl} + (1-\xi_{xstl})\kappa_{am} \tag{6}$$

In equations (4) through (6), $\xi_{sub} = 1$ when $\xi_{melt} = 0$ and vice versa. Values for Q in equation (1) are obtained using the expression $Q = 6.0 \times 10^{-3}\,(^{26}Al/^{27}Al)_o \exp(-\lambda_{26}t) + 1.2 \times 10^{-3}\,(^{60}Fe/^{56}Fe)_o \exp(-\lambda_{60}t)$, where λ_{26} (λ_{60}) is the decay constant for ^{26}Al (^{60}Fe), $(^{26}Al/^{27}Al)_o$ and $(^{60}Fe/^{56}Fe)_o$ are the initial radiogenic/stable isotope ratios at the time the body accretes, and the pre-exponentials include 6.4×10^{-13} J per decay of ^{26}Al and 3.8×10^{-14} J per decay for ^{60}Fe and typical chondritic concentrations of Al and Fe.

In the calculations that follow the fraction of sublimed ice, X_{sub}, represents the net loss of ice by sublimation from open pore walls in the comet. As a result, condensation of H_2O vapor is excluded as an explicit term in equation (2). The contribution of H_2O vapor to the thermal diffusivity is neglected ($\kappa_{vap} \sim 0$) because its contribution to the bulk diffusivity is minor, although advection of gas is an efficient agent for heat flow (*Prialnik et al.,* 2004).

For simplicity we adopt a fixed-temperature boundary condition across the body (the so-called fast-rotator approximation). The temperature at the outer boundary of the spherical body, T_s, is imposed by radiative heating from the star such that

$$T_s = [((1-A)L_\odot)/(4\pi R^2)/(\varepsilon\sigma)]^{1/4} \tag{7}$$

where R is the heliocentric distance from the star, ε is the surface emissivity (~1), σ is the Stefan-Boltzmann constant ($kg/(s^3\,K^4)$), $L_\odot$ is the solar luminosity (W), and A is the albedo of the comet surface.

Values for the various parameters in equations (1) through (7) are listed in Table 1. They are taken from the literature and are representative of the values used in most comet-related studies. Equations (1)–(6) with boundary condition (7) were solved using an explicit finite difference scheme in what follows.

5.2. Results Relevant to the Formation of Liquid Water

Previous work has shown that the most important control on the likelihood for liquid water early in the life of a comet is the degree of H_2O sublimation. This is because the enthalpy of sublimation is comparatively large and represents a substantial heat sink. For a given surface-to-volume ratio and temperature, the rate of sublimation of water ice is proportional to the difference between the vapor

TABLE 1. Parameters adopted for calculations shown in Fig. 4.

Description	Symbol	Value
Solar luminosity	$L_\odot$	3.83×10^{26} (W)
Surface albedo	A	0.05
Water volume fraction	ϕ	0.7
H_2O sublimation enthalpy	ΔH_{sub}	2.8×10^6 (J/kg)
H_2O crystallization enthalpy	ΔH_{xstl}	-9.0×10^4 (J/kg)
H_2O ice melting enthalpy	ΔH_{melt}	3.3×10^5 (J/kg)
Temperature interval for sublimation	ΔT_{sub}	273 K–180 K
Temperature interval for crystallization	ΔT_{xstl}	273 K–130 K
Temperature interval for melting	ΔT_{melt}	273 K–270 K
Thermal diffusivity of amorphous ice	κ_{am}	3.13×10^{-7} ($m^2\ s^{-1}$)
Thermal diffusivity of crystalline ice	κ_{xstl}	$[0.465 + 488.0/T(K)]/[\rho_{ice}\ (kg/m^3)\ 7.67\ T(K)]$ ($m^2\ s^{-1}$)
Thermal diffusivity of liquid water	κ_{melt}	$[-0.581 + 0.00634\ T(K) - 7.9 \times 10^{-6}\ T(K)]/\rho_w\ (kg/m^3)\ 4.186 \times 10^3)$ ($m^2\ s^{-1}$)
Thermal diffusivity of rock/dust	κ_{rock}	$3.02 \times 10^{-7} + 2.78 \times 10^{-4}/T(K)$ ($m^2\ s^{-1}$)
Mass density of ice	ρ_{ice}	917 (kg/m^3)
Mass density of liquid water	ρ_w	1000 (kg/m^3)
Mass density of rock/dust	ρ_{rock}	3000 (kg/m^3)
Initial $^{26}Al/^{27}Al$ of solar system	$(^{26}Al/^{27}Al)_o$	6×10^{-5}
Initial $^{60}Fe/^{56}Fe$ of solar system	$(^{60}Fe/^{56}Fe)_o$	1×10^{-6}

