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Is The Gefion Dynamical Asteroid Family The Source Of The L Chondrites?

Rachel Roberts

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IS THE GEFION DYNAMICAL ASTEROID FAMILY THE SOURCE OF THE L CHONDrites?

By

Rachel V. Roberts
Bachelor of Science, Oregon State University, 2010

A Thesis
Submitted to the Graduate Faculty
of the
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for the degree of
Master of Science

Grand Forks, North Dakota
May
2017
This thesis, submitted by Rachel Robeerts 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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                       the L Chondrites?

Department       Space Studies

Degree              Master of Science

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Rachel V. Roberts

May 5, 2017
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ABSTRACT

Identifying main belt asteroid sources of the ordinary chondrites (H, L, and LL) is a high priority. Ordinary chondrites account for approximately 75% of meteorite falls, of which the L chondrites account for approximately 35% of meteorite falls (Wasson, 1985; Schmitz et al., 2001). From detailed analysis of meteorites, composition and formation environment can be ascertained; pairing the meteorites to probable sources in the main asteroid belt increases our understanding of the compositional and temperature environment during the formation of the inner solar system (Burbine et al., 2002; Gaffey, 2011). Gaffey and Gilbert (1998) identified a probable main belt parent source (6 Hebe) for the H chondrites and the IIE irons (Burbine et al., 2002; Gaffey and Gilbert, 1998). Probable main belt sources for the L and LL chondrites remain to be confirmed (Burbine et al., 2002). Carruba et al., (2002; 2003), Bottke et al., (2009) and Nesvorny et al., (2009) suggest that the Gefion dynamical asteroid family is the source of the L chondrites (Carruba et al., 2002; Carruba et al., 2003; Bottke et al., 2009; Nesvorny et al., 2009). The age of the Gefion family, taxonomy, and proximity to the 5:2 resonance, coincide with an influx of L chondrites during the middle Ordovician (Schmitz et al., 2001; Schmitz et al., 2003; Bottke et al., 2009; Nesvorny et al., 2009). This study tests the claims of Carruba et al (2002; 2003), Bottke et al., (2009), and Nesvorny et al., (2009) that the Gefion dynamical asteroid family is the source of the L chondrites. Asteroids selected for observation and analysis are members of the
Nesvorny Gefion dynamical asteroid family (V2.0) as determined by the Hierarchical Clustering Method (Zappalà et al., 1990; Bendjoya et al., 1993; Bendjoya and Zappala, 2002; Nesvorny, 2012). Visible and near infrared (VNIR, 0.7 to 2.5 μm) spectra of 14 Gefion family asteroids were obtained from the SpeX instrument at the NASA Infrared Telescope Facility (IRTF) 3-meter telescope over several observations during 2011 to 2013 (Rayner et al., 2003). Average spectra were combined with available visible wavelength data from the Small Main-belt Asteroid Spectroscopic Survey, phases I and II, or the Small Solar System Objects Spectroscopic Survey (S^3OS^2) (Xu et al., 1995, Bus and Binzel, 2002a; 2002b; Lazzaro et al., 2004) to increase wavelength coverage to 0.3 μm (0.5 μm for S^3OS^2). A search for IRTF spectra of Gefion asteroids in the Small Bodies Database and R. P. Binzel’s asteroid spectroscopy database added one asteroid, (5159) Burbine (Binzel et al., 2014). Mineralogical assemblages were estimated from band parameter analysis and calibrations from Cloutis et al., (1986), Gastineau-Lyons et al., (2002), Gaffey et al (2002), and Dunn et al (2010), of S-type asteroid spectra. Pyroxene chemistry and olivine abundances estimated from band parameters of the S(IV) asteroids via the Gaffey et al., (2002), Gastieau-Lyons et al., (2002), and Dunn et al., (2010) calibrations are not consistent. Only two asteroids, (3910) Liszt and (4182) Mount Locke have assemblages consistent with the L chondrites, there is no dominant mineralogical assemblage, and the Gefion family is not a likely source of the L chondrites.
CHAPTER I
ASTEROIDS

Asteroids are the remnants of planetesimals that formed the terrestrial planets (Chapman et al., 1979; Wasson, 1985; McSween, 1999). Most asteroids are located in the region between 2 AU and 3.3 AU, known as the main asteroid belt but small populations of asteroids have Mars and Earth crossing orbits (Wasson, 1985; McSween, 1999). Asteroids vary in size from meter scale to the largest asteroid 1 Ceres with a diameter of 930 km; compositions vary from differentiated achondrite remnants to chondrites, which have not undergone any alteration (Chapman et al., 1979; Wasson, 1985; McSween, 1999). The first asteroid, (1) Ceres, was discovered by Piazzi in 1801, and was considered a planet (McSween, 1999; Serio et al., 2002). Ceres' location between Mars and Jupiter, along with the earlier discovery of Uranus by Herschel was consistent with the Titus-Bode law, an idea proposed in which the planets' semi-major axes followed a geometric series (McSween, 1999, pg.34 for equation; Serio et al., 2003). Since Ceres' discovery, many other bodies were found between Mars and Jupiter, designated asteroids due to their star-like appearance (asteroid means star-like), were originally considered to be remnants of a disintegrated planet (Chapman et al., 1979; Wasson, 1985; McSween, 1999; Gaffey, 2011). Asteroids are now considered remnants of the original population of planetesimals, of which the terrestrial planets were formed and asteroid-meteorite links provide insight into the conditions of the late solar nebula.
and early solar system (Chapman et al., 1979; Wasson, 1985; McSween, 1999; Gaffey et al., 2002; Gaffey, 2011). Asteroids with planet-crossing orbits are the cause of impact structures on Earth and other terrestrial planets and the discovery of Near Earth and potentially hazardous asteroids has led to an increase of interest in asteroids and the associated hazards to Earth (Maher and Stevenson, 1988; Gaffey, 2011). An asteroid impact played a role in the mass extinctions at the end of the Cretaceous period (65 Myr ago) in which close to 75% of species, including the dinosaurs, became extinct (Alvarez et al., 1980, Gaffey, 2011). Fresh impact craters observed on Mars, the Chelyabinsk bolide and close approaches of small asteroids such as 367943 Duende have increased awareness of hazards due to Near Earth asteroids (Malin et al., 2006; Harris et al., 2015). Awareness of these hazards has led to specialized programs for identifying additional Near Earth asteroids, determining physical properties, and dedicated missions to asteroids such as NEAR, Hayabusa, and Dawn (Chapman, 1975; Tholen, 1984; Xu et al., 1995; Russel, 1997; Bus and Binzel, 2002a, 2002b; Lazarro et al., 2004; Warner et al., 2009; Carvano et al., 2010; Masiero et al., 2013; Russel et al., 2015; Yoshikawa et al., 2015). While the probability of a kilometer scale or larger asteroid impact in the near future is very low, the effect on civilization is so large that an understanding of asteroid properties and populations are important (Chapman and Morrison, 1994; Harris et al 2015). The knowledge of orbital parameters, composition, internal structure, size, and rotation rate of a potentially hazardous asteroid can help planners determine the best deflection method, if these methods exist, and the time needed to implement a plan (Abell et al., 2015; Harris et al., 2015).
Asteroid Families

Hirayama proposed the concept of asteroid families in 1918 while investigating the cause of the Kirkwood gaps (Hirayama, 1918, 1927, 1933; Kozai, 1994). Hirayama observed clustering of asteroids when semi-major axes (a), inclination (i), and eccentricities (e) of known asteroids are represented in a phase space (a-e or a-i space) (Hirayama, 1918, 1927, 1933; Kozai, 1994). Asteroids in these clusters have similar orbital elements and Hirayama proposed that observed clusters were not due to chance and there must be a common origin for each of the clusters (Hirayama, 1918, 1927, 1933; Kozai, 1994). Since Hirayama's original set of asteroid families, researchers identified new asteroid families with numerical models, often with differences in membership when taxonomy and albedo are taken into account (Zappalà et al., 1990, 1995; Bendjoya and Zappala, 1994; Cellino et al., 2002; Nesvorny et al., 2012; Masiero et al., 2013).

Figure 1: Main-belt asteroids represented in a-sin(i) proper element space (figure 2 from Gaffey, 2011). The 3:1 and 5:2 mean motion resonance and the ν6 secular resonances are the main delivery mechanisms for asteroids to near Earth space. The clumps of asteroids are dynamical families.
Dynamical asteroid families are defined as groups of asteroids with similar proper orbital elements (semimajor axis, a; eccentricity, e; inclination, i), statistically significant above the background population (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013). Asteroid families form by a catastrophic collision, which disrupts the parent body, or collisions in which several small asteroids are produced while the parent body stays intact with (4) Vesta and Vestoids being an example (Zappalà et al., 1990, 1994, 1995; Bendjoya and Zappala, 2002; Masiero et al., 2013; Nesvorny, 2015). Collisional history and ejection velocity is preserved in the asteroid family by the velocities of members, which are essentially the fragments of the event that created the family (Zappalà and Cellino, 1994; Zappalà et al., 1995; Bendjoya and Zappala, 2002; Masiero et al., 2013).

Statistical methods such as the wavelet and hierarchical clustering method (HCM) are primarily used in the identification of dynamical families (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013; Nesvorny et al., 2015). Zappala et al., (1990) first introduced the HCM; Nesvorny, and others continue to refine family membership as new data become available (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Ivezic et al., 2001; Bendjoya and Zappala, 2002; Mainzer et al., 2011; Masiero et al., 2011, 2013; Nesvorny et al., 2015). The Hierarchical clustering and wavelet methods are repeatable, tested with simulated asteroid populations, and are a quantitative method of identification of asteroid families (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002;
Masiero et al., 2011, 2013; Nesvorny et al., 2012). The HCM utilizes a metric (velocity) measured from the proper elements (a, e, i) to determine which asteroids are included in a particular dynamical family (Zappalà et al. 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013). Clustering is determined by combining an asteroid with its nearest neighbor(s), at each metric which is increased, at step sizes as defined by the user, until all asteroids in the region are included (figure 2) (Zappalà et al 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013).

Figure 2: HCM results from Zappalà and Cellino 1994 – their fig. 3. The plot, known as a “stalactite diagram” (Zappalà and Cellino 1994), shows statistically robust families (the stalactites). “1272” identifies this particular stalactite as the Gefion dynamical family. N (x-axis) is the number of asteroids in the region (Zappalà et al 1990, Bendjoya et al 1993, Zappalà and Cellino 1994, Zappala et al 1995, Bendjoya and Zappala 2002, Nesvorny 2010, Masiero et al 2011, Nesvorny 2012, Masiero et al 2013, Nesvorny 2015). In this plot, asteroid families appear at a metric of 50 m/s. Additional asteroids merge into the clusters with increasing velocities (metrics).

The stalactite diagram (figure 2), from Zappalà and Cellino, (1994), is a visual representation from the application of the HCM to asteroids in the region from a = 2.5 AU to a = 2.825 AU which includes the Gefion family. Each stalactite is a potential
dynamical family, tested for robustness by defining the threshold metric, below which are the asteroids included in each of the families (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013). The threshold, known as the quasi-random level (QRL), defined, as the velocity for which a minimum number of asteroids are merged together, is determined individually for each of the families (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013). A quasi-random population of orbital elements (a, e, and i) generates the synthetic asteroid population and the HCM is applied multiple times (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al, 2011, 2013). Stalactite plots from the synthetic asteroid populations and the real asteroid population compared to one another; clusters with the minimum asteroids in the actual population are defined as those with stalactites reaching one standard deviation below the QRL (Zappalà et al., 1990, 1995; Bendjoya et al., 1993; Zappalà and Cellino, 1994; Bendjoya and Zappala, 2002; Masiero et al., 2011, 2013).

**Kirkwood Gaps**

Kirkwood gaps, identified by Kirkwood in 1886, are gaps in the heliocentric distribution of asteroids in the main asteroid belt and are seen graphically when all of the known semi-major axes of asteroids are plotted (figure 3) (Delgrande and Sloanes, 1943; Chapman et al., 1978; Greenberg and Scholl, 1979; Yoshikawa, 1990). Kirkwood predicted that perturbation of Jupiter on asteroids would give an increase in the eccentricity of the asteroids' orbits (Delgrande and Sloanes, 1943; Chapman et al., 1978;
Kirkwood gaps are regions in the asteroid belt in which there is a commensurability of orbital periods of the asteroids and Jupiter and to a lesser extent, Saturn (Chapman et al., 1978; Greenberg and Scholl, 1979; Yoshikawa, 1990).

Kirkwood, through exploration of commensurability of orbits, calculated the first four orders and found that order determined how much of an effect Jupiter had in perturbing asteroids (Delgrande and Sloanes, 1943; Chapman et al., 1978; Greenberg and Scholl, 1979; Yoshikawa, 1990). Commensurability is defined as the fraction of Jupiter's orbit completed for every full orbit of an asteroid and is given as a ratio, such as the 5:2, where the numerator is the number of asteroid orbits and the denominator is the number of Jupiter's orbits (Delgrande and Sloanes, 1943; Chapman et al., 1978; Greenberg and Scholl, 1979; Yoshikawa, 1990). For an asteroid located in the 5:2 resonance, Jupiter completes 2 orbits for every 5 orbits of the asteroid; commensurabilities, also known as mean motion resonances, are amplified to gravitational influences due to repeated encounters with Jupiter with Saturn having a lesser effect (Delgrande and Sloanes, 1943; Chapman et al., 1978; Greenberg and Scholl, 1979; Yoshikawa, 1990).
Resonances: Chaotic Mean-Motion Resonances, Secular Resonances

Chaotic mean-motion resonances and secular resonances can potentially deliver asteroid fragments to Earth; both resonances change the eccentricity of asteroids (Williams and Faulkner, 1981; Yoshikawa, 1990; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002; Dvorak, 2006). Chaotic mean-motion resonances, such as the 3:1 and 5:2, increase eccentricity and asteroids located in these resonances do not stay in the resonance for geologic timescales (Williams and Faulkner, 1981; Yoshikawa, 1990; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002; Dvorak, 2006). The instability is due to commensurability with Jupiter, which increases the eccentricity of the asteroid, removes the asteroid from the resonance (Williams and Faulkner, 1981; Yoshikawa, 1990; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002). Mean-motion resonances can also stabilize asteroid orbits with Jupiter's Trojan asteroids (1:1 resonance) and the Hilda asteroids serving as examples of stable mean-motion resonances (Williams and Faulkner, 1981; Yoshikawa, 1990; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002).

Mean motion resonances, such as the 3:1 and 5:2, deliver asteroids to Earth crossing orbits and meteorites to Earth on timescales short enough for fragile objects to survive long enough to become meteorites (Yoshikawa, 1990; Gladman et al., 1997; Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002, 2007,
Small asteroids are delivered into a chaotic mean-motion resonance by the Yarkovsky effect, directly by impact, or by a catastrophic disruption of a parent body in which fragments with sufficient velocities can be directly inserted into the resonance (Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998, Nesvorny et al., 2002, 2007, 2009). The 3:1, 5:2, and 7:3 resonances correspond to the three main Kirkwood gaps located at 2.50 AU, 2.82 AU, and 2.95 AU, respectively. Both the 3:1 and 5:2 mean-motion resonances are effective in increasing eccentricities of asteroids located in them in short timescales of approximately one million years (Yoshikawa, 1990; Gladman et al., 1997; Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002, 2007, 2009). Results from numerical modeling show that the orbits of asteroids in these resonances evolve into either Jupiter crossing, sun grazing orbits or encounter terrestrial planets such as Mars or Earth which change the asteroid's orbit (Yoshikawa, 1990; Gladman et al., 1997; Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002, 2007, 2009). Asteroids located in the 3:1 resonance experience large increases in their eccentricities with approximately 70% evolving into sun grazing orbits and 27% estimated to be ejected out of the solar system due to orbital evolution in which they fall under Jupiter's influence (Farinella et al., 1993; Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002). Approximately 3% encounter the terrestrial planets and potentially become meteorites (Farinella et al., 1993; Morbidelli and Gladman, 1998; Nesvorny and Morbidelli, 1998; Nesvorny et al., 2002). Estimated timescales of asteroids in the 3:1 resonance is 2 million years; 10% of asteroids have timescales up to 7 million years or more (Morbidelli and Gladman, 1998; Nesvorny and
Morbidelli, 1998; Nesvorny et al., 2002). Residence time in the 3:1 resonance is longer than the cosmic-ray exposure ages (CRE) of fossil L chondrites, which have cosmic-ray exposure histories between 0.05 million years to 1.5 million years (Marti and Graff, 1992; Schmitz et al., 2001; Heck et al., 2004; Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009). CRE ages for modern L chondrites are between 20 million and 40 million years (Marti and Graff, 1992; Schmitz et al., 2001; Heck et al., 2004; Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009).

