IS THE (20) MASSALIA FAMILY THE SOURCE OF THE L-CHONDRITES? Michael J. Gaffey[1,2] and Sherry K. Fieber-Beyer[1,2], [1]Space Studies Department, John D. Odegard School of Aerospace Sciences, Stop 9008, University of North Dakota, Grand Forks, ND 58202-9008. [2]Visiting astronomer at the IRTF under contract from the NASA, which is operated by the Univ. of Hawai'i Mauna Kea, HI 97620.Email: gaffey@space.edu

Introduction – The L-chondrites are the most common meteorite type currently falling to Earth and have been among the two most abundant types for the past million years or more. The parent body of the L-chondrites suffered a major shock event ~470 Myr ago as indicated by a pervasive shared shock history among the L-chondrites. The collisional event which produced this shock event may have formed an asteroid family. This event is also recorded in Middle and Late Ordovician marine sediments by a high abundance of fossil L-chondrites, and most probably by a correspondingly high terrestrial cratering rate. Identification of the specific asteroid family that is the source of the L-chondrites would provide several major scientific benefits, including: (a) a quantitative constraint on dynamical models of orbital evolution in the asteroid belt, (b) a spatial constraint on the early solar system location of the conditions and processes preserved in the L-chondrites from the formation epoch, and (c) by extension, a quantitative constraint on the ages of other asteroid families and on the historic rate of large collisions in the asteroid belt.

Background - The asteroid belt is the sole *in situ* population of objects preserving a relatively pristine record of the inner solar system from the formation epoch. Aside from collisional evolution, essentially all the physiochemical processes that affected these bodies occurred during the first few million years of solar system history. Studies of meteorites (*the vast majority of which are fragments of asteroids*) reveal the nature and chronology of these processes and conditions. Asteroids and meteorites provide "ground truth" for theoretical models of the formation epoch and of the subsequent evolution of the inner solar system.

The properties of the different meteorite types were established by conditions present and processes active in their formation locations of the late inner solar nebula and the very early inner solar system. Radiometric investigations of meteorites provide a chronology both relative and absolute for the major chemical and thermal events during the formation epoch.

However there is a serious limitation on the meteoritic perspective. It provides details of **what** happened and **when** it happened but not **where** it happened. It is like an unassembled jigsaw puzzle. It is not possible to clearly see the overall pattern until spatial relationships of the pieces are correctly established. The meteorites in our terrestrial collections have sampled ~135 different parent bodies [1] which formed in at least 135 isotopically, chemically, and/or thermally distinct regions of the solar nebula. Other investigations [2] put the number of different parent bodies between 100 and 150.

Models of the early solar system are constrained by assumptions concerning the spatial relationships of the formation regions for the various meteorite types. Identification of the specific main belt parent bodies of particular meteorite types can help establish the spatial context to assemble the meteorite data into a coherent spatial and temporal pattern of the formation epoch. Despite more than four decades of work, secure identifications have been established for only three meteorite types, the HEDs [e.g. 3,4] and the H-chondrites and IIE irons [5].

Parent bodies of the Ordinary Chondrites - Of particular priority has been on the identification of the ordinary chondrite (H-, L- & LL-chondrites) parent bodies. The ordinary chondrites comprise ~75% of the meteorite falls. Initially, this abundance was considered to indicate that the asteroid belt was dominated by ordinary chondrite assemblages. Since the early 1970's, the search for the sources of the ordinary chondrites has consumed significant observing time and investigator effort. Most preliminary identifications have remained untested or have evaporated in light of subsequent work.

However, dynamical studies demonstrated that the location of potential parent bodies was more important than the abundance of different compositional types in the asteroid belt [6] which showed that chaotic zones adjacent to mean motion and secular resonances are major escape hatches from the asteroid belt. Indeed, it was the proximity of asteroid (6) Hebe to the chaotic zones of both the 3:1 mean motion resonance and the ν_6 secular resonance that led to the proposal that Hebe should be the source of a common meteorite type [7-9]. Analysis of the visible and near-infrared spectra of Hebe concluded that the mineralogy matched that of the H-chondrites [5]. <u>The meteorite data points to a single parent body for each of the meteorite types including the ordinary chondrites</u> [e.g., 1, 2, 10 – 12] The suggestion that "*large groups of compositionally similar asteroids are a natural outcome of planetesimal formation*" [13] is difficult to reconcile with the meteoritic constraint that requires a minimum of ~135 chemically, isotopically, and/or thermally discrete nebular regions for the meteorite parent bodies [e.g. 1, 2].

Gefion Family as the L-chondrite source - Based on dynamical models, the Gefion family as proposed as the source of the L-chondrites [13, 14]. Spectral investigations showed that the Gefion family is not dominated by L-type assemblages as would be expected if it was the source of the L-chondrites [15-17]. The spectral data apparently precludes the Gefion family as the source of L-chondrites. Since the L-chondrites almost certainly derive from an asteroid family, we need to investigate other families, especially families located close to one of the major resonances in the asteroid belt.