pressure of H_2O in the void space and the equilibrium vapor pressure. This difference in turn depends upon the details of the gas permeability within the comet. Models suggest that sublimation is limited in the deep interior while it is rampant nearer to the surface with the effect that the comet develops a weak zone composed of a fragile structure of sublimed ice (*Prialnik and Podolak,* 1999).

In order to estimate the amount of melting, one must specify the concentrations of ^{26}Al and ^{60}Fe in the dust/rock comprising the comet upon accretion. The concentration of ^{60}Fe turns out to be relatively unimportant as an agent for forming liquid water in comets as the heat contributed by ^{60}Fe is small in comparison to that provided by ^{26}Al. These initial concentrations depend on the initial $(^{26}Al/^{27}Al)_o$ and $(^{60}Fe/^{56}Fe)_o$ in the protoplanetary disk where the comet ultimately forms, and the time interval between formation of the solar protoplanetary disk and the accretion of the comet, i.e., the "free decay time" for each radionuclide. Some workers have considered the results of a protracted accretion interval (*Merk et al.,* 2002). The essential features of the thermal history can nonetheless be described by considering the free decay time followed by instantaneous accretion.

Weidenschilling (2000) suggested that the time τ required for accretion of planetesimals is expected to have varied across the disk according to the expression $\tau \sim 2000$ (yr) $(R/1\ AU)^{3/2}$. We can therefore consider the melting of water ice in comets as a function of radial distance R from the Sun. The result is that even relatively small bodies on the order of 10 km in diameter (Fig. 4a) could have had liquid water in their interiors if the transport properties of the gas phase allowed for ≤5% of the mass of water ice to be lost to sublimation. We should expect that Oort cloud comets of even small sizes (e.g., 5 km), having formed within the planet-forming region of the early solar system ($\tau \sim 0.02$ m.y.), will have had liquid water in their interiors for perhaps as long as 2 m.y. (Fig. 4a).

Liquid water could have been present in comets formed in or near the Kuiper belt (R > 40 AU), where the free decay time is longer ($\tau \geq 0.5$ m.y.), if their diameters approached 50 km or greater (Fig. 4b), and if the amount of ice sublimed in the interior was restricted to 30% or less by H_2O vapor buildup (Fig. 4b). The combined effects of sublimation and melting could serve to keep the maximum temperatures in the interiors of such comets to near the melting point of water ice several million years. This buffering capacity is overwhelmed for comets formed inside 35 AU (unshown calculations).

The simple models shown in Fig. 4 illustrate the fundamental point that liquid water could have persisted within comets for >1 m.y. Smaller bodies of ~5 km diameter formed in the region of planet formation (e.g., Oort cloud comets) will have contained liquid water in their first few million years if H_2O ice sublimation was limited by restricted gas transport to 5% of total solid water or less. Comets formed further out in the Kuiper belt will have contained liquid water for a million years or more if they formed as bodies with diameters approaching 50 km or more.

CI chondrites appear to have been altered at or very near to the melting temperature of water (*Young et al.,* 1999; *Young,* 2001). An argument can be made that the regulating effect on comet thermal histories by sublimation and the record of aqueous alteration in CI meteorites may be causally linked. Many model calculations, including those in

Fig. 4, result in maximum temperatures at or near the melting point of solid H_2O as a result of a balance between the buffering capacity of enthalpies of melting and the radiogenic heat remaining after sublimation. One can infer that many relatively ice-poor bodies (asteroid precursors) may have had too little water ice to prevent raising liquid water temperatures substantially above the melting point of H_2O. The result may have been aqueous alteration at higher temperatures.

