PERSPECTIVES ON THE COMET-ASTEROID-METEORITE LINK

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Abstract. We discuss the possibility that CI and CM carbonaceous chondrites are fragments of extinct cometary nuclei. Theoretical and observational work suggests that comets evolve into asteroids, and several extinct cometary nuclei are now suspected to be among the near Earth object population. This population is the most likely source of meteorites and consequently, we may expect that some meteorites are from extinct comets in this population. The mineralogy and chemistry of CI and CM chondrites is consistent with the view that they originate from asteroidal objects of carbonaceous spectral classes, and these objects in turn may have a cometary origin. We do not suggest that CI or CM chondrites are directly delivered by active comets during perihelion passage or that these chondrites come from cometary debris in meteor streams. Instead, we summarize arguments suggesting that CI and CM chondrites represent fragments of cometary nuclei which evolved into near Earth asteroids after losing their volatiles.

1. Introduction

It is a widely held view that meteorites are fragments of larger asteroidal bodies delivered via near Earth objects (NEOs). With estimated lifetimes of only 1-100 Ma due to collisional destruction, the NEO population must be continuously replenished to explain cratering rates on the terrestrial planets over geologic time and the current meteorite influx (e.g., Shoemaker *et al.*, 1979). The proposal of a cometary source for meteorites via Apollo asteroids has been discussed in the literature, but no firm conclusions have been reached about whether or not some carbonaceous chondrites could be cometary fragments (e.g., Öpik, 1963, 1966; Anders, 1971, 1975; Wetherill, 1971; Wasson and Wetherill, 1979).

Recently, Binzel *et al.* (1998) showed that S-type asteroids are the most likely source of ordinary chondrites, the most abundant meteorites, but we also need parent bodies for other chondrite and achondrite meteorites among the NEO population. As pointed out by Anders (1971), the mineralogy and chemistry of the major meteorite classes are consistent with an asteroidal parent body (e.g., metamorphic temperatures > 400 K). However, he also notes that comets may be sources of some micrometeorites and carbonaceous chondrites.

Orbits have been determined for four ordinary chondrites from camera network observations and their aphelia extend into the main asteroid belt. Such observations are not available for carbonaceous chondrites but would be useful because orbital characteristics may indicate either an asteroidal or cometary source.

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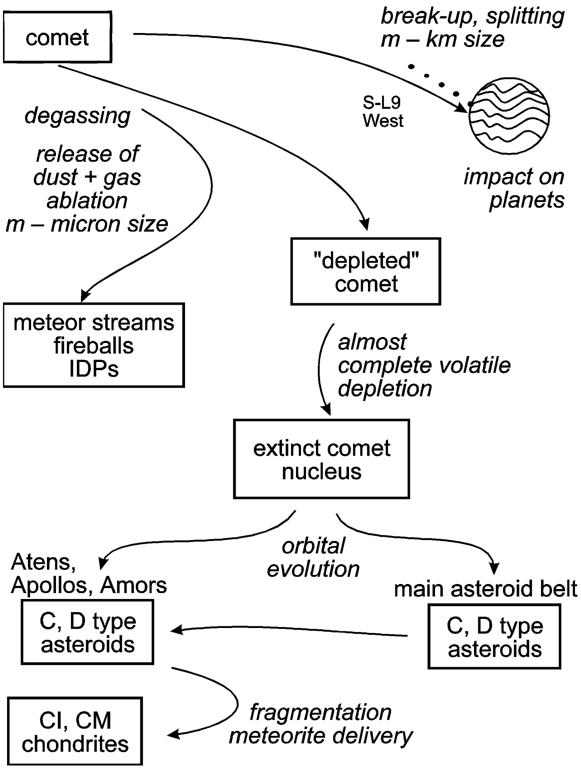

Figure 1. A schematic diagram showing how CI and CM chondrites may be delivered to Earth from extinct comet nuclei. During successive perihelion passages a comet becomes depleted in volatile ices and eventually cometary activity (tail, coma) ceases and only the more refractory cometary nucleus remains. The degassing process leads to ablation and the release of gas and fine-size dust, which leads to the formation of meteor streams. These streams are likely sources for interplanetary dust particles (IDPs) but are unlikely to produce recoverable meteorites. Degassing and cometary splitting (e.g., Comets West and Shoemaker-Levy 9) can also lead to changes in the comet's orbital path and to comet impacts on planets. Extinct cometary nuclei evolve into asteroids of carbonaceous spectral types (e.g., C, D type asteroids). If such cometary nuclei are among the near Earth asteroids (Apollos, Atens, Amors), further collisions and fragmentation may provide the CI and CM chondrites. See text for more details.

