PERCENTAGE OF ORDINARY CHONDRITE MINERALOGIES AMONG S-COMPLEX AND Q-TYPE NEAR-EARTH ASTEROIDS. T. H. Burbine[1], R. P. Binzel[2], and B. J. Burt[2], [1]Department of Astronomy, Mount Holyoke College, South Hadley, MA 01075 (tburbine@mtholyoke.edu), USA, [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

Introduction: A number of planetary science questions have been definitively answered in the last few years. Two of these questions are whether ordinary chondrites can be derived from S-complex asteroids and whether space weathering occurs on asteroidal surfaces. Both of these questions were answered by analyses of samples of (25143) Itokawa that were returned to Earth by the Hayabusa mission. Itokawa was predicted to have an LL chondrite mineralogy from ground-based reflectance spectra obtained by Binzel et al. [1]. The returned grains had LL chondrite mineralogies [2,3] and evidence of space weathering [4].

However, it is unclear on how abundant ordinary chondrite mineralogies are among near-Earth asteroids (NEAs). To answer this type of question, the MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance [5] was instituted to routinely obtain near-infrared reflectance spectra of NEAs. As part of this ongoing program, near-infrared data were obtained on over 500 NEAs. These spectra are analyzed to try to understand how prevalent ordinary chondrite mineralogies are among S-complex and Q-type NEAs, which tend to have absorption features due to olivine and pyroxene. Binzel et al. [6] has previously found that there was a continuum of spectral properties between ordinary chondrites, Q-types, and S-complex bodies.

Data: Ordinary chondrite spectra have characteristic absorption bands centered at ~0.9 (Band I) and ~2 (Band II) µm that are due to olivine and pyroxene. The positions of these bands are functions of mineralogy. Among ordinary chondrites, LL chondrites tend to have band centers at the longest wavelengths since they are the most olivine-rich (which moves the Band I center to longer wavelengths and contain the most Fe-rich pyroxenes (which moves the Band II center to longer wavelengths). H chondrites tend to have band centers at the shortest wavelengths since they are the most pyroxene-rich and contain the most Fe-poor pyroxenes. L chondrites have intermediate band centers. Other meteorite types also have bands due to olivine and pyroxene. Acapulcoites/lodranites have band centers similar to the values for H chondrites [7]. Ureilites have band centers [8] that span the range found for ordinary chondrites but the bands are much weaker. However, ureilites have been definitively linked with C-complex bodies [9].

L chondrites are 35% of all falls, H chondrites are 32%, and LL chondrites are 8% [10]. H and L chondrites also dominate the Antarctic meteorites finds with L chondrites having 42% of the mass of all the collected meteorites, H chondrites having 31%, and LL chondrites having 17%.

The Band I and II centers and uncertainties for ~50 ordinary chondrites [5] were determined using a specially written computer program [11]. There was considerable overlap for the Band I and II center values for the H and L chondrites, but the LL chondrites had band centers that were distinctively different.

This program was then used to determine band centers and uncertainties for ~170 S-complex and Q-type NEAs that had wavelength coverage both in the visible and near-infrared. The near-infrared spectra were primarily obtained at the IRTF while the visible data were obtained using various telescopes. The asteroid band centers can then be directly compared to the ranges found for the ordinary chondrites. For the asteroids, the Band II center uncertainties tend to be larger [12] than those for the Band I centers due to the atmospheric water feature at ~1.9 µm and the shallowness and flatness of Band II. Band Area Ratios were not calculated due to problems in determining the long wavelength edge of Band II for the asteroids, which will significantly affect the calculated Band Area Ratios.

Results: Approximately 70% of the analyzed S-complex and Q-type NEAs had band centers (within uncertainties) consistent with those of ordinary chondrites. This is likely a lower limit on the percentage of S-complex and Q-type NEAs with ordinary chondrite-like mineralogies. For example, the band centers for Itokawa have relatively large uncertainties and fall slightly outside the LL chondrite range. Hiroi et al. [13] noted how the Band II for Itokawa measured by Hayabusa varied in structure depending on distance to Itokawa and discussed the problems in directly comparing the spectra of uniform samples (meteorite powders) with asteroids that have a variety of surface properties (large boulders to a fine-grained regolith). Many other NEAs also have band centers that fall slightly outside the calculated ranges for ordinary chondrites.

There are many possible complications in directly comparing meteorite and asteroid band centers. The measured meteorites might not be fully encompass the possible range of ordinary chondrite mineralogies. Some of the NEA spectra could have atmospheric artifacts that could affect the determination of the Band II center. The continua that are divided out over the

Band I and the Band II before determining the band centers are assumed to be linear, which may not be completely accurate. Temperature effects are assumed to be negligible but could slightly alter the positions of the band centers [14] for some of the NEAs.

