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Review of asteroid-family and meteorite-type links

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Abstract. The materials of large asteroids and asteroid families are sampled by meteorites that fall to Earth. The cosmic ray exposure age of the meteorite identifies the collision event from which that meteorite originated. The inclination of the orbit on which the meteoroid impacted Earth measures the inclination of the source region, while the semi-major axis of the orbit points to the delivery resonance, but only in a statistical sense. To isolate the sources of our meteorites requires multiple documented falls for each cosmic ray exposure peak. So far, only 36 meteorites have been recovered from observed falls. Despite these low numbers, some patterns are emerging that suggest CM chondrites originated from near the 3:1 resonance from a low-inclined source (perhaps the Sulamitis family), LL chondrites came to us from the ν_6 resonance (perhaps the Flora family), there is an H chondrite source at high inclination (Phocaea?), and one group of low shock-stage L chondrites originates from the inner main belt. Other possible links are discussed.

1. Introduction

Our meteorites are the remains of meteoroids that were created during a significant cratering event on a large asteroid or during the disruption of a small asteroid. Those are discrete events in time.

The cosmic ray exposure (CRE) age of a meteorite measures the time since that event took place. It is the time since the meteoroid was no longer shielded from exposure to cosmic rays by several meters of overlaying burden. CRE ages have been measured for many meteorite types (Eugster *et al.* 2006), and they show distinct peaks (Fig. 1).

Peaks are broadened by measurement error, by two-phase exposure (where material was pre-exposed near the surface before being excavated), and by later disruptions into smaller meteoroids. Even so, it appears that most of our meteorite classes originated in more than one collision event (tentatively labeled A, B, C, ... in Fig. 1, in order of their contribution to the influx on Earth).

The CRE diagrams are dominated by the biggest collision events in the past 10s of millions of years (Ma). Some classes have dominant events that must have been impact craters of at least about 10-km in size, or disrupted asteroids that were at least about 1-km in size, in order to create sufficient debris to impact Earth. The influx does not seem to be dominated by a background of smaller collision events, which would create a continuous age-distribution with a shape determined by the timescales on which 0.5 – 5 m sized meteoroids diffuse from their source region into resonances, and subsequently evolve dynamically to reach Earth.

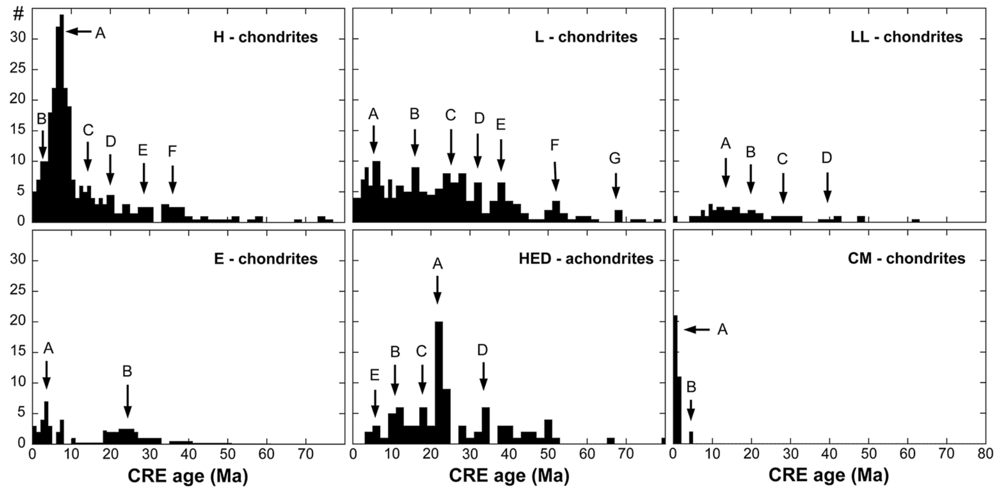

Figure 1. Cosmic ray exposure age distributions for six meteorite classes. Data from: Eugster *et al.* 2006.

2. Methods

When evolving for 5 – 50 Ma, most meteoroids will impact Earth on orbits that still have a semi-major axis close to the delivery resonance (Fig. 2). They will also mostly still have an inclination close to that of the source asteroid. Asteroid families, as well as large asteroids, have the most surface area for collisions, more so than the background asteroids (Dermott *et al.* 2018). That identifies a discrete number of potential source regions for the individual CRE peaks in Fig. 1. The spectroscopic properties of those asteroids can further constrain which asteroids or families are good candidates.