Asteroids in the 5:2 resonance have their eccentricities increased in very short timescales with an average timescale of 500,000 years; 10% of asteroids in the 5:2 resonance have lifetimes longer than 3 million years (Morbidelli and Gladman, 1998; Morbidelli and Nesvorny, 1999; Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009). From numerical simulation, approximately 90% of objects in the 5:2 resonance experience increases in their eccentricities, fall under Jupiter's influence, or the orbits become hyperbolic, with the remaining experiencing gravitational encounters with terrestrial planets (Morbidelli and Nesvorny, 1999; Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009). In addition to fast timescales, asteroids located close to the 5:2 resonance can move into the resonance through slow chaotic diffusion with timescales estimated at a few million years (Morbidelli and Gladman, 1998; Morbidelli and Nesvorny, 1999; Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009). The estimated timescales to reach the 5:2 resonance and reach Earth is consistent with the range of cosmic-ray exposure ages of both fossil and modern L chondrites (Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009).
Secular resonances are repeated perturbations of orbital precession of an asteroid due to encounters with Jupiter and Saturn in which the orbital precession is the cyclical change of the longitude of perihelion and the node with typical periods estimated to be between 50,000 and 2,000,000 years (Williams and Faulkner, 1981; Dvorak, 2006). Since asteroids and planets are not on perfect coplanar orbits, the inclinations and eccentricities of the asteroids lead to forced oscillations of the longitude of perihelion and nodes (Williams and Faulkner, 1981; Dvorak, 2006). Repeated encounters with Jupiter and other planets cause a change the direction of perihelion by an increase or decrease of both inclination and eccentricity; The change in eccentricity moves the asteroid to Mars or Earth crossing orbits and potentially delivers meteorites to Earth (Williams and Faulkner, 1981; Dvorak, 2006). The perturbations of asteroid orbit precession from encounters with Jupiter and other planets are complex surfaces that intersect one another (figure 4) as well as chaotic mean-motion resonances (Williams and Faulkner, 1981; Dvorak, 2006). Secular resonances form boundaries in inclination within the asteroid belt when represented in three dimensional proper element spaces (Williams and Faulkner, 1981; Dvorak, 2006).

Figure 4: The $\nu_6$ secular resonance (lower surface), $\nu_5$ resonance (upper surface), and $\nu_{16}$ resonance (dashed lines) are represented in three-dimensional proper element space (figure from Williams and Faulkner, 1981, their fig. 14). The z-axis is the sine of the inclination, the y-axis is eccentricity, and the x-axis is the semimajor axis (in AU).
Proximity to one of the chaotic mean-motion or secular resonances is necessary in the search for asteroidal sources of stony meteorites which have insufficient strength to survive long delivery timescales to reach a resonance (Schmitz et al., 2001, 2003; Carruba et al., 2002, 2003; Nesvorny et al., 2002, 2007, 2009; Bottke et al., 2009; Gaffey, 2011). Delivery to a fast acting resonance is quicker if the asteroids are close to the resonance at the time of breakup (Schmitz et al., 2001, 2003; Carruba et al., 2002, 2003; Nesvorny et al., 2002, 2007, 2009; Bottke et al., 2009; Gaffey, 2011). Cosmic-ray exposure ages of L chondrites confirm the short timescales for delivery to Earth and potential locations in the search for probable parent bodies for the L chondrites are expected to be close to these resonances (Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009). The delivery timescales of the 5:2 mean-motion resonance are consistent with cosmic-ray exposure ages of the fossil L chondrites (but not modern L chondrites); probable sources of the L chondrites are likely to be near this resonance (Carruba et al., 2002, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009).

**Yarkovsky Effect**

The Yarkovsky effect is a radiation force that has a measurable effect on asteroids with sizes up to 40 km in diameter (Opik, 1951; Bottke et al., 2002, 2006; Scheeres et al., 2002; Carruba et al., 2003; Nesvorny and Bottke, 2004). The effect is most effective for asteroids less than 20 km in diameter, and is a mechanism that delivers asteroids into a resonance (Opik, 1951; Bottke et al., 2002, 2006; Scheeres et al., 2002; Carruba et al., 2003; Nesvorny and Bottke, 2004). Yarkovsky first proposed the radiation force in 1900, but the original paper was lost for many years (Nieman et al., 1965). Opik (in
1951) remembered the paper and its discussion of a mechanism for delivering small asteroids to Earth and O’Keefe, Radzievskii, Paddack, and Peterson, and others refined the theory (Paddack, 1969; Nieman et al., 1965; Peterson, 1976; Hartmann et al., 1999; Scheeres et al., 2002; Nesvorny and Bottke, 2004; Beekman, 2005; Bottke et al., 2006). The Yarkovsky effect reconciles the discrepancy between the short delivery times (less than a million years) of objects inserted into resonances and long term cosmic-ray exposure ages of meteorites (Scheeres et al., 2002; Nesvorny and Bottke, 2004; Bottke et al., 2006; Nesvorny et al., 2007, 2009).

The diurnal Yarkovsky effect (figure 5) is due to asymmetric emission of thermal radiation by a rotating asteroid whose axis is approximately normal to the orbital plane; the sun facing part absorbs solar radiation and emits the radiation in the thermal infrared as it rotates (Rubincam, 1995, 1998; Vokrouhlicky, 1998; Bottke et al., 2006). The thermal infrared radiation emitted from the asteroid’s surface imparts a momentum and the asteroid experiences an equal but opposite momentum, which slowly changes its orbit through the increase or decrease of the eccentricity (Rubincam, 1995, 1998, 2000; Vokrouhlicky 1998; Bottke et al., 2006). Asteroids with prograde rotation experience an increase in eccentricity, while retrograde rotation circularizes orbits (Rubincam, 1995, 1998, 2000; Vokrouhlicky, 1998; Bottke et al., 2006). The time required for the diurnal Yarkovsky effect to change the orbit of an asteroid is proportional to its rotation rate (Rubincam, 1995, 1998, 2000; Vokrouhlicky, 1998; Bottke et al., 2006). The diurnal Yarkovsky radiation is most effective for asteroids with rotational axes normal to the orbital plane and decreases to no effect for asteroids whose rotational axes lie in the orbital plane (Rubincam, 1995, 1998, 2000; Vokrouhlicky, 1998; Bottke et al., 2006).
Figure 5: Diurnal Yarkovsky effect. Figure from Bottke et al 2006 – their fig 2a. As the asteroid rotates, the area that has received solar radiation re-radiates as thermal radiation that imparts an equal and opposite force on the asteroid, changing the semimajor axis over time.

The seasonal Yarkovsky effect (figure 6) is the dominating component of thermal radiation force for asteroids whose spin poles lie in the orbital plane and is dependent on distance and position with respect to the sun (Rubincam, 1995, 1998; Bottke et al., 2006). Similar to the diurnal Yarkovsky effect, the seasonal Yarkovsky effect is due to emission of infrared radiation and is most effective on small bodies less than 20 km in diameter (Rubincam, 1995, 1998; Bottke et al., 2006). The difference is that the object's position in its orbit, not its rotation rate, is of importance since the timescale for the effect is dependent on the orbital period (Rubincam, 1995, 1998; Bottke et al., 2006). When one of the rotation poles is facing the sun, it receives all of the radiation and as the asteroid moves along its orbit, this region emits the radiation with the equal and opposite force imparted on the object from the emission, circularizing the orbit (Rubincam, 1995, 1998; Bottke et al., 2006). The seasonal Yarkovsky effect is most effective for small asteroids with low eccentricities (Rubincam, 1995, 1998, Bottke et al., 2006).
Asteroid Taxonomy

Asteroid taxonomy is a classification method in which objects that share observational properties such as U-V-B colors, visible wavelength spectral shape, and albedo are grouped together (Chapman, 1975; Tholen, 1984; Zellner et al., 1985, 2009; Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazarro et al., 2004, Carvano et al., 2010, Masiero et al., 2013). Taxonomy has the advantage of classifying large numbers of asteroids, for example, the Sloan Digital Sky Survey and WISE catalogs include over 100,000 objects (Chapman, 1975; Tholen, 1984; Zellner et al., 1985, 2009; Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazarro et al., 2004; Carvano et al., 2010, Masiero et al., 2013). Taxonomy also gives insight on the compositional trends of the asteroid belt (Chapman, 1975; Tholen, 1984; Zellner et al., 1985, 2009; Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazarro et al., 2004; Carvano et al., 2010, Masiero et al., 2013). Asteroids in the same taxonomic class exhibit broad similarities with one another, differ in composition
from asteroids in other classes, but do not necessarily share the same mineralogy, or genetic origin (Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011). Tholen (1984) and, later, Bus and Binzel (2002a, 2002b) noted that the S taxonomic class exhibited variation, due to variations of shape near the 1μm absorption feature, and the S class subdivisions in the Bus and Binzel taxonomic scheme reflect this variation (Tholen, 1984; Bus and Binzel, 2002a, 2002b). The variations seen in the S class visible wavelength spectra could hold clues of the composition if the observations extended to longer wavelengths (Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011).

Asteroid taxonomy became important as the number of asteroid discoveries increased and with a large number of known asteroids, categorizing them and grouping those that share physical properties such as U-B-V colors and/or albedo was the start of an attempt at understanding of the thermal and collisional history in the asteroid belt (Tholen, 1984; Chapman et al., 1975). Early researchers such as Chapman et al., (1975) created classifications based on observation techniques that were available at that time such as spectrophotometry, polarimetry, and radiometry observations, and from these, two broad groups of asteroids were seen (Tholen, 1984; Chapman et al., 1975). The asteroid classifications were compared to spectral-albedo curves of meteorites, and asteroids were grouped in the C (carbonaceous) class and the S (silicate) class based on U-B-V colors; asteroids that did not fall into either group were placed in a third class, designated U (Tholen, 1984; Chapman et al., 1975). The number of taxonomic classes grew and membership often changed from study to study due to additional data and new observational methods (Tholen, 1984; Bus and Binzel, 2002a, 2002b; Lazzaro et al., 2004). The Eight Color Asteroid Survey (ECAS) took eight filter broadband
photometric measurements (from 0.337 μm to 1.04 μm) of 589 asteroids, 405 of which provided the database which Tholen (1984) used for a more detailed taxonomy (Tholen, 1984; Zellner et al., 1985, 2009). Tholen introduced 12 (the E, M, and P classes were grouped together as the X class) spectral classes based on albedos and color indices from the survey via a new clustering algorithm based on principle component analysis (Tholen, 1984). The new spectral classes introduced were A, B, C, D, F, G, Q, R, S, T, V, and X with the C and the S classes having the largest sample sizes: 88 asteroids in the C class and 144 asteroids in the S class (Tholen, 1984). Tholen noted that the well-defined S spectral class exhibited evidence of variation and his taxonomic classification has been the basis for all subsequent classification schemes (Tholen, 1984; Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazzaro et al., 2004).

Subsequent taxonomic classifications, based on Tholen’s spectral classes, were defined based on higher resolution visible wavelength spectra from large surveys of the asteroid belt: Small Main-belt Asteroid Spectroscopic Survey, phases I and II (SMASS and SMASSII), and Small Solar System Objects Spectroscopic Survey (S^3OS^2) (Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazzaro et al., 2004). The wavelength intervals ranged from 0.3 μm to 0.925 μm for SMASSII and S^3OS^2 and 0.3 μm to 1.0 μm for SMASS (Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazzaro et al., 2004). The new taxonomic classifications were based on spectra taken with long slit spectrographs and charged-coupled devices (CCD’s) which produced higher resolution spectra (Xu et al., 1995; Bus and Binzel, 2002a, 2002b; Lazzaro et al., 2004). Subtle variations in shapes, slopes, and the presence of absorption features, which were not apparent in the Eight Color Asteroid Survey data, were apparent (Xu et al., 1995; Bus
and Binzel, 2002a, 2002b; Lazzaro et al., 2004). Spectra from phase I of SMASS revealed variation between the new dataset and Tholen's taxonomic classification, particularly with the C, S and X class (Xu et al., 1995; Bus and Binzel, 2002a, 2002b). New S-type classifications were added to account for spectra intermediate between two types: S, Sa, Sk, Sl, Sq, and Sr; for example, an asteroid spectrum with a shape intermediate between A and S is classified as Sa (Bus and Binzel, 2002a, 2002b). The Small Solar System Objects Spectroscopic Survey (S³OS²), had an objective of classifying additional asteroids, and resulted in spectra for 820 asteroids classified with both the Tholen and Bus and Binzel taxonomies (Lazzaro et al., 2004).

Figure 7: Representative visible wavelength spectra for all 26 taxonomic classes from the SMASSII data (Bus and Binzel 2002b). The spectra represented illustrate where the individual taxonomic classes fit in the spectral component space in which the 1 μm band depth increases from top to bottom and the average slope increases from left to right (Bus and Binzel 2002b). The S taxonomic subtypes that are intermediate (Sa, Sk, Sl, Sq, ans Sr) fall between S and A, K, L, Q, and R (Bus and Binzel 2002b).

The Sloan digital sky survey (SDSS) was a five filter photometric survey of 104,687 asteroids in the 0.3 to 1 μm interval, with taxonomic classification of 63,487 asteroids (Ivezic et al., 2001; Stoughton et al., 2002; Abazajian et al., 2003; Parker et al., 2008;
Carvano et al., 2010; DeMeo and Carry, 2013). The SDSS database was compared with meteorite spectra (from RELAB, Brown University) for a new set of taxonomic classifications based on comparisons of asteroid and meteorite properties with the goal of classifying meteorite and asteroid spectra under the same classification scheme to better understand the large scale variations in composition within the asteroid belt (Carvano et al., 2010). DeMeo and Carry (2013, 2014) used Principal Component Analysis of the SDSS data along with albedos from the Infrared Astronomical Satellite (IRAS), the Wide-field Infrared Survey Explorer (WISE), and AKARI (light) surveys to further refine previously defined taxonomic classes and distribution of taxonomic classes in the asteroid belt (Tedesco et al., 2002a, 2002b; Murakami et al., 2007; DeMeo and Carry, 2013, 2014).

Gaffey et al (1993a) utilized all good quality spectra of S type asteroids from 52-color survey database, which extended spectral coverage to the 2.5 μm region. Previous studies with laboratory meteorite spectra have shown that meteorites with iron-bearing silicate minerals such as pyroxene and olivine, exhibit absorption features in the 0.8 μm to 2.5 μm region (Adams, 1974, 1975; Gaffey, 1976; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey 2011). Meteorite spectra were compared with spectra of laboratory mineral mixtures of varying olivine/pyroxene abundances and diagnostic parameters were identified (Adams, 1974, 1975; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey 2011). Three main spectral parameters, Band 1 (BI), Band 2 (BII), and Band Area Ratio (BAR) provide insight into mineralogical content and relative abundance of olivine (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey 2011). Band analysis for S type asteroid spectra were utilized in subdividing the
S asteroids into subclasses based on composition and degree of differentiation (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey 2011). Seven distinct subgroups (figure 17) were identified including S(IV) region include the ordinary chondrites and parent bodies for the H, L, and LL chondrites will fall in this region (Gaffey et al., 1993a, 1993b, 2002, Gaffey, 2011).
CHAPTER II
METEORITES

Meteorite Types

Meteorites have been revered and utilized by humans for millennia; iron meteorites, with their unusual properties, have led to iron metallurgy (McSween, 1999; Hutchison, 2004). While early civilizations and philosophers believed meteorites were from the heavens, for a while, scholars attributed the source of meteorites as volcanic or atmospheric in origin (McSween, 1999; Hutchison, 2004). The scientific study of meteorites started in 1794 with a publication by Ernst Chladni, who determined that iron meteorites were extraterrestrial in origin and not due to volcanic or atmospheric phenomena (McSween, 1999; Hutchison, 2004). A subsequent fall and chemical/mineralogical analysis within ten years of Chladni's book provided additional evidence and acceptance of the extraterrestrial origin for meteorites, at least in Europe (McSween, 1999; Hutchison, 2004). Further advances in petrology, metallurgy, and chemistry advanced the study of meteorites and led to the complex classification of meteorites in use today (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004).

Meteorites are collected as either finds or falls (Wasson, 1985; McSween, 1999; Hutchison, 2004). Meteorite falls occur when a meteor is observed and the corresponding meteorites that survived entry are collected very soon after with recent
examples being Tagish Lake and Chelyabinsk (Wasson, 1985; McSween, 1999; Brown et al., 2000; Hutchison, 2004; Borovicka et al., 2013). Falls are important due to the short interval between phenomenon (the observed meteor) and collection of the meteorite and ensure the least amount of terrestrial contamination (Wasson, 1985; McSween, 1999; Hutchison, 2004). A find is a meteorite that has been present on Earth for any number of years before collection and has varying states of weathering and oxidization depending on environment and duration of time before collection (Wasson, 1985; McSween, 1999; Hutchison, 2004). In the past few decades, dedicated searches for meteorites have been occurring, primarily in the Sahara Desert and Antarctica due to the ease of finding meteorites and the environment being preferable to preserving meteorites (McSween, 1999; Bischoff, 2001; Burbine et al., 2002; Hutchison 2004).