Do the interpreted percentages of different ordinary chondrite assemblages among the S-complex and Q-type NEAs match the fall statistics? Approximately two-thirds of the bodies with ordinary chondrite-like band centers had their best matches with LL chondrites while 11% of ordinary chondrite falls are LL chondrites. This high proportion of LL-like mineralogies among NEAs is consistent with the analyses of Vernazza et al. [15], de León et al. [16], and Dunn et al. [17]. Vernazza et al. [15] used radiative transfer modeling while de León et al. [16] and Dunn et al. [17] used Band I centers and Band Area Ratios. Also using Band I centers and Band Area Ratios, Thomas et al. [12] found that S-complex and Q-type NEAS did have a higher proportion of interpreted LL-like mineralogies compared to H- and L-like mineralogies. However, Thomas et al. [12] did not find as high a percentage of LL-like mineralogies among the NEAs.

The observed NEAs and meteorite source bodies tend to have very different diameters. The NEAs tend to have diameters of hundreds of meters or larger while the ordinary chondrite source bodies have diameters of tens of meters or less, which causes them to break up in the atmosphere.

To understand the high proportion of LL-like mineralogies among NEAs relative to the fall statistics, we must look at the possible parent bodies of these meteorites. H chondrites have been linked with (6) Hebe (a=2.43 AU) [18] due to spectral similarities and this body's location near the 3:1 meteorite-supplying resonance (2.50 AU). No asteroid family has been identified with this object. However, a number of other asteroids near the 3:1 and 5:2 (2.82 AU) resonances have also been identified as having H-like mineralogies [19].

L chondrites have been dynamically linked [20] with the (1272) Gefion family (a=2.70-2.82 AU), located near the 5:2 resonance. A large percentage of L chondrites have ^{39}Ar-^{40}Ar ages of ~470 Myr [21], indicating a major impact at that time. Nesvorný et al. [20] found that the Gefion family had a modeled formation age consistent with ~470 Myr and that L chondrites had cosmic ray exposure ages consistent with originating from the Gefion family. Mineralogical analyses [22] of Gefion family members appear consistent with ordinary chondrites but do not definitively indicate an L-like mineralogy.

LL chondrites have been linked [15] to the (8) Flora family (a=2.16-2.40 AU) due to interpreted mineralogical similarities between Flora family members and LL chondrites. The Flora family has an estimated formation age of ~950 Myr [23].

The Yarkovsky effect, which can cause semi-major axis drift, decreases in strength with increasing size for km-sized bodies and increasing distance from the Sun [24]. If we assume the proposed meteoritic linkages, the relatively old age of the Flora family, its relative nearness to the Sun, and its proximity to the ν_6 secular resonance [15] may have allowed a higher proportion of NEA-sized LL-like bodies to reach meteorite-supplying resonances compared to NEA-sized H-like bodies derived from Hebe and L-like bodies derived from the Gefion family.

It is also possible that H chondrite and L chondrite source bodies were disrupted in near-Earth space, which could substantially increase the flux of H and LL chondrite meteorites to Earth relative to LL chondrites.

Conclusions: LL-like mineralogies dominate the S-complex and Q-type NEAs. More work needs to be done to determine exactly why LL-like material dominates the NEAs while H and L chondrites dominate the current meteorite flux.

Acknowledgments: THB would like to thank the Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS^{4}E) Solar System Exploration Research Virtual Institute (SSERVI) for support.

References: [1] Binzel R. P. et al. (2001) *Meteoritics & Planet. Sci., 36,* 1167-1172. [2] Nakamura T. et al. (2011) *Science, 333,* 1113-1116. [3] Mikouchi T. et al. (2014) *Earth, Planets and Space, 66*, 82. [4] Noguchi T. (2011) *Science, 333,* 1121-1125. [5] Binzel R. P. et al. (2006) *LPS XXXVII,* Abstract #1491. [6] Binzel R. P. et al. (1996) *Science, 273*, 946-948. [7] Burbine T. H. et al. (2001) *LPS XXXII*, Abstract #1860. [8] Cloutis E. A. et al. (2010) *Meteoritics & Planet. Sci., 45,* 1668-1694. [9] Jenniskens P. et al. (2009) *Nature, 458*, 485-488. [10] Burbine T. H. (2013) *Treatise on Geochemistry (2nd Edition),* 365-415. [11] Burbine T. H. (2014) *LPS XLV,* Abstract #1646. [12] Thomas C. A. et al. (2014) *Icarus, 228,* 217-246. [13] Hiroi T. et al. (2008) *Meteoritics & Planet. Sci., 43,* A58. [14] Moroz L. et al. (2000) *Icarus, 147,* 79-93. [15] Vernazza P. et al. (2008) *Nature, 454,* 858-860. [16] de León J. et al. (2010) *Astron. & Astrophys., 517,* A23. [17] Dunn T. L. et al. (2013) *Icarus, 222,* 273-282. [18] Gaffey M. J. and Gilbert S. L. (1998) *Meteoritics & Planet. Sci., 33,* 1281-1295. [19] Vernazza P. et al. (2014) *Astrophys. J., 791,* 120. [20] Nesvorný D. et al. (2009) *Icarus, 200,* 698-701. [21] Korochantseva E. V. et al. (2007) *Meteoritics & Planet. Sci., 42,* 113-130. [22] Roberts R. V. and Gaffey M. J. (2014) *LPS XLV,* Abstract #1263. [23] Dykhuis M. J. et al. (2014) *Icarus, 243,* 111-128. [24] Bottke W. F. Jr. et al. (2002) *Asteroids III*, 395-408.