To find the source asteroids and asteroid families, we need to measure a statistically relevant sample of impact orbits of observed meteorite falls to identify the delivery resonance and inclination of the source for each meteorite type with given CRE age peak. Figure 1 tentatively identifies at least 25 collision events for just these six meteorite

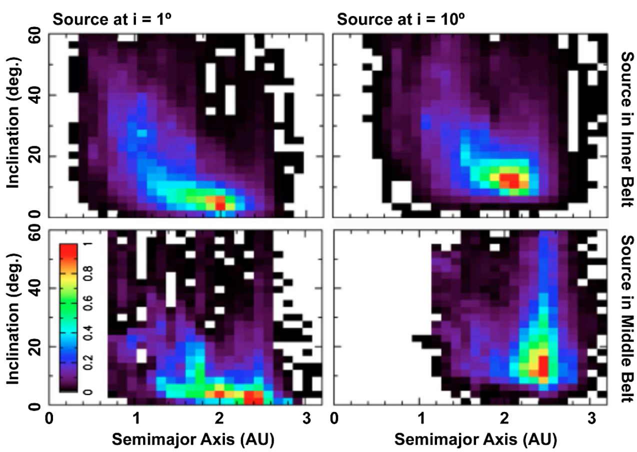

Figure 2. Relative density of Earth impact orbital elements for 20-cm meteoroids that were ejected from the Inner Main Belt (2.1-2.4 AU) or Central Main Belt (a = 2.55-2.85 AU) at initial inclinations of 1 and 10 degrees, respectively. Meteoroids are followed to perihelion distance q < 1.1 AU for 50 Ma, in calculations by David Nesvorny (priv. corr.), using methods by (Nesvorny *et al.* 2009).

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classes. Figure 2 shows that while the semi-major axis tends to cluster near the delivery resonance (a = 2.0 AU for the ν_6 secular resonance and a = 2.5 AU for the 3:1 mean-motion resonance), there is a wide tail to each distribution following close encounters with the terrestrial planets.

3. Results

As of today, only 36 meteorite falls have been observed well enough to derive a pre-impact orbit. Several case studies are ongoing. Even so, some patterns are already emerging (Fig. 3). The two *CM chondites* Sutters's Mill and Maribo show low-inclined eccentric orbits that appear to originate in the 3:1 mean motion resonance (Jenniskens *et al.* 2012). Recently, two *LL chondrites* were observed to fall, Stubenberg and Hradek Kralove, that have a similar short orbit as Chelyabinsk pointing to an origin in the ν_6 resonance (Popova *et al.* 2013). Dingle Dell is classified as an L/LL5 chondrite (Eugster *et al.* 2006), but has an L-like orbit.

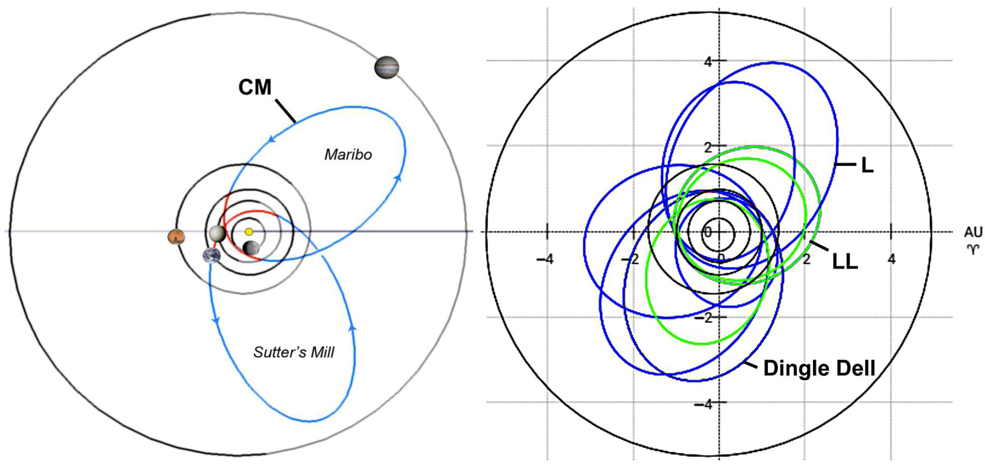

Figure 3. Orbits of CM chondrites (left) and both LL and L ordinary chondrites (right).