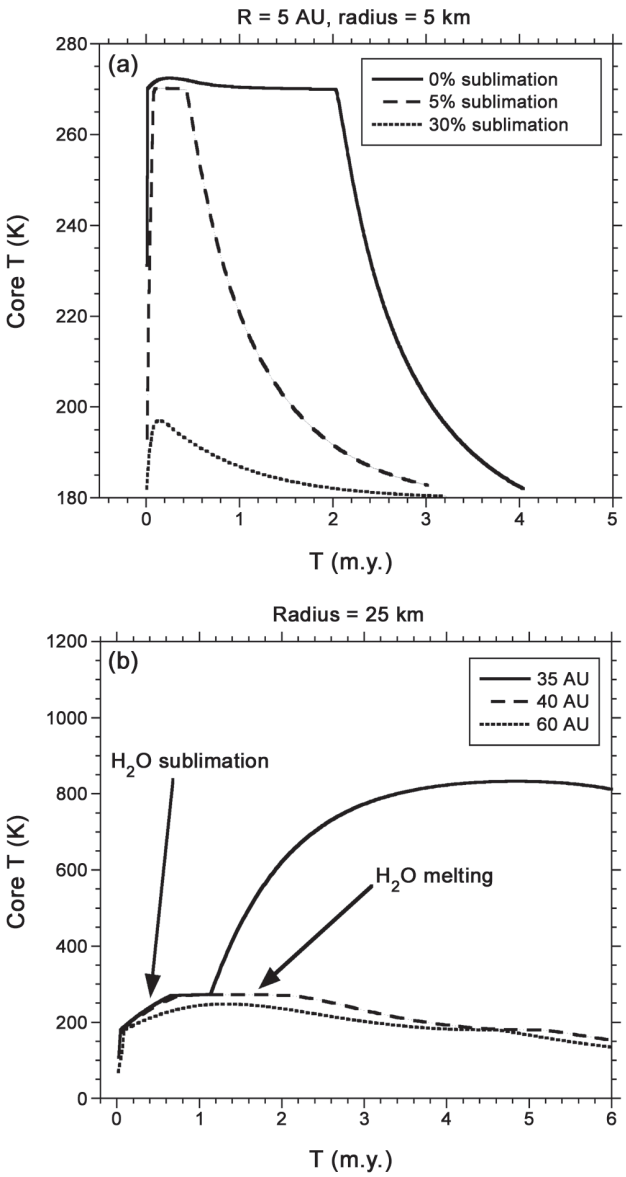

Fig. 4. **(a)** Calculated temperatures at the centre of a spherical comet formed in the planet-forming region at 5 AU as a function of time. The radius of the comet is 5 km. Different curves show the effects of different fractions of sublimed water ice. Results show that, with modest amounts of water ice sublimation, liquid water (occurring where $T \geq 273$ K) is expected to have been present in small comets formed in the planet-accretion region of the solar protoplanetary disk. Calculations are based on equations described in the text and the parameters shown in Table 1. **(b)** Calculated temperature at the center of a 25-km-radius comet as a function of time. Plateaux correspond to the thermal buffer capacity of sublimation and melting of H_2O ice. Different curves refer to accretion of the comet at different distances from the Sun (R) based on the accretion rates of *Weidenschilling* (2000). At R = 35 AU liquid water also begins to heat up substantially.

6. THE ASTEROID-COMET CONTINUUM

In the previous sections, we implicitly assumed that comets were similar enough to each other to be distinguished, either on a dynamical or compositional basis, from asteroids. In the present section, we aim at criticizing that assumption. We will show that the closer one goes to a comet, the more different comets look (section 6.1), and that comets and water-rich asteroids might be more similar than once thought (section 6.2).

6.1. Comet Geological Diversity

Although all active comets undoubtedly share the common property of having a coma and look the same at a distance, it becomes increasingly clear that the term "comet" covers a large diversity of bodies. We already mentioned the fact that this diversity might explain the differences between the dust of 9P/Tempel 1 and 81P/Wild 2 (section 4.5).

