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TESTING THE GEFION FAMILY AS A POSSIBLE PARENT BODY FOR THE L-CHONDRITE METEORITES

by

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A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
In partial fulfillment of the requirements

for the degree of
Master of Science

Grand Forks, North Dakota
May
2012
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This thesis, submitted by Jessica Ronnie Blagen in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done, and is hereby approved.

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Dean of the Graduate School

May 3, 2012

______________________________
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Title                   Testing the Gefion Family as a Possible Parent Body for the L-Chondrite Meteorites

Department     Space Studies

Degree              Master of Science

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May 3, 2012
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For my Mother who is always there for me and puts up with my grumpiness.
ABSTRACT

The L-chondrite meteorites are the most abundant meteorites falling to Earth. Identifying a parent body for them has been an important goal of asteroid science for more than thirty years. A link between the two could help to decipher the history of thermal regimes and evolutionary processes that occurred in the early solar system. A plausible or probable parent body can be identified based on two main criteria. A plausible body will either be located favorably to deliver the relevant amounts of meteoroids to the Earth, or will possess a surface mineralogy compatible with that of the L-chondrite meteorites. A probable parent body will meet both criteria (Gaffey, 2011).

Based on research performed on fossil L-chondrite meteorites, and dynamical modeling of various resonances and asteroid families, the Gefion family has been hypothesized as a plausible source of the L-chondrite meteorites. It is favorably located within the asteroid belt for delivery of fragments to Earth, so in an effort to test the possibility that this family is a probable parent to these meteorites, this study used near-infrared spectral data gathered with the NASA Infrared Telescope Facility (IRTF) to characterize the mineralogy of two asteroids of the Gefion Family.

Although not solidly proven to be L-chondrites, both asteroids are grossly consistent with the mineralogy of this type of meteorite. Taking error into
account, whether human, meteorological, or instrumental, both asteroids can reasonably be considered to fall within the L-chondrite realm. More spectra of these and other Gefion asteroids are needed to come to a valid conclusion regarding the family as a source for these meteorites, but at this point the hypothesis is still a viable one.
CHAPTER I

INTRODUCTION

Asteroids

From the time the first asteroid was found until the present day, asteroid science has undergone many changes and challenges. The discovery of 1 Ceres in 1801 was celebrated as confirmation of a theory surmising the existence of a ‘missing planet’ between the orbits of Mars and Jupiter. As more asteroids were detected in the ensuing years, some speculated these objects were the remains of a planet that had disintegrated, whilst others thought them pieces that had never quite consolidated into a single planet. Dozens of objects were located in the following decades and with the emergence of astronomical photography in the late nineteenth century, hundreds more were added to the list. By the mid-twentieth century, the abundant asteroid population led some astronomers to dub them ‘the vermin of the skies’ for the inconvenient markings they made on astronomical photographs, and for their apparent uselessness (Kowal, 1996).

Times have changed in the world of asteroid science however, and asteroids are now looked upon as important for a myriad of reasons. Perhaps one of the most motivating rationales for studying asteroids comes from the knowledge of what can happen to our planet should one strike into it. As evidenced by the impact believed to have caused, or at least exacerbated, the mass extinctions associated with the Cretaceous-Tertiary boundary, including the demise of the
Dinosaurs. The hazards concomitant with such an impact have galvanized many asteroid watch programs around the world, and reinforced interest in determining physical make up, which is important both for emergency planning as well as deflection programs.

Another inducement for recent asteroid science is both financial and farsighted. There is a belief that asteroids are potential sources of precious metals and minerals no longer easily obtainable on Earth, and that business ventures may one day travel to nearby asteroids to harvest their resources. With many new companies jumping into the space arena, this idea is not as farfetched as it might once have seemed. The concept has also been postulated that future space travelers use asteroids as way stations en route to far distant destinations. Spacecraft have already been sent to flyby, rendezvous, and bring samples back from asteroids; it may not be such a giant leap to send humans there someday.

Finally, research on asteroids can teach us about the past history of the solar system. Bottke et al. (2002), describes the current scientific outlook on asteroids thusly:

“This new century begins with asteroids no longer being starlike points of light in our telescopes, but resolved worlds with distinctly measurable, sizes, shapes, and surface morphologies. Each has a unique history to unravel, a history that begins at the time of formation of our own planet and the entire solar system.”

The asteroids have a unique standing as remnants of the original material that formed the terrestrial planets some 4.6 billion years ago, and because the planets have undergone significant transformation since that time, asteroids comprise
the only relatively pure record of processes and conditions existing in the late inner solar nebula and early solar system. Interpretation of the subsequent thermal, dynamical, and collisional events that befall these remnants can inform us about the evolution of other solar system bodies (Gaffey et al., 2002).

**Meteorites**

The study of meteorites, or meteoritics, has had a relatively more dramatic history. Rocks falling from the sky tend to garner one’s attention, no matter what civilization or era to which one is referring. Many early peoples enshrined and worshiped these relicts from the heavens, whilst others believed they heralded important events and were seen as either good or bad omens. According to McSween (1999), “most ancient philosophers viewed meteorites as heavenly bodies that had somehow been freed from their celestial moorings and had tumbled to Earth.” Later scholars attached them to atmospheric processes such as lightning and volcanoes.

It wasn’t until 1794 that meteorites began to be looked at scientifically. Ernst Chladni, a German physicist, wrote a small book in which he asserted that meteorites made up of metallic iron originated extraterrestrially, and did indeed come from the sky, rather than the atmosphere. He believed that meteorites had once traveled through space as small bodies before succumbing to Earth’s gravity. With the help of a fortuitous meteorite fall, a British chemist, and a French mineralogist, Chladni’s theory gained general, if not complete, acceptance within a decade of publication. However, the field really began to take hold with advances in metallurgy, analytical chemistry, and the invention of the petrographic microscope a century or so later (McSween, 1999).
The original system for classification of meteorites separated them into three main categories as seen in figure one. The iron meteorites are nearly completely composed of nickel-iron alloys, whilst the stony meteorites contain oxide and silicate minerals, often additionally including small metal grains. The stony-iron meteorites have approximately equivalent amounts of both silicates and metals. The stony meteorites are subdivided into two basic groups: achondrites and chondrites. Achondrites consist of igneous rock that was created by partial melting and crystallization. Chondrites, on the other hand, are described as a sort of space breccia, made up of early solar system substances that have undergone very little, or no, chemical change since their inception (McSween, 1999). Chondritic meteorites are interesting to investigators because they are considered to be the most primitive material in the Solar system.
Ordinary Chondrites

Today, the chondrites have as many as 13 defined subclasses, with the aptly named Ordinary Chondrites making up an overwhelming majority of fallen meteorites at ~80% (Burbine et al., 2002). Based on the ratio of metallic iron to oxidized iron, the ordinary chondrites are themselves sorted into three subgroups called (from highest ratio to lowest) the H-, L-, and LL-chondrites, as depicted in figure two. Among the ordinary chondrites, the L-chondrites make up ~38% of the ordinary chondrite falls (Burbine et al., 2002). This dominance of the terrestrial meteorite flux, as evidenced by the Antarctic meteorite collections, has been sustained for at least the last million years (Britt and Pieters, 1994; Gaffey, 2011).

From: http://www4.nau.edu/meteorite/Meteorite/Book-GlossaryO.html

Figure 2. The Ordinary Chondrites are differentiated by the ratio of metallic iron to oxidized iron.
So, where do these L-chondrites come from? Making a connection between an asteroid parent body and these prolific meteorites has long been a planetary science research goal. Its discovery may contribute to the precise determination of thermal and compositional gradients within the solar nebula (Burbine et al., 2002), which will help us to better understand the formation and evolution of our Solar system. Based on recent research into the orbital dynamics of the asteroid belt (Nesvorný et al., 2009), the Gefion family of asteroids has been suggested as a possible parent for these abundant meteorites. By characterizing two members of the Gefion family of asteroids, this work will begin to test this hypothesis.
CHAPTER II

L-CHONDRITE METEORITES

Shocked Black Chondrites

The L-chondrite meteorites drew attention to themselves quite early on in meteorite science. The black hypersthene chondrites, as they were known for their abundance of the low-calcium orthopyroxene mineral, were an anomaly within the ordinary chondrites for their dark color and short gas retention ages. Both aspects were thought to be a consequence of one or two major impacts within the asteroid belt, rather than a long sequence of smaller collisions (Anders, 1964).

The dark color appeared to be shock-induced, supported by pervasive petrologic shock features, most likely resulting from a significant impact received by the parent asteroid (Heymann, 1967; Britt and Pieters, 1991). The short gas retention ages studied by Heymann (1967) led to an estimated date of 520 ±60 Myr for the break-up event that produced these chondrites. According to the revised geologic timescale (Cooper and Sadler, 2004), that date would place the L-chondrite parent body catastrophe somewhere within the Cambrian or Ordovician time period. During that time period the Earth had a number of shallow seas, within which coral reefs were created. Presently, the lithified reefs are the source of valuable limestone, and the resting place of over 90 fossil L-chondrite meteorites as well (Schmitz et al, 2009).
Swedish Quarries

The first fossil meteorite, recently determined to be of L-chondrite composition (Alwmark and Schmitz, 2009), was found in a limestone quarry in central Sweden. Quarried since the 12th century as a decorative and building stone, the sawed plates of the beautiful pinkish Orthoceratite Limestone occasionally contained imperfections similar to the one shown in figure three, which were discarded.

Figure 3. At left, a quarry worker saws just above an imperfection in the limestone. At right, a fossil meteorite in a limestone slab.

In 1952, one such plate was sent to a Professor of Geology at Uppsala, Per Thorslund, who misidentified the black clast it contained as an “altered terrestrial ultramafic rock that had been transported with floating algae to the deeper parts of the Ordovician sea.” (Alwmark and Schmitz, 2009) Twenty-five years later,
research into terrestrial impacts was becoming more ubiquitous and Per Thorslund was working on a description of the impact breccia of the Lockne crater. He decided to reevaluate the black clast from the quarry, which subsequently has become known as Brunflo, the first confirmed fossil meteorite found (Nield, 2009).

In 1988 a second fossil meteorite, Österplana, was discovered in another quarry south of the Brunflo site. Amateur Geologist Mario Tassinari queried the quarrymen there, and soon more were found. Four years later, in collaboration with Professor Birger Schmitz of Lund University, Tassinari began a systematic sampling project to search for more meteorites (Blixt, 2011). Speaking with the Meteoritical Society at the 72nd Annual Meteoritical Society meeting in 2009, Professor Schmitz described the project as follows:

“IT is remarkably predictable. Each year in Thorsberg Quarry, another 750 square metres of Ordovician sea floor is quarried, and each year it produces six, plus or minus two meteorites. Up till now, 12,000 square metres of seafloor have been excavated. Of the 90 meteorites found, 65 have been analysed and all have been diagnosed as L chondrites. I think there is a very high probability that they are all L chondrites!” (Nield, 2009)

The limestone strata of the Thorsberg Quarry, as well as research ongoing in other parts of the world, has yielded much information regarding the influx of meteorites to Earth originating from the catastrophic disruption of the L-chondrite parent body.
Ordovician Limestone

Dated using marine fossils and the revised geologic timescale (Cooper and Sadler, 2004) the limestone strata of the Thorsberg Quarry are sedimentary deposits that were laid down during the Ordovician period when the Earth was covered with shallow seas, as shown in figure four. Although deposition varied from rapid pulses of sedimentation to long periods of non-deposition and hardground formation, the average rate of limestone precipitation was from 1 to 3 mm/Kyr. The ~3.2 m thick quarried section had been deposited in an epicontinental sea that covered several 100,000 km² of the Baltoscandian Shield.