Early classifications subdivided meteorites into three main categories: iron, stony iron (mesosiderites and pallasites), and stony meteorites (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Meteorites are classified as chondrites, which have not undergone melt and are undifferentiated, and achondrites, which are from differentiated parent sources (figure 8); primitive achondrites have experiences some melt but have experienced little to no differentiation (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Based on chemistry, texture (petrologic type for chondrites), isotopes, and mineralogy, chondrites, primitive achondrites and achondrites are sorted into classes and individual groups within each class (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004).
Figure 8: Classification chart of meteorite classes, groups, and subgroups. Note that primitive achondrites are classified as differentiated meteorites. Figure is from the Astromaterials Acquisition and Curation Office, JSC, http://curator.jsc.nasa.gov/education/classification.cfm.

Petrologic type, originally defined for increasing levels of thermal metamorphism in ordinary chondrites, describes the level of alteration of a chondrite (Miyamoto et al., 1981; Wasson, 1985; McSween, 1999; Keil, 2000; Hutchison, 2004; Rubin, 2005; Grady et al., 2014). Petrologic types 1 and 2 describe aqueous alteration from more altered (type 1) to less altered (type 2) and are limited to carbonaceous chondrites (Wasson, 1985; McSween, 1999; Hutchison, 2004; Rubin, 2005; Grady et al., 2014). Petrologic type 3 meteorites have experienced little to no alteration and petrologic types 4 through 6 describe increasing levels of thermal metamorphism and occur in all chondrites (Miyamoto et al., 1981; Wasson, 1985; McSween, 1999; Keil, 2000; Hutchison, 2004; Rubin, 2005; Grady et al., 2014).

The irons (except IAB, IIICD and IIE) and pallasites, classified as achondrites, are remnants of cores and core mantle boundaries, respectively, of disrupted differentiated asteroids (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004; Grady et al., 2014). Iron meteorites, composed of nickel-iron alloys, were originally classified into
groups based on the width of kamacite and taenite crystals that are visible in cut and etched surfaces and known as Widmanstatten patterns (Goldstein and Ogilvie, 1965; Goldstein and Short, 1967; Wasson, 1985; McSween, 1999; Hutchison, 2004). The width of the kamacite crystals is dependent on both cooling rates and Ni weight percent (wt.%) in which a negative correlation exists between Ni wt.% and kamacite width and kamacite crystals disappear at Ni wt.% greater than 16% (Goldstein and Ogilvie, 1965; Goldstein and Short, 1967; Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Iron meteorites were originally classified into one of eight groups: hexahedrites (low Ni wt%), four subgroups of octahedrites, plessitic octahedrites, or ataxites (high Ni wt.%) (Goldstein and Ogilvie, 1965; Goldstein and Short, 1967; Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Iron meteorites are now divided into chemically distinct groups based on the Ga (gallium), Ge (germanium), and Ir (iridium) content (Goldberg et al., 1951; Scott and Wasson, 1975; Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Magmatic irons exhibit a positive correlation between Au (gold) and Ni (nickel), preferentially incorporated in fractional crystallization of a Fe-Ni melt, while non-magmatic irons have no correlation between Ni and Au content indicative of incomplete melting (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004). Pallasites are classified based on mineralogy; most are identified as Main Group Pallasites (MGP) while Eagle Station and pyroxene pallasites grouplets have few members (Mittlefehldt et al., 1998; McSween, 1999; Hutchison, 2004). Pallasites consist of large olivine crystals and minor minerals such as troilite in a NiFe matrix, pyroxene pallasites contain approximately 1% to 35% enstatite (magnesium orthopyroxenes) in addition to olivine (Mittlefehldt et al., 1998; McSween,
Mesosiderites are a polymict breccia consisting of clasts of orthopyroxene abundant silicates and NiFe metal in a silicate matrix that has been recrystallized (Wasson, 1985; Rubin, 1997; McSween, 1999; Hutchison, 2004; Grady et al., 2014). Mesosiderites are classified into 12 categories based on mineralogy and texture: texture reflects the degree of metamorphism and mineralogy is categorized from pyroxene and plagioclase abundances (Rubin, 1997; McSween, 1999; Hutchison, 2004; Grady et al., 2014).

Stony meteorites were classified, based on the presence or absence of chondrules, into two main groups: achondrites and chondrites (Wasson, 1985; Rubin, 1997; Mittlefehlt et al., 1998; McSween, 1999). Achondrites form from total melting and differentiation of chondritic material (Wasson, 1985; Rubin, 1997; Mittlefehlt et al., 1998; McSween, 1999; Hutchison, 2004). Primitive achondrites (Acapulcoites, Lodranites, Brachinites, Ureilites and Winonaites) have mineral abundances and chemistry similar to chondrites, have not experienced extensive melting, and are undifferentiated (Wasson, 1985; Rubin, 1997; Mittlefehlt et al., 1998; McSween, 1999; Hutchison, 2004). Lodranites and Acapulcoites in particular have modal abundances similar to the ordinary chondrites; Lodranites are depleted in plagioclase and troilite and are coarser grained than Acapulcoites (Mittlefehlt et al., 1998; Rubin, 2007). Winonaites have reduced assemblages between the Enstatite chondrites and H chondrites and are related to the IAB-IIICD iron meteorite clan (Benedix et al., 1998, 2000; Mittlefehlt et al., 1998; Hutchison, 2004). Ureilites and Brachinites are both olivine dominated with a high Ca pyroxene component, have chemical composition similar to chondrites, and have
fractionated rare Earth elements (REE) indicative of some fractionation (Mittlefehlt et al., 1998; Hutchison, 2004; Rubin, 2006; Goodrich et al., 2007).

Basaltic Achondrites, products of extensive melting and differentiation, include Angrites, Aubrites, and Howardite-Eucrite-Diogenites (HEDs) (Mittlefehlt et al., 1998; Hutchison, 2004). Angrites are basaltic in composition with Ca bearing olivine, clinopyroxene and plagioclase (anorthite) as the main mineral phases (Mittlefehlt et al., 1998; Floss et al., 2003; Hutchison, 2004). Aubrites, also known as enstatite achondrites, are highly reduced brecciated meteorites with oxygen isotopes and mineralogy consistent with enstatite chondrites and an absence of basalt (Keil, 1989; Mittlefehlt et al., 1998; Fogel, 2005). Howardite-Eucrite-Diogenites (HEDs) are a clan of related achondrites derived from a differentiated asteroid (Takeda, 1997; Mittlefehlt et al., 1998; Hutchison, 2004). Eucrites are classified as cumulate or non-cumulate, depending on texture and pyroxene chemistry, and have an assemblage of approximately 60% pyroxene and 40% plagioclase (Takeda, 1997; Mittlefehlt et al., 1998; Hutchison, 2004). Diogenites have an assemblage of primarily orthopyroxene with less than 15% olivine and are usually coarse grained and brecciated and Howardites are polymict breccias consisting of a mix of primarily Diogenites and Eucrites (Takeda, 1997; Mittlefehlt et al., 1998; Hutchison, 2004).
Figure 9: From Franchi, (2008), fig 1, p. 348. Oxygen isotope plot of chondritic meteorites, illustrating oxygen isotope ranges for each chondrite type, obtained from whole rock samples. The TFL is the Terrestrial Fractionation Line, CCAM is the Carbonaceous Chondrite Anhydrous Mineral line, and Y&R is the Young and Russel line defined by an alteration free inclusion in Allende (CV3) (Franchi, 2008). The ordinary chondrites (H, L, LL) have separate oxygen isotope distributions indicating a separate parent body for each ordinary chondrite type.

Chondrites, originally classified due to the presence of chondrules, are meteorites that have not experienced melting and are considered the most primitive of the meteorite classes (Wasson, 1985; Rubin, 1997; McSween, 1999). Chondrites are divided into three classes based on chemistry and isotope ratios: carbonaceous, ordinary, and enstatite (Schulze et al., 1994; Rubin and Kalamoeyn, 1994; Kalamoeyn et al., 1996; Hutchison, 2004; Bischoff et al., 2011; Grady et al., 2014). The Rumuruti (R chondrites) and Kakangari (K chondrites) do not have affinities to any of the classes though R chondrites have been associated with ordinary chondrites but their different oxygen isotope ratios (figure 9) negate a close relationship (Schulze et al., 1994; Rubin and Kalamoeyn, 1994; Kalamoeyn et al., 1996; Hutchison, 2004; Bischoff et al., 2011; Grady et al., 2014). Carbonaceous chondrites consist of eight groups: CI (Ivuna), CM
The enstatite chondrite class, divided into the EH (high iron) and EL (low iron), are highly reduced (Brearley and Jones, 1998; McSween, 1999; Hutchison, 2004; Grady et al., 2014). The ordinary chondrite class consists of the H (high iron), L (low iron), and LL (low iron, low metal) groups (Wasson, 1985; Rubin, 1997; Brearley and Jones, 1998; McSween, 1999; Hutchison, 2004; Grady et al., 2014).

**Ordinary Chondrites and L Chondrites**

Ordinary chondrites are grouped into three types, H (high iron), L (low iron), and LL (low iron, low metal) chondrites, increasing in oxidization respectively (figure 10) (Wasson, 1985; Clayton et al., 1991; Clayton, 1993; Clayton and Mayeda, 1996; Rubin, 1997; Brearley and Jones, 1998; McSween, 1999; Burbine et al. 2002; Greenwood et al., 2007; Rumble et al., 2007). H, L, and LL chondrites have unique $\Delta^{17}$O isotope ratios that do not fall on the Terrestrial Fractionation Line (TFL) (figure 9) (Wasson, 1985; Clayton et al., 1991; Clayton, 1993; Clayton and Mayeda, 1996; Rubin, 1997; Brearley and Jones, 1998; McSween, 1999; Burbine et al. 2002; Greenwood et al., 2007; Rumble et al., 2007). The TFL (figure 9) is defined by oxygen isotope isotope fractionations ($\delta^{18}$O and $\delta^{17}$O) that deviate from the international reference standard Vienna-Standard Mean Ocean Water (V-SMOW) (Clayton et al., 1991; Clayton, 1993; Clayton and Mayeda, 1996; Greenwood et al., 2007; Rumble et al., 2007). L chondrites, with 38% of
falls (45% of recent falls), are of interest due to their abundance (Wasson, 1985; Britt and Pieters 1991, 1994; Rubin, 1997; Brearley and Jones, 1998, Schmitz et al., 2001, 2003; Burbine et al., 2002; Nesvorny et al., 2007, 2009; Bottke et al., 2009). Antarctic finds have confirmed this percentage for the past million years (Wasson, 1985; Britt and Pieters 1991, 1994; Rubin, 1997; Brearley and Jones, 1998, Schmitz et al., 2001, 2003; Burbine et al., 2002; Nesvorny et al., 2007, 2009; Bottke et al., 2009).

Figure 10: Reduced Fe/Si (molar) content versus oxidized Fe/Si (molar) content (Urey-Craig plot) with chondrite groups illustrating the variation of oxidation states. The H, L, and LL chondrites exhibit a decrease in metal-silicate fractionation with increasing oxidation. The plot is from Mittlefehldt et al., (2008), fig 3, p. 404.

The percentage of L chondrites, and ordinary chondrites in general, in the Antarctic meteorite collection implies that the parent bodies of the L chondrites are either very common in the asteroid belt or there is a preferential sampling of the parent bodies (Nesvorny et al., 2007, 2009; Bottke et al., 2009; Gaffey, 2011). L chondrites, subsets of
which are black L chondrites, consist of olivine and low calcium pyroxenes as the main silicate minerals (Heymann, 1967; Miyamoto et al., 1981; Marti and Graf, 1992; Keil, 2000; Eugster, 2003; Greenwood et al., 2007). Shock features (decreases albedo) and low gas retention ages (radiogenic $^{4}$He and $^{40}$Ar, $^{40}$Ar-$^{39}$Ar, and K-Ar) are consistent with outgassing due to catastrophic breakup of a parent body; oxygen isotope analysis indicates a single parent source (Heymann, 1967; Miyamoto et al., 1981; Marti and Graf, 1992; Keil, 2000; Eugster, 2003; Greenwood et al., 2007; Korochantseva et al., 2007; Heck et al., 2010; Weirich et al., 2012; Meier et al., 2014). L chondrites vary in petrologic type from 3 to 6 which provides constraints to the extent and timing of metamorphism and an estimation of the size of the parent body (Miyamoto et al., 1981; Keil, 2000; Rubin, 2005). $^{26}$Al decays to $^{26}$Mg and is effective in heating small asteroid sized bodies and the timing of accretion is determined from the amount of $^{26}$Al incorporated in the parent body (Miyamoto et al., 1981; Keil, 2000; Rubin, 2005). $^{26}$Al is a short-lived isotope only formed under certain conditions such as a supernova, or in smaller quantities from cosmic rays hitting interstellar dust (Miyamoto et al., 1981; Keil, 2000). The combination of the shock features, noble gas retention ages, isotopes, and outgassing (shock) ages are consistent with a catastrophic disruption of a parent body and a fast delivery to Earth (Heymann, 1967; Bogard, 1995; Schmitz et al., 2001, 2003; Greenwood et al., 2007; Nesvorny et al., 2007, 2009; Burbine et al., 2009). The age of the breakup event corresponds to an abundance of fossil L chondrites in the Middle Ordovician period where the abundance of shallow inland seas provided ideal conditions for the formation of large limestone deposits (Schmitz et al., 2001, 2003;
Nesvorny et al., 2007; Heck et al., 2008, 2010; Alwmark et al., 2012; Meier et al., 2014).

The majority (2/3) of L chondrites exhibit extensive shock features and $^{40}\text{Ar}^{39}\text{Ar}$ degassing, determined to be around 470 myr to 500 myr, and indicative of a catastrophic event that probably resulted in an asteroid family (Heymann, 1967; Bogard, 1995; Haack et al., 1996; Schmitz et al., 2001, 2003; Greenwood et al., 2007; Korochantseva et al., 2007; Heck et al., 2008, 2010; Nesvorny et al., 2007, 2009; Alwmark et al., 2012; Weirich et al., 2012; Meier et al., 2014). Cosmic-ray exposure times for both modern and fossil L chondrites and a shower of L chondrites during the Middle Ordovician provide constraints on locations in the asteroid belt for the source of L chondrites (Haack et al., 1996; Schmitz et al., 2001, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009, Meier et al., 2014). The CREs implies a single asteroidal source for the initial large influx during the Middle Ordovician via the catastrophic breakup of the single parent body; the family members are sources for the consistent influx thereafter (Haack et al., 1996; Schmitz et al., 2001, 2003; Nesvorny et al., 2007, 2009; Bottke et al., 2009; Heck et al., 2010). The increase in fossil L chondrites above the background flux seen in Middle Ordovician sediments points to a catastrophic event that injected fragments directly into a fast delivering resonance and strongly suggests that an asteroid family is the source of modern L chondrites (Haack et al., 1996; Schmitz et al., 2001; Nesvorny et al., 2007, 2009; Bottke et al., 2009).
**Fossil L Chondrites, Ordovician Limestones, Swedish Limestone Quarries**

The discovery of fossil L chondrite meteorites in the Thorsberg limestone quarry at Kinnekulle in Southern Sweden has provided additional evidence of a common source of the L chondrites due to a catastrophic breakup of a parent body (Schmitz et al., 2001, 2003; Chronholm and Schmitz, 2010; Heck et al., 2010). Twelve distinct limestone beds, with estimated thicknesses between 11 cm and 62 cm, were deposited in an epicontinental sea depositional environment (figure 11) at a rate of approximately 2 mm/kyr and a time span of about 1.75 myr at Kinnekulle (Schmitz et al., 2001, 2003; Chronholm and Schmitz, 2010). Biostratigraphy from conodonts and trilobites found in the limestone gives a geologic age of Middle Ordovician for the limestone quarry (Schmitz et al., 2001, 2003; Chronholm and Schmitz, 2010).

The Middle Ordovician limestone deposits in Sweden and other localities determine the paleo-flux of L chondrites because the average deposition rate of limestone of each quarry bed can be determined (Schmitz et al., 2001; Schmitz and Haggstrom, 2006; Heck et al., 2008, 2010; Chronholm and Schmitz, 2010; Alwmark et al., 2012; Lindskog et al., 2012; Meier et al., 2014). The abundance of fragile nautiloid fossils indicate a quiescent environment in which material (meteorites or other) are in their original location and not derived from afar (Schmitz et al., 2001; Schmitz and Haggstrom, 2006; Heck et al., 2008, 2010; Chronholm and Schmitz, 2010; Alwmark et al., 2012; Lindskog et al., 2012, Meier et al., 2014).
Limestone quarry beds (figure 12), and the presence of fossils, are useful in determining paleo-influx rates of the fossil L chondrites (Schmitz et al., 2001; Schmitz and Haggstrom, 2006; Heck et al., 2008, 2010; Chronholm and Schmitz, 2010; Alwmark et al., 2012; Lindskog et al., 2012; Meier et al., 2014). The Swedish limestone quarry has been in use for more than a century; limestone slabs with imperfections, mostly due to the fossil meteorites, were usually discarded (Schmitz et al., 2001, 2003). Originally misidentified as transported terrestrial ultramafic rocks, oxygen isotope ratios measured from chromite grains (Fe$^{2+}$Cr$_2$O$_4$) identified the imperfections as extraterrestrial in origin, and match oxygen isotope ratios of modern L chondrites (Schmitz et al., 2001, 2003, Schmitz and Haggstrom, 2006; Greenwood, 2007; Heck et al., 2008, 2010; Alwmark et al., 2012; Lindskog et al., 2012).
Figure 12: Hallekis and Thorsburg limestone quarries from Schmitz and Haggstrom 2006 – fig. 2 in their paper. The limestone beds at Thorsburg quarry (expanded section at left) correspond to a small section of the total quarry section at Hallekis. The black dots represent locations in the strata of the limestone quarry where fossil L chondrites were found. Conodonts and nautiloid fossils identify the series/stage and correlate to other Middle Ordovician sites where fossil L chondrites are found. The entire sequence estimates an average deposition rate of the limestone and rate of the L chondrite flux during the Middle Ordovician (Schmitz et al., 2001, 2003; Schmitz and Haggstrom, 2006; Greenwood, 2007).