The fact that comets are different from one another when looked at in detail is dramatically demonstrated by the different shapes and geological features exhibited by the three cometary nuclei explored by spacecraft (19P/Borrelly, 81P/Wild 2, and 9P/Tempel 1). 81P/Wild 2 and 9P/Tempel 1 are roughly spherical, while 19P/Borrelly and 1P/Halley are elongated (*A'Hearn et al.,* 2005; *Britt et al.,* 2004; *Brownlee et al.,* 2004). Comet 19P/Borrelly is characterized by the absence of impact craters and a diversity of complex geological units (smooth and mottled terrains, mesas) and features (*Britt et al.,* 2004). The dichotomy between mottled and smooth terrains in 19P/Borrelly is not observed in 81P/Wild 2 (*Britt et al.,* 2004; *Brownlee et al.,* 2004). The sculpting of the nucleus of 19P/Borrelly is attributed to sublimation processes (*Britt et al.,* 2004). In contrast, 81P/Wild 2 does not possess as many mesas as 19P/Borrelly (*Brownlee et al.,* 2004). Both 81P/Wild 2 and 9P/Tempel 1 have impact craters (*A'Hearn et al.,* 2005; *Brownlee et al.,* 2004). While the surface of 81P/Wild 2 is cohesive (*Brownlee et al.,* 2004), that of 9P/Tempel 1 is loosely bound (*A'Hearn et al.,* 2005). The geological diversity of comets is in agreement with the significant differences observed in the comets' molecular abundances (*Biver et al.,* 2006) and dust properties (*Lisse et al.,* 2004).

6.2. Continuum Between Asteroids and Comets

Although clear at first sight, the distinction between asteroids and comets might be more complex, as both objects are defined *observationally* and *dynamically*, as well as *compositionally*. Observationally, comets are defined by the presence of a coma of sublimated ice and dust. Dynamically, comets have a Tisserand parameter below 3 (see section 2). Compositionally, comets are ice-rich objects. All

three definitions are linked, since ice-rich objects can develop a substantial coma only if they have orbits eccentric enough to be significantly heated by the sunlight. The limit between asteroids and comets is therefore blurred as, for example, an ice-rich object in a roughly circular orbit might be too far from the Sun to develop a coma and will appear observationally and dynamically as an asteroid, while it would be more of a comet compositionally.

Some objects having the dynamical properties of asteroids look indeed like comets as far as their composition is concerned. The Trojan binary asteroid 617 Patroclus has a density ($\rho = 0.8^{+0.2}_{-0.1}$ g/cm^3) compatible with that of an ice-rich body (*Marchis et al.,* 2006). Asteroid 1 Ceres is possibly made of a water-rich mantle (*Thomas et al.,* 2005). Water ice has been detected in the primitive asteroid 773 Irmintraud (*Kanno et al.,* 2003). The Centaur asteroid 2060 Chiron appears to have a cometary activity when close to perihelion (*Meech and Belton,* 1990). The dark B-type asteroids (3200) Phaeton and 2001 YB_5 are associated with meteor showers, suggesting some kind of so far undetected cometary activity (*Meng et al.,* 2004). Based on their albedos, there is a significant fraction of extinct comets in the near-Earth asteroids population (*Fernández et al.,* 2001). Recently, the existence of a new class of objects, main-belt comets, has been established by *Hsieh and Jewitt* (2006). 133P/Elst-Pizzaro, P/2005 U1 (Read), and 118401 (1999 RE_{70}) exhibit cometary activity, i.e., dust ejection driven by ice sublimation, while they are on asteroid-like orbits (*Hsieh and Jewitt,* 2006). This discovery of main-belt comets or *active asteroids* will probably be followed by others as the technological ability to detect faint comae will increase. The identification of such objects demonstrates the important point we were making above: Cometary bodies are hidden in the asteroid belt because their water emission is too faint to be detected.

It is also worth mentioning that recent results weakened the idea that comets are dirty snowballs. For example, it was recently realized that comets are richer in dust (dust/water ratios >1) (*Keller et al.,* 2005; *Lisse et al.,* 2006) than previously thought (*Lisse et al.,* 2004). It is also known that the active (i.e., water-rich) regions of comets cover a small surface of the nucleus (e.g., *Soderblom et al.,* 2004). If comets are more of an equal mixture of dust and ice rather than a water-rich body peppered with a small amount of dust, what differentiates dust-rich comets from water-rich asteroids? We note that *Clayton and Mayeda* (1999) estimate that water/dust ratios larger than 10 are needed to explain the O-isotopic composition of some carbonaceous chondrites conventionally considered to originate from asteroids. This water content is far larger than the expected water content of comets having water/dust ratios ~1 (*Keller et al.,* 2005; *Lisse et al.,* 2006).

A continuum between comets and asteroids is therefore expected. If we had the technical ability to tow a water-rich asteroid close enough to the Sun, it would undoubtedly display clear cometary activity. If we could observe a comet on sufficiently long timescales (~10^4 yr), we would observe the gradual disappearance of its cometary activity.