From: http://www.britannica.com/bps/media-view/146748/1/0/0

Figure 4. Ordovician landmasses circa ~480 Myr ago. Present day Sweden would have been part of the landmass Baltica.
and, based on a deposition rate of 2mm/kyr, spanned a time period of \( \leq 1.75 \) Myr (Schmitz et al., 2001).

Within the first decade of the search, 40 fossil meteorites were discovered within the quarried section (as depicted in figure five), representing approximately 6000 m\(^2\) of seafloor. The meteorites commonly collected on hardgrounds with other sizable objects, like the nautiloid shells in figure six.

Figure 5. The stratigraphic section of the Thorsberg Quarry, illustrating the beds in which fossil meteorites were found.
The fragility of the nautiloids lends credence to the belief that the meteorites accumulated due to sediment winnowing rather than a harsher process. It is unlikely that the meteorites arrived at or near the same point in time and were distributed throughout the sediment layers by processes such as strong bottom currents, sea floor erosion, shake-sorting, or sea level changes. In fact, the meteorites gathered on twelve different hardgrounds, periods of non-deposition, implying at least twelve falls. That means that the L-chondrite meteorites were falling throughout the time period that the limestone deposits were being laid down, or for approximately two million years (Schmitz et al., 2001).

*Fossil meteorite and nautiloid shells in Ordovician limestone*

Figure 6. Fossil meteorite amongst fragile nautiloid shells.
Fossil Meteorite Paleoflux

The influx rate of the meteorites during the Ordovician time period compared to the present day influx has been determined in two ways. The first method estimated the total mass of the fossil meteorites found in the quarry deposits over the 2 Myr it represents, and compared that to the estimated meteorite flux today. The second method measured amounts of dispersed chromite within the interval of the limestone strata (Schmitz et al., 2001, 2003). Chromite is a mineral of the spinel group that has a distinct composition dependant upon its host meteorite. It is commonly found as a trace mineral in ordinary chondrites, and has shown that all, or most of the fossil meteorites in Thorsberg Quarry are of L-chondrite composition (Schmitz et al., 2001, 2003; Schmitz and Häggström, 2006; Greenwood et al., 2007).

Whilst most of the fossil meteorites have been completely pseudomorphosed by calcite, barite, and phyllosilicates, chromite and chromium spinel are very resilient to erosion and most acid treatments, and are the only relict minerals to survive diagenesis. Both techniques return results that suggest the paleoflux of meteorites during the Ordovician period was increased by two orders of magnitude compared with today (Schmitz et al., 2001, 2003; Schmitz and Häggström, 2006).

Radiochronometry of Fossil Meteorites and Chromite

Heck et al. (2004), measured cosmic ray exposure (CRE) ages of extraterrestrial chromite grains found in the quarry using the noble gases He and Ne. It was found that as the sediment ages get relatively younger, from bottom to top of the sediment column, exposure ages increase. Also, the difference between
the oldest and youngest cosmic ray ages agrees with the total deposition time of the sediments of 1-2 Myr. These results support the proposition that “the fossil meteorites are all derived from one single very large asteroid collision.” (Heck et al., 2004) The cosmic ray exposure age data further allows for deduction of delivery times from the site of the asteroid break-up event to the Earth. These times are remarkably short compared with transfer times of modern ordinary chondrites. The shortest estimated transport time is on the order of 100,000 to 200,000 years, with the longest taking closer to 1-2 Myr to reach Earth (Heck et al., 2004, 2008). This has implications for the timing of the L-chondrite break-up event.

Based on radiometric ages of shocked L-chondrite meteorites, estimations of the age of the event that disrupted the L-chondrite parent body have not been reconciled over the years, ranging from as old as 520 ± 60 Myr (Heymann, 1967), to as young as 340 ± 50 Myr (Alexeev, 1998). In an effort to determine a more precise date, Korochantseva et al. (2007) used a multiple isochron $^{40}$Ar - $^{39}$Ar method, by which they recommended an age of 470 ± 6 Myr for the L-chondrite parent break-up. This date corresponds well with the transport times calculated by Heck et al. (2004, 2008), as well as the relative date of the limestone strata in which the fossil meteorites were deposited. The earliest bed that includes fossil meteorites is marked by the disappearance of the marine fossil Lenodus antivariabilis, and the appearance of Lenodus variabilis (Korochantseva, 2007). According to the revised geologic time scale (Cooper and Sadler, 2004), these species correlate to the lowermost Darriwilian stage in the Ordovician, with an age of 468.1 ± 1.6 Myr. All of these age values are in excellent accord, which leads
to the supposition that the fossil meteorites fell to, and were deposited on Earth within a few Myr after the break-up of the L-chondrite parent body.

**Global Implications**

The Ordovician limestone sediment beds in Sweden show strong evidence that over a stratigraphic interval of a few million years, there was a significant increase in the flux of L-chondritic material to Earth. Recent work performed in the Puxi River section of central China examined the distribution of extraterrestrial chromite grains in strata of the same age as those studied in Sweden (Cronholm and Schmitz, 2007). During the Ordovician period, Sweden was a part of the continent Baltica, close to the equator and shrouded by a shallow sea. Central China, where the Puxi River section of strata formed, lay some two thousand kilometers to the East, but at nearly the same latitude (see figure four).

The Chinese chromite grains were found to be very homogenous across the section, and they proved to be fairly identical in elemental composition to the chromite grains recovered from the Thorsberg Quarry fossil meteorites as well. Also, the general trend in abundance of extraterrestrial chromite within the Chinese strata coeval with the Swedish strata is very similar to the trend found in Sweden. Furthermore, a very recent investigation into L-chondritic extraterrestrial chromite discovered in the middle Ordovician Osmusaar Breccia, of Estonia, supports the notion that an increased flux was not only a local Swedish phenomenon, but a global incident as well (Alwmark et al., 2012).

Together, these studies give compelling credence to the belief that the enrichment of fossil meteorites and extraterrestrial chromite found within
Ordovician sediments are a global occurrence, and indicative of a remarkable increase in the flux of L-chondrite matter to Earth following the disruption of its parent body. So, where did these meteorites originate, and how is a meteorite-parent body connection hypothesis tested?

**Plausible vs. Probable Parent Bodies**

An unequivocal determination of a genetic relationship between the L-chondrite meteorites and an asteroidal source body will most likely require a sample return mission. However, an asteroid or asteroid family can be classified as a plausible or probable parent body based on two main criteria. A plausible parent body will be an asteroid that either has a surface mineralogy compatible with that of the L-chondrite meteorites, or will be in an orbital location that can provide quantitative yields of the relevant amount of meteoroids to the Earth. A probable parent body will meet both criteria (Gaffey, 2011). Therefore, a good test of a meteorite-parent body relationship will evaluate evidence for both a favorable orbital location within the asteroid belt, as well as the surface mineralogy of the prospective parent asteroid.
Asteroids can be found in a number of places within the inner solar system, but they are predominantly located within what is considered the main asteroid belt. This doughnut shaped area stretches from about 2.1 AU to around 3.3 AU from the Sun, lying between the orbits of the planets Mars and Jupiter, as seen in figure seven. The strong gravitational forces caused by Jupiter’s giant mass are what primarily shape the main belt, but Saturn’s gravity also plays a role (Dvorak, 2006; Gaffey, 2011).

Figure 7. Placement of the main asteroid belt within the solar system.
In the histogram presented in figure eight, the number of asteroids within the main belt is shown versus their distance from the Sun. Where there are very few asteroids, major gaps can be seen. These gaps, known as the Kirkwood gaps for their discoverer Professor Daniel Kirkwood, “occur at distances from the Sun such that an imaginary asteroid traveling in one of the gaps would have a period of revolution which would be a simple fraction of that of Jupiter.” (Delgrande and Soanes, 1943) For example, in the time it takes Jupiter to circle the Sun once, an asteroid orbiting in the gap labeled 3:1 in the above diagram would journey around the Sun three times. Also called mean motion resonances, these gaps

From: en.wikipedia.org.

Figure 8. Histogram of the main asteroid belt showing the Kirkwood gaps.
bound the main belt on the inside with the 4:1 resonance, and on the outer edge with the 2:1 resonance. There are three major gaps within the body of the main belt, corresponding to the 3:1, 5:2 and 7:3 resonances with Jupiter.

There are other types of resonances acting within the asteroid belt as well as throughout the Solar System. Secular resonances form complex curved structures resulting from the cyclical variation of planetary eccentricities and inclinations. As two planets perturb each other, the line of intersection of the two orbit planes slowly moves, as does the direction of perihelion (Dvorak, 2006). The precessional perturbations can be quite sizable, with periods of 50,000 to 2,000,000 years (Williams and Faulkner, 1981), and can have a profound effect on the shape of the asteroid belt. As illustrated in figure nine, the surfaces of

From: Williams and Faulkner, 1981

Figure 9. Depiction of the interaction between three main secular resonance surfaces. The $v_5$ is the topmost lined plane, the $v_6$ is the lined plane below, and the dashed lines represent the intersection of the $v_{16}$ resonance with the previous two.
these resonances are curved and convoluted, often intersecting one other. The \( \nu_6 \) resonance, which is the bottom lined plane in the figure above, is an upper and inner boundary for the asteroid belt. Although the types of resonances differ in how they are produced, and what form they take in space, they do have a commonality in that they are each capable of moving asteroidal material into new orbits.

Material Movement

When an object enters a resonance, it encounters a chaotic zone where orbits are disordered and unstable (Wisdom, 1983). This disarray promotes an increase in the object’s orbital eccentricity. As the orbit becomes extended, the asteroid can become Mars-, Earth-, or Venus-crossing depending on which resonance was entered. If it doesn’t get thrown out past Jupiter, or slung into the Sun, in all likelihood it will then be pulled out of the resonance by the gravitational attraction of one of these planets, perhaps on very swift timescales (Gladman et al., 1997; Nesvorný et al., 2002, 2009). The resonances, therefore, are conduits that allow material from the main belt to travel considerable distances to reach Earth, and perhaps land as meteorites.

Within the main asteroid belt, the 3:1 and 5:2 mean motion resonances, as well as the central parts of the \( \nu_6 \) secular resonance, are very effective in raising the eccentricities of bodies within them. In the late 1990’s, a number of numerical integration modeling studies were performed that focused on these three resonances and the role they play in bringing meteorites from the main belt to Earth (Gladman et al., 1997; Morbidelli and Gladman, 1998). Evolutionary paths from all of these resonances, typically, entail propelling objects into Sun-
grazing or Jupiter-crossing orbits on time scales of approximately one million years, with extraction from the resonances possible due to inner planet gravitational effects as their eccentricities reach planet-crossing orbits (Gladman et al. 1997).

