CM CHONDRITES FROM COMETS? – NEW CONSTRAINTS FROM THE ORBIT OF THE MARIBO CM CHONDRITE FALL.

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Introduction: CM chondrites show evidence of early aqueous alteration, suggesting that they accreted beyond the snowline. A cometary origin for CM chondrites have therefore been suggested. The Maribo meteorite is the first CM chondrite with an instrumental record of its fall [1,2]. The observations of the fall makes it possible to determine the preatmospheric orbit of the meteorite and its possible connection to comets. The orbit of Maribo is unusual in the sense that it has a very high eccentricity. It is also one of the few meteorite orbits with a semimajor axis within the main belt. The combination of eccentricity and semimajor axis for the Maribo orbit is not only unusual they are also almost identical to those of Comet Encke. The orbit falls within the Taurids, a massive swarm of objects including the largest object, Comet Encke, several other large NEOs as well as fireball producing objects. If Maribo is genetically related to these objects it implies that CM chondrites are related to comets.

CM chondrites and comets: Extinct cometary nuclei are omnipresent in the inner solar system and could therefore, potentially, be a source of meteorites. Shortperiod comets remain active for approximately 10 ky. After the comet has depleted its source of volatiles the now extinct cometary nucleus remains in the inner Solar System as a member of the near Earth population. This group of objects have dynamical lifetimes of ca. 100 My and could therefore serve as a source of meteorites long after they became extinct. Provided fragments of these objects can survive atmospheric entry, we should expect to see samples of extinct nuclei in our collections of meteorites.

CI and CM chondrites show ubiquitous evidence of aqueous alteration of their components. Other groups of chondrites have also been aqueously altered but not to the same extent as CI and CMs. These two groups are therefore the most likely candidates as samples of extinct cometary nuclei. Studies comparing the available information on chemistry and petrology of comets and chondrites have suggested that CI and CM chondrites could represent samples of extinct cometary nuclei [3,4].

Evidence from Stardust and Deep Impact: Spitzer Space telescope observations of the Deep Impact ejecta from comet 9P/Tempel 1 gave the first data on the mineralogy in the interior of comets. The observations demonstrated the presence of crystalline silicates, carbonates and phyllosilicates [5]. The crystalline silicates (olivine and pyroxene) require annealing temperatures up to 1400 K and thus demonstrate the presence of materials processed at high temperatures. Carbonates and phyllosilicates were a surprising discovery as they can can only form in the presence of liquid water.

The Stardust mission collected and returned samples of the tail of comet 81P/Wild 2. The returned samples include pyroxene and olivine grains similar to those found in carbonaceous chondrites [6]. A single CAI-like particle was also discovered. The CAI is more finegrained but otherwise similar to those seen in carbonaceous chondrites. The Stardust samples also shows sulfide minerals which show evidence of aqueous activity. The sulfide minerals must have formed in a low temperature aqueous environment [7]. The sulfides are similar to sulfides found in CI chondrites .

Astronomical observations: Astronomical observations have also provided new data on the composition of comets that allow us to further test a connection to chondrites. D/H ratios in water detected in the tails of Halley and Hyakutake are ca. 30 10^{-5} [8]. This is within error of the D/H ratios measured in CM chondrites (18-20 10^{-5}) [9].

The preatmospheric orbit of Maribo: The fall of the Maribo meteorite was recorded by a surveillance video camera, an all sky camera, a meteor radar observatory as well as numerous eye witnesses. The observations made it possible to determine the entry velocity and the trajectory through the atmosphere. The entry velocity was 28.5 km/s, which is the highest observed for a meteorite producing fireball. The observations allowed a very accurate orbit to be determined with a= 2.23 AU, e =0.80, and I = 0.26°. The orbit determined for Maribo allows a first test of a possible dynamic link between CM chondrites and comets. The semimajor axises and the eccentricities are very near identical for Maribo and Encke whereas Enckes inclination (11.76°) is much bigger than Maribo's. However, objects with very high eccentricities, such as Maribo and Encke, undergo periodic variations in inclination of as much as 20° with a period of a few thousand years [10]. The near identical semimajor axis and eccentricities for Maribo and Encke therefore constitute a strong argument in favor of a connection between the two bodies - despite the differences in inclinations.