7. CONCLUSIONS

Although simple, the question asked at the beginning of this chapter has a complex answer. It is extremely puzzling that, given the ~30,000 samples present in museum collections, it is so difficult to positively identify a cometary meteorite. There can only be two solutions to that thought-provoking paradox. Either there are no cometary meteorites, or cometary meteorites are so similar to some of the asteroidal meteorites that there is no definitive way to identify them.

If no cometary meteorites exist, it means that there is an extremely powerful mechanism preventing them from reaching Earth. That possibility seems unlikely given the numerical simulations of the dynamical evolution of comets. Dynamical studies indeed show that JFCs can find direct and indirect dynamic routes to Earth. The existence of indirect routes (trapping of outer solar system objects in the asteroid belt) is experimentally confirmed by the presence of dormant comets in the near-Earth object population and by the recent discovery of active asteroids. Interestingly, the average entry velocity of these JFCs in Earth's atmosphere is similar to that of asteroids (21 vs. 20 km/s), relieving the caveat of destruction upon impact on the atmosphere (cometary fragments are usually thought to penetrate Earth's atmosphere at a high velocity, generating total destruction). When respective flux, collision probabilities, and entry velocities are taken into account, it appears that the proportion of cometary meteorites relative to their asteroidal counterparts is small but significantly *above zero*. Given that more than 30,000 meteorites are present in museum collections, dynamical observations clearly favor the existence of cometary meteorites. Although fireball observations have failed to positively identify a cometary meteorite so far, there is evidence for solid and dense material (i.e., meteorites) being contained in objects with cometary orbits.

Type 1 (and maybe type 2) carbonaceous chondrites are the best candidates for being cometary meteorites. They are rare, dark, have an unfractionated chemical composition, are rich in volatile elements, and are rich in the light elements H, C, N, and O. The orbit of the Orgueil CI1 chondrite is compatible with that of a JFC. The infrared spectrum of the ungrouped C2 chondrite Tagish Lake is similar to that of D asteroids, which have been linked to comets, while the infrared spectrum of Comet 162P/Siding Spring is not unlike that of the CI1 chondrite Alais. Some differences between comets and low petrographic type carbonaceous chondrites exist, however. The orbit of the Tagish Lake meteorite is asteroidal rather than cometary. The D/H ratio of CI1 chondrites is lower than that of comets, although this discrepancy is based on the *single* measurement of Comet 1P/Halley. The D/H ratio of JFCs is unknown. We also show that the distinctive organics record of CI1 chondrites could be the result of parent-body processes unrelated to its asteroidal or cometary nature. The 81P/Wild 2 cometary samples delivered to Earth by the Stardust spacecraft are unlike CI1 chondrites. On the other hand, the ejecta of the 9P/Tempel 1 exposed by the Deep Impact mission might contain abun-

dant phyllosilicates and carbonates, minerals typical of CI1 chondrites and Tagish Lake. The differences between the two comets illustrates that there might be huge differences from one comet to the other, complicating the task of identifying cometary meteorites.

If CI1 (and some C2) chondrites originate from comets, this has strong implications for the evolution of cometary nuclei. It means that they endured vigorous hydrothermal alteration as recorded by CI1 chondrites. We show that the history of sublimation of water ice is the crucial parameter determining the prospects for liquid water in a comet. Importantly, this alteration would take place in the interior of the comet, meaning that the spectroscopic record, which samples the outer surface of celestial bodies, should be taken with caution. It might also explain why the results of Stardust are different from that of Deep Impact. If comets endured hydrothermal activity and were, to some extent, heated, it also implies that we should keep in mind the provocative possibility that other carbonaceous chondrites [such as CBs, which are enriched in ^{15}N and contain osbornite (TiN), a rare refractory mineral found among Stardust samples] also have a cometary origin.

Although it is possible that some carbonaceous chondrites originate from comets, it is probably not the case for all of them. Dark asteroids such as C types are still a significant source for carbonaceous chondrites. We would argue, however, that there is a continuum between comets and asteroids rather than a sharp distinction. This continuum is easy to understand as the cometary (ice-rich) or asteroidal (ice-poor) nature of a given object depends on its position at formation relative to the snow line. There is no reason for the snow line to have always occupied the same location in the protoplanetary accretion disk, nor to define an abrupt transition between water-poor and water-rich bodies. Type 1 and 2 carbonaceous chondrites might sample the continuum between asteroids and comets. The answer to our question is therefore *yes*.

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