The 3:1 mean motion resonance, located at 2.5 AU, has a strong ability to push objects to extreme eccentricities, but even with an eccentricity of 0.999... objects do not cross Jupiter's orbit. The resonance itself helps protect objects from close encounters with Jupiter that would send them out of the Solar System. According to Moribidelli and Gladman (1998), about 27% of their simulated objects were pulled from the resonance and propelled to a larger semi-major axis where they fell under Jupiter's control and were ejected. Another 70% or so perished by spiraling into the Sun. That leaves only a few percent that were pulled from the resonance by interactions with the terrestrial planets to subsequently collide with one. The mean lifetime of objects in this resonance were calculated to be roughly two million years, with only 10% surviving more than 7 Ma (Moribidelli and Gladman, 1998).

Positioned at 2.8 AU, the 5:2 mean motion resonance intensifies the eccentricities of 90% of the simulated objects enough to give control over to Jupiter's influence, resulting in hyperbolic orbits. Also, this resonance is capable of increasing an object's eccentricity on the shortest timescale. The average lifetime of simulated objects is as brief as 500,000 years, with only 10% surviving longer than three million years. Furthermore, this resonance displays a curious circumstance in that objects originally placed just outside of the resonance can
move into the resonance through slow chaotic diffusion after several million years (Moribidelli and Gladman, 1998).

The $v_6$ secular resonance, as opposed to the previous mean motion resonances, has a less chaotic structure. On time scales of about one million years, simulated objects undergo recurrent fluctuations in eccentricity, rather than a continuous increase. The center of the resonance employs the strongest forces, sending objects into Earth- or Venus-crossing orbits, but during the portion of its cycle with the highest eccentricities, objects may also collide with the Sun. The outer regions of the resonance produce Mars-crossers, which then must rely on Martian encounters to slowly evolve down into the more powerful area of the resonance. When an object reaches the powerful central section of this resonance, it is generally removed within a few million years. Close to 80% of the objects fall into the Sun and around 12% eventually reach a large enough semi-major axis to be expunged by Jupiter. The remaining population spends a longer time in evolved orbits at less than 2 AU (Moribidelli and Gladman, 1998; Gladman et al., 1997).

As can be seen in figure ten, a graph depicting the number of active objects versus time, there is a process that creates a tail of long-lived objects in all three resonances. As stated earlier, the 5:2 resonance incorporates a practice whereby objects from outside of the resonance can slowly disseminate in space until they reach a strong region, thereafter living out the typical lifetime of the resonance. The objects do not leave the resonance and then enjoy long lives, however, rather they spend tens of millions of years moving into proximity of the resonance, and then expire at the resonance-specific rate of time. The tail produced in the 3:1
resonance is partly due to this practice, but also involves objects that drift into long-lived orbits under two astronomical units. The tail of the $v_6$ secular resonance is almost completely due to the latter process (Gladman et al, 1997).

![Graph](http://www.sciencemag.org)

**Figure 10.** This graph expresses decay of the number of active objects within a resonance versus time. The three main resonances described ($v_6$, 3:1, and 5:2) all portray very short lifetimes for most objects within them, with long tails denoting extended lifetimes.

All three resonances are capable of putting meteoroids on a path to Earth on geologically fast time scales, but how do these objects reach the resonances in the first place? Mechanisms for movement into one of these orbital freeways range from being shepherded gently along to one by thermal forces, which can be a slow haphazard meander, to being directly injected into one following a catastrophic collisional event.
The slow haphazard meander is accomplished by what is known as the Yarkovsky Effect. Originally proposed over a century ago by a civil engineer who worked on scientific problems as a hobby, Ivan Osipovich Yarkovsky (1844-1902) noted that “diurnal heating of a rotating object in space would cause it to experience a force that, while tiny, could lead to large secular effects in the orbits of small bodies, especially meteoroids and small asteroids.” (Bottke et al., 2002) This radiation force is capable of pushing objects from 0.1 to 20 km in size into an inward or outward spiral of varying rates, dependent upon their orbit, spin, and material properties (Bottke et al., 2002, 2006). Furthermore, it is the primary mechanism delivering asteroids and meteoroids to the resonances that expedite their departure from the main belt (Nesvorný and Bottke, 2004).

In essence, the Yarkovsky Effect is a thermal force generated when small bodies that are orbiting the Sun absorb sunlight, which heats them up, then reradiates the thermal energy to space a short time later. The asymmetric absorption and emission of energy by the object causes it to expend a small thrust directed away from the hotter area, which, depending on the spin direction of the meteoroid, can move it into a larger or smaller orbit, as illustrated in figure eleven.

The object will move outward if it has a prograde rotation because the reradiated thermal emission aligns with the direction of travel, giving the object a slight boost. On the other hand, the object will move inward if it has a retrograde rotation because the reradiated thermal emission counteracts the direction of travel, slightly slowing its forward motion. The Yarkovsky Effect and its companion
Figure 11. The Yarkovsky Effect. (a) The object has a prograde rotation, so the reradiated thermal emission causes it to move outward from the sun. (b) An object rotating in a retrograde direction emits the thermal radiation in the direction of travel, slowing the object and causing it to fall inwards toward the Sun.

mechanism Poynting-Robertson Drag, which provokes a Sunward spiral in dust-sized particles, work as mechanisms to send meteoroids and smaller particles on a slow meandering journey toward the various resonances within the asteroid belt (Bottke et al., 2003).

Direct Injection – Asteroid Families

The catastrophic collisional events that can directly inject fragments into a mean motion or secular resonance are generally thought to simultaneously create asteroid families. First described by Kiyotsugu Hiyama in 1918, asteroid families appear as relatively tight clusters of objects in the phase space of three proper orbital elements: semi-major axis, eccentricity, and inclination (Bendjoya
and Zappalà, 2002; Cellino et al. 2009). Hypothesizing that the nearly identical orbits and proximity that family members show couldn’t be due to chance, Hirayama proposed a shared origin for members of these clusters. This idea is still viable today, and has been made more robust with observational and theoretical research results (Cellino et al., 2002; Zappalà et al., 2002).

Essentially, asteroid families are comprised of a myriad of fragments, engendered by energetic collisions between asteroids that either create large craters on the target asteroid, or precipitate a complete break-up event (Hirayama, 1918, Bendjoya and Zappalà, 2002; Zappalà et al., 1990, 1994, 1995). Determined using various computational techniques, there are 20 statistically reliable asteroid families recognized currently (Bendjoya and Zappalà, 2002; Zappalà et al., 2002). Along with proper orbital element relationships, the members of asteroid families keep a sort of “dynamical memory” that permits family clusters to be identified by the ejection velocity field of the fragments after disruption (Mothé-Diniz et al., 2005). Studies of asteroid family evolution have helped to constrain the parameters used for modeling the strong connection between dynamical operations, and physical processes associated with the origin and growth of the asteroid belt (Marzari et al., 1999; Zappalà et al., 1995, 2002; Dell’Oro et al., 2004).

Many of the families in the main belt are bounded on one or more sides by resonances, which may have significantly affected their overall structure (Morbidelli et al., 1995), and all have undergone various aging processes such as close encounters with large asteroids, collisional evolution, and the Yarkovsky effect (Dell’Oro et al., 2004). Families created near resonances will often produce
a surge of meteorites to the terrestrial planets lasting from 2-30 Myr (Zappalà et al., 1998), very like that which occurred during the Earth’s Ordovician geologic time period. Modeling of likely candidate families, for example those of the right age located near a major resonance, have helped narrow the search for a possible parent to the L-chondrite meteorites (Nesvorný et al., 2007, 2009).

Flora Family

In 2007, Nesvorný et al. developed a model to track the orbits of meteoroid-sized objects as they evolve from the $v_6$ resonance to Earth-crossing orbits. The model was applied to a hypothetical asteroid family positioned in the inner main belt approximating the Flora family location (see figure twelve), with a starting asteroid diameter of roughly 200 Km. The group’s goal, in an effort to establish the likely resonance and parental orbital location for the Ordovician fossil L-chondrite meteorites, was to determine the number of Earth bound meteorites, calculated as a function of time and for various ejection velocity fields, to arrive directly following a collisional break-up event in the $v_6$ resonance.

The data gathered from the Ordovician fossil evidence puts three constraints on the model. The first is an increased meteorite flux of 10 to 100 times over the present day flux (Schmitz et al., 2001). The second requires that a large number of fragments reach Earth within the short time period of between 100,000 and 1.5 Myr following the break-up event (Heck et al., 2004). The third constraint is that after the event’s abrupt start, the increased meteorite flux should continue for at least a few million years (Schmitz et al., 2001).
Although the experiment was fairly successful in some respects (it does show that Flora could match amounts of meteorites sent to Earth during the Ordovician), there are a number of discrepancies that keep the Flora family from standing out as a potential parent for the L- chondrite meteorites. For example, to produce the extremely short delivery times of some of the fossil meteorites, meteoroid-sized fragments would need to be propelled at very high ejection speeds in order to reach the fast acting center of the $\nu_6$ resonance. Additionally, the age of the Flora family is uncertain, perhaps too old to be reconciled with the
ages found for the L-chondrite break-up event. Finally, the mineralogy of the Flora family may be too olivine rich, with a composition some researchers think is better coordinated with the LL-chondrites (Nesvorný et al., 2009), and some think may not be chondritic at all (Gaffey, 1984). While the Flora family and the $v_6$ resonance might not quite be the right fit, there is a resonance in the main belt that can transfer meteoroids from a neighboring family to Earth within the very short timescales measured.

*Gefion Family*

In 2009, Nesvorný et al. expanded the previous experiment by analyzing all recognized asteroid families for a connection to the ~470 Ma L-chondrite break-up event. Most were eliminated based on incompatible mineralogy classifications and/or family age. The group concentrated on investigating families with a semi-major axis greater than 2.5 AU, because the 5:2 resonance at 2.8 AU could bring meteoroids to Earth on the exceedingly short timescales of the most extreme fossil meteorites (Gladman et al. 1997).

There are only two large enough families close to the 5:2 resonance with a mineralogical classification broadly compatible with ordinary chondrite mineralogy (Nesvorný et al., 2009). The Gefion family (figure thirteen) and the Koronis family are both located in the mid-main belt and have potential to be the source of the L-chondrite meteorites. The Koronis family, however, is estimated to be much older than ~470 Ma, so that leaves the Gefion family as a best bet.
Figure 13. The location of the Gefion family in the mid-main belt, near the 5:2 resonance.