The paleo-flux of L chondrites was estimated from the total mass of L chondrites in each limestone bed and combining the rate of deposition, ordinary chondrite masses from earlier and later limestone beds were compared with ordinary chondrite masses of the quarry (Schmitz et al., 2001, 2003; Schmitz and Haggstrom, 2006). The conclusion is that the meteorite flux during the Middle Ordovician, when the quarry limestone beds were deposited, was about 25 times higher than the current flux (Schmitz et al., 2001, 2003; Schmitz and Haggstrom, 2006). Efforts in finding additional specimens have since been carried out and fossil L chondrites have been identified in additional Middle
Crystal Field Theory

Crystal field theory is a quantum mechanical theory describing various chemical bonds involving the first transition element metals and, less often, the lanthanides (Burns, 1970, 1993; Burns et al., 1972). According to crystal field theory, there are three types of minerals defined in terms of spectral properties: conductive, dielectric transparent, and semiconductor opaque (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). Conductive minerals are metallic NiFe mineral phases, while semiconductor opaque minerals are carbon minerals/compounds often seen in carbonaceous chondrites (Burns, 1970, 1993; Burns et al., 1972; Gaffey 1976). The dielectric minerals, which include the olivine, pyroxene, feldspars, and other silicates, are of importance here due to their low optical density in the VNIR region and have end members that include bonds with the first transition metals, specifically Fe$^{2+}$ (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). The bonds most useful in meteorite-asteroid studies are those involving the M1 and M2 crystallographic sites in which Fe$^{2+}$, Mg$^{2+}$, and Ca$^{2+}$ in olivine and pyroxene produce absorptions in the 0.3 μm -2.5 μm intervals and the various hydroxyl (OH) bonds (Burns, 1970, 1993; Burns et al., 1972). Crystal field theory describes how chemical bonds and interactions between electron configurations of
transition metals in octahedral coordination are responsible for the observed absorption features (Burns, 1970, 1993; Burns et al 1972).

### Transition Metals and D-Orbitals

The transition metals are elements that have their outer electrons in d-orbitals, 5 symmetric configurations of angular probability distributions (figure 13) (Burns, 1970, 1993; Burns et al., 1972). The first series of transition metals, from Sc to Zn, includes iron (Fe) which is incorporated in silicates such as olivine and pyroxene, found in ordinary chondrites and achondrites (Gaffey, 1976; Burns, 1993). In iron atoms, d-orbitals are not completely filled so electrons can be excited to a higher energy orbit; a completely filled orbit has two electrons of opposite spin by Pauling exclusion in which same spin electrons cannot occupy the same orbit (Burns, 1970, 1993; Burns et al., 1972; Gaffey 1976). With one or more unfilled orbitals, electrons have another orbit to occupy (Burns, 1970, 1993; Burns et al., 1972; Gaffey 1976).

![Figure 13: The 5 d-orbital configurations for transition metals such as iron. The top three configurations, dxy, dxz, and dyz, are off axis and have threefold degeneracy. The bottom two on-axis configurations, dx2-y2 and dz2 are the twofold degeneracy where the orbits have the same energy. The figure is from scienceworld.wolfram.com/chemistry/d-Orbitals.html](scienceworld.wolfram.com/chemistry/d-Orbitals.html)
When not incorporated in a crystal or bond, three of the five orbits (off axis, top three in figure 13) have threefold degeneracy ($t_{2g}$), the remaining two on axis configurations has twofold degeneracy ($e_g$); all of the orbits have the same energy (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). The orientations become important when the Fe ion occupies the M1 and M2 crystallographic sites of silicate minerals such as pyroxene and olivine and the orbits are no longer degenerate (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976).

**Pyroxene and Olivine**

Pyroxenes are a group of minerals with a chain structure of SiO$_4$ tetrahedra (oxygen atoms are shared when the tetrahedral are linked) with octahedral cations such as Ca$^{2+}$, Fe$^{2+}$, and Mg$^{2+}$ occupying the M1 and M2 crystallographic sites where two or more chains are connected (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). Two pyroxene series (figure 15) are important for ordinary chondrites: the orthopyroxene series and the clinopyroxene series (Keil and Fredriksson, 1964; Gaffey, 1976; Burns, 1970, 1993; Burns et al., 1972). The orthopyroxene series is a solid solution series, enstatite (Mg$_2$Si$_2$O$_6$) and ferrosilite (Fe$_2$Si$_2$O$_6$), with orthorhombic crystal structure, while the clinopyroxene series has a monoclinic crystal structure and includes endmembers diopside (CaMgSi$_2$O$_6$) and hedenbergite (CaFeSi$_2$O$_6$) (Keil and Fredriksson, 1964; Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976; Cloutis et al., 1986). All four end-members make the pyroxene quadrilateral, which includes all naturally occurring pyroxene compositions with Fe$^{2+}$, Mg$^{2+}$ and Ca$^{2+}$. Olivine (figure
14) is a group of minerals with an orthorhombic structure and chemical formula of (Mg, Fe, Mn) SiO$_4$ with the solid solution series with forsterite (Mg$_2$SiO$_4$) to fayalite (Fe$_2$SiO$_4$) are of importance for chondrites (Keil and Fredriksson, 1964; Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976).

Figure 14: Crystal structure of olivine with the SiO$_4$ tetrahedra and the M1, M2 crystallographic sites (from http://www.britannica.com/science/olivine). Fe$^{2+}$ is preferentially incorporated in the M2 site.

Figure 15: Crystal structure of pyroxene (from http://www.britannica.com/science/pyroxene). The M1 and M2 crystallographic sites are where the Fe, Mg, and Ca cations are incorporated. The M1 crystallographic site is larger than M2 and can accommodate cations with larger atomic radii. Iron preferentially incorporates in the M2 site.
The electrons in d-orbitals of iron (Fe$^{2+}$) atoms located in the M1 or M2 crystallographic sites of pyroxene and olivine experience field splitting due to non-symmetric bonds between the SiO$_4$ or Si$_2$O$_6$ anions and the symmetric electron d-orbitals of the Fe cation (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). The crystal field splitting (figure 16) is due to the different configurations of the five d-orbitals which results in different energy levels between the two degeneracy groups, t$_{2g}$ and e$_g$, with t$_{2g}$ having a greater energy rise compared to e$_g$ and is designated $\Delta_0$ (Burns, 1970, 1993; Burns et al., 1972; Gaffey 1976).

Figure 16: Crystal field splitting (figure from Gaffey 1976, figure 1b). The location of the Fe cation in the M1 and/or M2 site in pyroxene leads to non-symmetric electronic bonds and the degenerate d-orbitals, t$_{2g}$ and e$_g$, split into different energy levels.

The crystal field splitting energy, $\Delta_0$, is the energy required for an electron to be excited from one level to another, and is dependent on the crystallographic site, M1 or
M2 (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). For Fe$^{2+}$ in olivine and pyroxene, the crystal field splitting energy leads to absorption features in the near infrared region of the electromagnetic spectrum (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). The M1 and M2 crystallographic sites have different distortions and therefore different crystal field splitting energies; the M1 crystallographic site experiences the most distortion, the M2 site less distortion (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). The M1 and M2 crystallographic sites differ in size (M1 is smaller than M2) and the larger cations (Mg$^{2+}$ < Fe$^{2+}$ < Ca$^{2+}$) preferentially occupy the M2 site (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). For olivine, Mg$^{2+}$ and Fe$^{2+}$ occupy both crystallographic sites but the Fe$^{2+}$ favors the M2 site due to its larger size (Burns, 1970, 1993; Burns et al., 1972; Gaffey, 1976). For pyroxenes, Ca$^{2+}$ occupies the M2 site with the Fe$^{2+}$ cations occupying the M1 sites and remaining M2 sites (Burns, 1970, 1993; Burns et al., 1972 Gaffey, 1976). The crystal field splitting energy for Fe$^{2+}$ in the M1 site is lower than for the M2 site therefore, increasing Ca$^{2+}$ content corresponds to decreasing energy and increasing wavelengths (Burns, 1970, 1993; Burns et al., 1972 Gaffey, 1976). Increasing Fe$^{2+}$ content in silicates has a similar effect when all M2 sites are occupied with Fe$^{2+}$ cations, additional Fe$^{2+}$ must occupy the M1 sites (Burns, 1970, 1993; Burns et al., 1972 Gaffey, 1976).
Absorption Features and Spectral Analysis

Olivine exhibits three absorption features centered around 1 μm, pyroxene has two absorption features, near 1 μm and 2 μm (figure 17), and increasing Fe$^{2+}$ content and the presence of Ca$^{2+}$ shifts these towards longer wavelengths (Burns, 1970, 1993; Adams, 1974, 1975; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey 2011).

The positions and intensities of these absorption features in the visible and near infrared provides information of the relative abundance (or lack of) olivine and pyroxene and the presence of Ca$^{2+}$ in pyroxenes (Adams, 1974, 1975; Cloutis et al.,
1986; Gaffey et al., 1993a, 1993b, 2002; Dunn et al., 2010; Gaffey, 2011; Reddy et al., 2015). For the 1 μm feature, increasing Fe$^{2+}$ content leads to the B1 position shifting towards longer wavelengths; the presence of Ca$^{2+}$ in pyroxene has a similar effect with B2 (Adams, 1974, 1975; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Dunn et al., 2010; Gaffey, 2011). Olivine/pyroxene relative Abundances and mineralogical composition of asteroids are ascertained from visible and near infrared spectra if absorption features are present (Adams, 1974, 1975; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Dunn et al., 2010; Gaffey, 2011; Reddy et al., 2015).

Spectral analysis is the utilization of the spectral parameters extracted from absorption features due to the presence of Fe bearing silicate minerals, pyroxene and olivine (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986, Gaffey et al., 2002; Dunn et al., 2010; Reddy et al., 2015). The abundance of olivine and pyroxene is estimated from the structure, intensities, and positions of absorption features (figures 17 and 18) (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002). The band center is the central wavelength of an absorption feature with pyroxene having two distinct features near 0.9 μm and 1.9 μm (Burns, 1970, 1993; Burns et al., 1972; Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002). Olivine has one broad absorption feature centered at 1 micron which is a combination of three absorption features (Burns, 1970, 1993; Burns et al., 1972; Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002).
The first method in determining the relative abundances of pyroxenes to olivine was the position on the Band II center vs Band I center plot (figure 19) (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002). Regions are defined by the ranges of BI and BII positions measured from laboratory spectra of HED, H, L and LL chondrites; the trend of increasing Fe$^{2+}$ and Ca$^{2+}$ content is derived from laboratory spectra from meteorites and pyroxenes (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002). From the band positions obtained from meteorite and laboratory sample spectra, position on the BII/BI plot represents compositional effects of iron and calcium in pyroxene on band position (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002). The BII/BI plot outlines regions of known ordinary chondrites as known olivine/pyroxene ratios and orthopyroxene/clinopyroxene content (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey, 2002).
Band centers provide clues on how the asteroid composition compares to known ordinary chondrite or HED assemblages when plotted on the BII/BI plot (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002; Burbine et al. 2007, 2009). Band II centers shift to longer wavelengths with increasing Ca$^{2+}$ and Fe$^{2+}$ and band I centers are sensitive to Ca$^{2+}$, Fe$^{2+}$, and olivine content (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002). This is seen as a shift along the trend of increasing Fe$^{2+}$ and Ca$^{2+}$ content (Figure 19, black x’s and open squares) in the BII/BI plot; the presence of olivine will shift the BI center to longer wavelengths and off the pyroxene trend (Adams, 1974, 1975; Gaffey, 1976, 2011; Cloutis et al., 1986; Gaffey et al., 2002).

The band area ratio (BAR), when plotted against BI, represents olivine/pyroxene relative abundances and is valid for most ranges of olivine/pyroxene relative

![Figure 19: Band-band plot with orthopyroxene-clinopyroxene trend (black x's and open squares, respectively), illustrating the effect of increasing Fe$^{2+}$ and Ca$^{2+}$ has on BI and BII center. Increasing olivine increases the BI center and moves an assemblage up and off the pyroxene trend (Gaffey et al., 2002; Gaffey, 2011).]
abundances seen in meteorites (Cloutis et al., 1986; Gaffey et al., 2002; Gaffey 2011). The percentages of pyroxene vs measured band area ratios of laboratory mixtures with varying pyroxene/olivine abundances and particle sizes were plotted (figure 20) (Cloutis et al., 1986). The least squares fit to the data, valid for pyroxene abundances between 10% and 90%, describes the relationship between pyroxene abundance and BAR (Cloutis et al., 1986).

\[ \text{BAR} = \frac{\text{Area I}}{\text{Area II}} \]

![Figure 20: From Cloutis et al 1986 – (fig 2b). The interval of the best fit corresponds to the range of olivine-pyroxene ratios. The least squares regression is valid for pyroxene (or olivine) percentages between 10% and 90.](image)

Taking into account the change in BI center with orthopyroxene abundance, the least squares fit to the olivine-orthopyroxene abundances translate to the olivine-pyroxene mixing line on the BI/BAR plot (figure 21). The BAR/BI plot illustrates the effect of olivine on the band area ratio and the BI center; for pyroxene percentages close to 0%, the band 2 area is nonexistent (Cloutis et al., 1986). Assemblages with clinopyroxene fall off the olivine-orthopyroxene trend (figure 22, S(III) and S(VI) regions) (Cloutis et al., 1986, Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011).
By using the ratio of measured band areas, the effects of any space weathering on band depth/strength is eliminated as space weathering is observed to affect both bands (Gaffey, 2010, 2011). Combining the information from the BI position and the BAR contribution of the percentage of pyroxene, discrete zones (S(I) to S(VII) and HED) along with the olivine/pyroxene mixing line are designated on the BAR/BI plot (figure 21) (Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011).

Figure 21: From Cloutis et al., 1986 – (fig. 3) from their paper. The plot illustrates the change in band 1 position (minimum) as a function of increasing pyroxene percentage. The band 1 minimum shifts to longer wavelengths with increasing olivine content with significant shifts occurring with pyroxene percent less than 40%.
The olivine/pyroxene mixing line ranges from mostly olivine assemblages designated (SI) to mostly pyroxene assemblages, S(VII), with the S(IV) region being where ordinary chondrite assemblages plot (Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011). The S(IV) region includes the unaltered (no melt or limited fractional melting) asteroids; moving either up the mixing line towards olivine or down along the mixing line to increasing pyroxene represents increasing differentiation through melt or partial melt (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011). An asteroid’s position on the BAR/BI plot provides information pertaining to composition and degree of differentiation (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gaffey, 2011).

The BI, BII, and BAR parameters are utilized quantitatively by a set of iterative equations developed for the estimation of orthopyroxene (ferrosilite, or Fs), clinopyroxene (Wollastonite, Wo), and relative olivine abundance (Cloutis et al., 1986;
Gaffey et al., 1993a, 1993b, 2002; Gastineau-Lyons et al., 2002; Dunn et al., 2010). For orthopyroxene abundances (percentages), the following relationship, \( (\text{Opx} \% = \frac{\text{Opx}}{\text{Opx} + \text{Ol}}) \times 100 \) is defined based on laboratory measurements of mixtures of olivine and pyroxenes (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Gastineau-Lyons et al., 2002; Dunn et al., 2010). Olivine percentage is obtained from the pyroxene percentage (olivine \% = (1 – (\text{Opx}/(\text{Opx} + \text{Ol})) \times 100); the olivine percentages are compared to known ranges calculated from normative mineralogies of ordinary chondrites: H, L, and LL (McSween et al., 1991; Gaffey et al., 2002; Dunn et al., 2010). Dunn et al., (2010) developed olivine abundance, defined as \( (\text{ol}/(\text{ol} + \text{px}) \), ferrosilite, and fayalite content from the modal abundances and spectral analysis of ordinary chondrites. Dunn et al., (2010) found a correlation between fayalite content and BI position (figure 23) and a similar correlation between ferrosilite content and BI position. The polynomial fits to the data are the equations to estimate fayalite and ferrosilite content from the BI center where fayalite content is estimated by \( \text{Fa} = -1284.9 \times (\text{BI})^2 + 2656.5 \times \text{BI} – 1342.3 \) and ferrosilite content by \( \text{Fs} = -879.1 \times (\text{BI})^2 + 1824.9 \times \text{BI} – 921.7 \) (Dunn et al., 2010).
Dunn et al., (2010) also defined a relationship between olivine abundance and fayalite content and a similar relationship with ferrosilite content. H, L, and LL chondrites plot in distinct groups (figure 24). Olivine abundance measured from x-ray diffraction (XRD) and fayalite content, when plotted together, exhibited covariance where an increase in fayalite (or ferrosilite) content corresponds with an increase in olivine abundance (Dunn et al., 2010). Fayalite (ferrosilite) and olivine covariance can distinguish H, L, and LL chondrites as in figure 24.
For an asteroid, the position on the BII/BI and BAR/BI plots, ferrosilite, wollastonite, fayalite, and olivine abundances are compared to those of H, L, or LL chondrites to determine if the asteroid is a probable parent body (Gaffey et al., 1993a, 1993b, 2002; Dunn et al., 2010).

