THE GEFION FAMILY AS THE PROBABLE SOURCE OF THE L CHONDRITE METEORITES. W. F. Bottke [1], D. Nesvorný[1], D. Vokrouhlický[2], A. Morbidelli[3], *(1) Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, Colorado 80302, USA; bottke@boulder.swri.edu , (2) Institute of Astronomy, Charles University, V Holesovickach 2, CZ-18000, Prague 8, Czech Republic, (3) Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, B.P. 4229, 06304 Nice Cedex 4, France*.

Abstract. We show that fragments from the Gefion family-forming event are the probable source of the shocked L chondrite meteorites, which represent about 2/3 of all L chondrite falls. The 100-150 km diameter Gefion parent body, which had semi-major axis $a \approx 2.8$ AU, experienced a super-catastrophic disruption ~ 470 Ma. This event injected tiny fragments immediately into the 5:2 mean motion resonance with Jupiter at 2.823 AU (J5:2) that quickly evolved onto Earth-crossing orbits. They most likely produced the fossil L chondrite meteorites and iridium enrichment found in an ≈467 Ma old marine limestone quarry in Sweden. Since that time, meteoroid precursors from Gefion have collisionally and dynamically evolved down to the J3:1 resonance at 2.5 AU, a better location for meteorite delivery than the J5:2. This would allow meteoroid-sized fragments from the Gefion family to make up a large fraction of all meteorite falls.

Introduction. Nearly 80% of all meteorite falls are ordinary chondrites (OCs) and about 40% of those are L chondrites. Because 2/3 of L chondrites were heavily-shocked and degassed 470 Ma [1], it has been suggested that the L chondrite parent body, which was larger than 100 km, catastrophically disrupted at this time [e.g., 2]. Interestingly, the timing of this shock event coincides with the stratigraphic age (467 ± 2 Ma) of the mid-Ordovician strata where abundant fossil L chondrites, meteorite-tracing chromite grains, and iridium enrichment were found in Swedish marine limestone quarry [e.g., 3]. These shocked and fossil L chondrites likely record the same event and can be used to constrain the identify and location of L chondrite remnants in the main asteroid belt.

We analyzed all existing asteroid families for their potential relationship to this 470 Ma event. Most can be ruled out because they have Yarkovsky/YORP effect-derived ages older than 1 Ga or they have taxonomic signatures incompatible with L chondrites [4]. Further constraints come from the short Cosmic Ray Exposure (CRE) ages of fossil L chondrites and the narrow interval of sediment depths in which they were found. Their derived delivery times of $<$ 1-2 Myr [5] indicate that the breakup event had to occur close enough to a powerful resonance that fragments could be transferred to Earth on this timescale.

Flora Family. Our two main candidates for the source of the L chondrites are the Flora and Gefion families. Flora, however, has many problems. It is located near the ν_6 secular resonance in the inner main belt. To produce the most extreme CRE ages of fossil meteorites (∼50-200 kyr; [5]), meteoroid-sized fragments would have to be launched from the Flora parent body with ejection speeds > 1 km/s [6]. Its olivine/pyroxene composition is also most consistent with LL chondrites [7].

Gefion Family. The Gefion family, on the other hand, is a better fit. We have identified 2240 dynamical family members to date that are located near the J5:2. The age of the Gefion family, according to Yarkovsky/YORP models of family member evolution [8], is 485^{+40}_{-10} My (assuming that family members have bulk densities of 2.0 g cm^{-3} and albedos of 0.2). This formation time is consistent with the 470 Ma shock event of L chondrites, though we caution that our age estimate is sensitive to the precise location of the parent body. Gefion family members have estimated olivine fractions between 62-68%, very consistent with L chondrite values [7]. Finally, the size frequency distribution (SFD) of the Gefion family starts at $D \approx 15$ km, steeply rises down to $D \approx 3$ km and flattens for $D < 3$ km from observational incompleteness. Using SPH/N-body results [e.g., 9], we estimate that the parent body was 100-150 km in diameter and that it experienced a super-catastrophic disruption event. These results are consistent with the above constraints.

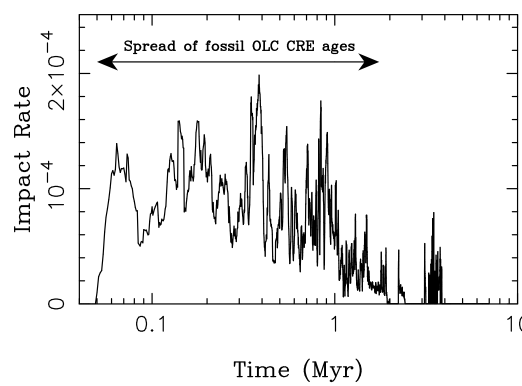

Figure 1. *The impact rate of meteorites from the 5:2 resonance matches the CRE age range of fossil L chondrites (0.05-1.5 Myr; shown by the two-headed arrow). On average, one out of ∼500 fragments inserted into the resonance impacts Earth within 2 Myr after the Gefion family breakup.*