The Nesvorný et al. (2009) group began by defining the family members using the Hierarchical Clustering Method (Zappalà et al., 1990), and determining their Size Frequency Distribution with the absolute magnitude of the family member and an assumed albedo of 0.2. Then, they estimated the size of the parent body using a code capable of modeling asteroid collisions (Benz and Asphaug, 1999). Their results suggest that the Gefion family parent body was originally around
100-150 Km in diameter and underwent a super-catastrophic break-up that created over 2,200 fragments with an average size range of 3-15km (smaller fragments may be too faint for detection). Next, they modeled the break-up event, accounting for ejection speeds and dynamical spreading, to come up with an age for the family formation. Their outcome of $485^{+40/-10}$ Myr fits reasonably with the established age of the shocked L-chondrites of $470^{\pm6}$ Myr (Korochantseva et al., 2007).

The L-chondrite fossil meteorites have very short cosmic ray exposure (CRE) ages, necessitating a very fast delivery system from the main belt. To estimate the quantity and amount of time it takes for objects to reach Earth by injection into the 5:2 resonance, Nesvorný et al. (2009) used an N-body integrator (Levinson and Duncan, 1994) and a numerical algorithm (Wetherill, 1967). It was determined that the Gefion family should have CRE ages between 50,000 and $\sim1$-2 Myr, and be distributed over $\sim1$-2 Myr of terrestrial sediments. These amounts agree well with the measured CRE ages and the stratigraphic record found in the Swedish Quarries. The correlation between the measured CRE ages and the modeled values can be discerned from figure fourteen.
Figure 14. This graph represents the number of objects versus their cosmic ray exposure ages. The step-like structure represents measured CRE ages of L-chondrites, and the peaked line designates the modeled values.

The experiment shows that the Gefion family is located in an orbital position that is capable of sending meteorites to Earth on a timescale congruent with the fossil meteorites (Heck et al. 2004), and has a formation age that is compatible with the timing of the L-chondrite break-up event (Korotchanseva et al., 2007). Therefore, the Gefion family meets one of the two criteria a parent body must meet to be considered probable; it has a favorable orbital location within the main belt for delivering the relevant amount of meteoroids to Earth. The next test of the hypothesis, then, is to characterize the surface mineralogy of Gefion family members to ascertain whether they are consistent with L-chondrite composition.
CHAPTER IV

ASTEROID MINERALOGY

Taxonomy

As the number of known asteroids has grown larger, it has become increasingly important to attempt to organize them into categories. There has been any number of asteroid taxonomies created over the years, with older groupings morphing into new ones as more and more data becomes available. Although the goal of sorting these objects is to distinguish groups that share similar surface compositions, collisional evolution, and thermal history, the parameters used for classification are observational in nature. Therefore, the categories suggest groupings that have broadly similar properties, but it cannot be construed that asteroids of the same taxonomic class necessarily have similar compositions, mineralogies, or genetic histories (Gaffey et al., 1993a).

Chapman et al., (1975) produced the earliest classification scheme in which categories were formed based on a combination of polarimetry, radiometry, and spectrophotometry. Sampling 110 asteroids, they came up with two formally recognized classes (C and S). This was based on comparisons with meteorite spectral albedo curves suggesting that the two groups were compositionally similar to carbonaceous (C) and stony-metallic (S) meteorites. Unusual specimens were designated as U. Other researchers added and deleted new classes over the next few years as more asteroid information was gathered,
considerably muddling the distinctions between the classes (i.e. Zellner and Gradie, 1976; Zellner et al., 1977; Zellner and Bowell, 1978; Bowell et al. 1978; Degewij and van Houten, 1979; Gradie and Tedesco, 1982).

In 1984, Tholen took advantage of data from the Eight-Color Asteroid Survey (ECAS) containing eight-filter broadband photometric measurements of asteroids within the 0.3 to 1.1 μm wavelength range. Together with thermal flux measurements at 10 and/or 20 μm, combined with surface reflectance measurements (to estimate albedo), and cluster analysis techniques, he produced an improved asteroid taxonomic system with groupings based on albedo and comparable spectral characteristics. The endeavor resulted in fourteen spectral groups, including seven or eight major groups (A, C, D, E, M, P, S, and perhaps T), three sub-groups (B, F, and G), and three unique groups designated for asteroids literally in a class by themselves (R, Q, and V). The Tholen taxonomy has subsequently been tested by other researchers using disparate techniques (i.e. Barucci et al., 1987; Tedesco et al., 1989; Burbine, 1991), but the basic construct of the Tholen taxonomy has remained valid.

Small Main-Belt Asteroid Spectrographic Survey (SMASS)

Until the 1990’s, knowledge of the asteroids came primarily from observations of the largest objects, mainly due to the faintness of the smaller objects. Motivated by the belief that observations of small main-belt objects may help solve some fundamental problems in asteroid science, Xu et al. (1995) undertook a CCD spectrographic survey of small main-belt asteroids with wavelength coverage ranging from 0.4 μm to 1 μm. The second phase of the project, SMASSII, was originally meant to accurately assign a spectral type to each object.
based on the Tholen taxonomy. It was found, however, that the higher resolution CCD spectra reveal subtle details, such as shallow absorption features, which are not always resolvable in the ECAS measurements, so the goal of this second phase became instead an exploration of a new way to define a taxonomy based on the alternative information (Bus and Binzel, 2002).

Because near-infrared spectral data has only recently become more readily available for relatively faint objects, the previous taxonomies were all based on visible data. It has been largely due to the SpeX instrument on the NASA Infrared Telescope Facility (IRTF) that the catalog of spectral data in the infrared range has increased dramatically in the last decade or so (Rayner et al., 2003). In 2009, DeMeo et al. incorporated the near-infrared spectral data into the Bus and Binzel (2002) taxonomic scheme in an effort to extend the classification from visible to infrared wavelengths. The objective was to make use of a repeatable method of codifying new data for a complete set of asteroid qualities. They measured the reflectance spectra of 371 asteroids over wavelengths ranging from 0.45 \( \mu \text{m} \) to 2.45 \( \mu \text{m} \) and came up with 24 classes.

\textit{S-Type and S-Subtype Asteroids}

Of the 132 Gefion family asteroids observed by the SMASS group, all were designated as S- or S-subtypes (http://sbn.psi.edu/ferret/, 11/22/11). This class of asteroids has been around as long as the first acknowledged taxonomy scheme (Chapman et al., 1975) and represents a significant fraction of the inner main belt asteroids (Gaffey et al., 1993b). Produced by varied heating regimes, the general S-class contains an assortment of seven subtypes, divided based on the compositions of surface silicate assemblages (Gaffey et al., 1993b). The
assemblages characterize a range of asteroid types, from undifferentiated bodies, to partially melted and fully differentiated bodies, to the metamorphosed and compositionally distinct units exposed from within them (Gaffey et al., 1993b).

The compositions of the seven subtypes follow a progression, created by the melting and extraction of magma from the residual melts, which proceeds from pure olivine through olivine-pyroxene mixtures to basalt-like pure pyroxene or pyroxene-feldspar mixtures, often including an additional phase of FeNi metal (Gaffey et al., 1993b). Based on olivine and pyroxene spectral absorption features, zones representing these subtypes have been designated on a plot that illustrates the olivine-pyroxene mixing line, shown in figure fifteen. Because the

From: Gaffey et al., 1993b

Figure 15. Plot of S-class subtypes based on absorption features associated with mixtures of olivine and pyroxene minerals. The sub-type relating to the ordinary chondrite meteorites is the S(IV) zone situated at bottom left.
minerals present in the compositions of the S-asteroid surfaces invoke a particular thermal regime, it is possible to infer the relative conditions under which the asteroids formed. Linking meteorites to these asteroid subtypes would help identify where in the early solar system these conditions occurred (Gaffey et al., 1993b). Table one lists the general mineralogy and potential meteorite analogs of the seven S-subtypes.

The silicate mineralogy of the S(IV)-subtype is the only subgroup of the S-types compatible with ordinary chondrite assemblages (Gaffey et al., 1993b). With partial to complete melting, and mineral phase segregation, the primitive ordinary chondrite mineralogy slides up or down the mixing line dependant on the composition of the extracted melt. Enrichment of pyroxene and feldspar, or depletion of olivine, will move an S(IV) assemblage out toward the S(VII) position, whilst enriched olivine, or depleted pyroxene and feldspar, will move the mineralogy up toward the S(I) position (Gaffey, 2011). Determining the abundance and end member compositions of the surface minerals of an S-asteroid will place it in one of the seven subclasses. Therefore, when looking at the Gefion family as a possible parent for the L-chondrite meteorites, it becomes important to determine whether the compositions of its members fall into the S(IV)-subclass.
Table 1. General mineralogy and potential meteorite analogues of the S-subtypes.

<table>
<thead>
<tr>
<th>Subtype</th>
<th>Mineralogy</th>
<th>Possible Meteorite Analogues</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(I)</td>
<td>Olivine &gt;&gt; pyroxene (+/− FeNi metal)‡</td>
<td>Pallasites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyroxene-poor ureilites</td>
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<tr>
<td></td>
<td></td>
<td>Pyroxene-poor brachinites</td>
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<tr>
<td></td>
<td></td>
<td><em>Olivine-metal partial melt residues</em></td>
</tr>
<tr>
<td>S(II)</td>
<td>Olivine &gt;&gt; clino.pyroxene (+/− FeNi metal)‡</td>
<td>Cpx-bearing ureilites</td>
</tr>
<tr>
<td></td>
<td>(0.05 &lt; cpx/(ol+cpx) &lt; 0.20)</td>
<td>Cpx-bearing brachinites</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Olivine-Cpx cumulates</em></td>
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<tr>
<td></td>
<td></td>
<td>Cpx-bearing pallasites*</td>
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<tr>
<td></td>
<td></td>
<td><em>Highly metamorphosed C-type assemblages</em></td>
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<tr>
<td>S(III)</td>
<td>Olivine &gt; clino.pyroxene + orthopyroxene (+/− FeNi metal)‡</td>
<td>Cpx- and opx-bearing ureilites</td>
</tr>
<tr>
<td>S(IV)</td>
<td>Olivine + orthopyroxene (+/− FeNi metal)‡</td>
<td>Opx-bearing ureilites</td>
</tr>
<tr>
<td></td>
<td>(0.20 &lt; cpx/(ol+opx) &lt; 0.50)</td>
<td>Lodranites</td>
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<td></td>
<td></td>
<td>Winonites &amp; IAB irons</td>
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<tr>
<td></td>
<td></td>
<td>H,L,L Chondrites</td>
</tr>
<tr>
<td>S(V)</td>
<td>Olivine − clino.pyroxene (+/− FeNi metal)‡</td>
<td>Lodranites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cpx-basal intergrowths into H-chondrite matrix*</td>
</tr>
<tr>
<td>S(VI)</td>
<td>Olivine − orthopyroxene (+/− FeNi metal)‡</td>
<td>Siderophytes (Steinbach)</td>
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<td></td>
<td></td>
<td>Lodranites</td>
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<td></td>
<td></td>
<td>Winonites &amp; IAB irons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subsolidus-reduced chondrites*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anorthosites*</td>
</tr>
<tr>
<td>S(VII)</td>
<td>Pyroxene &gt; olivine (+/− FeNi metal)‡</td>
<td>Mesosiderites</td>
</tr>
<tr>
<td></td>
<td>(Orthopyroxene &gt; clino.pyroxene)</td>
<td>Siderophytes (Steinbach)</td>
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<td>Lodranites</td>
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<td>Winonites &amp; IAB irons</td>
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<td>Cpx-poor mesosiderites*</td>
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<td>Subsolidus-reduced chondrites*</td>
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<td></td>
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<td>Anorthosites*</td>
</tr>
</tbody>
</table>

† Characterizations from Gaffey et al. (1993a).
‡ Metal abundance is poorly constrained and appears to be highly variable.
# Assemblages not presently identified in the meteorite collections.