**Space Weathering and Absorption Features**

Space weathering is a general term describing surface processes on airless bodies that can alter the optical properties of these bodies such as albedo, spectral slope, and band depth from impacts, solar wind, and cosmic-rays (Pieters et al., 2000, 2013; Noble et al., 2001; Taylor et al., 2001; Chapman, 2004; Loeffler et al., 2008; Gaffey, 2010; Shestopalov et al., 2013). Lunar space weathering was first documented when the
Apollo lunar samples were examined (Pieters et al., 2000; Noble et al., 2001; Taylor et al., 2001; Chapman, 2004; Gaffey, 2010; Loeffler et al., 2008). Laboratory spectra of fresh lunar samples exhibited stronger band depths, less spectral reddening and higher albedo than those from lunar soil or regolith breccia (Pieters et al., 2000; Noble et al., 2001; Taylor et al., 2001; Chapman, 2004; Gaffey, 2010; Loeffler et al., 2008). The change in optical properties is due to nanophase metallic iron (npFe\(^0\)) which covers the smallest size fraction of lunar soil particles (Pieters et al., 2000; Noble et al., 2001; Taylor et al., 2001; Loeffler et al., 2008). The npFe\(^0\) forms from vaporization due to hypervelocity impacts of micrometeorites and a chemical reduction of FeO from the implantation of hydrogen atoms into the regolith from the solar wind (Pieters et al., 2000; Taylor et al., 2001; Noble et al., 2001; Loeffler et al., 2008). The hydrogen ions react with the oxygen in the FeO, removing the oxygen, and leaving the Fe in the reduced form: Fe\(^0\) (Pieters et al., 2000; Noble et al., 2001; Taylor et al., 2001; Noble et al., 2001; Loeffler et al., 2008).

In searching for asteroidal sources of the numerous ordinary chondrites, many researchers have invoked lunar style space weathering to explain the lack of main belt asteroid matches in optical spectra matches for the ordinary chondrites (Fornasier et al., 2003; Jedicke et al., 2004; Sasaki et al., 2004; Sunshine et al., 2004; Marchi et al., 2005; Nesvorny et al., 2006; Brunetto et al., 2006, Hiroi et al., 2006, 2007). It was believed that sources of common ordinary chondrites had to be numerous and that the S asteroids, the second largest taxonomic class, were the source of these meteorites (Fornasier et al., 2003; Chapman, 2004; Jedicke et al., 2004; Sasaki et al., 2004; Sunshine et al., 2004; Marchi et al., 2005; Nesvorny et al., 2006; Brunetto et al., 2006;
Hiroi et al., 2006, 2007). The mismatch between available visible wavelength spectra of S asteroids and those of laboratory spectra of the ordinary chondrites was thought to be due to lunar style space weathering (Fornasier et al., 2003; Jedicke et al., 2004; Sasaki et al., 2004; Sunshine et al., 2004; Marchi et al., 2005; Nesvorny et al., 2006; Brunetto et al., 2006; Hiroi et al., 2006, 2007). While it is definitive that some form of space weathering is operating on asteroid surfaces, it was not until spacecraft visited (243) Ida and (433) Eros that different space weathering mechanisms were found (Helfenstein et al., 1996; Veverka et al., 1996; Bell et al., 2002, Murchie et al., 2002). (243) Ida, a main belt asteroid, exhibited little variation in albedo but large variations in band depth, while (433) Eros (a near Earth asteroid) showed albedo variations and no variations in band depth (Helfenstein et al., 1996; Veverka et al., 1996, Bell et al., 2002; Murchie et al., 2002). Both asteroids are S type and while (433) Eros is a near Earth object, its aphelion lies in the main belt so proximity to the Sun (and higher velocity micrometeorite impacts) cannot account for all of the differences in space weathering effects (Helfenstein et al., 1996; Veverka et al., 1996; Bell et al., 2002; Murchie et al., 2002; Chapman, 2004; Gaffey, 2010). Two recent spacecraft visits to asteroids, (4) Vesta and (25143) Itokawa, revealed two additional effects of space weathering (Pieters et al., 2013; Shestopalov et al., 2013). On Vesta, when compared to the background regolith, the spectra of “freshly exposed dark areas” were bluer than that background and “the freshly exposed bright areas” were redder than the background regolith (Pieters et al., 2013). Due to Vesta's location in the asteroid belt, the lower average velocity (approximately 5 km/s) is not sufficient to produce vaporization/melting; instead, it was found that mechanical brecciation and mixing of the regolith (Pieters et al., 2013). For
(25143) Itokawa, a near Earth S asteroid, the very small sample returned revealed that both npFe$^0$ and sulfur coated many of the grains, compared to the npFe$^0$ dominated lunar space weathering (Pieters et al., 2013).

In conclusion, four different asteroids, visited by spacecraft, had different forms of space weathering and none resembled the lunar style space weathering (Helfenstein et al., 1996; Veverka et al., 1996; Bell et al., 2002; Murchie et al., 2002; Pieters et al., 2013). Laboratory experiments simulating various space weathering effects on meteorite samples revealed that slopes, albedos, and band depths changes but band positions did not change (Moroz et al., 1996; Chapman, 2004; Noble et al., 2007; Gaffey, 2010; Shestopalov et al., 2013). Only in extreme cases, in which the simulation involved impact melt and quench crystallization or irradiation levels well above natural levels did band centers shift and the band area ratio become affected and in both these extreme cases, the original mineralogy (from complete melting) would be erased (Moroz et al., 1996; Gaffey, 2010). It cannot be assumed that other asteroids experience any of these types of space weathering (Gaffey, 2010). Space weathering examined on asteroids and in the laboratory samples has been shown to have a negligible effect on band centers; band depths are found to be equally reduced, in which taking the band area ratio negates the affect (Moroz et al., 1996; Chapman, 2004; Noble et al., 2007; Gaffey, 2010, 2011).
Previous Meteorite-Probable Parent Body Links

Concurrent with the taxonomic classification of asteroids, identifying asteroidal sources for meteorites has been occurring (McCord, 1970; Chapman and Salisbury, 1973; Adams, 1974, 1975; Chapman et al., 1975; Gaffey, 1976; Gaffey et al., 1993a, 1993b; Gaffey and Gilbert 1998). While Chapman et al., (1975) defined the first taxonomic classification, various researchers were investigating meteorite spectra (McCord et al., 1970; Adams, 1974, 1975; Gaffey, 1976). While some meteorite types were linked with a particular asteroid taxonomic class, such as iron meteorites and M type asteroids, the match was based on similarities in spectra and not diagnostic parameters (Gaffey, 1976; Cloutis et al., 1986; Gaffey et al. 1993a, 1993b; Burbine et al., 2002; Gaffey, 2011). The HED (Howardite-Eucrite-Diogenite) meteorite group was the first to have a plausible parent body identified: (4) Vesta (McCord et al., 1970; Chapman and Salisbury, 1973; Gaffey, 1997; Burbine et al., 2002).

Nomenclature of meteorite-parent body associations is explicitly defined as follows: possible parent body, plausible parent body, and probable parent body (Gaffey, 2011). An asteroid is considered a possible parent body when observed albedos, color, and spectra of an asteroid match those of a particular meteorite (Gaffey, 2011). If the assemblage of an asteroid closely resembles the mineralogy of the meteorite, the asteroid is considered a plausible parent body (Gaffey, 2011). Pyroxene and olivine abundances as obtained from band parameters via VNIR spectroscopy of (4) Vesta are consistent with those measured from the HED meteorites (McCord et al., 1970; Gaffey, 1997, 2011; Burbine et al., 2002). A probable parent body is an asteroid that both matches the mineralogy of the meteorite and is located close to an efficient mean-
motion resonance such as the 3:1 and 5:2 (Gaffey, 2011). Asteroid (6) Hebe, located close to the 3:1 resonance has a surface composition which is consistent with the H chondrites and is a probable parent body for the H chondrites (Gaffey and Gilbert, 1998; Gaffey, 2011).

To date, probable parent bodies have been identified for the HED meteorites (4 Vesta and select V-type asteroids), the H-chondrites and IIE iron meteorites ((6) Hebe), the mesosiderites (the Maria asteroid family) and the aubrites ((3103) Eger) (McCord et al., 1970; Gaffey et al., 1992; Gaffey and Gilbert, 1998; Burbine et al., 2002; Fieber-Beyer et al., 2011b; Hardersen et al., 2014, 2015). With the exception of (4) Vesta which does not have a direct delivery mechanism, the asteroid-meteorite links for (6) Hebe and the Maria family were first identified by their proximity to a viable delivery route (Gaffey and Gilbert, 1998; Fieber-Beyer et al., 2011b; Gaffey, 2011).

The Gefion Dynamical Asteroid Family and the L Chondrite Source:

Testing the Hypothesis

The Gefion dynamical family has been proposed as a source for the L chondrites partly due to the close proximity to an effective mean-motion resonance (the 5:2 mean-motion resonance at 2.82 AU) and one should expect meteorite samples from asteroids close to this resonance (Carruba et al., 2002, 2003; Bottke et al., 2009; Nesvorny et al., 2009). To test this hypothesis, mineralogical abundances estimated from band parameters from VNIR spectra for several Gefion dynamical family asteroids are compared with the L chondrites. Prior observations of Gefion family members included
(2905) Plaskett and (3910) Liszt (Blagen et al., 2012; Blagen, 2012). Mineralogical
abundances for 2905 Plaskett were very similar to the L and LL chondrites, and the
ferrosilite content obtained for 3910 Liszt fell within the range of the LL chondrites
(Blagen, 2012). (2905) Plaskett and (3910) Liszt, along with (1433) Geramtina and
(7735) Scorzelli, were reduced and analyzed again for the present study in order to have
all data reduced by a single consistent procedure. Ten additional Gefion family asteroids
((527) Euryanthe, (1839) Ragazza, (2373) Immo, (2521) Heidi, (2911) Miahelena,
(3788) Steyaert, (4182) Mount Locke, (7272) Darbydyar, (12275) Margelgoffin, and
(17109) 1999 JF52) were observed. All but three of the ten were reduced and analyzed:
Asteroids (7272) Darbydyar and (12275) Marcelgoffin have noisy spectra, (2373) Immo
had no spectra in the raw data.
CHAPTER III
OBSERVATIONS

VNIR spectra of Gefion family asteroids are obtained with SpeX, a 0.8 to 5.5 micron medium resolution spectrograph and imager, at the NASA IRTF 3 meter telescope located on Mauna Kea (Rayner et al., 2003). All observations were done remotely. Asteroid, solar analog, and standard star spectra are all taken in the low resolution (asteroid) prism mode from 0.7 to 2.5 micron which allows any wavelength dependent instrument response to be canceled and increases the signal to noise ratio for fainter objects (Gaffey et al., 2002; Rayner et al., 2003; Gaffey, 2011). Flats and arcs are taken at the beginning and end of each observation run; arcs are taken from an argon lamp and are required for wavelength calibration converting channels to wavelength (Gaffey et al., 2002; Rayner et al., 2003; Gaffey, 2011). Standard stars (extinction stars), essential for removing atmospheric effects, along with available solar analogs (from Hardorp, 1978, 1980a, 1980b) are selected from Simbad (an astronomical database). Extinction stars ideally match the optical path lengths of the asteroid with solar type (G2V) stars being preferable (Chapman and Gaffey, 1979; Gaffey et al., 2002; Gaffey, 2003, 2011). Main sequence G stars are used if no G2V standard stars are available in which solar analogs, essential for removing slope, are used in addition to extinction stars (Chapman and Gaffey, 1979; Gaffey et al., 2002; Gaffey, 2003, 2011). Since the sky is often not uniform throughout the observations, spectra for extinction stars are taken numerous
times throughout each asteroid observation in order to closely match the airmass of the asteroid (Chapman and Gaffey, 1979; Gaffey et al., 2002; Gaffey, 2003, 2011). Asteroid spectra are often taken in sets of 10-20 spectra each for a total of 3600 s integration time to obtain a good signal to noise ratio (Gaffey et al., 2002; Gaffey, 2003, 2011). Total integration time for each asteroid is estimated based on the visual magnitude, the signal-to-noise ratio desired, and integration time for individual asteroid spectra (usually 120 s per spectrum for faint objects) (Rayner et al., 2003). During the observation run, test spectra are obtained for each new object to ensure linearity and to avoid saturation in the counts (Rayner et al., 2003). Once an exposure time is determined, spectra are taken in the AB format in which the telescope nods between two parts of the detector (sky) (Rayner et al., 2003). Spectra, arcs, and flats are recorded as flexible image transport system (FITS) files (Rayner et al., 2003). VNIR spectra of asteroids are taken at low phase angles to minimize non-compositional effects such as phase reddening (Nathes et al., 2005; Nathes, 2010; Reddy et al., 2015).

Data Reduction: IRAF, Transpex, and SpecPR

IRAF, Transpex, and SpecPR (Spectrum Processing Routine) are utilized during data reduction (Gaffey et al., 2002; Gaffey, 2003, 2011). Subtracting the background sky and extracting the spectra is completed with IRAF (Image Reduction and Analysis Facility), a Unix/Linux based program available from the National Optical Astronomy Observatories (NOAO). Transpex converts the extracted spectra into a format that SpecPR can use, with each spectrum consisting of six files: odd file numbers are
wavelengths and even file numbers are reflectance data. Once the text files are all converted, a starpack is created in SpecPR to produce a solar corrected average reflectance spectrum (Gaffey et al., 2002; Gaffey, 2011):

\[ \text{asteroid/"sun"} = (\text{asteroid/star-pack})/(\text{solar analog/star-pack}) \text{ or,} \]

Final Spectrum = asteroid/star-pack,

where the star-pack is from a G2V star (asteroid/star-pack) or a G type star (in which case a solar analog is needed).

**Creating the Star-Pack and Average Spectrum**

All spectra obtained are spectral flux measurements and to obtain a reflectance spectrum of an asteroid, the raw flux spectrum of the asteroid is ratioed (divided by) to the raw flux spectrum of the extinction star (Chapman and Gaffey, 1979; Gaffey et al., 2002; Gaffey 2003, 2011). This is accomplished by ratioing each raw flux spectrum of the asteroid to the star-pack (figure 25) which is the combination of all raw flux spectra for that asteroid’s extinction star (Gaffey et al., 2002; Gaffey, 2003, 2011). The star-pack models the atmospheric transmission for the asteroid within the time interval of observation and a good star-pack is essential to effectively remove or reduce telluric absorption features (Gaffey et al., 2002; Gaffey, 2003, 2011).
Differences in airmass between the star and the asteroid are often unavoidable due to instability of the atmosphere during the observation interval (Gaffey et al., 2002; Gaffey, 2003, 2011). The star-pack is used to calculate the atmospheric transmission as a function of wavelength for the extinction star (Gaffey et al., 2002; Gaffey, 2003, 2011). Additionally, during observations, the SpeX instrument flexes very slightly, resulting in sub-pixel shifts between sets of spectra, and introduces offsets in the spectral dispersion (Gaffey et al., 2002; Gaffey, 2003, 2011). To minimize noise produced by the effect, several shifts are tested for each set of extinction star spectra (Gaffey et al., 2002; Gaffey, 2003, 2011). Each test is accomplished by a sub-pixel shift (offset) of +/- 0.1 pixel (offsets can be done for up to +/- 2 pixels) until the interference from instrument flexure is minimized (figure 26) (Gaffey 2003, Gaffey 2011). Once the star-pack is created, each asteroid spectrum is ratioed to the star-pack with sub-pixel shifts to reduce instrument flexure interference (Gaffey 2003, Gaffey 2011).

Figure 25: Starpack (HD 197081) for (2521) Heidi. The telluric features near channels 320 and 445 are the 1.4 μm and 2 μm features the starpack is used to remove. The noise near channel 610 is from the crack in the SpeX chip.
Figure 26: Interference in the starpack affects the final average asteroid spectrum. The left figure shows interference from a 1 pixel (channel) shift in the ratios of two sets of extinction star observations. Several sub-pixel shifts are tested until the shift producing the least interference is found. The interference is a signal and has an effect on the average asteroid spectra (right) whereas noise is canceled out during the averaging process. The three spectra illustrate interference on the shape of the 2 μm feature where the middle spectrum is the correct shift in the starpack (from Gaffey, 2011, figure 5).

