Do L chondrites come from the Gefion family?

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ABSTRACT

Ordinary chondrites (H, L, and LL chondrites) are the most common type of meteorites comprising 80 per cent of the meteorites that fall on Earth. The source region of these meteorites in the main asteroid belt has been a basis of considerable debate in the small bodies community. L chondrites have been proposed to come from the Gefion asteroid family, based on dynamical models. We present results from our observational campaign to verify a link between the Gefion asteroid family and L chondrite meteorites. Near-infrared spectra of Gefion family asteroids (1839) Ragazza, (2373) Immo, (2386) Nikonov, (2521) Heidi, and (3860) Plovdiv were obtained at the NASA Infrared Telescope Facility (IRTF). Spectral band parameters including band centres and the band area ratio were measured from each spectrum and used to constrain the composition of these asteroids. Based on our results, we found that some members of the Gefion family have surface composition similar to that of H chondrites, primitive achondrites, and basaltic achondrites. No evidence was found for L chondrites among the Gefion family members in our small sample study. The diversity of compositional types observed in the Gefion asteroid family suggests that the original parent body might be partially differentiated or that the three asteroids with non-ordinary chondrite compositions might be interlopers.

Key words: methods: observational – techniques: spectroscopic.

1 INTRODUCTION

Linking meteorites to their source asteroids is an important goal of planetary sciences. At present, there are less than 10 meteorite types that have been linked to their parent bodies (e.g. Gaffey et al. 1993; Vernazza et al. 2014; Reddy et al. 2015). For example, lunar samples collected from the Apollo missions have been linked to lunar meteorites, Martian meteorites have been linked to surface compositions through information gathered from Martian landers, and HED meteorites (howardites, eucrites, and diogenites) have been compositionally linked to the asteroid (4) Vesta (e.g. Reddy et al. 2012). Ground-based spectral characterization of asteroids would enable us to link these objects with their meteorite analogues in our collection (e.g. Reddy et al. 2012; Sanchez et al. 2015).

Ordinary chondrites (OC) are the dominant meteorite type to fall on Earth and are likely derived from some S-type asteroids. H, L, and LL chondrites are the three types of OC and differ in their metal abundance, silicate composition, and reduction-oxidation (redox) state. A number of parent bodies/families have been proposed for OC (Vernazza et al. 2014). These include asteroid (6) Hebe or the Koronis family for the H chondrites (Gaffey & Gilbert 1998; Sanchez et al. 2015), the Gefion asteroid family for L chondrites (Nesvorny et al. 2009), and the Flora family for LL chondrites (Vernazza et al. 2009). Identifying the formation location of the OC is important for understanding the thermal and redox gradients of the early Solar system.

Constraining the distribution of thermal and redox gradients across the inner Solar system would help us understand the conditions under which our terrestrial planets formed. Silicate mineralogy assemblages often depict planetary processes; they leave behind information that represents temperature and pressure conditions inside a small body or a planet at a given time in its history. By determining the source regions for silicate meteorites such as H, L, LL, primitive achondrites, and basaltic achondrites (BA), a more reasoned understanding of the mineralogical gradient of the Solar system may be obtained. Each of the silicate meteorite types depicts a unique, yet significant, history that indicates different geological associations. For instance, the significance of BA is important when considering that basalt covers 80 per cent of Earth’s surface. Some primitive achondrite meteorites show partial melting features which require high temperature and pressure environments to induce melting of the pyroxene minerals present, likely within a parent body. The Gefion family has been proposed to be the source of the L chondrite meteorites by various authors (Nesvorny et al. 2009; Vernazza et al. 2014). The family lies close to the 5:2 mean motion.
responsible for fossil L chondrite meteorites found in Ordovician Limestone (Haack et al. 1996). Haack et al. (1996) argued that a catastrophic collision 500 million year ago ejected L chondrite material from the parent body into an Earth crossing orbit causing a greater flux of these meteorites at that time. The estimated age of the fossil meteorites is roughly 467 million years, and would have impacted near a critical time for biologically and evolutionary changes for life on the Earth.