From: Gaffey et al., 1993a

Reflectance Spectroscopy

Short of a spacecraft mission to bring back samples, visual and near-infrared reflectance spectroscopy is the best technique for characterizing the surfaces of
most asteroids (Gaffey et al. 1993a). It is a sensitive and widely applied remote sensing method that is used to determine asteroid surface compositions, as well as the particularly important olivine and pyroxene mineral phases. Basically, the presence, abundance, and/or composition of one or more mineral or chemical species on an asteroid surface can be interpreted using observable diagnostic processes (Gaffey, 1993a). The wavelength region of most interest for studies of planetary objects is between 0.35 to 5 µm, within which the dominant source of flux from the asteroid surface is derived from reflected solar incident light (Adams, 1974).

Clark (1995) defines reflectance spectroscopy as “the study of light as a function of wavelength that has been reflected or scattered from a solid, liquid, or gas.” When photons enter a mineral they can take one of three paths. They may pass through the grain, reflect off its surface, or be absorbed. The first two options create scattered light, which can be detected and measured. The third option is a process of absorption, which becomes slightly more complicated as there is more than one means of absorbing light. Nevertheless, it is the very complexity of the absorption processes, and their respective wavelength dependences, that allows mineral chemistry information to be derived from the reflected light (Clark, 1995).

Crystal Field Theory

The method for determining what minerals the absorption features in spectra acquired from an asteroid surface represent is based on a model of chemical bonding applicable to the transition and lanthanide elements, called Crystal Field Theory (Burns, 1970). The source of the spectral absorption features, at specific
wavelengths, stem from a number of processes. The most common electronic process is a consequence of unfilled electron shells in the transition elements. The most prevalent transition element in silicate minerals is iron (Clark, 1995).

In an isolated ion, d orbitals have uniform energies, but if the atom is in a crystal structure the energy levels split. This circumstance allows an electron to move from a lower energy level to a higher one when a photon having an energy that matches the difference between the states is absorbed. The valence state of the atom, its coordination number (the number of other atoms in the crystal that surround it), and the symmetry of the site it occupies determine the energy levels, though ligand type, site distortion, and interatomic distance may also play a role. The idiosyncratic crystal structures of discrete minerals will produce diverse crystal fields, resulting in varied quantities of energy level splitting. Consequently, identical cations (i.e. Fe$^{2+}$) can produce demonstrably different absorptions for each mineral (Clark, 1995).

A second key process creating wavelength specific absorption features in mineral spectra involves molecular vibrations. The bonds in a molecule or crystal structure vibrate at particular frequencies and have particular types of motion that are dependent on their strengths and elemental masses. With added energy equal to the frequency of vibration (say from a photon), additional vibrations can be induced that occur at approximate multiples of the original frequency, creating harmonics and overtones which are also capable of producing absorption features. The particular combination of vibrational motions produces absorption features diagnostic of specific molecules (Clark, 1995).
The absorption features caused by the vibrational motions of the water and hydroxyl molecules, for example, are remarkably diagnostic. Figure sixteen illustrates the vibrational motions of the water molecule. At 1.4 µm, the first overtones due to the stretching motion of hydroxyl appear, and at 1.9 µm the combination of the hydroxyl stretches and the bending motion of water become visible. In some cases, there may be more than one hydroxyl absorption feature contingent upon the ion to which it is attached. It is possible then, to determine

From: [http://www.lsbu.ac.uk/water/vibrat.html](http://www.lsbu.ac.uk/water/vibrat.html)

Figure 16. The various vibrational motions of the water molecule.

from absorption features whether a mineral contains hydroxyl, water, or both (Clark, 1995).

The most important collection of crystal field absorption features emerges as a result of specific crystallographic sites bearing transitional metal ions, usually bivalent iron (Fe$^{2+}$). The structure and composition of a mineral control the wavelength position, width, and intensity of the crystal field absorptions, from which the mineralogical characterization of an asteroid surface can be interpreted (Gaffey et al., 2002). The absorption features of greatest consequence for
asteroid and meteorite spectra are supplied by the iron-bearing mafic and silicate minerals (i.e. olivines, pyroxenes, and phyllosilicates), as well as oxides like spinels (Gaffey, 2011). An example of typical spectra for mafic silicate minerals and FeNi metal can be seen in figure seventeen.

Figure 17. Typical spectra for mafic silicate minerals olivine and pyroxene, as well as FeNi metal.

*Mafic Silicate Minerals*

The chemistry and structure of the silicate minerals control the positions of the absorption features used to interpret asteroid mineralogy from reflectance spectra. The silicon tetrahedra are the fundamental building blocks of all silicate minerals. The relatively small silicon cation (Si<sup>4+</sup>) is well suited to fit in
tetrahedral coordination with the oxygen anions (O²⁻). As can be seen in figure eighteen, the arrangement consists of four O²⁻ anions residing in the corners of

From: https://www2.bc.edu

Figure 18. The silica tetrahedra is made up of a Si⁴⁺ cation surrounded by four O²⁻ anions.

the tetrahedron, with the center occupied by a single Si⁴⁺ cation. Each O²⁻ anion satisfies one of its two valence charges by bonding with the Si⁴⁺ in the center. The other -1 valence charge is free to bond with another Si⁴⁺ cation at the center of another tetrahedron, allowing for polymerization. The foundation for the structural classification of the silicate minerals is the extent to which adjacent tetrahedra share oxygen ions (Nesse, 2000).

Olivine

Olivine is an orthosilicate, which has a mineral structure in which no oxygen anions are shared with neighboring silicon tetrahedra. The net negative charge is instead balanced by bonding with other cations such as Mg²⁺ and Fe²⁺. The basic structure is made up of isolated silicon tetrahedra bonded laterally through the other cations and held with the oxygen anions in octahedral or higher
coordination. The size and charge of the other cations dictate the differences in structures. Ideally, the structure would have identical octahedral sites, but in reality two separate sites are produced (see figure nineteen). The M1 sites form edge-sharing chains that get stretched apart and distorted. The M2 sites are attached to the sides of these chains and are somewhat less distorted (Nesse, 2000).

Olivine is a solid solution series mineral in which there is a compositional range between its end members. Forsterite (Mg$_2$SiO$_4$) and Fayalite (Fe$_2$SiO$_4$) share the same basic chemical formula, but elements are substituted in one or more atomic sites. In this series the Fe$^{2+}$ ions are distributed nearly equally over the M1 and M2 sites in the olivine structure. But, because the Fe$^{2+}$ cation is

From: http://www4.nau.edu

Figure 19. Olivine mineral structure. The M1 sites form octahedral chains that stretch in the C axis direction. The M2 sites attach to the sides of the octahedral chains and to isolated terahedra.
slightly larger than the Mg$^{2+}$ cation, the Fe$^{2+}$ ions prefer the somewhat larger M2 position. If the mineral contains even larger cations, such as Ca$^{2+}$ or Mn$^{2+}$, the Fe$^{2+}$ will concentrate in the M1 positions (Burns, 1970).

The positions and intensities of absorption features reveal which cations are where within the crystal structure of the mineral, and because minerals are distinguished by a particular composition or range of compositions within a particular crystallographic structure, the surface mineralogy of the remotely sensed object can be inferred (Gaffey et al., 1993a). The primary diagnostic characteristic for olivine is a broad complex absorption feature near 1.0 μm that consists of several overlapping absorption bands (see figure twenty).

From: King and Ridley, 1987

Figure 20. The 1.0 μm composite feature is prominent in this olivine spectrum of forsterite (66). The strongest feature, at 1.04 μm, is attributed to Fe$^{2+}$ in six fold coordination.
The general position of this composite feature will shift toward longer wavelengths with increasing iron content (Burns, 1970). The overall spectral characteristics of the range of olivine compositions change only subtly as a function of the iron/magnesium ratio, so notable compositional information can only be drawn out of relatively high-resolution spectra (King and Ridley, 1987). The 1 µm absorption feature is not only significant for determining olivine composition, though. It plays a strong role when it comes to mineral mixtures as well. Aside from olivine and excluding hydrous minerals, another typical mineral to condense out of a solar nebula gas is pyroxene (Cloutis et al., 1986). Unraveling the absorption features of both minerals can be a difficult task.

**Pyroxene**

Pyroxene is a chain silicate made up of single chains of silicon tetrahedra bonded together by cations such as Fe$^{2+}$, Mg$^{2+}$, and Ca$^{2+}$. Although they can be somewhat kinked, the chains stack one above another so that the bases of one chain of tetrahedra face another tetrahedral chain’s bases, and the unshared oxygen anions opposite to the bases also face each other (Nesse, 2000). The ends with unshared oxygen anions share a cation in six-fold coordination, forming the M1 site. The M2 site is situated between the tetrahedral bases, and the shared cation there occupies a moderately distorted six- or eight-fold coordination. The crystal field is dependant on the size of the cation and the structure of the stacked chains (Nesse, 2000). The stacking structure is illustrated in figure twenty-one.

The general formula for a pyroxene is depicted as $\text{XYZ}_2\text{O}_6$. The Z element is usually Si$^{4+}$ occupying the tetrahedral sites. The X and Y elements sit in the M2 and M1 sites respectively. The classification of the pyroxene depends on two
Figure 21. The pyroxene structure. (a) Top and end views of a single chain. (b) Stacked chains that alternate M1 and M2 sites, both vertically and horizontally. (c) M1 sites and their neighboring tetrahedra form an “I-beam” shape. (d) The same image as in (b), but using the “I-beam” iconography.
things: the symmetry of the structure, and the specific cation that occupies the M2 site. When Fe\(^{2+}\) and Mg\(^{2+}\) are present, the Fe\(^{2+}\) tends towards the M2 site for two reasons. First, the Fe\(^{2+}\) cation is a bit bigger than the Mg\(^{2+}\) cation and it prefers the slightly larger M2 site. Secondly, the distortion of the M2 site gives greater crystal field stabilization energy to the Fe\(^{2+}\) cation over the Mg\(^{2+}\) cation (Nesse, 2000). The low-calcium, magnesium-iron pyroxenes (orthopyroxenes) are of the most interest for this study, although calcium pyroxene (clinopyroxene) can also be important. Table two displays the classification of the pyroxene mineral based on chemical makeup.

Table 2. The Pyroxene Classification. X cations occupy the M2 sites, Y cations occupy the M1 sites, and Z cations occupy the tetrahedral sites.