Figure 27: A final average spectrum for (1839) Ragazza exhibiting the two absorption features near 1 μm and 2 μm. The feature near 1.4 μm is due to an incomplete correction for telluric features. The noise near 2.4 μm is from the crack in the SpeX chip.
Best offsets for each asteroid spectrum are identified along with a rating (very poor to good). Typically, an average of all spectra and an average of moderate and good spectra are made, with the best average being used to obtain band parameters. If spectra for a solar analog were obtained, an average of the solar analog spectra is obtained in the same manner as the asteroid and then fitted with a polynomial outside of the telluric bands (the telluric bands are deleted in the polynomial fitting routine in SpecPR). The polynomial removes non-solar characteristics of asteroid spectrum (figure 27) (Gaffey et al., 2002; Fieber-Beyer, 2010; Gaffey, 2011).

Asteroid final average spectra are normalized to the 380 to 410 channel interval (1.6900 to 1.8108 μm) and featureless asteroid spectra are normalized to 1.22 μm (based on the least noisy region of the average spectrum of (17109) 1999 JF52) for slope calculation. Normalization to the 380 to 410 interval occurs when the raw flux asteroid spectrum is ratioed to the star-pack. Meteorite spectra used for comparison to (527) Euryanthe and (17109) 1999 JF52 are normalized to 1.22 μm.
CHAPTER IV
ANALYSIS

Obtaining Band Parameters: B1, B2, and BAR

Band parameters are calculated using routines in SpecPR. First, the continuum is removed/ratioed for each band (B1, BII) in order to have the band minimum and band center coincide (figure 28) (Gaffey et al., 2002; Gaffey, 2011).

![Figure 28: From Gaffey 2011 – fig. 11. The importance of removing the continuum before determining band positions is illustrated here. The top curve is the continuum-removed spectrum and the band minimum is at the same wavelength as the band center. The bottom curve is the spectrum prior to removing the continuum: the band minimum is offset from the band center.](image)

Removing the continuum and determining band position is accomplished by first selecting endpoints for BI and BII by fitting a tangent line (figure 29) between the peaks on either end of the absorption feature (Gaffey et al., 2002; Gaffey, 2011). The ratioed curves are used for band area calculations and polynomial fits for band positions, which
are determined by fitting an n-order polynomial to each band interval (Gaffey et al., 2002; Gaffey, 2011). If poorly corrected telluric features are present, the polynomials are fitted to both the uncorrected and the corrected interval.

![Spectral Reflectance](image)

**Figure 29:** Tangent lines (squares) fitted to band 1 and band 2 of an LL chondrite spectrum. The endpoints for each tangent line are used in the routine for removing the continuum (Gaffey et al 2002, their figure 3).

Multiple trials provide uncertainty estimates for the band parameters and averages and standard deviation/errors are reported and used for analysis. The assumptions are a smooth curve (no sharp features are present in the spectra), noise is random, and fitting a multipoint spectrum (dealing with large numbers) is essentially a smoothing function which takes care of the noise (Gaffey et al., 2002; Gaffey, 2011).

**Calculating Abundances From Band Parameters**

Band parameters (BAR, BI, BII) are inputs for both the Gaffey et al., (2002) and Dunn et al., (2010) calibrations which developed from the pyroxene and olivine-
pyroxene mixture spectral database of Adams (1974, 1975), Cloutis et al., (1986), and from ordinary chondrite assemblages (Gaffey et al., 2002; Dunn et al., 2010). Pyroxene chemistry and olivine abundances are estimated from these calibrations. The Gaffey et al., (2002) tests for ordinary chondrites (mode 2) and the Dunn et al., (2010) calibrations are used for S(IV)-type asteroids that also fall within the ordinary chondrite regions of the BII/BI plot and the Gaffey et al., (2002) mode 1 calibration is used for all other S-type spectra.

Meteorite silicate assemblages may have one or two pyroxenes depending on the formation conditions (Gaffey et al., 2002; Gaffey, 2007, 2011). For ordinary chondrites, the BII position is affected by the Ca$^{2+}$ bearing pyroxene abundance and a BII correction based on the differences between expected band 2 positions (from orthopyroxene) and observed BII positions is used with the Gaffey et al., (2002) equations to estimate the ferrosilite and wollastonite content (Gaffey et al., 2002; Gaffey, 2007, 2011). The Dunn et al., (2010) calibrations are only appropriate for ordinary chondrite assemblages and will give spurious results if applied to spectra of single pyroxene assemblages (e.g. igneous or partially differentiated) just as the Gaffey et al., (2002) calibration (mode 1) does not give reliable results for ordinary chondrite assemblages (Gaffey, 2011). In deciding which calibration to use, it is necessary to
decide if a particular S type asteroid could be an ordinary chondrite assemblage (Gaffey et al., 2002; Gaffey, 2007, 2011).

To be considered as a plausible ordinary chondrite assemblage, the asteroid must fall in the S(IV) region of the BAR/BI plot (Gaffey et al., 1993a), and one of the ordinary chondrite zones on the BII/BI plot (e.g. figure 34). If an asteroid meet both criteria (or falls very close), the Gaffey et al., (2002) mode 2 calibrations with BII offsets modified from Gaffey (2007) and the Dunn et al., (2010) calibration are used and reported. These requirements are necessary but not sufficient. Lodranites, which have band parameters that fall in the S(IV) region of the BAR/BI plot (figure 40) and in one or more of the ordinary chondrite zones on the BII/BI plot (figure 41), are partially melted (Brearly and Jones, 1998; McCoy et al., 2000). The Gaffey et al., (2002) mode 2 and the Dunn et al., (2010) calibrations will not give reliable results for these assemblages but there is no way to, a priori, determine if an asteroid that meets the requirements is a plausible ordinary chondrite or Lodranite parent body.

The Gaffey et al., (2002) mode 1 and 2, Dunn et al., (2010), and Gastineau-Lyons et al., (2002) calibrations (adapted from Cloutis et al., 1986) utilize meteorite and mineral mixture spectra measured at approximately 300 K (room temperature) (Sanchez et al., 2012 Reddy et al., 2015). Asteroid surface temperatures depend on heliocentric distance
and vary from around 140 K to 440 K (Sanchez et al., 2012 Reddy et al., 2015). An asteroid’s surface temperature, $T$, is defined as:

$$T = \frac{1 - A L_0}{16 \eta \varepsilon \sigma \pi r^2}^{1/4}$$

where $A =$ asteroid albedo; $L_0 =$ solar luminosity ($3.827 \times 10^{26}$ W); $\eta =$ beaming parameter (assumed to be 1); $\varepsilon =$ thermal emissivity (assumed to be 0.9); $\sigma =$ Stefan-Boltzman constant ($5.67 \times 10^{-08}$); $\pi =$ 3.14; $r =$ heliocentric distance of asteroid (in meters) (Burbine et al., 2009; Reddy et al., 2015). Three of the S-type Gefion family asteroids observed had no albedo and an average albedo, estimated from the WISE albedos for 36 Gefion family S-type asteroids, was substituted (Masiero et al., 2011; Reddy et al., 2015).

For ordinary chondrites, the BII center and the band area ratio measurements are affected, which can lead to overestimated or underestimated olivine/pyroxene relative abundances and ferrosilite content when using the Gaffey et al., (2002) and the Gastineau-Lyons et al., (2002) equations (Sanchez et al., 2012; Reddy et al., 2015). The Dunn et al., (2010) equations for ferrosilite and fayalite are dependent on the BI position and are unaffected since temperature effects on the BI center are negligible and corrections to BI positions are not required for ordinary chondrite assemblages.
(Sanchez et al., 2012; Reddy et al., 2015). Temperature has effects on both bands for basaltic achondrite (HEDs and asteroids that fall in the HED region of the BAR/BI plot) assemblages (Burbine et al., 2009; Reddy et al., 2015). Temperature corrections for howardites-eucrite and for diogenite assemblages are only applicable to basaltic achondrite assemblages and were not applied to the S(V) asteroids (Burbine et al., 2009; Reddy et al., 2015).
CHAPTER V
THE ASTEROIDS


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<th>Phase Angle</th>
<th>Airmass Range</th>
<th>Total Integration Time (sec)</th>
<th>Total # Spectra</th>
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<th>Solar Analog</th>
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Table 1: Observation Parameters

Table 1: Observation parameters: Extinction star and solar analog classifications are from SIMBAD. Individual asteroid spectra exposure times were 120 s. Spectra for (2373) Immo were unusable as no visible spectra were seen in the FITS images. (5159) Burbine is not included as this asteroid was observed by Binzel's spectroscopy group (Binzel et al., 2014).
Discussions of the asteroids are by type starting with the two featureless asteroids. The ten S-type asteroids are grouped by S subtype and possible ordinary chondrite assemblage based on position on the BII/BI and BAR/BI plots. (2905) Plaskett and (3190) Lizst, were originally reduced and analyzed by Blagen (2012); (5159) Burbine (IRTF spectra) was observed, reduced and merged with SMASHII spectra by Binzel’s spectroscopy group (Binzel et al., 2014).

Mineral properties/abundances for individual asteroids (exhibiting 1 μm and 2 μm absorption features) are derived from parameters extracted from reflectance spectra using three calibrations: BAR to abundance (Cloutis et al., 1986; Gastineau-Lyons et al., 2002; Dunn et al., 2010), ferrosilite content and ordinary chondrite tests (Gaffey et al., 2002; Gaffey, 2007), and fayalite content (Dunn et al., 2010). These spectral parameters

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<th>Absolute Magnitude (H)</th>
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<th>IRAS Diameter (Km)</th>
<th>WISE Albedo</th>
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Table 2: Physical Properties of asteroids observed: IRAS albedos and diameters are from Tedesco et al., (2004), WISE albedos and diameters are from Masiero et al., (2011), rotation periods are from Harris et al., (2014), SMASS taxonomy is from Neese (2010), SDSS taxonomy is from Hasselman et al., (2012), and proper elements are from (Gefion asteroids) Nesvorny (2012). (5159) Burbine spectrum is from Binzel et al., (2014).
are the wavelength positions of the mafic silicate absorption features near 1 μm (BI) and 2 μm (BII) and the ratio of the areas of Band II and Band I (BAR) (Cloutis et al., 1986; Cloutis and Gaffey, 1991; Gaffey et al., 2002). Uncertainties for band parameters are obtained by taking the difference between the average and the maximum and minimum values with the larger difference being used as the uncertainty. Uncertainties, standard deviation, and standard error are listed in table 3. Standard deviations are used as the error bars in the BII/BI and the BAR/BI plots.

S type spectra are in figures 30 and 31; featureless asteroid spectra are in figure 32. NIR spectra are merged with SMASSII (Bus and Binzel 2002) when available and are offset by 0.5 for clarity with the exception of (7272) Darbydyar and (7735) Scorzelli which are offset by 1.0 due to the noisy spectra of Darbydyar. Spectra in figures 30 and 31 exhibit absorption features at around 1 and 2 μm due to the presence of iron bearing silicates: olivine and pyroxene (Cloutis et al., 1986; Cloutis and Gaffey, 1991; Gaffey et al., 2002). Band extraction and analysis was done for all S-types except (7272) Darbydyar and (12275) Marcelgoffin, due to the poor quality of these two spectra. The band parameters and the position on the BII/BI and BAR/BI plots are compiled in table 3, with corresponding ferrosilite and olivine/fayalite abundances obtained from the Gaffey et al., 2002, Gastineau-Lyons et al., 2002, and Dunn et al., 2010 equations.
Figure 30: (1433) Geramtna (bottom), (1839) Ragazza, (2521) Heidi, (2905) Plaskett, (2911) Miahelena, and (3788) Steyaert (top). Triangles are the SMASHI data and dots are the IRTF spectra obtained for this project. The 1 and 2μm absorption features are due to olivine and pyroxene. The scatter near 2.4 μm is from a crack in the chip in SpeX (before the upgrades). Poorly corrected 1.4 μm telluric features are evident in the spectra of Geramtna, Plaskett, Miahelena, and Steyaert. The top three spectra also have 2μm telluric features.

Figure 31: (3910) Liszt (bottom), (4182) Mount Locke, (5159) Burbine (crosses), (7272) Darbydyar, (7735) Scorzelli, and (12275) Marcelgoffin (top). Triangles are SMASHI visible wavelength spectra and the dots are the IRTF spectra. All have the 1 and 2 μm absorption features due to olivine and pyroxene. Darbydyar, Scorzelli, and Marcelgoffin have no available visible wavelength spectra. The spectra for Darbydyar and Marcelgoffin are too noisy for analysis. Binzel’s spectroscopy group (Binzel et al., 2014) observed (5159) Burbine.
(527) Euryanthe and (17109) 1999 JF52: Asteroids with Featureless Spectra

(527) Euryanthe and (17109) 1999 JF52 have spectra lacking diagnostic absorption features (figure 32). The absorption features seen in the spectrum of (17109) 1999 JF52 are poorly corrected telluric absorptions (seen at 1.4 µm) or artifacts from noise.

![Figure 32: (527) Euryanthe (bottom) and (17109) 1999 JF52 (top), offset by 1 for clarity. 1.4 µm and 2 µm absorption features are due to poorly corrected telluric features. The additional absorption features seen in (17109) 1999 JF52 are most likely from the reduction process and not from composition.](image)

(527) Euryanthe and (17109) 1999 JF52 (figure 32) are not S-type asteroids and are interlopers in the S-type dominated Gefion dynamical family (Carruba et al., 2003; Bottke et al., 2009; Nesvorny et al., 2009). Slopes and albedos (IRAS and WISE) were compared to slopes and albedos (at 0.56 µm) of featureless meteorite spectra to determine a possible assemblage (figure 33) (Tedesco et al., 2004; Masiero et al., 2011; Cloutis et al., 2011a, 2011b). Both (527) Euryanthe and (17109) 1999 JF52 have IRAS/WISE albedos (table 2) consistent with C type asteroids and CI/CM chondrites (Tedesco et al., 2004; Masiero et al., 2011; Cloutis et al., 2011a, 2011b). (527)
Euryanthe’s spectrum is similar to the CM unusual chondrite Y-86789 while (17109) 1999 JF52 has a spectrum that is similar to the CI chondrite Alais (Figure 34) (Cloutis et al., 2011a, 2011b).

(527) Euryanthe and (17109) 1999 JF52 were both observed at low phase angles (<15 degrees) which minimizes phase reddening but no solar analog was obtained for 1999 JF52 (table 1) (Reddy et al., 2015). Non-compositional effects from the use of a non-solar type extinction star (G1/G2V for 17109, table 1) introduce uncertainties in the slope of 1999 JF52 (Reddy et al., 2015) and comparisons to meteorite analogs is suggestive at best. Albedos of the meteorites are obtained at 0.56 µm (in the V band) from spectra taken at 300 K (Kelvin); asteroid albedos are from thermal infrared observations at varying heliocentric distances (Tedesco et al., 2004; Masiero et al., 2011; Reddy et al., 2015). There is a strong correlation between asteroid albedos and taxonomic type and CI/CM chondrites are possible meteorite analogs for low albedo (dark) asteroids (C complex, Bus taxonomy), therefore, meteorite albedos are assumed to be comparable to the asteroid albedos (Mainzer et al., 2011a, 2011b, 2015). Neither (527) Euryanthe or CM unusual chondrite Y-86789 exhibit a feature at 0.7 µm which has been identified in both CM2 and Ch-type asteroid visible wavelength spectra; the comparison of Euryanthe to the CM chondrites is tenuous (Bus and Binzel, 2002a). These uncertainties need to be taken into account when using slopes and albedos as diagnostic of assemblage.
Figure 33: Slopes and albedos obtained for CI (black triangles) and CM (black squares) chondrite spectra from RELAB. (527) Euryanthe (open diamond) and (17109) 1999 JF52 (open circle) have slopes/albedos consistent with the CI and CM chondrites. Spectra are normalized to 1.22 μm, meteorite albedos are from reflectance values at 0.56 μm (in the visible V band) and slopes were obtained from least squares fit to the spectra.

Figure 34: (527) Euryanthe (dots) and CM unusual chondrite Y-86789 (dashes) (from Cloutis et al., 2011b) are the lower two spectra. Y-86789 has an albedo (at 0.56 μm) of 0.0595, the IRAS albedo for 527 Euryanthe is 0.0576 (Tedesco et al., 2004; Cloutis et al., 2011b). (17109) 1999 JF52 (squares) and the CI chondrites Alais (triangles), Orgueil (diamonds), Ivuna (crosses) and Tagish Lake (X’s) are the upper five spectra (Cloutis et al., 2011a). The IRAS albedo of 17109 is 0.0265 +/- 0.008 and the albedo of Alais (at 0.56 μm) is 0.0395 (Tedesco et al 2004, Cloutis et al 2011a).
S-Type Asteroids

Band parameters for the S-type Gefion asteroids are represented in the BII/BI and BAR/BI plots (figures 35 and 36, respectively) with the exclusion of (7272) Darbydyar and (12275) Marcelgoiffin due to noisy spectra. All asteroids (except (1433) Geramtina and (5159) Burbine) fall in or on the border of the ordinary chondrite zones of the BII/BI plot (figure 35). Three asteroids are classified as S(V), six as S(IV), and one does not fall in any of the Gaffey et al., (1993a) S classes (figure 36).