To match the short CRE ages of fossil meteorites (0.05-1.5 Myr) [5], Gefion fragments must rapidly evolve from the main belt to Earth-crossing orbits. To estimate the expected CRE ages of meteorites delivered from the Gefion family, we placed test particles in the J5:2 resonance and used numerical integration results combined with collision probability codes to determine the timing and expected number of impacts on the Earth. Note that speeds of only ≈50 m s^{-1} are required to reach the resonant orbits at $a \approx 2.82$ AU from the core of the Gefion family at $a \approx 2.8$ AU. We found that the first Gefion meteorites arrive on Earth about 50 kyr after they had been placed in the J5:2 resonance and peak between 1-2 My (**Fig. 1**). Therefore, most Gefion meteorites are expected to have CRE ages between 50 kyr and 1-2 Myr and should be spread over ≈1-2 Myr of terrestrial sediments. These findings fit the measured CRE and stratigraphic ages of fossil meteorites.

The CRE ages of most OC meteorites are between ∼5-100 Myr [10]. Because resonant delivery takes <10 My, most OCs must be slowly delivered to resonances via the Yarkovsky effect. We used our code known as TrackMet to estimate the expected CRE ages of recent Gefion meteorites. TrackMet follows Yarkovsky semimajor axis drift of test asteroids and the collisional cascade of 10-cm to 10-km-diameter fragments (via impacts from background objects). Upon reaching the ν_6, J3:1 or J5:2, TrackMet objects can be trapped on resonant orbits with size-dependent capture probability values determined from N-body simulations. Trapped particles are removed from the main belt and produce terrestrial impacts with overall rates set individually for each resonance (1×10^{-2} for ν_6, 2×10^{-3} for J3:1, and 2×10^{-4} for J5:2). We start the CRE clock when a meteoroid first becomes smaller than 3 m in diameter and stop it upon Earth impact.

Our CRE age distribution of Gefion meteorites obtained using TrackMet is consistent with nearly all CRE ages occurring between 5-100 My, with 30-40 My the most common ages (**Fig. 2**). We also note that the most efficient route for Gefion meteoroids to reach Earth at the present time is to evolve from $a = 2.8$ AU down to 2.5 AU and be delivered via the J3:1. This is consistent with previous work suggesting that half of the bolides capable of dropping meteorites should reach the Earth-crossing orbit by the J3:1 [11].

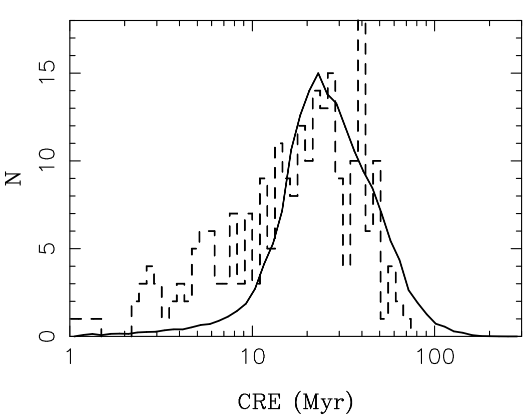

Figure 2. *The comparison between model CRE ages of Gefion meteorites (solid line) and measured CRE ages of recent L chondrites (dashed line). The overall agreement is good, though our model produces a slightly deficient number of meteorites with CRE ages* < 10 *My. We assume a surface thermal conductivity* $K = 0.01$ *W* m^{-1} K^{-1}*, which would correspond to porous or fragmented rocks. The delivery of recent Gefion meteorites to Earth via the J5:2 is inefficient relative to the J3:1.*

Implications. It was previously thought that the OC meteorites mainly sample the inner asteroid belt, the same source region that provides most HED meteorites and NEAs [12]. We find, however, that most L chondrites instead come from $a > 2.5$ AU. Perhaps other meteorite classes also come from parent families in the central/outer main belt.

A potential problem with this work is that Gefion meteoroids exiting the main belt via the J3:1 have a factor of ≈5 lower probability of striking the Earth than meteoroids coming out of the ν_6 resonance [12]. All things being equal, one would expect meteoroids from the ν_6 resonance to dominate meteorite fall statistics. Strangely, though, observations suggest that all things may not be equal. If [7] is correct, the most likely source of the LL chondrites is the large Flora family located near the efficient ν_6 resonance. The fraction of LL falls is ≈3 times smaller than the shocked L chondrites, which we predict are coming from the 3:1 resonance. This raises the question; why are LL chondrites so underrepresented in our meteorite collections relative to the shocked L chondrites?

One way to resolve this problem is to assume that ∼50 times more Gefion meteoroids are currently reaching the 3:1 resonance than the number of Flora meteoroids reaching the ν_6 resonance. This would imply that: (i) the Gefion breakup produced a much larger number of sub-km fragments than the Flora breakup; and/or (ii) the sub-km precursor objects to Flora meteoroids has been efficiently depleted over the Flora family age. Though we lack sufficient constraints to resolve this issue at this time, the fact that the Gefion family was produced by an exceptionally super-catastrophic breakup event may mean its SFD produced many more meteoroid-sized bodies than the more mundane Flora family breakup.

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