<table>
<thead>
<tr>
<th>Group</th>
<th>X cations</th>
<th>Y cations</th>
<th>Z cations</th>
<th>Minerals(s)</th>
<th>Symmetry</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium-iron</td>
<td>Mg, Fe</td>
<td>Mg, Fe</td>
<td>Si(_2)O(_6)</td>
<td>Enstatite–ferroilite</td>
<td>Orthorhombic</td>
<td>Orthopyroxene (opx)</td>
</tr>
<tr>
<td></td>
<td>Mg, Fe, Ca</td>
<td>Mg, Fe</td>
<td>Si(_2)O(_6)</td>
<td>Pigeonite</td>
<td>Monoclinic</td>
<td>Low-Ca clinopyroxene</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>Mg, Fe</td>
<td>Si(_2)O(_6)</td>
<td>Diopside–hedenbergite</td>
<td>Orthorhombic</td>
<td>Ca clinopyroxene (Ca-opx or opx)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mg, Fe, Al</td>
<td>(Si,Al)(_2)O(_6)</td>
<td>Angite</td>
<td>Monoclinic</td>
<td>Sodic–calcic clinopyroxene</td>
</tr>
<tr>
<td>Calcium sodium</td>
<td>Ca, Na</td>
<td>Mg, Fe(^{3+}), Al, Fe(^{3+})</td>
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<td>Spodumene</td>
<td>Orthorhombic</td>
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</tr>
</tbody>
</table>

From: Nesse, 2000

The spectra of pyroxenes exhibit two main absorption features, or bands, near the 1 and 2 µm wavelengths. Both bands are created by the occupancy of the Fe\(^{2+}\) cation in the more distorted M2 sites within the mineral structure (Cloutis et al., 1986). In low-calcium pyroxenes, which typically contain less than 11 mol% CaSiO\(_3\) (wollastonite), both bands shift to longer wavelengths with increasing iron content. In high-calcium clinopyroxenes, the absorption bands shift to
longer wavelengths with increasing calcium content, because the Ca\textsuperscript{2+} cation preferentially fills the M2 sites compelling the Fe\textsuperscript{2+} to occupy the M1 sites. This alters both the crystal structure and the crystal field relationships of the mineral (Adams, 1974).

Figure twenty-two shows a Band I Center vs. Band II Center plot. There is a regular shift in wavelength positions of the two bands with composition, illustrating a pyroxene trend line. Fe\textsuperscript{2+} and/or Ca\textsuperscript{2+} content increases from bottom left to upper right, and the shift from orthopyroxene to clinopyroxene structure follows in the same direction (Adams, 1974; Gaffey, 2011). Over a broad range of abundances, orthopyroxene is the primary influence on band positions in olivine-pyroxene mixtures. Clinopyroxene, on the other hand, only

![Figure 22. Band I Center vs. Band II Center plot representing the pyroxene trend, in which the bands shift to longer wavelengths with increasing iron and calcium composition.](image-url)
noticeably appears when abundance nears 75 wt % (Cloutis and Gaffey, 1991).

Band position ratios that leave the trend of points on the Band I Center vs. Band II Center plot typically indicate the presence of more than one type of pyroxene, or a pyroxene mixed with another mineral (Adams, 1974).

In spectra of mixed olivine-pyroxene mineral assemblages, the blended absorption features near the 1 and 2 µm bands are sensitive not only to the composition, but to the relative amounts of olivine and pyroxene as well. In asteroid and meteorite spectroscopy, the ratio of the band II area over the band I area is quite often used to gauge olivine and pyroxene abundances (Cloutis et al., 1986; Dunn et al., 2010). When the Band I Center vs. Band Area Ratio plot is compiled for the ordinary chondrite meteorites (figure twenty-three), each type

![Graph](image)

From: Dunn et al., 2010

Figure 23. The H-, L-, and LL-chondrite meteorite trends as plotted on the S(IV) region of the S-Class Band I Center vs. Band Area Ratio graph.
seem to form linear trends with a fairly restricted band I center range, but spanning a broader range of band area ratio (Dunn, 2010). By using both types of calibrations, Band I Center vs. Band II Center for composition, and Band I Center vs. Band Area Ratio for abundance, the minerals of ordinary chondrite-type assemblages can be fairly well constrained.

Reflectance spectra absorption features can be very complex to unravel, and the calibrations that have been defined so far (Burns, 1970; Adams, 1974; Cloutis et al., 1986; King and Ridley, 1987; Cloutis and Gaffey, 1991; Gaffey et al., 1993b; Sunshine and Pieters, 1998; Gaffey et al., 2002) are limited. For example, the 1 and 2 μm band position to pyroxene composition calibrations work well for spectra taken from material made up of a single pyroxene, but if a substantial quantity of a second pyroxene is present, the calibrations founder (Gaffey et al., 2002). Although low-calcium pyroxene is the dominant phase in ordinary chondrites, there is often a high-calcium pyroxene phase present as well (Adams, 1974). McSween et al. (1991) added a clinopyroxene component to their normative calculations of the ordinary chondrites to estimate the high-calcium percentages within the H-, L-, and LL-chondrite mineralogies, which were estimated to be ~ 12%, 17%, and 19% respectively.

Furthermore, the minerals spinel and chromite may also be present in the relatively unaltered ordinary chondrites and can contribute additional absorption features at wavelengths between 0.3 and 3.3 μm. These features can be quite numerous in high-resolution spectra, but the designation of these bands is complicated by the presence of multiple cations in most natural samples. Unfortunately, there are only a few bands for which there is broad agreement, so
the use of spinel and chromite calibrations is not currently practicable (Cloutis et al., 2004).

Space Weathering

Finally, much has been made about the space weathering processes on asteroid surfaces and their possible effect on reflectance spectra (Gaffey et al., 2002; Clark et al., 2002; Chapman, 2004; Brunetto, 2009; Gaffey, 2011). The term ‘space weathering’ is a general one encompassing activities that can alter the optical properties of surface material exposed to space on airless bodies (Chapman, 2004). The processes range from soil grains coated with vaporized regolith, caused by micrometeorite bombardment, to deposition of atoms sputtered off of soil grains due to solar wind particles (Gaffey et al., 2002).

Space weathering was originally studied in lunar soils, with later researchers proffering it as a rationale for a popular theory’s paradoxical reflectance spectra. It was thought that the abundant S-type asteroids should logically be the sources of the most common meteorites falling to Earth, the ordinary chondrites. However, hardly any main-belt S-asteroids resembled the ordinary chondrites spectrally. The discrepancies were explained by space weathering. Spacecraft missions have found evidence of space weathering on asteroid 243 Ida during the Galileo flyby, and on asteroid 433 Eros during the Near Shoemaker rendezvous. Unfortunately, the space weathering mechanisms working on the asteroids and the Moon appear to differ from one another, complicating the issue further (Gaffey et al., 2002; Gaffey, 2011).

What matters most about space weathering as a concept is the extent to which it can affect spectral interpretation. The albedo is often lowered, the spectral
slope is reddened, and the mafic mineral absorption features in a spectrum can be weakened. These effects rule out the use of a curve-matching interpretation regime, as the calibrations needed to amend the reflectance spectra for each mechanism are undefined. However, by concentrating on the diagnostic parameters of a spectrum, such as absorption features and their band centers, intensities, widths, and areas, identifying compositions and abundances of cosmically important minerals is achievable (Gaffey et al., 2002; Gaffey, 2011).
CHAPTER V
METHODS AND TECHNIQUES

Observation

Near-infrared observations of the two Gefion family asteroids 2905 Plaskett and 3910 Liszt, were taken on June 4, and July 18, 2011, respectively. Reflectance spectra were collected using the 0.8-5.5 Micron Medium-Resolution Spectrograph and Imager (SpeX) at the NASA Infrared Telescope Facility (IRTF) situated atop Mauna Kea, on the Big Island of Hawai’i. The spectra were acquired using the low-resolution, or asteroid mode. This mode has a relatively high signal to noise ratio even for fainter objects with weaker signals (Rayner et al., 2003). Also, it is able to resolve the broad absorption features that are created by magnesium and iron silicates, the important minerals in ordinary chondrites and S-type asteroids.

The first step in obtaining a high quality average nightly reflectance spectra, is to put together a comprehensive observing plan before heading to the summit. The plan for the night of July 18, 2011 is shown in figure twenty-four. Standard, or extinction, star observation sets (~10 spectra) are alternated with sets of asteroid observations. The standard star measurements effectively sample a range of optical path lengths through the atmosphere (airmass) over the course of the night. An accurate model of the Mauna Kea sky can then be derived from
these measurements, which is used to remove the effects of atmospheric water vapor absorptions from the asteroid spectra (Hardersen, forthcoming).

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<th>DEC (2000)</th>
<th>Airmass</th>
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<th>#Spec</th>
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</table>

Figure 24. The observing plan for the night of July 18, 2011, showing alternating sets of standard star (blue), asteroid (red), and solar analog star (green) observations.

Next, either preceding or following each grouping of asteroid and standard star sets, a set of solar analog star observations is made. The solar analog star, usually a G2 star near in the sky to the asteroid being observed, theoretically experiences the same atmospheric conditions as the asteroid, and is used to remove the continuum effects of the Sun. Finally, as the SpeX instrument uses an argon lamp as its reference, a number of argon arc spectra are acquired for wavelength calibration purposes. All observations (asteroid, standard star, and
solar analog) are measured using the same equipment, so instrumental wavelength-dependent response is cancelled out during the data reduction process, although the spectra does need to be corrected for channel shift due to instrumental flexure (Fieber-Beyer, 2010).

Data Reduction

The purpose of reducing the spectral data is to produce high quality (high signal to noise) asteroid spectra from which the absorption band parameters can be identified and interpreted. The general equation for this process is as follows:

\[
\text{Reflectance}_\lambda(\text{obj}) = \frac{\text{Flux}_\lambda(\text{obj})}{\text{Flux}_\lambda(\text{star})} \times \frac{\text{Flux}_\lambda(\text{star})}{\text{Flux}_\lambda(\text{Sun})}
\]

Basically, the final spectra of the asteroid is found by first dividing its spectra by that of the standard star. This removes the telluric water effects. The resulting quotient is then multiplied by the quotient of the standard star spectra divided by the solar analog spectra, which further removes the effects of the solar continuum. The final outcome is a reflectance spectrum resulting from the particular mineralogy present on the surface of the object observed (Gaffey et al., 2002).

Image Reduction and Analysis Facility (IRAF)

To reduce the data, two software packages are used. The first is the Unix-based Image Reduction and Analysis Facility (IRAF) created by the National Optical Astronomy Observatories (NOAO). The second is a Windows-based program, called SpecPR, designed to reduce and analyze near-infrared spectra stored in one-dimensional arrays (Clark, 1980; modified by Gaffey, personal communication). The raw spectra from the SpeX instrument are recorded in the
form of Flexible Image Transport System (FITS) images. The IRAF program extracts the spectra from the FITS images, subtracts the background sky, adds together the rows on the spectrographic array surrounding the flux of the object, and converts it all to a text file. Then, using the arc spectra, argon peaks are measured and input into an excel spreadsheet, from which a polynomial fit is made to the data. This determines the wavelength calibration by transforming the array channel numbers into wavelengths (Fieber-Beyer, 2010).