The ordinary, enstatite, and carbonaceous chondrites span a wide range in chemical and stable isotope composition and oxidation state, which is surprising if all chondrite parent bodies formed in the asteroid belt. The rare CI (5 falls) and CM (16 falls) carbonaceous chondrites with high contents of carbonaceous and volatile matter and aqueous alteration features may not have originated there.

In the next sections, we discuss the possibility that carbonaceous chondrites of type CI and CM are fragments of extinct cometary nuclei. Figure 1 schematically shows the model of the evolution of a comet to an asteroid delivering meteorites. Section 2 summarizes the arguments in support of comets evolving into asteroids. Section 3 describes the mineralogy and chemistry of CI and CM chondrites, which are consistent with their origin from asteroids of carbonaceous spectral classes, which may have a cometary origin. We are not suggesting that CI or CM chondrites are directly delivered by active comets during their perihelion passage or that these chondrites come from cometary debris in meteor streams. The CI and CM chondrites may represent fragments of cometary nuclei which evolved into near Earth asteroids after the parent comets lost their volatiles. We use the term ”extinct” comets for the degassed cometary nucleus remaining after loss of volatile ices. Extinct comets appear as asteroids, if we adopt the observational definition that an asteroid is a body not displaying cometary activity, such as a coma or tail, during any time on its orbit. Orbital characteristics and surface properties derived from reflectance spectroscopy can be used to genetically distinguish between extinct comets and ”real” asteroids.

2. The Comet-Asteroid Link

Weissman *et al.* (1979) review the possible evolution of comets into asteroids and we limit our discussion to a few examples. Orbital and dynamical studies suggest that both fragments of main belt asteroids and comets replenish the NEO population (e.g., Öpik, 1963; Shoemaker *et al.*, 1979; Wetherill, 1971; 1988). Extinct comets may contribute up to half the NEO sample (Wetherill, 1988).

Observations of nearly extinct comets support these dynamical models. Comets displaying weak activity include 2P/Encke, 28P/Neujmin 1, and 49P/Arend-Rigaux (e.g., Degewij and Tedesco, 1982). One well known example is Comet 107P/Wilson-Harrington, which had a tail but no coma in 1949. This comet was then ”lost” and rediscovered as asteroid 1979 VA.

Several asteroids have cometary orbital characteristics. Kresak (1979), Hahn and Rickman (1985) and Hartmann *et al.* (1987) use the Tisserant parameter (T) with respect to Jupiter to single out asteroids which may be extinct comets (see also Weissman *et al.*, 1979). Asteroids with $T < 3$ among the NEOs include 3552 Don Quixote (T = 2.31) and 1984 BC (T = 2.78). Extinct cometary candidates outside the NEO population include 944 Hidalgo, 5335 Damocles, and 1996 PW (e.g., Weissman and Levison, 1997).

Hartmann *et al.* (1987) find that all asteroids with cometary orbital characteristics are of spectral type C, D, or P, indicating surfaces containing carbonaceous matter. Their comparison includes the D-type cometary nuclei of P/Neujmin 1 and Arend-Rigaux, which are among the candidates for the comet-asteroid transition.

Meteor streams related to asteroids may also indicate that these asteroids were once active comets. One well known example is 3200 Phaethon (spectral class F) associated with the Geminid meteors. Discussions of asteroids with associated meteor streams are given by Drummond (1981) and Olsson-Steel (1988).

3. The Asteroid-Meteorite Link

Meteorite cosmic ray exposure ages are within the dynamical lifetimes of the NEOs. Ordinary chondrites (H, L, LL) show exposure ages ranging from 10 to 30 Ma, while carbonaceous chondrites tend to have younger exposure ages; 0.2 to 8 Ma for CI and CM chondrites, and 2 to 40 Ma for CO and CV chondrites (Mazor *et al.*, 1970; Crabb and Schultz, 1981). Lower exposure ages of CI and CM chondrites may indicate that resurfacing of their parent bodies is faster because they are more friable and less stable against collision than ordinary chondrites.

Asteroids of type C, B, F, and G with silicate hydration spectral features and low albedos indicating carbonaceous surfaces are believed to be parent bodies of CI and CM chondrites. In all carbonaceous asteroids (except the K type) the presence of ice is likely. The presence of ice may be important with respect to low exposure ages of carbonaceous chondrites, because ice coatings can prevent exposure of rocky material to cosmic rays. In that case, irradiation can only occur after sublimation of ice during perihelion passage.