In this paper, we present results of our observational campaign to verify a link between the Gefion asteroid family and L chondrite meteorites as proposed by Nesvorny et al. (2009) and Vernazza et al. (2014). Our goal was to use the mineralogy of the observed asteroids derived from their near-infrared (NIR) spectra to verify the link with L chondrite meteorites. We used laboratory spectral calibrations of OC to confirm our results. These new data increase the number of Gefion family members studied so far, which allow us to discuss our results in the context of those presented in previous work (Blagan 2012; Roberts et al. 2013, 2014, 2015, 2017).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

We observed five asteroids belonging to the Gefion family as defined by Carruba et al. (2003) using the NASA IRTF on Mauna Kea, Hawai‘i between 2014 September and 2015 September. NIR spectra (0.7–2.5 μm) of asteroids (1839) Ragazza, (2373) Immo (2386) Nikonov, (2521) Heidi, and (3860) Plovdiv were obtained using the SpeX instrument (Rayner et al. 2003). Observational circumstances for each of the asteroids are listed in Table 2. Spectra were collected using the nodding technique, where the asteroid target is switched between two different slit positions, A and B. Standard stars and solar analogue stars were also observed in order to correct for telluric features and correcting the spectra for solar continuum. The asteroid targets have an exposure time of 200 s.

2.2 Data reduction

The data reduction process utilized the IDL-based software package known as SPEXTOOL (Cushing et al. 2004). SPEXTOOL is a data reduction package provided by the NASA IRTF for reducing SpeX data. The data reduction protocols include: removal of the background sky by subtracting the A-B spectral pairs, flat-field calibration, cosmic ray removal, wavelength calibration, dividing the asteroid spectra by spectra of the respective solar analogue star observation (Table 2), and finally median combining individual spectra to get the final spectrum.

The initial steps of the data reduction process within SPEXTOOL involved creating master flat images, extracting the 2D spectra from the image, and combining the individual spectra from a set of observations. The next step is telluric correction where the asteroid spectrum is ratioed to a local standard star spectrum. During telluric correction, subpixel offset is also carried out to account for instrumental flexure. The solar analogue star is treated the same way as the asteroid and the resulting ratio between the solar analogue star and the local standard star is used to derive the solar continuum correction by fitting a low-order polynomial. The final step is dividing the asteroid spectrum with the solar continuum curve. The average spectra of our five asteroids are shown in Fig. 2 and are offset vertically for clarity.
Table 2. Observational circumstances for the asteroids observed for this campaign.

| Target         | Observation date UTC (GMT) | Solar analogue star | Airmass | α (degrees) | R (au) | Mag. (V) | No. of Spectra |
|----------------|----------------------------|---------------------|---------|-------------|--------|----------|----------------|
| (1839) Ragazza | 2014/11/24 17:00:00        | SAO 93936           | 1.031   | 21.6        | 2.551  | 17.0     | 12             |
| (2373) Immo    | 2014/09/23 23:00:00        | SAO 93936           | 1.345   | 23.6        | 2.505  | 17.1     | 32             |
| (2386) Nikonov | 2015/01/17 23:00:00        | SAO 120107          | 1.087   | 17.0        | 3.162  | 17.3     | 6              |
| (2521) Heidi   | 2014/09/04 10:00:00        | SAO 75021           | 1.011   | 15.6        | 3.013  | 16.7     | 10             |
| (3860) Plovdiv | 2015/09/22 17:00:00        | SAO 93936           | 1.322   | 22.8        | 2.384  | 15.8     | 14             |

Table 3. The measured band parameters values for the Band I centre, Band II Center, and the BAR.

| Target         | Band I centre (μm) | Band II centre (μm) | BAR       |
|----------------|--------------------|--------------------|-----------|
| (1839) Ragazza | 0.93 (+/− 0.01)    | 1.86 (+/− 0.01)    | 0.76 (+/− 0.15) |
| (2373) Immo    | 0.93 (+/− 0.01)    | 1.97 (+/− 0.01)    | 1.56 (+/− 0.15) |
| (2386) Nikonov | 0.92 (+/− 0.01)    | 1.99 (+/− 0.01)    | 1.24 (+/− 0.15) |
| (2521) Heidi   | 0.95 (+/− 0.01)    | 1.91 (+/− 0.01)    | 0.98 (+/− 0.15) |
| (3860) Plovdiv | 0.93 (+/− 0.01)    | 1.91 (+/− 0.01)    | 1.31 (+/− 0.15) |

3 RESULTS

All spectra shown in Fig. 2 exhibit absorption features centred at roughly 0.9 μm (Band I) and 1.9 μm (Band II). These features are attributed to crystal field transitions in Fe2+ in minerals olivine and pyroxene. From each spectrum, band centres and the band area ratio (BAR) were measured using a PYTHON code following the protocols of Cloutis et al. (1986). Band centres correspond to the position of the minimum value in reflectance of a continuum removed absorption feature, and are determined by fitting third- and fourth-order polynomials over the bottom of each band. The BAR is given by the ratio of the area of Band II versus Band I. The band parameters were measured multiple times and from these measurements the mean values and 1σ errors were calculated. The band parameters and their uncertainties are presented in Table 3.

