**SHORT COSMIC-RAY EXPOSURE AGES OF CI AND CM CHONDRITES MAY REFLECT DISINTEGRATION OF VOLATILE-RICH ASTEROIDS AT PERIHELION.** Edward R. D. Scott[1] and Gregory F. Herzog[2], [1] Hawai‘i Inst. Geophysics & Planetology, University of Hawai‘i at Manoa, Honolulu, HI 96822, USA, escott@hawaii.edu, [2] Dept. of Chemistry and Chemical Biology, Rutgers University, Piscataway, New Jersey 08854, USA, herzog@chem.rutgers.edu.

**Introduction:** Cosmic-ray exposure (CRE) ages of meteorites measure the times spent in space by their precursory, meter-size meteoroids. Nearly all CM chondrites have CRE ages of 0.1-5 Myr, while CI ages are slightly longer [1-4]. By contrast, ordinary chondrites and achondrites have CRE ages that are mostly 5-50 Myr. The surprisingly short ages of CI, CM and ungrouped C1 and C2 chondrites are generally attributed to their low strength, although 1) there are weak stony meteorites with long ages such as the L/LL6 Holbrook [5-7], and 2) weak porous bodies may survive hypervelocity impacts better than strong ones [7]—“survival of the weakest” [45].

Most chondrites and achondrites are thought to have been exposed to space following collisions in the asteroid belt where they first drifted under the influence of Yarkovsky thermal forces, and then escaped via a mean-motion resonance with Jupiter into a near-Earth orbit: perihelion < 1.3 AU [9-12]. The shorter CRE ages of CI/CM chondrites, in contrast, have been considered to result from impacts on asteroids already in near-Earth orbits [1] However, such impacts have lowered frequency because of competition from dynamic processes viz., capture by the Sun or planets other than Earth or ejection from the Solar System [9, 10, 13]. Some other process, e.g. tidal disruption near the Earth [13], appears to be required to account for the short CRE ages of CI/CMs.

We propose, therefore, that CI and CM chondrites were exposed to space by the destruction or erosion of volatile-rich asteroids near the Sun [14, 15]. Because Tagish Lake, for example, had a perihelion of 0.9 AU [16], one could argue that perihelion effects are not important for CI and CM chondrites. However, orbits of near-Earth asteroids are very chaotic over periods of more than $10^2$ years so that a large fraction may have had small perihelia in the recent past and most end up in the Sun [8, 10, 22].

**Disruption of volatile-rich asteroids at perihelion:** Two studies of near-Earth asteroids provide direct evidence supporting a near-perihelion liberation of CI and CM meteoroids from their parent bodies. 1) 3200 Phaethon, which is a B-type (C-complex) asteroid with a diameter of 5 km, a perihelion distance of 0.14 AU and semi-major axis of 1.27 AU, appears to be disintegrating due to solar heating at perihelion [18]. Phaethon is dynamically related to two kilometer-sized asteroids and is the source of the Geminid meteors and kilogram mass Geminids, some of which may survive passage through the Earth’s atmosphere. 2) Granvik et al. [14] and Morbidelli et al. [15] found that the proportion of near-Earth asteroids with low albedo (<0.1)—C-complex, P and D asteroids with links to carbonaceous chondrites [19]—increased with increasing semi-major axis. They inferred that low albedo asteroids disintegrate more readily at perihelion as a result of solar heating. Disintegration of volatile-rich dark asteroids near the Sun may result from their greater susceptibility to thermal cracking [20, 21] or disruption due to sublimation of volatiles in the interior. Alternatively, low albedo asteroids may be spun up by the anisotropic emission of thermal photons (Yarkovsky forces) so that they lose mass.

**Perihelion Heating of Meteorites:** If a near-Earth asteroid approached within 0.1 AU of the Sun the surface temperature could reach ~600°C. We might therefore expect to find evidence for solar heating, assuming that the proto-meteorite was located within a few cm of the asteroid/meteoroid surface and that heat effects were not lost (or introduced) by ablation [23]. Evidence for perihelion heating of meteorites can be derived from analyses for various cosmogenic nuclides ($^{10}$Be, $^{26}$Al and $^{36}$Cl) and cosmogenic and radiogenic isotopes of the light noble gases (He, Ne, Ar). For example, petrographic studies showed that the 16 g H/L5 chondrite LaPaz Icefield 031047 was briefly reheated above 700°C after metamorphism then cooled quickly [24]. Noble gas contents for this meteorite gave conflicting CRE ages from which Welten et al. [25] inferred that cosmogenic He and radiogenic $^{4}$He and $^{40}$Ar were lost when the meteoroid was heated ~0.5 Myr ago during one or more close approaches to the Sun.