Both comets and C-type asteroids appear to be very porous. The C-type asteroid Mathilde has a density of only 1.3 g cm^{-3} (Veverka *et al.*, 1997), which is lower than the density of hydrous silicates ($\sim$ 2.5 g cm^{-3}). If the low density is due to porosity, about 40-45% of this asteroid is pore space. Similarly, CI chondrites have about 35% porosity and are stable enough to survive passage through the atmosphere. With respect to the stability of such matter passing the atmosphere, it should be recalled that sun-grazing comets survived even passage through the solar corona.

4. The Comet-Meteorite Link: Mineralogy and Chemistry

This section summarizes mineralogical and chemical arguments supporting the hypothesis that CI and CM chondrites are fragments of cometary nuclei. In Table I, we summarize some properties of CI and CM chondrites for reference. CI chondrites are the most chemically primitive meteorites, with elemental abundances resembling those of the solar photosphere. All elements forming compounds more refractory than H_2O have solar abundances in CI chondrites, indicating that CI chondrites were made from material formed in the solar nebula where temperatures were low enough to allow complete condensation of volatiles. The CM parent body also accreted low temperature condensates, but the volatile content in CM chondrites is somewhat lower than in CI chondrites.

Both CI and CM chondrites experienced aqueous alteration on their parent bodies. This means that water (ice) must have accreted to their parent bodies in a low temperature region. The accretion of ice along with rock to the CI and CM parent bodies indicates a similarity between them and comets, which are commonly thought to be assembled from rock and ice. The major unresolved questions are (1)

TABLE I

Selected Properties of CI- and CM-chondrites

Property	CI	CM
number of observed falls	5	16
bulk density, g cm^{-3}	1.6 - 2.2	2.6 - 2.8
porosity, vol%	10 - 35	2 - 23
fraction of fine grained, opaque matrix, vol%	95 - 100	50 - 90
aqueous alteration products and features	phyllosilicates (Mg & Fe-serpentines and chlorites) magnetite, elemental sulfur Mg-, Na-, Ca- sulfates Ca-, Mg-, Fe-carbonates NH_4Cl abundant salt-bearing veins	phyllosilicates (tochilinite, cronstedite, and Mg & Fe-serpentines) some elemental sulfur Mg-, Na-, Ca-sulfates Ca-, Mg-, Fe-carbonates few salt-bearing veins
other minerals and constituents	chondrules absent olivine very rare, with fo$\sim$ 100 pyrrhotite, pentlandite present CAI absent presolar diamonds 1000-1500 ppm	chondrules present olivine present with fo$\sim 98 - 99$ pyrrhotite, pentlandite present CAI present presolar diamonds > 270 to > 750 ppm
elemental abundances	refractory elements* = solar moderately volatile elements = solar highly volatile elements = solar	refractory elements = solar moderately volatile elements $\sim 0.4 - 0.6\times$ solar highly volatile elements $\sim 0.4\times$ solar
bulk water content, wt%	3 - 10	1 - 16
bulk carbon content, wt%	3 - 5	0.8 - 2.8
bulk sulfur content, wt%	5.4	2.7
D/H	$(18 - 20) \times 10^{-5}$	$(14 - 31) \times 10^{-5}$
aqueous alteration T, °C	$<$ 25, 50 - 150 (model dependent)	1-25 (model dependent)
time of aqueous alteration after CAI formation, Ma	50 - 100	not determined
percent of meteorites that are gas-rich	100	57
cosmic-ray exposure age, Ma	0.19 - 8	0.14 - 5.9

CAI = Ca, Al-rich inclusions. fo = mole percent forsterite in olivine.

* refractory elements = Ca, Al, Mg, Si, Fe...; moderately volatile elements = alkalis, halogens, S, Zn...; highly volatile elements = Bi, Cd, In, Tl... .

at which heliocentric distances did comets and the parent bodies of the CI and CM meteorites form, and (2) what is the rock to ice ratio in comets and what was this ratio in the CI and CM parent bodies?

The aqueous alteration conditions required to explain the presence of carbonates, sulfates, and hydrous silicates in CI and CM chondrites have been investigated by DuFresne and Anders (1962) and Boström and Fredriksson (1966). They infer that fluids containing H_2O, CO_2, SO_2, NH_3, H_2S, and organics are required. Clayton and Mayeda (1984) determine temperatures for aqueous alteration of 50 to 150°C for CI, and 1 to 25°C for CM chondrites, depending on the rock to ice ratio assumed. Currently the reactions forming the CO_2, SO_2, NH_3 etc. required for the alteration processes are not well known, but these reactants must have formed from organics, ices, and FeS originally accreted to the CI and CM parent bodies. All these required compounds are observed in comets.