Once the IRAF conversions for all observed spectra are completed, there is an intermediate step taken before beginning data reduction in the SpecPR program. The Transpex transition program uses the text files produced in IRAF to construct a format compatible with SpecPR. It takes the single text file resulting from IRAF processing and converts it into alternating records of channel and data. This step must be repeated for each spectrum of each target object. When that has been accomplished, the data is ready to be processed through SpecPR, which performs a number of important operations that lead to a final, reduced spectrum ready for analysis (Fieber-Beyer, 2010).

**SpecPR**

The first step in the SpecPR process is to develop a starpack. Essentially, a starpack consists of multiple sets of standard star observations taken over a broad airmass range. Derived from log-flux versus airmass plots at each wavelength, the starpack is a set of wavelength-dependent atmospheric extinction coefficients that models the atmosphere for that night. The set of slopes and intercepts is used to correct for differences in airmass between the standard star and the asteroid. A starpack for standard star SAO 190089 is
shown in figure twenty-five. It may be necessary, on some nights, to break a full night’s starpack into partial night starpacks that better represent the airmass at the time of the asteroid observation. The partial night starpack will model the sky more accurately than the all-night starpack, but it will cover a smaller airmass range and is only useful for those asteroids observed within that range.

\[ \text{SAO 190089 sp12 shift -4 : Slopes} \]

Figure 25. The Slope vs Channel plot of a starpack for standard star SAO 190089, which is used to correct for differences in airmass between the standard star and the asteroid.

It is important to mention here that due to effects such as gravity and positioning, the telescope and spectrograph may make small shifts throughout the night, causing the incoming light that is separated onto the array to land on
different areas of a pixel, or perhaps on different pixels for individual observed spectra (Hardersen, forthcoming). This slight deviation between channels can introduce unwanted noise into the spectra and must be corrected by manually shifting the channels. For starpacks, one standard star set is used as a reference to which all other sets are normalized. Then, for each spectrum, it is necessary to iteratively shift the channels by as little as 0.1 pixel to perhaps 1.0 pixel, and gauge the correct shift by eye. Compare figure twenty-six (below) with the previous figure to see why shifting is required.

Figure 26. Starpack of standard star SAO 190089 with shift zero. An offset is visible near channels 325 and 450. Figure 25 is the outcome of making a corrective shift of -0.4 pixel.
At this point, each asteroid spectrum is divided by the starpack appropriate for its airmass, which should remove the telluric water vapor absorption features at 1.4 and 1.9 µm. The resulting spectra must also be corrected for any channel offsets by iteratively shifting the channels and gauging the correct shift by eye. The next step in the SpecPR process is to create a normalized average reflectance spectrum in which all of the asteroid/starpack spectra are averaged together. There may be some spectra that are well corrected for atmospheric absorption features and others that are not. It is best to use as many spectra as possible to make a nightly average, but especially noisy spectra are generally omitted from the operation (Hardersen, forthcoming).

A similar sequence of operations is performed on the set of solar analog spectra. Using the same starpack as is used for the asteroid ratio, each solar analog spectrum is corrected for channel offset and then divided. The total number of spectra is then averaged together, and the resulting average spectrum is fit with a polynomial. This removes water absorption features and outlier points from the spectrum. Based on the polynomial terms, a curve is calculated that is subsequently used to ratio to the average nightly spectrum (Fieber-Beyer, 2010). This corrects for non-solar characteristics of the standard star and accomplishes the goal of creating a solar corrected final spectrum for the asteroid as can be seen in figure twenty-seven.
Analysis

The creation of the final spectrum is the beginning of the analysis phase. The band centers of both absorption features are isolated and determined first, then the band areas are calculated. Initially, each feature is isolated by dividing every wavelength by a straight-line continuum through the reflectance peaks at either side of the feature. This process puts the feature in a horizontal position, or removes the slope, and it is then saved as a ratioed curve. An n-order polynomial is fit to the ratioed curve of the horizontal feature, and using those polynomial terms the band center is determined iteratively (Fieber-Beyer, 2010). The band centers of absorption features are used to characterize the minerals present on an object’s surface.
The procedure for calculating the band areas is fairly simple. Again, the feature is isolated by dividing each wavelength by a straight-line continuum through the reflectance peaks at either side, and then the area under the line is calculated. The technique is performed for both features near the 1 μm and 2 μm wavelengths. To determine the band area ratio (BAR), the band II area is divided by the band I area. The unitless number produced is an indication of the relative mineral abundance on the object’s surface (i.e. Cloutis et al, 1986). Together, band centers and band areas constrain the types and amounts of minerals present on an asteroid’s surface.
CHAPTER VI
RESULTS AND CONCLUSIONS

Spectral Analysis

Before the details of the two asteroids observed for this project are revealed, it is important to remember the purpose for this endeavor. The idea of finding a source for an ordinary chondrite meteorite type, especially for the L-chondrites that make up a majority of the ordinary chondrite falls (Burbine et al., 2002), has been an aspiration of meteorite and asteroid scientists for many years. The connection would enable us to place a specific composition at a particular location within the asteroid belt, providing a record of the processes and conditions present in the early Solar system (Gaffey, 2011).

In order to justify the probability of a meteorite-parent body connection, there are two main criteria to be met. First, the potential parent body must be positioned in a favorable orbital location within the main belt where a recognized dynamical mechanism can deliver the relevant meteorite flux to Earth. In this case, the Gefion family appears to satisfy this qualification. It is located in an orbital position (near the 5:2 mean motion resonance) that is capable of sending meteorites to Earth on a timescale congruent with the fossil L-chondrite meteorites (Heck et al. 2004), and has a model formation age that is compatible with the timing of the L-chondrite break-up event (Korotchanseva et al., 2007).
The second of the probable parent body criteria requires that the mineralogy of the potential parent body match that of the L-chondrite meteorites. The main focus of this project is to test this requirement. Two members of the Gefion family, 2905 Plaskett and 3910 Liszt, were observed in an effort to characterize their surface mineralogy for comparison with that of the L-chondrite meteorites.

The spectral parameters extracted from the spectra of these asteroids during the data reduction process make it possible to decipher a number of mineralogical characteristics. To begin with, the composition and structure of a mineral are described by the positions and intensities of individual absorption features. The central wavelength of an absorption feature, its band center, is a function of the crystal structure of the mineral, which is influenced by the composition. Therefore, it is possible to derive the composition of the surface minerals of an asteroid from the band centers of its absorption features. This is typically visually represented on a plot of the Band I Center vs. the Band II Center (i.e. Adams, 1974, Gaffey 2011).

When pyroxene is the only, or dominant, mineral contributing to an asteroid’s average spectra, the band centers will plot along a compositional trend line on the Band I Center vs. Band II Center plot that moves from lower left to upper right with increasing Fe$^{2+}$ and Ca$^{2+}$ content. If there is olivine present in the surface assemblage as well, the band I center will also plot at a longer wavelength, causing the assemblage to move up off the trend line. Basically, an asteroid’s position on the trend line gives a good indication of the crystal structure of the pyroxenes (orthopyroxene or higher-calcium clinopyroxene) on its surface and, hence, an estimation of its chondritic type (Gaffey, 2011). Figure twenty-eight
portrays the Band I Center vs. Band II Center plot, with marked regions within which mineral assemblages compare with particular meteorite types.

Figure 28. Band I Center vs. Band II Center plot used to interpret composition. The trend moves from bottom left to upper right with increasing iron and calcium content. Boxes outline areas enveloping particular meteorite types.

Another parameter, used to distinguish the relative mineral abundance, is the band area ratio (BAR). For olivine-orthopyroxene assemblages, the BAR value not only correlates with the amount of orthopyroxene in the mixture, but is applicable over nearly the whole abundance range as well (Cloutis et al., 1986). This relationship is generally illustrated with a graph of the Band Area Ratio vs. the percent pyroxene abundance (% Opx/(Opx + Ol)), displayed in figure twenty-nine, that shows a least squares linear fit to all the BAR values between 10 and 90% pyroxene.
From: Cloutis et al., 1986

Figure 29. Plot of BAR vs. % Opx/(Opx+Ol) abundance.

The respective amounts of orthopyroxene and olivine in the assemblage (BAR value), as well as the composition of the olivine and orthopyroxene (band center values), are what designate the discrete mineralogical zones that divide the S-type asteroids. As seen once again in figure thirty, the asteroids spread out along an olivine-pyroxene mixing line with olivine as the major silicate phase in the top left S(I) area, and with pyroxene as the major silicate phase in the S(VII) region at bottom right. Although not uniquely diagnostic, the S(IV)-subtype (located in the sock-shaped region in the lower left corner) represents assemblages consistent with the ordinary chondrites.
Making use of both band parameters, the average pyroxene composition is estimated using equations defined by Gaffey et al. (2002). The iterative use of the equations produces values for the average amounts of ferrosilite (Fs), or iron orthopyroxene, and wollastonite (Wo), a high-calcium clinopyroxene. The mineral abundance ratio of orthopyroxene \((\text{Opx}/(\text{Opx} + \text{Ol}))\) is also computed based on measured mixtures of silicates (Cloutis et al., 1986). McSween et al. (1991) have calculated the normative mineralogies of the ordinary chondrites, which can be used to compare the olivine-pyroxene ratios, but not mineral compositions. And, Dunn et al. (2010) have derived a new mineral abundance calibration for olivine \((\text{Ol}/(\text{Ol} + \text{Pyx}))\), as well as mafic silicate composition calibrations (fayalite (Fa) in olivine and ferrosilite in pyroxene) based on actual
measured ordinary chondrite modal abundances. In this study, each of these calibrations are calculated and compared.

Ultimately, to be deemed mineralogically congruent with the L-chondrite meteorites, the asteroids examined here must satisfy three conditions. First, they must fall within the L-chondrite zone on the orthopyroxene trend line of the Band I Center vs. Band II Center plot. Second, they need to chart inside the S(IV) region on the Band I Center vs. Band Area Ratio plot. Third, they must have mineral abundance ratios compatible with L-chondrite mineral abundance ratios.

2905 Plaskett

The final solar corrected average spectrum of 2905 Plaskett is displayed in figure thirty-one. As can be seen, the telluric water features are evident in this spectrum, which was taken on a night with very poor weather at the summit of Mauna Kea. It is still a usable spectrum, however, and the parameters obtained
from this spectrum indicate a band I center value of 0.93 ± 0.02, a band II center value of 1.95 ± 0.01, and a band area ratio value of 1.3 ± 0.15. A second measurement of the band II area with a slightly different long wavelength endpoint for the continuum placed across the absorption feature, discussed later in the text, gives a smaller band area ratio value of 0.95±0.15.