Several other ordinary chondrites probably experienced solar heating at perihelion. A general association between low $^{21}$Ne contents and $^{3}$He losses among ordinary chondrites suggests that chondrites with short exposure lifetimes may have had small perihelia [26]. Graf et al. [27] identified five H4 and H5 chondrites with low $^{3}$He/$^{38}$Ar ratios in metal grains but normal $^{3}$He/$^{21}$Ne ratios in bulk samples. They inferred that $^{3}$H, a progenitor for about half the $^{3}$He, had diffused out of metal during a close approach to the Sun. The L chondrite, Farmington, which has an exceptionally short CRE age of ~25 kyr [see ref. 2], contains ubiquitous melted metal-troilite grains suggesting ambient heating to ~1000°C, possibly close to the Sun [28]. Iron meteorites with low $^{3}$He/$^{4}$He and microstructural evidence for cyclical reheating and recrystallization of shocked metal at <500°C are also strong candidates for solar heating [29].

**Were CM and CI Chondrites Heated at Perihelion?** There are hints that CI and CM chondrites may have been heated at perihelion as radiogenic $^{40}$Ar and cosmogenic $^{3}$He appear to have been lost concurrently during cosmic ray exposure [30]. Delaney et al. [31] measured $^{40}$Ar/$^{39}$Ar ages of Murchison samples and speculated that radiogenic $^{40}$Ar may have been removed aqueously from an ice-bearing meteoroid (or asteroid). About 20 CM and two CI chondrites contain partially or completely dehydrated phyllosilicates, secondary anhydrous minerals, carbonized organic matter, low concentrations of volatiles, and Fe,Ni minerals that appear to have formed during secondary heating after aqueous alteration [32-36]. Model Rb-Sr model ages for five heated CM chondrites confirm that reheating occurred >3 Gyr after alteration consistent with impact heating during parent body breakup or in some cases, solar heating [37]. U-series isotopic disequilibria also favor recent alteration [46].

**Clues from asteroids Bennu and Ryugu**: Sample return missions to the C-complex asteroids, Bennu and Ryugu, may help to elucidate how and where some CM chondrites were reheated [38]. Unlike Bennu, which has prominent spectral evidence for phyllosilicates like those in aqueously altered CM chondrites [39], Ryugu, has only a weak 2.7 μm hydroxyl feature and low albedo similar to thermally or shock metamorphosed carbonaceous chondrites [40]. Morota et al. [41] infer from Hyabusa2 data that the surface of Ryugu was partly reddened (but not dehydrated) by solar heating during an earlier orbital excursion.

The asteroid Bennu was found by the OSIRIS-REx spacecraft to be emitting particles ≤6 cm in size episodically [42]. Thermal fracturing, phyllosilicate dehydration, and other processes have been invoked. However, Bottke et al. [43] argue that as the particles were ejected near perihelion (0.90 AU), cometary debris impacting at speeds of up to 60 km/s might be responsible. Since the flux of debris is high closer to the Sun, they suggest that the impact of this material together with thermal fracturing and electrostatic levitation [44] may account for the lack of fine material on Bennu and Ryugu as well as the dearth of low-albedo asteroids near the Sun.

**Summary:** The short cosmic-ray exposure ages of CI, CM, and ungrouped C1 and C2 chondrites have been attributed to low strength and inferred susceptibility to destruction by asteroidal impacts. However, the short ages more plausibly result from the disintegration of dark, volatile-rich asteroids near the Sun—a process invoked by refs. [14, 15] to explain the inverse correlation between the albedo and semimajor axis of near-Earth asteroids. Several mechanisms may be responsible for breakup including thermal fracturing, volatile release, impact of cometary debris, tidal stresses, and mass loss due to spin up by Yarkovsky thermal forces or escaping volatiles. Perihelion heating has previously been invoked to explain anomalously low abundances of cosmogenic isotopes in several meteorites and may have affected some CI and CM chondrites.

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