Aqueous alteration after accretion of rock and ice requires a heat source sufficient to melt ice and produce a reactive fluid. Grimm and McSween (1989) suggest a model with ^{26}Al as a heat source. Aqueous alteration and salt formation seem to have occurred early in CI chondrites, supporting this model. Endress *et al.* (1996) determined from ^{53}Cr excesses that carbonates in CI chondrites formed within 20 Ma after Ca-Al-rich inclusions. Macdougall *et al.* (1984) used Rb-Sr systematics to find that aqueous alteration occurred within 100 Ma of formation of the CI parent body. Macdougall *et al.* also find that the Rb-Sr systematics are disturbed and that some of the Ca-sulfate deposits may be more recent. The disturbance of the Rb/Sr isotope systematics in CI and CM chondrites was already noted by Mittlefehldt and Wetherill (1979), who suggest the possibility of partial re-equilibration of Rb and/or Sr after chondrite formation during devolatilization of comets near perihelion. Devolatilization could cause element redistribution during removal of ice mantles and heating of ice plus rock as well as leaching and salt deposition, and formation of duricrust on the cometary core.

Enzian and Weissman (1998) developed thermal models for Comets 46/Wirtanen and 9P/Tempel 1. A cometary nucleus surrounded by a dust mantle may reach 320 K (47°C) at about 1 AU after five perihelion passages. These temperatures compare well to the aqueous alteration temperatures derived for CI and CM chondrites. Repeated heating and melting may cause repeated salt deposition in outgassing fractures or freezing cracks, so that on a small scale a cometary nucleus appears cemented together. This cementing can be compared to that illustrated for CI chondrites in Figure 1 of Richardson (1978) showing carbonate- and sulfate-filled veins and cracks. Due to space limitations, we refer to the detailed discussion by McSween and Weissman (1989) about possible aqueous alteration settings in cometary nuclei.

One open question is whether or not hydrous silicates, carbonates and sulfates are present in cometary nuclei as they are in CI and CM chondrites. The analyses of Comet Halley's dust particles by the PUMA mass spectrometer reveals the presence of Fe-poor, Mg-silicates; probably pyroxene and olivine (Schulze *et* *al.* 1997; Jessberger, this proceedings). Olivine and pyroxene are also detected in cometary spectra (Hanner, this proceedings). CI chondrites contain very few olivine and pyroxene grains and consist mainly of phyllosilicates, a situation not markedly different for CM chondrites (see Zolensky *et al.*, 1997, for the range in CM chondrite alteration). Hydrous silicates are not yet detected in comets, but this does not mean that they indeed are absent in comets. We should keep in mind that spectra sample the outer layer of cometary debris undergoing devolatilization, which may lead to dehydration of hydrous silicates, especially at close heliocentric distances where comets are most visible. It is also necessary to investigate whether or not the PUMA data clearly exclude the presence of hydrous silicates in Comet Halley.

Another connection of comets and carbonaceous meteorites may be derived from the study of interplanetary dust particles (IDPs), which form three major groups: olivine-rich, pyroxene-rich, and phyllosilicate-like IDPs. The last group is often compared to CI and CM chondrites. Sandford and Bradley (1989) argue that the olivine- and pyroxene-rich IDPs are from comets while the lattice silicate-rich IDPs are from asteroids. These conclusions do not necessarily conflict with the scenario that CI and CM chondrites (and hence, the phyllosilicate IDPs) are from extinct cometary nuclei because these nuclei may have evolved into asteroids. For example, such IDPs could originate from the hydrated F-type asteroid 3200 Phaeton, which is associated with the Geminid meteor stream.

We conclude this section with another argument linking CI and CM chondrites, as well as phyllosilicate IDPs, to comets. The CI and CM chondrites possess high D/H ratios of $(18 - 31) \times 10^{-5}$ (Zinner, 1988) which are comparable to the D/H ratios of $\sim 30 \times 10^{-5}$ seen in comets (Irvine *et al.*, 1998). Similarly, phyllosilicate IDPs are known to be strongly enriched in D (Zinner, 1988). These high D/H ratios cannot be explained by formation of the CI and CM chondrites in the asteroid belt because higher temperatures at these heliocentric distances in the solar nebula would decrease the D/H ratios. The high D/H ratios in the phyllosilicates of CI meteorites can only be caused by D-enriched fluids present during alteration. As discussed above, comets indeed possess all the ingredients as well as the high D/H ratios to explain the hydrous alteration features observed in CI and CM chondrites.

5. Outlook

We believe that the arguments above support the claim that CI and CM chondrites are fragments of cometary nuclei. Further work is needed to investigate whether the scenario outlined above also applies in modified form to other carbonaceous chondrites. In situ analyses and samples returned from cometary nuclei might provide proof that CI and CM chondrites originate from cometary nuclei.

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