The Band I Center vs. Band II Center plot is depicted in figure thirty-two. The asteroid plots on the pyroxene trend line, and lands on the edge of the L- and H-chondrite zones. Unfortunately, the error bars give the precise position of this asteroid some ambiguity, but it is at least consistent with the L-chondrites.

Figure 32. The position of 2905 Plaskett on the Band I Center vs. Band II Center plot.
The second graph, the Band I Center vs. Band Area Ratio plot (figure thirty-three), shows the asteroid located close to the olivine-pyroxene mixing line just longward of the S(IV) ordinary chondrite zone. It appears to lie in the S(VI) zone, but is within error of the very edge of the ordinary chondrite zone. This position is based on the larger of the two measured band area ratios, resulting from the calculation of the band II area seen in figure thirty-four. The continuum for this measurement has a second endpoint that may have been placed higher than is reasonable for the quality of this data, which leads to a higher band area ratio, and consequently to a higher orthopyroxene abundance. The second measurement of band II area has a second endpoint to its continuum that may be a better fit to the data, as shown in figure thirty-five. This measurement gives a
Figure 34. Spectrum of 2905 Plaskett showing the continuum under which the first band II area was calculated.

Figure 35. The continuum of the second band II area measurement.
smaller band area ratio value that, when plotted, puts 2905 Plaskett inside the ordinary chondrite region on the Band I Center vs. Band Area Ratio plot (figure thirty-six). The degree of uncertainty due to the poor weather conditions under which this asteroid was observed makes it difficult to state conclusively its olivine-pyroxene abundance ratio, but it is believable that this asteroid is within reasonable doubt of the L-chondrite realm.

The Gaffey et al. (2002) equations convey the relationships between absorption band center and pyroxene composition in the form of molar calcium content, wollastonite (Wo), and molar iron content, ferrosilite (Fs) with an error of ±3 (Gaffey, personal communication). The process involves iterative computations of the iron and calcium content with corrections for high calcium
content based on the category of the ordinary chondrite (H-, L-, or LL-). High
calcium content can affect band centers, but over a broad range of abundances,
low calcium pyroxene is the primary influence on band positions in olivine-
pyroxene mixtures, so Fs content is most important in determining which
subtype an object might be. The object in question is tested for each group, and if
the calculated values do not fall within the range of values for that group, it is
eliminated as a possibility.

The band centers for the spectra of 2905 Plaskett give average values for Fs of
21.9, 22.7, and 18.9 (±3) for the H-, L-, and LL-subtypes respectively. The first
value is higher than the range of values consistent with an H-chondrite, and the
third value is lower than the range consistent with LL-chondrites. These options
can be discarded. The second value falls right at the very top end of the L-
chondrite range, which is between Fs 19 and 22, but this group appears to be the
most likely of the three subtypes as a possible match. Again, the error allows for
a bit of wiggle room within these numbers, but the L-chondrite type seems
reasonable.

According to the Dunn et al. (2010) equations, however, the value for Fs of this
asteroid is 15.12±1.4 (rms value from Dunn et al., 2010), which places it in the H-
chondrite range. It should be noted though, that Dunn et al., (2010) use a
relationship between the band I center and the measured Fs of ordinary
chondrite meteorites to determine the amount of Fs. As can be seen on the graph
in figure thirty-seven, an object with a band I center of 0.93, like 2905 Plaskett,
could potentially be either an H- or an L-chondrite depending on the amount of
Fs present, again contributing to some ambiguity in characterization.
Based on the band area ratio, the abundance calibration developed by Cloutis et al. (1986) indicates the relative mineral abundance in olivine-orthopyroxene mixtures. The abundance of pyroxene \((\text{Opx}/(\text{Opx} + \text{Ol}))\) in 2905 Plaskett is calculated to be 59%, with a corresponding olivine content, then, of 41%. This value is well correlated with the value derived for olivine abundance \((\text{Ol}/(\text{Ol} + \text{Pyx}))\) using the Dunn et al. (2010) equation.

McSween et al. (1991) determined the average normative mineral abundances for the ordinary chondrites. The collated values can be seen in table three. The abundance values for 2905 Plaskett, 41% olivine and 59% pyroxene, do not overtly fit into any of the ordinary chondrite categories, having not enough olivine, and too much pyroxene. It would seem, from the abundance ratio, that...
Table 3. Normative olivine-pyroxene abundances as compiled from calculations produced by McSween et al. (1991). A clinopyroxene component is also computed as a percentage of the pyroxene.

<table>
<thead>
<tr>
<th>Normative</th>
<th>Ol</th>
<th>Pyx</th>
<th>Cpx (Cpx + Pyx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>54%</td>
<td>46%</td>
<td>12%</td>
</tr>
<tr>
<td>L</td>
<td>60%</td>
<td>40%</td>
<td>17%</td>
</tr>
<tr>
<td>LL</td>
<td>66%</td>
<td>34%</td>
<td>19%</td>
</tr>
</tbody>
</table>

This asteroid is farther down the olivine-pyroxene mixing line than the S(IV)-subtype, perhaps likened more to an S(VI)-subtype as was also inferred by the Band I Center vs. Band Area Ratio plot (figure thirty-three) made using the first set of continuum endpoints, with the resulting higher band area ratio.

Taken all together, the information derived from the different research groups can be confusing to sort out. It must be remembered that each group is basing their calibrations on different variables and/or different sample collections, and that comparisons must be made with these discrepancies in mind. However, even though the different calibrations give slightly different results, they are basically consistent with each other, or at least not grossly inconsistent. 2905 Plaskett was also observed during very poor weather, creating noise in the data that could affect the band parameters. So, while it appears that 2905 Plaskett is not definitively a match to the L-chondrite mineralogy, it is at the same time not prohibitively far off that mineralogy either.
3910 Liszt

The final solar corrected average spectrum for 3910 Liszt is portrayed in figure thirty-eight. This spectrum was taken on a night with fairly good seeing, but it still had some water vapor to contend with, as can be noted by the noisy spectrum near the 1.9 μm wavelength. When merged with the SMASS visible wavelength data, the reflectance peak near 0.7 μm matched up well in both data sets, so the first endpoint of the band I continuum was set using the near-infrared spectrum. The continuum removed band parameter values for this spectrum were measured to be $0.94 \pm 0.01$ for band I, $1.98 \pm 0.14$ for band II, and $0.69 \pm 0.1$ for the band area ratio.
The Band I Center vs. Band II Center plot of 3910 Liszt, figure thirty-nine, depicts the position of the asteroid as situated on the edge of the LL-chondrite zone, but within error of the L-chondrite zone. Although this asteroid may not appear to be a good fit for the L-chondrites on this graph, it is placed more favorably on the Band I Center vs. Band Area Ratio plot visible in figure forty.

This plot places 3910 Liszt directly on the olivine-pyroxene mixing line, and well inside the ordinary chondrite zone. Comparing this placement with the graph portraying the apparent linear trends of the ordinary chondrites from Dunn et al. (2010), figure twenty-three, this asteroid seems to fall somewhere
Figure 40. The position of asteroid 3910 List on the olivine-pyroxene mixing line, and well within the ordinary chondrite zone.

around the line between the L- and H-chondrites. The calculated abundance of Fs, on the other hand, gives contrasting results.

The calculations made from the Gaffey et al. (2002) equations give values for Fs in asteroid 3910 Liszt of 29.9, 30.7, and 26.9 (±3) for the H-, L-, and LL-subtype tests respectively. The first value is quite a bit higher than the range of Fs compatible with the H-chondrites, and the second value is also higher than the L-chondrite compatible range. It would appear that this object is closest to the LL-chondrite range, which spans from Fs22 to Fs26. The Fs amount obtained from the Dunn et al. (2010) equations, however, are much lower, at 16.9±1.4 (rms from Dunn et al., 2010). Again, the band I center of 0.94, depending on the amount of Fs, could potentially place 3910 Liszt in either the H- or L-chondrite
groups according to their graph (figure thirty-seven) giving some uncertainty to
the results. So, there is a spread there, but the data are still grossly consistent.

The pyroxene abundance value for this object, obtained using the Cloutis et al.
(1986) equation, is 34%, with an associated olivine percentage of 66%. These
abundances match quite well with the normative abundances calculated for the
LL-chondrites by McSween et al. (1991). The Dunn et al. (2010) olivine equation,
however, gives this asteroid 44% olivine, and 56% pyroxene, which places it
nearer to the H-chondrites.

Again, the different calibrations place this asteroid in contrasting categories
with regard to the ordinary chondrites, though the fact that it is reconciliable with
these meteorite types is important to note. In terms of mineral composition,
3910 Liszt is within error of the L-chondrite meteorites, though the mineral
abundances are more ambiguous. Nevertheless, this asteroid is generally
consistent with the ordinary chondrites and could be construed to be broadly
congruent with the L-chondrite meteorite mineralogy.

Conclusion

In terms of the hypothesis that the Gefion family could be the parent body of
the L-chondrite meteorites, 2905 Plaskett is more ambiguous, but could be
reconciled with the L-chondrites. 3910 Liszt leans towards the LL-chondrites, or
the H-chondrites if looking at the Dunn calibrations, but is also still a reasonable
candidate for an L-chondrite. So, we have one questionable contender, and one
reasonably good one. However, they are both grossly consistent with the
ordinary chondrites and the L-chondrites in general. Noisy spectra raises
uncertainty, and it cannot be concluded that both of these asteroids are solidly
proven to be compatible with the L-chondrites, but both are ordinary chondrite assemblages that could feasibly be considered to reconcile with the L-chondrites. So, the supposition that the Gefion family is parent to the L-chondrites is still a viable option.

Future work

In the effort to test this hypothesis, there is much future work to be done. It would be prudent, first of all, to obtain more observations of 2905 Plaskett and 3910 Liszt to better confirm their mineralogies. Beyond that, it is vital to obtain spectra of a representative sample of Gefion family members. Zappalà et al. (1995), using the Hierarchical Clustering Method (HCM), found close to 90 core members residing in the Gefion family. The two asteroids characterized here are a good start, but many more asteroids need to be observed and characterized before the family can be considered both a genetic family, and the parent body of the L-chondrites.

Another area to explore is a test of the various compositional calibrations. It is possible now to compare spectral band parameters of the asteroid Itokawa (Abell et al., 2007) with the values computed for the particles returned from its surface via the Hayabusa spacecraft (Nakamura, 2011). This would act as a check on the formulas used in the compositional calibrations used for this work (i.e. Gaffey et al., 2002; Dunn et al., 2010).

Furthermore, according to Masiero et al. (2011), members of genetic families should typically show a characteristic albedo. Albedo measurements by the WISE mission suggest that the core members of the Gefion family are actually two separate overlapping families, the members of each having significantly different
albedoes. The properties of these members can be more easily identified once we have built up a reasonable list of members that have been observed and characterized. Another potential investigation for this project, then, will be to examine the albedo values for the Gefion members in an effort to ascertain the genetic history of the family. All in all, although the work done so far on this project is informative, it is only a small part of the work that is to come.
REFERENCES


http://sbn.psi.edu/ferret/, 11/22/11