Most observed *L chondrites* appear to come from longer orbits, arriving from both the ν_6 and 3:1 resonances (Fig. 3). Recent work on Creston showed that there is a source of L chondrites of moderate shock stage that originated in the inner asteroid belt. This group lacks the 470 Ma K-Ar age found in many shock blackened L chondrites (Jenniskens *et al.* 2018).

H chondrites stand out because so far three have been found on steeply inclined orbits (24 - 32 degrees), some on short orbits. These may be the source of the 7 Ma CRE peak (source A in Fig. 1), because the only observed H chondrite fall so far with a 7-Ma CRE age had such a high inclined orbit.

4. Discussion

Figure 4 provides an overview of where we are now. Since my previous review (Jenniskens 2013), it has become clear that the Eulelia (and Polana) family lacks water bands in spectra (de Leon *et al.* 2018), which makes the Sulamitis family, in my opinion, a more likely candidate for CM chondrites among the current eight known primitive collisional families located in the inner belt. Like Eulalia, this C-class family also hugs the 3:1 mean motion resonance and is relatively low inclined (de Leon *et al.* 2018). The Eulelia and Polana families may, instead, be the source of our ureilites. The optical

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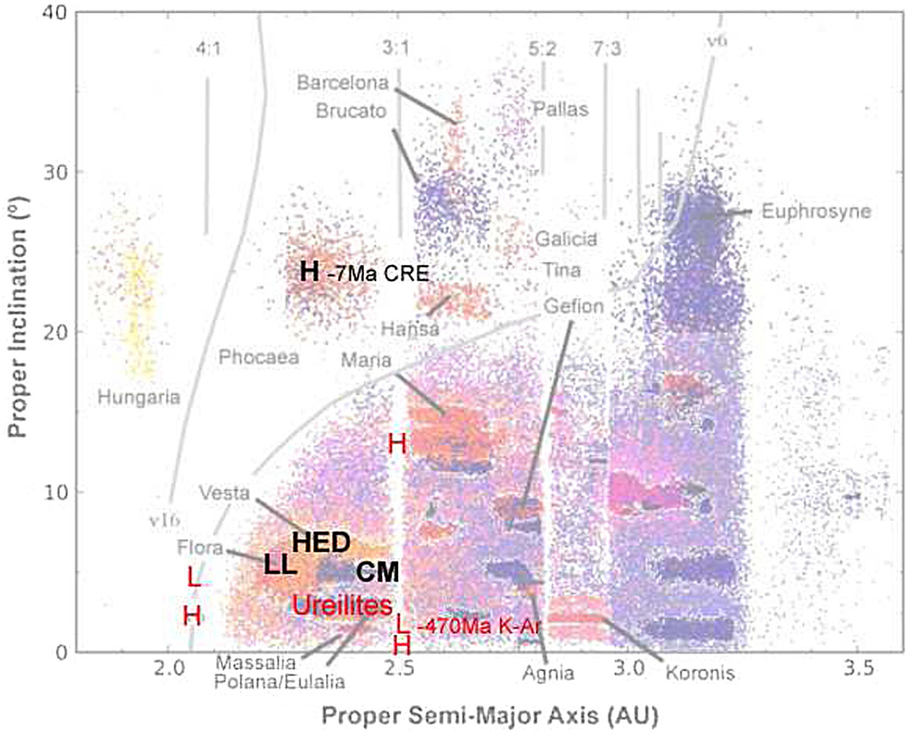

Figure 4. Possible source asteroids and families based on observed meteorite falls. Background image is based on Wise data (Masiero *et al.* 2013)

spectra of Polana-Eulalia B-types (de Leon *et al.* 2018) resemble that of asteroid 2008 TC3 (Jenniskens *et al.* 2010).

Recent work by Granvik & Brown 2018 provides more nuanced insight into the most likely delivery resonance for the first 25 observed meteorite falls. Based on the tabulated results for the high-inclined H chondrites, they suggest these come to Earth from the Hungaria family, or from an inner main belt source via the ν_6 resonance. However, the Hungaria family is poor in S class asteroids. Further dynamical calculations may show that they originated from the Phocaea family via the 4:1 and 3:1 resonances, instead.

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