Figure 35: BII/BI plot (zoomed in for clarity. Black triangles are pyroxene and black squares are high calcium pyroxene. The labeled polygons are the HED zone, the H, L, and LL chondrite zones. The large symbols are the S type asteroids: Geramtina (cross), Ragazza (diamond), Heidi (open diamond), Plaskett (triangle), Miahelena (open triangle), Steyaert (square), Liszt (circle), Mount Locke (open circle), Burbine (x with line), and Scorzelli (x). Error bars for the asteroids are the standard deviation for clarity.

All S-type Gefion asteroids, with the exception of (1433) Geramtina and (5159) Burbine fall within the ordinary chondrite regions. Geramtina falls outside the H chondrite region and on the orthopyroxene-clinopyroxene trend while Burbine falls
above the pyroxene trend (figure 35). This eliminates the possibility of an ordinary chondrite assemblage for (1433) Geramtina and (5159) Burbine.

Figure 36: BAR/BI plot (the S(IV), S(V), and S(VI) regions labeled for clarity). The black curve is the olivine - low Ca pyroxene mixing line from Cloutis et al (1986). Error bars are the standard deviation. The symbols are the S type asteroids: Geramtina (cross), Ragazza (diamond), Heidi (open diamond), Plaskett (triangle), Miahelen (open triangle), Steyaert (square), Liszt (circle), Mount Locke (open circle), Burbine (x with line), and Scorzelli (x). Error bars for the asteroids are the standard deviation for clarity. Six asteroids (Ragazza, Miahelen, Steyaert, Liszt, Mount Locke, and Burbine) fall within or on the edge of the S(IV) region.

In the BAR/BI plot (figure 36), (1839) Ragazza, (2911) Miahelen, (3788) Steyaert, (3910) Liszt, (4182) Mount Locke, and (5159) Burbine fall within or on the border of the S(IV) region. Excepting Burbine, five Gefion asteroids have a plausible ordinary chondrite assemblage and temperature corrections for ordinary chondrites were applied to the BAR and BI for these asteroids (table 3; figures 37 and 38) (Sanchez et al., 2012; Reddy et al., 2015). (1433) Gerantina falls below the S(IV) region and (2521) Heidi, (2905) Plaskett and (7735) Scorzelli lie in the S(V) region. Band parameters for Geramtina, Heidi, Plaskett, Burbine, and Scorzelli do not satisfy the requirements for an
ordinary chondrite or basaltic achondrite assemblage so temperature corrections are not estimated for these asteroids.

Table 3: Gefion Asteroid Band Parameters

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Table 3: Band parameters (BI, BII, BAR), standard error, and BII/BI, BAR/BI criteria. The BII and BAR temperature corrections are applicable for 1839, 2911, 3788, 3910, and 4182 which satisfy the criteria for possible ordinary chondrite assemblage (Sanchez et al., 2012; Reddy et al., 2015). No temperature corrections were calculated for Geramtina, Heidi, Plaskett, Burbine, and Scorzelli. These asteroids do not meet requirements for basaltic achondrites or ordinary chondrites (Burbine et al 2009, Reddy et al 2015).

(1839) Ragazza, (2911) Miahelena, (3788) Steyaert, (3910) Liszt, and (4182) Mount Locke: Ordinary chondrite candidates

These five asteroids meet the minimum requirement for possible ordinary chondrite assemblages. (2911) Miahelena, (3788) Steyaert, and (4182) Mount Locke place in the ordinary chondrite zones of the BII/BI plot and in the S(IV) region of the BAR/BI plot (figures 35 and 36, respectively). (1839) Ragazza lies on the border of the H chondrite zone of the BII/BI plot and (3910) Liszt places in the ordinary chondrite zones of the BII/BI plot (figure 35) but places on the border of the S(IV) of the BAR/BI plot (figure 36). Ordinary chondrite temperature corrections for BII and BAR (Sanchez et al., 2012; Reddy et al., 2015) were applied for these asteroids (figures 37 and 38). All five
asteroids fall within one of the ordinary chondrite zones of the BII/BI plot and within the S(IV) region of the BAR/BI plot, including (3910) Liszt. The temperature corrections systematically shifted BII positions to longer wavelengths and reduced the band area ratios.

Figure 37: BII temperature corrections for Ragazza (diamond), Miehela (open triangle), Steyaert (square), Liszt (circle), and Mount Locke (open circle). The temperature corrections result in a shift of BII to longer wavelengths. Ragazza is now in both the H and L chondrite zones, Miehela lies in the H chondrite zone and on the border of the L chondrites, Steyaert falls within the L chondrite zone, Liszt and Mount Locke are in the LL chondrite region.

Figure 38: Temperature corrected band area ratios for (1839) Ragazza (diamond), (2911) Miahelena (open triangle), (3788) Steyaert (square), (3910) Liszt (circle), and (4182) Mount Locke (open circle); band 1 positions have no change. All five asteroids are now within the S(IV) region: 3910 fell on the border of the S(IV) region in figure 36. Temperature corrections to the band area ratio systematically reduce the band area ratios for these asteroids.
Ragazza: Ferrosilite content estimated from Dunn et al., (2010) is consistent with an H chondrite assemblage; pyroxene chemistry from the Gaffey et al., (2002) is more consistent with the L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Olivine abundances for H chondrites range from 46% to 55% and the olivine content of Ragazza from the Gastineau-Lyons et al., (2002) equation is inconsistent with H and L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). The Dunn et al., (2010) olivine abundance is at the upper end of the H chondrite range and within the range of the L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). The covariation of ferrosilite and fayalite content with olivine, all estimated from the Dunn et al., (2010) equations (figures 39 and 40, respectively), place Ragazza within the H chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). The WISE albedo of (1839) Ragazza is 0.4561 (+/- 0.0753) is higher than albedos of ordinary chondrites (Gaffey, 1976; Masiero et al., 2011). The albedo could be due to high metamorphism, a reduced

<table>
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<th>Wo (+/- 3)</th>
<th>Dunn Fs (+/- 1.4)</th>
<th>Dunn Fa (+/- 1.3)</th>
<th>% Olivine</th>
<th>Dunn Olv %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1433 Gerartina</td>
<td>39.31 a</td>
<td>0.5 a</td>
<td>N. A</td>
<td>N. A</td>
<td>45%</td>
<td>N. A</td>
</tr>
<tr>
<td>1839 Ragazza</td>
<td>20.1 b</td>
<td>4 b</td>
<td>16.93</td>
<td>19.47</td>
<td>66%</td>
<td>55.86</td>
</tr>
<tr>
<td>2521 Heidi</td>
<td>42 a</td>
<td>16.5 a</td>
<td>N. A</td>
<td>N. A</td>
<td>49%</td>
<td>N. A</td>
</tr>
<tr>
<td>2905 Plaskett</td>
<td>39 a</td>
<td>14 a</td>
<td>N. A</td>
<td>N. A</td>
<td>39%</td>
<td>N. A</td>
</tr>
<tr>
<td>2911 Miahelena</td>
<td>22.9 b</td>
<td>2 b</td>
<td>15.12</td>
<td>16.93</td>
<td>59%</td>
<td>51.75</td>
</tr>
<tr>
<td>3788 Steyaert</td>
<td>22.9 b</td>
<td>0 b</td>
<td>16.93</td>
<td>19.47</td>
<td>70%</td>
<td>58.52</td>
</tr>
<tr>
<td>3910 Liszt</td>
<td>22.9 b</td>
<td>9 b</td>
<td>20.03</td>
<td>23.78</td>
<td>68%</td>
<td>57.31</td>
</tr>
<tr>
<td>4182 Mount Locke</td>
<td>59.1 a</td>
<td>6 a</td>
<td>18.57</td>
<td>21.75</td>
<td>67%</td>
<td>56.83</td>
</tr>
<tr>
<td>5159 Burbine</td>
<td>34 a</td>
<td>0 a</td>
<td>N. A</td>
<td>N. A</td>
<td>72%</td>
<td>N. A</td>
</tr>
<tr>
<td>7735 Scorzelli</td>
<td>42 a</td>
<td>14 a</td>
<td>N. A</td>
<td>N. A</td>
<td>38%</td>
<td>N. A</td>
</tr>
</tbody>
</table>
assemblage with a small percentage of iron in the silicates, or small particle size (Gaffey, 1976). Unless the WISE albedo is incorrect, the high albedo is difficult to reconcile with an ordinary chondritic assemblage for (1839) Ragazza.

(2911) Miahelena and (3788) Steyaert: The Dunn et al., (2010) equations give a ferrosilite content consistent with an H chondrite assemblage for both asteroids while pyroxene chemistry from the Gaffey et al (2002) mode 2 equations places both within the L/LL chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Olivine abundances estimated from the Gastineau-Lyons et al., (2002) calibration are inconsistent with H chondrites and for (3788) Steyaert, the olivine abundance is too high (70%) to be consistent with any ordinary chondrite assemblage (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Olivine abundance for Miahelena estimated from Dunn et al., (2010) is consistent with the H chondrites; for Steyaert, olivine abundance is consistent with L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Covariation of ferrosilite and fayalite with olivine abundance, measured from the Dunn et al., (2010) equations place Miahelena and Steyaert with the H chondrites (figures 39 and 40) (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). The Gaffey et al., (2002) and the Dunn et al., (2010) calibrations differ in which ordinary chondrite class these asteroids are consistent with but agree that (2911) Miahelena and (3788) Steyaert are likely parent bodies for one of the ordinary chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010).

(3910) Liszt: Pyroxene chemistry from Gaffey et al., (2002) is consistent with L/LL chondrites, while olivine abundance from Gastineau-Lyons et al., (2002) is above the
range of olivine abundance for both L and LL chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Covariation of both ferrosilite and fayalite content with olivine abundance, estimated from the Dunn et al., (2010) equations, place Liszt with the L chondrites (figures 39 and 40). (3910) Liszt is a likely match for the L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010).

(4182) Mount Locke: This asteroid fails the Gaffey et al., (2002) mode 2 tests for ordinary chondrite assemblages. Pyroxene chemistry from mode 1 of the Gaffey et al., (2002) equations suggests a low Ca orthopyroxene. Covariation of ferrosilite and fayalite content with olivine abundance, all estimated from the Dunn et al., (2010) equations (figures 39 and 40), indicate that Mount Locke has an assemblage consistent
with L chondrites (McSween et al., 1991; Brearley and Jones, 1998; Dunn et al., 2010). Although the Gaffey et al., (2002) and the Dunn et al., (2010) calibrations give conflicting results, (4182) Mount Locke is a possible match for the L chondrites.

(2521) Heidi, (2905) Plaskett, (7735) Scorzelli: S(V) asteroids

(2521) Heidi, (2905) Plaskett and (7735) Scorzelli all fall within the S(V) region on the BAR/BI plot (figure 36) and fall within or on the border of the HED region of the BII/BI plot (figure 35). (2905) Plaskett and (7735) Scorzelli fall towards the basaltic
achondrite (HED) region but fail the Burbine equations (Burbine et al., 2009). (2905) Plaskett BI pyroxene chemistry is Fs\textsubscript{78.9}, Wo\textsubscript{23.7}, for BII, Fs\textsubscript{41.2}, Wo\textsubscript{9.11}; (7735) Scorzelli BI pyroxene chemistry is Fs\textsubscript{78.9}, Wo\textsubscript{23.7}, BII pyroxene chemistry is Fs\textsubscript{51.5}, Wo\textsubscript{13.11}. Pyroxene chemistries estimated from BI and BII positions should be very close, within errors, from one another but this is not the case with (2905) Plaskett or (7735) Scorzelli (Burbine et al., 2009). Pyroxene chemistry for (2521) Heidi, (2905) Plaskett, and (7735) Scorzelli (table 4) estimated from the Gaffey et al., (2002) mode 1 equations indicate that these asteroids are consistent with an orthopyroxene dominated assemblage.

Olivine abundances, estimated from Gastineau-Lyons et al., (2002), for Heidi, Plaskett, and Scorzelli are 49%, 39%, and 38%, respectively. Acapulcoites have olivine abundances between 20% and 40%, but the pyroxene chemistry has low ferrosilite content: Fs\textsubscript{3.3-13.3} (Mittlefehldt et al., 1998; Grady et al., 2014). Winonaites are excluded due to the lower olivine abundance (7% to 20%), Ureilites were excluded due to their high olivine abundance and trace amounts of orthopyroxene, and mesosiderites were not a plausible assemblage due to similarity with Howardite-Eucrite-Diogenite pyroxene abundances and chemistry (Benedix et al., 1998; Mittlefehldt et al., 1998; Grady et al., 2014). (7735) Scorzelli has a high WISE albedo, 0.4704 (+/- 0.0735), indicative of a reduced assemblage (Masiero et al., 2011).

(1433) Geramtina and (5159) Burbine

The positions of (1433) Geramtina on the BII/BI and BAR/BI plots (figures 35 and 36, respectively) indicate an assemblage that has subequal pyroxene and olivine
abundances with pyroxene abundance slightly higher (Cloutis et al., 1986; Gaffey et al., 1993a, 1993b, 2002; Dunn et al., 2010). Olivine abundance for (1433) Geramtina estimated from Gastineau-Lyons et al., (2002) is 45% and pyroxene chemistry from the Gaffey et al., (2002) mode 1 equations indicate an orthopyroxene with little to no calcic component. The olivine abundance and absence of clinopyroxene limits possible meteorite analogs. Olivine percentage is above the range for Winonaites but is within the olivine content range of the Lodranites (Mittlefehldt et al., 1998; Grady et al., 2014). Ferrosilite content of (1433) Geramtina is well above that of Lodranites, estimated to be from Fs$_{3.9}$ to Fs$_{13.8}$ (Mittlefehldt et al., 1998; Grady et al., 2014). (5159) Burbine falls in the S(IV) region of the BAR/BI plot (figure 36) but is above the pyroxene trend on the BII/BI plot (figure 35), indicative of a significant olivine component which is confirmed from the Gastineau-Lyons et al., (2002) equation. Pyroxene chemistry from the Gaffey et al., (2002) mode 1 equations is similar to that of (1433) Geramtina (table 4) and olivine abundance is 72%. Lodranites and Winonaites are not meteorite analogs for (5159) Burbine due to olivine abundance and pyroxene chemistry (Mittlefehldt et al., 1998; Grady et al., 2014).