We plotted the Band I centre and BAR of our target asteroids in the S-asteroid subtype plot from Gaffey et al. (1993), as shown in Fig. 3. The distribution of these parameters across many spectral meteorite types suggests a wide range of silicate compositions and abundances. Asteroids (1839) Ragazza and (2521) Heidi have spectral properties and features that are similar to S(IV) subtype (analogous to OC), and in particular they fall into the H chondrite zone. Asteroids (2386) Nikonov and (3860) Plovdiv plot in the S(VI) region. These objects are spectrally similar to silicate inclusions in iron meteorites or residue left behind after partial melting (Gaffey et al. 1993). Asteroid (2373) Immo plots in the BA region with spectral properties similar to asteroid (4) Vesta.

4 ANALYSIS

Based on our small sample study, the mafic mineral composition of these Gefion family asteroids suggests most are not analogous to L chondrites. Instead, they belong to a range of compositions from H chondrites, primitive achondrites, and BA.

We found that the olivine and pyroxene chemistry are consistent with that of H chondrites for asteroids (1839) Ragazza and (2521) Heidi. H chondrites are OC that possess higher iron content, roughly 25 percent molar content, and have higher pyroxene ratios than olivine content, as they are thought to have formed under reduced conditions compared to L and LL chondrites. We used laboratory spectral calibrations derived by Dunn et al. (2010) to determine the surface composition of (1839) Ragazza and (2521) Heidi. These calibrations are valid only for asteroids that plot in the S(IV) region of the plot. Using this calibration technique, we derived their olivine and pyroxene chemistry, which are given by the molar content of fayalite (Fa) and ferrosilite (Fs), respectively. Their Fa and Fs values are consistent with H chondrites rather than L chondrites (Fig. 4).

Similarly, the olivine abundances defined as the fraction olivine content to the olivine plus pyroxene content (ol/(ol+px)) for these
Do L chondrites come from the Gefion family?

out that asteroids (2386) Nikonov and (2860) Plovdiv could be background asteroids to that of the Gefion family, belonging to a different asteroid family altogether.

Mineralogical analysis of asteroid (2373) Immo reveals a surface consistent with high abundances of orthopyroxene similar to that of BA. While HED meteorites derived from Vesta are the dominant achondrites in the terrestrial collection, ground-based observations (e.g. Hadersen et al. 2015) have shown non-Vesta basaltic families to exist in the main asteroid belt. Hadersen et al. (2015) propose that some Vesta-type asteroids from the inner location of the main asteroid belt could be from non-Vesta basaltic parent bodies, but could have also possibly derived from Vesta. It is possible that the asteroid (2372) Immo was derived from one such uncertain asteroid family, and is perhaps unrelated to Vesta.

We have not found any evidence for L chondrites in the Gefion family based on our small sample study. Vernazza et al. (2014) have previously suggested that the Gefion family is a mixture of both H chondrites and L chondrites. The observations in this study partly support this finding as asteroids (1839) Ragazza and (2521) Heidi have compositions that are consistent with that of H chondrite meteorites. These results also support previous work done by Roberts et al. (2013, 2014, 2015, 2017) and Blagen & Gaffey (2012). These authors have suggested that Gefion asteroid family asteroids display a varied range of compositions ranging from H, L, and LL chondrites. Based on the range of the observed compositions, we can suggest that the parent body of the Gefion family was a partially differentiated asteroid with a mixture of unaltered chondrite material, partial melt residues, and BA. Alternatively, the non-OC asteroids in the Gefion family could be interlopers that are unrelated to the original family.

5 CONCLUSIONS

Finding asteroid-meteorite linkage is vital for improving our understanding of the conditions in the early Solar system. In this study, we attempted to test one such link between the Gefion asteroid family and the L chondrite meteorites proposed by dynamical studies (Nesvorny et al. 2009). Based on our small sample study here is what we can summarize:

(i) the five asteroids we observed, (1839) Ragazza, (2373) Immo, (2386) Nikonov, (2521) Heidi, and (3860) Plovdiv, all have spectral properties unlike L chondrites. These asteroids have properties similar to H chondrites, primitive, and BA.

(ii) The diversity of compositional types observed in the Gefion asteroid family suggests that the original parent body might be partially differentiated.

(iii) Alternatively, the family might be contaminated with large number of interlopers from other families creating a diverse set of compositions.

(iv) Our results are consistent with similar studies of the Gefion asteroid family by Blagen et al. (2012) and Roberts et al. (2013, 2014, 2015, 2017).

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