Accretion and heating of icy planetesimals: Aqueous alteration of parent body components require that there was a heat source present to melt the ice. With ^{26}Al as the preferred heat source, accretion would have to be early in order for ^{26}Al to be sufficiently abundant to melt the ice. One class of objects may be particularly relevant in connection with CM chondrites. The fast formation of Jupiter and Saturn implies that these planets developed solid cores of 10-15 $M_{\oplus}$ within ~1 My after the birth of the Solar System. The fast growth of planetesimals feeding into these cores were likely facilitated by the presence of ice beyond the snowline. Icy planetesimals formed at this early stage included live ^{26}Al suffiently abundant to cause melting in planetesimals with diameters larger than ~10 km. If some of these early planetesimals escaped accretion to Jupiter and Saturn we should expect to see icy bodies with evidence of early melting. Icy planetesimals accreting within 1 My after CAIs would include sufficient ^{26}Al to not only melt but also vaporize a significant fraction of the water [11]. This could lead to explosive disruption and/or ejection of aqueously altered material [12]. Subsequent accretion of these altered materials together with unaltered components may help explain the diversety of alteration features observed in CM chondrites.

Aqueous alteration features in CM chondrites: CM chondrites display a large diversity of aqueous alteration features ranging from pristine phases to completely altered phases. Altered phases are often rimmed by fine-grained dust and often found in close contact with unaltered phases.

The diverse aqueous alteration features in CM chondrites have been attributed to pre-accretion alteration in the nebula [13], local variations in liquid composition during alteration in a single parent body [14], and accretion of altered phases from multiple generations of parent bodies [15]. The latter model allowed for the components to be coated with nebula dust prior to the final accretion event. The disruption of the earlier parent body was assumed to be due to an impact but disruption due to explosive release of volatiles [12] would have similar consequences and would also allow the altered components to reenter the nebula and acquire dust mantles.

The age of the Taurid complex: If Maribo is genetically linked to the Taurids, as the orbit of Maribo suggests, then all of the other CM chondrites should also be linked to the Taurids. Peaks in the cosmic ray exposure ages of CM chondrites suggest their parent body suffered several large disruption events 0.2, 0.6, and 1.5 My ago [16]. This is difficult to reconcile with the proposed origin of the Taurid complex.

Due to the high eccentricity of the objects in the Taurid complex their orbital elements evolve on short timescales. A number of streams (objects with near-identical orbital elements) within the complex, have therefore been inferred to have young ages. It has been suggested that the source of the Taurid complex was a large comet disruption event only 20-30 ky ago [10]. However, if the CM chondrites come from the Taurid complex its age must be at least a few million years to be consistent with the exposure ages.

If the complex is several million years old the streams must represent more recent disruption events. Comets are known to undergo fragmentation events at a rate of once every hundred years [17]. These events are either triggered by tidal interactions, rapid rotation or happen for unknown reasons [18]. It is therefore possible that the streams are due to recent fragmentation of Taurid members and not related to the original formation of the complex. If this is true the age of the complex itself could be much older – consistent with the exposure ages of CM chondrites.

Conclusions: The similarity between the unusual orbits of Comet Encke and Maribo supports earlier suggestions that CM chondrites could come from comets. The similar orbits suggest that Maribo and the other CM chondrites are dynamically liked to comet Encke and other members of the Taurid complex. The properties of CM chondrites are consistent with a cometary origin in icy planetesimals that formed at an early stage, beyond the snowline. Early accretion of the bodies allowed for subsequently heating by ^{26}Al. However, if the CM chondrites originate from the Taurid complex the age of the complex must be significantly higher than previously assumed.

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