Pyroxene chemistry and olivine abundances from the Gaffey et al., (2002) mode 2 calibrations and Gastineau-Lyons et al., (2002) indicate ordinary chondrite assemblages for (1839) Ragazza, (2911) Miahelena, (3788) Steyaert, and (3910) Liszt. (4182) Mount Locke fails the test for ordinary chondrite assemblages from Gaffey et al., (2002). Ferrosilite and olivine content for Liszt and Mount Locke from the Dunn et al., (2010) calibrations are consistent with an L chondrite assemblage; Ragazza, Miahelena, and Steyaert have assemblages that are consistent with H chondrites (Brearly and Jones,
1998; Dunn et al., 2010). Pyroxene chemistry for (1433) Geramtina, (2521) Heidi, (2905) Plaskett, (5159) Burbine, and (7735) Scorzelli (table 4), calculated from mode 1 of the Gaffey et al., (2002) equations were compared with the mineralogy of select meteorites that have cosmic ray exposure ages expected for the 5:2 resonance. Acapulcoites and Winonaites have low olivine abundances, 20-40% and 7-20% respectively (Mittlefehldt et al., 1998; Grady et al., 2014). Lodranites have olivine/pyroxene abundances similar to ordinary chondrites, have experienced partial melting, and are identified as possible meteorite analogs for the S(IV) and S(V) subtypes (Hiroi and Takeda, 1991; McCoy et al., 2000; Gaffey et al., 1993a; Mittlefehldt et al., 1998; Patzer et al., 2004; Rubin, 2007; Grady et al., 2014). Pyroxene chemistry of (1433) Geramtina, (2521) Heidi, (2905) Plaskett, (5159) Burbine, and (7735) Scorzelli is not consistent with the Lodranites and no meteorite analogs with assemblages consistent with those estimated for these asteroids were identified (Mittlefehldt et al., 1998; Grady et al., 2014).
CHAPTER VI
DISCUSSIONS AND CONCLUSIONS

VNIR spectra were obtained for fourteen Gefion family asteroids; (2373) Immo has no data, (7272) Darbydyar and (12275) Marcelgoffin had final average spectra that were too noisy for analysis. (527) Euryanthe and (17109) 1999 JF52 have featureless spectra and low IRAS/WISE albedos and (Tedesco et al., 2004a; Masiero et al., 2011). Binzel’s MIT asteroid spectroscopy group (Binzel et al., 2014) observed a fifteenth asteroid, (5159) Burbine. Twelve asteroids, (1433) Geramtina, (1839) Ragazza, (2521) Heidi, (2905) Plaskett, (2911) Miahelena, (3788) Steyaert, (3910) Liszt, (4182) Mount Locke, (5159) Burbine, (7272) Darbydyar, (7735) Scorzelli, and (12275) Marcelgoffin exhibit absorption features due to Fe bearing silicates. (7272) Darbydyar and (12275) Marcelgoffin were not analyzed, leaving ten S-types for analysis. The S-type asteroids, with the exception of (5159) Burbine, fall within or close to one of the ordinary chondrite regions of the BII/BI plot (figure 35). For the BAR/BI plot (figure 36), (2521) Heidi, (2905) Plaskett and (7735) Scorzelli fell in the S(V) region, (1433) Geramtina fell in the S(VI) region, and the remaining asteroids fell within or close to the border of the S(IV) region (figure 36). Table 5 lists the probabilities (from the standard errors of the band parameters) that each asteroid plots in the S(IV) region of the BAR/BI plot and the ordinary chondrite regions of the BII/BI plot.
From the Gaffey et al., (2002) tests for ordinary chondrites, (1839) Ragazza, (2911) Miahelena, (3788) Steyaert and (3910) Liszt have pyroxene chemistries consistent with the L/LL chondrites. (4182) Mount Locke meets the criteria to test for ordinary chondrites but its pyroxene chemistry is inconsistent with the H, L, or LL chondrites. According to the Dunn et al., (2010) equations, all of the S(IV) asteroids have ferrosilite, fayalite and olivine compositions indicative of ordinary chondrite assemblages: three H chondrites (Ragazza, Miahelena, 3788 Steyaert) and two L chondrites (Liszt, and Mount Locke). (2521) Heidi, (2905) Plaskett and (7735) Scorzelli, S(V) asteroids, (5159) Burbine (S(IV) asteroid), and 1433 Gerantina failed the requirements for a possible ordinary chondrite assemblage. In addition, (1839) Ragazza and (7735) Scorzelli both had very high WISE albedos, if the albedos are correct (Masiero et al., 2011). High metamorphism (petrologic type 6), particle size, and reduced assemblages with a few percent iron in the silicates can increase albedo (Gaffey, 1976; Masiero et al., 2011). From this sample of 12 Gefion dynamical family

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>BII/BI OC</th>
<th>H</th>
<th>L</th>
<th>LL</th>
<th>BAR/BI</th>
<th>S(IV)</th>
<th>S(V)</th>
<th>OC ? (Dunn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1433 Gerantina</td>
<td>None</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>S(VI)</td>
<td>0%</td>
<td>0%</td>
<td>No</td>
</tr>
<tr>
<td>1839 Ragazza</td>
<td>H and L</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
<td>S(IV)</td>
<td>100%</td>
<td>0%</td>
<td>H</td>
</tr>
<tr>
<td>2521 Heidi</td>
<td>LL</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>S(V)</td>
<td>0%</td>
<td>100%</td>
<td>No</td>
</tr>
<tr>
<td>2905 Plaskett</td>
<td>L and LL</td>
<td>0%</td>
<td>100%</td>
<td>100%</td>
<td>S(V)</td>
<td>0%</td>
<td>100%</td>
<td>No</td>
</tr>
<tr>
<td>2911 Miahelena</td>
<td>H and L</td>
<td>100%</td>
<td>50%</td>
<td>0%</td>
<td>S(IV)</td>
<td>100%</td>
<td>0%</td>
<td>H</td>
</tr>
<tr>
<td>3788 Steyaert</td>
<td>L</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>S(IV)</td>
<td>100%</td>
<td>0%</td>
<td>H</td>
</tr>
<tr>
<td>3910 Liszt</td>
<td>LL</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>S(IV)</td>
<td>75%</td>
<td>0%</td>
<td>L</td>
</tr>
<tr>
<td>4182 Mount Locke</td>
<td>LL</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>S(IV)</td>
<td>100%</td>
<td>0%</td>
<td>L</td>
</tr>
<tr>
<td>5159 Burbine</td>
<td>None</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>S(IV)</td>
<td>100%</td>
<td>0%</td>
<td>No</td>
</tr>
<tr>
<td>7735 Scorzelli</td>
<td>LL</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>S(V)</td>
<td>0%</td>
<td>100%</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 5: Probabilities that band parameters and associated standard errors plot within the ordinary chondrite regions of the BII/BI and the S(IV) or S(V) regions of the BAR/BI plots (figures 35 and 36). Note that some asteroids fall in two overlapping ordinary chondrite zones and are estimated as 100% probability for both zones (see figure 28). Also of note is the probability of (1839) Ragazza falling in the H chondrite zone. This asteroid has a WISE albedo consistent with a reduced assemblage (Masiero et al., 2011)
asteroids, there are only two probable L chondrite matches: (3910) Liszt and (4182) Mount Locke.

**Conclusion and Recommendations**

(1839) Ragazza (ignoring albedo), (2911) Miahelena, and (3788) Steyaert have assemblages consistent with H chondrites, (3910) Liszt and (4182) Mount Locke are both consistent with L chondrites. (1433) Geramtina, (2521) Heidi, (5159) Burbine have olivine abundances consistent with Lodranites but their pyroxene chemistries are not consistent with any meteorite in the collections (Mittlefehldt et al., 1998; Grady et al., 2014). (2905) Plaskett and (7735) Scorzelli have olivine percentages consistent with Acapulcoites but the pyroxene chemistries for these two asteroids are not consistent with an Acapulcoite assemblage or any meteorite assemblage in the collections (Mittlefehldt et al., 1998; Grady et al., 2014). Lacking diagnostic absorption features, slopes and albedos for (527) Euryanthe and (17109) 1999 JF52 were compared with slopes and albedos of featureless meteorite soectra and found to be consistent with CI/CM chondrites (Cloutis et al., 2011a, 2011b). With only two asteroids having assemblages consistent with L chondrites, the Gefion dynamical family is not a likely source of the L chondrites, and there is no definitive dominant assemblage.

(1433) Geramtina, (2905) Plaskett, (2911) Miahelena, (3788) Steyaert, (7272) Darbydyar, (7735) Scorzelli, (12275) Marcelgoffin, and (17109) 1999 JF52 would benefit from additional observations to obtain better spectra. (1433) Geramtina, (2905) Plaskett, (2911) Miahelena, (3788) Steyaert, and (7735) Scorzelli had poorly corrected
1.4 μm telluric features in which the band area ratios estimated for these asteroids are spurious. (7735) Scorzelli is also noisy towards the long wavelength part of its spectrum, also leading to a spurious band area ratio. One of the necessary criteria to be considered a possible ordinary chondrite assemblage is the position within the S(IV) region of the BAR/BI plot. Band area ratios from less noisy spectra of the aforementioned asteroids may change which equations used to estimate assemblages. Temperature corrections need to be identified for compositions that are neither ordinary chondrite, olivine dominated, nor basaltic achondrite (Sanchez et al., 2012; Reddy et al., 2015). Five asteroids, (1433) Geramtina, (2521) Heidi, (2905) Plaskett, (5159) Burbine, and (7735) Scorzelli did not meet criteria for any assemblage in which an appropriate temperature correction could be applied.

VNIR spectra for additional Gefion family asteroids are required for a representative composition of the Gefion dynamical family. A sample of 30 or more asteroids can provide a reasonable cross section of the entire population of the Gefion dynamical family. Ideally, a similar sample size of S-type background population asteroids can ascertain the range of background population compositions. Both the Gaffey et al., (2002) tests for ordinary chondrite (mode 2) and the Dunn et al., (2010) ferrosilite calibrations would benefit from consideration of primitive achondrites and other assemblages not found in the meteorite collections. Assemblages such as Lodranites and Acapulcoites place in the ordinary chondrite regions on the BII/BI plot (figure 41) and/or the S(IV) region of the BAR/BI plot (figure 42) (Gaffey et al., 1993a; McCoy et al., 2000).
Figure 41: BII/BI plot with pyroxene trend (black triangles and squares), H chondrites (open diamonds), L chondrites (x's), and LL chondrites (open squares). Acapulcoites (open triangles) plot outside the H chondrite zone and Lodranites (black crosses) plot within or on the borders of the H and L chondrite region. Band centers obtained from the following meteorite spectra: Acapulco, ALHA81261,3, GRA95209, Lodran, MAC88177, and Y-791491,20 (Hiroi, 2014; McCoy, 2014; Pieters, 2014).

Figure 42: BAR/BI plot with H chondrites (open diamonds), L chondrites (x's), and LL chondrites (open squares) defining the S(IV) region. Both Acapulcoites (open triangles) and Lodranites (black crosses) plot in this region. Band centers and band area ratios obtained from the following meteorite spectra: Acapulco, ALHA81261,3, GRA95209, Lodran, MAC88177, and Y-791491,20 (Hiroi, 2014; McCoy, 2014; Pieters, 2014).
Band parameters from Lodranite spectra meet the criteria for ordinary chondrite assemblages by falling within the S(IV) region on the BAR/BI plot (figure 42) and in or on the border of the H and L chondrite regions of the BII/BI plot (figure 41). These band parameters fail the Gaffey et al., (2002) tests for ordinary chondrites, but have ferrosilite, fayalite content and olivine abundances consistent with H chondrites according to the Dunn et al., (2010) equations. Correlations between ferrosilite, fayalite, olivine abundances to band parameters, similar to the correlations for the ordinary chondrites, need to be identified. Appropriate equations to estimate pyroxene chemistry and abundances for primitive achondrites that fall in the ordinary chondrite regions of the BII/BI plot and in the S(IV) region need to be derived. Additional calibrations for other assemblages could help distinguish if an asteroid whose band parameters meet the criteria for an ordinary chondrite assemblage has an assemblage consistent with ordinary chondrites.

Four of the five S(IV) asteroids have assemblages consistent with ordinary chondrites from the Gaffey et al., (2002) tests for ordinary chondrites and the Dunn et al (2010) equations (tables 4 and 5). (4182) Mount Locke has an assemblage consistent with the L chondrites according to the Dunn et al., (2010) equations only. It cannot be assumed that an asteroid that meets the criteria from the BII/BI and BAR/BI plots has one of the three ordinary chondrite assemblages as other assemblages fall in these regions (figures 40 and 41) (Gaffey et al., 1993a; McCoy et al., 2000). If the Dunn et al., (2010) calibrations are preferentially used, an asteroid assemblage could be erroneously classified as consistent with the ordinary chondrites. Ferrosilite, fayalite, and olivine content from Lodranite band parameters are consistent with those of H chondrites.
according to the Dunn et al., (2010) equations (figures 43 and 44, table 6). The Lodranite band parameters are used as a stand-in for hypothetical asteroids, which meet requirements to be considered as plausible ordinary chondrite assemblages.

Figure 43: Covariation of spectrally derived olivine and fayalite content for Lodranites (red crosses and yellow crosses, temperature corrections). H (black crosses), L (black triangles), and LL (black x’s) chondrites are from Dunn et al (2010). Olivine abundances and fayalite content for (1839) Ragazza (black diamond), (2911) Miaeheleka (open triangle), (3788) Steyaert (square), (3910) Liszt (circle) and (4182) Mount Locke (open circle) are included for comparison. The Lodranites plot in the H chondrites with asteroids Ragazza, Miaeheleka, and Steyaert. Plot adapted from figure 5b in Dunn et al., (2010).
The results present several questions. How many other S-type Gefion family asteroids have assemblages consistent with L chondrites? Which of the calibrations (Gaffey et al., 2002 or Dunn et al., 2010) is the most reliable for asteroids that meet the criteria for a possible ordinary chondrite assemblage? Or should an asteroid’s assemblage estimated
from both callibrations be consistent: for example, ferrosilite content and olivine abundances from both calibrations are consistent with L chondrites? Ferrosilite and olivine content from the Dunn et al., (2010) equations are preferentially used for asteroids, which meet the criteria for a possible ordinary chondrite assemblage. Olivine abundances estimated from Dunn et al., (2010) are covariant with the ferrosilite content for each of the ordinary chondrite group (figures 39 and 40). In contrast, olivine abundances calculated from the Gastineau-Lyons et al., (2002) are above the ranges of olivine abundance for each of the ordinary chondrite groups (table 4). Ferrosilite content estimated from the Gaffey et al., (2002) tests for ordinary chondrites are higher than ferrosilite content from the Dunn et al., (2010) equations (table 4). The Dunn et al., (2010) equation for estimating ferrosilite content utilizes the band I center which does not require any temperature corrections (Sanchez et al., 2012; Reddy et al., 2015). In contrast, the Gaffey et al., (2002) equations (both modes) uses the band II center to calculate ferrosilite content. Temperature corrections applied to the BII centers increases the estimated ferrosilite content, and the ordinary chondrite group to which the asteroid’s assemblage is consistent with (table 7).

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>BII center, no temp. correction</th>
<th>BII center, with temp. correction</th>
<th>Fs (+/- 5) no temp. correction</th>
<th>Fs (+/- 5) with temp. correction</th>
</tr>
</thead>
<tbody>
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<td>1839 Ragazza</td>
<td>1.93</td>
<td>1.94</td>
<td>10.3b</td>
<td>20.1b</td>
</tr>
<tr>
<td>2911 Miahleena</td>
<td>1.92</td>
<td>1.95</td>
<td>13.1b</td>
<td>22.9b</td>
</tr>
<tr>
<td>3788 Steyaert</td>
<td>1.92</td>
<td>1.95</td>
<td>13.1b</td>
<td>22.9b</td>
</tr>
<tr>
<td>3910 Liszt</td>
<td>1.94</td>
<td>1.97</td>
<td>20.1b</td>
<td>22.9b</td>
</tr>
<tr>
<td>4182 Mount Locke</td>
<td>1.97</td>
<td>2.00</td>
<td>22.9b</td>
<td>59.1a</td>
</tr>
</tbody>
</table>

Table 7: Ferrosilite content estimated from mode 1 (a) and mode 2 (b) of the Gaffey et al., (2002) equations. Without temperature corrections to the BII center, Ragazza, Miahleena, and Steyaert have ferrosilite content close to that of the H chondrites; Liszt and Mount Locke are consistent with L and LL chondrites, respectively. The temperature corrected BII positions have Ragazza consistent with L chondrites, Miahleena, Steyaert, and Liszt with L/LL chondrites, and Mount Locke not consistent with any ordinary chondrite assemblage.
If the Gaffey et al., (2002) tests for ordinary chondrites (with temperature corrections for BII) are used exclusively, 1839 Ragazza would be consistent with an L chondrite assemblage and 2911 Miahelena, 3788 Steyaert, and 3910 Liszt would all be consistent with L/LL chondrites; 4182 Mount Locke is not consistent with any of the ordinary chondrite assemblages (table 6). The Dunn et al., (2010) equations have 1839 Ragazza, 2911 Miahelena, and 3788 Steyaert consistent with H chondrites; 3910 Liszt and 4182 Mount Locke are consistent with L chondrites. What additional constraints can be identified to confirm if an asteroid is consistent with one of the ordinary chondrites?

If there is a genetic Gefion family, what is its composition? Or are there overlapping genetic families with other silicate assemblages? The mean albedos for the Gefion dynamical family are between 24% and 34%; the range of albedos for ordinary chondrites is between 20% and 30% (Gaffey, 1976; Tedesco et al., 2004a; Masiero et al., 2011, 2013). To determine if there are any additional Gefion dynamical family asteroids with mineralogical assemblages consistent with ordinary chondrites, and if there is a genetic family within the dynamical family, spectra need to be obtained of Gefion asteroids that have albedos that fall in this range.

If there are one or more genetic families found within the Gefion dynamical family, what are their formation ages? The conclusion thus far is that the Gefion dynamical family is a collection of disparate compositions. The formation age was estimated with the assumption that the dynamical family is a genetic family, which is unlikely, based on results from this study. Observations of additional Gefion dynamical members along with observations of background S-type asteroids could give insight into the distribution
of mineralogical compositions for the region near the 5:2 resonance and the validity of
the methods used to determine family membership.

Is there a relationship between asteroids with assemblages consistent with the
ordinary chondrites to those found near the 3:1 resonance? A small group of asteroids
whose assemblage is consistent with the L chondrites was recently found near the 3:1
resonance (Fieber-Beyer and Gaffey, 2015). Approximately 2/3 of L chondrites exhibit
shock features due to a catastrophic breakup, $^{40}\text{Ar} - ^{39}\text{Ar}$ degassing ages and the presence
of influx 2 orders of magnitude above the background in Middle Ordovician deposits
indicate that this occurred during the Middle Ordovician (Haack et al., 1996;
Korochantseva et al., 2007; Nesvorny et al., 2007, 2009). If L chondrite sources are
found near both mean motion resonances (3:1 and 5:2), how can this be reconciled? If
the Gefion dynamical family is found to not be the source of the L chondrites, where is
the parent asteroid family? Is it instead near the 3:1 resonance instead? Could there have
been multiple regions in the early solar nebula in which L ordinary chondrite parent
sources formed? Due to the proximity to the 5:2 mean motion resonance, what
percentage of NEAs are from this resonance?
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