Why the 20 Massalia Family? – Four criteria were used to identify specific asteroid families as strong candidates for the source of the L-chondrites.

A) Given the abundance of modern falls and the high Ordovician flux we initially focus on the largest families.
B) Focused on families close to the chaotic zones associated with important resonances in the asteroid belt. For a family close to a chaotic zone, collisional acceleration and the Yarkovsky effect can readily deliver meter-scale meteoroids into the chaotic zone for efficient transfer into near-Earth space. The 3:1 and 5:2 mean motion resonances and the ν6 secular resonance have been identified as the most efficient (fastest) resonances to transfer main belt objects into Earth-crossing orbits [18]. Large families near these three resonances were considered.
C) To be considered as the possible source of the L-chondrites, a family must be of taxonomic type S. By itself, classification of an asteroid as S-type is not diagnostic of an ordinary chondrite assemblage. However, in the S-type taxonomy, the ordinary chondrite assemblages fall into the S(IV) subtype [19].
D) Characterized members of the L-chondrite source family should be subtype S(IV) and compatible with an L-chondrite mineralogy. Ordinary chondrites, and their subtypes such as the L-chondrites, have specific ranges of compositions (mineral assemblages). As a consequence, the various meteorite types have specific ranges of the values of diagnostic spectral parameters (e.g., Band I & Band II Centers, Band Area Ratios – [5, 10]).

Unlike the other large families which were considered, the Massalia family meets all four critical criteria for a strong candidate as the source of the L-chondrites. An additional weaker line of evidence also favors the Massalia Family. The orbital inclinations of the meteoroids producing observed ordinary chondrite falls show a spread of inclinations as would be expected even for meteoroids derived from a single source. The H-chondrites scatter approximately equally to higher and lower inclinations around the orbital inclination of 6 Hebe, the probable H-chondrite parent body. The spread for the H-chondrite falls is ~±16 degrees away from the inclination of 6 Hebe (14.75 degrees). The L-chondrite falls are clustered at significantly lower inclinations suggesting a low inclination source. However, the spread relative to a putative Massalia family source is similar (~12 degrees). If the spread of the H-chondrite fall inclinations is typical for meteoroids transferred into near-Earth orbits from individual main belt sources, the L-chondrite fall inclinations would be consistent with a very low (near zero) inclination source. The Massalia Family is located between 1.09 and 1.89 degrees inclination. This information supports the previous conclusion that the 20 Massalia family is a strong candidate for investigation as the possible source of the L-chondrites.

Our research group has undertaken an observing program to obtain visible and near-infrared spectra of Massalia family members to test this proposal.

References: [1] Keil K. (2000). *Planet. Space Sci.* **48**, 887-903. [2] Burbine T. H. et al. (2002) *Asteroids III* (W. F. Bottke Jr. et al. Eds.), pp. 653-667. University of Arizona Press, Tucson. [3] Drake M. J. (2001) *Meteoritics & Planetary Science* **36**, 501-513. [4] De Sanctis M. C. and 21 members of the DAWN Science Team (2013) *Meteoritics & Planetary Science* **48**, 2166–2184. [5] Gaffey M. J. and S. L. Gilbert (1998) *Meteoritics & Planet. Sci.* **33**, 1281-1295. [6] Wisdom, J. (1985) *Icarus* **63**, 272-289. [7] Farinella P. et al. (1993) *Celest. Mech. Dynam. Astron.* **56**, 287-305. [8] Morbidelli A.(1994) *Astron. Astrophys.* **282**, 955-979. [9] Migliorini F. et al. (1997) *Icarus* **128**, 104-113. [10] Dunn T. L. et al. (2010) *Icarus* **208**, 789–797. [11] Henke S. et al. (2012) *Astron. & Astrophys*. **545**, A135. [12] Delbó M. et al. (2017) *Science* **357**, 1026-1029. [13] Bottke W. F. et al. (2009) *Lunar Planet. Sci. Conf. XXXX*, Abstract # 1445. [14] Nesvorný D. et al. (2009) *Icarus* **200**, 698-701. [15] Blagen J. R. et al. (2012) *Lunar and Planetary Science XXXXIII*, Abstract #1643. [16] Roberts R. (2017) *Testing the Gefion Family as the Source of L-Chondrites*. MS Thesis, Space Studies Dept., University of North Dakota. [17] McGraw A. M. et al. (2018) *MNRAS* **476**, 630–634. [18] Gladman B. J. (1997) *Science* **277**, 197-201. [19] Gaffey M. J. et al. (1993) *Icarus* **106**, 573-602.