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New Infrared Spectral Data for 27 Asteroids: An Investigation of Meteorite-Asteroid Relationships by Using the Modified Gaussian Model

Katherine Marie Gietzen
University of Arkansas

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NEW INFRARED SPECTRAL DATA FOR 27 ASTEROIDS: AN INVESTIGATION OF METEORITE-ASTEROID RELATIONSHIPS BY USING THE MODIFIED GAUSSIAN MODEL
NEW INFRARED SPECTRAL DATA FOR 27 ASTEROIDS: AN INVESTIGATION OF METEORITE-ASTEROID RELATIONSHIPS BY USING THE MODIFIED GAUSSIAN MODEL

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Space and Planetary Sciences

By

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December 2009
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ABSTRACT

Asteroids provide unique insights into the origin and early history of the solar system. Since asteroids are considered to be fairly pristine, studying them provides opportunities to learn more about the primordial solar system, its materials, processes and history. Since the discovery in 1801 of the first asteroid, Ceres, during the era when everyone was searching for the “missing planet”, astronomers have been trying to understand what they are, where they came from, why they exist and what they can tell us about how our solar system formed and evolved.

Within the asteroid population are a number of sub-populations, the primary division is due to the locations of the asteroids. There are the Main Belt Asteroid (MBA) population that resides between the orbits of Mars and Jupiter (1.8 – 3.5 AU) and the Near-Earth Asteroid (NEA) population whose orbits have an aphelion ≤ 1.3 AU. Within both the MBA and NEA populations are further subdivisions (taxonomic classes) based on physical properties of the asteroids such as albedo, spectral curve and probable composition. There have been a number of taxonomic classification schemes, the most current iteration splits the asteroids into three complexes (C, S, and X) that combined are comprised of twenty-six distinct taxonomic classes.

Since the lifetimes of the NEAs are short (10^6 – 10^7 yrs), it is thought that the NEA population is and continues to be populated by the MBA population through various mechanisms like resonances and thermal forces. We have conducted a statistical comparison of the two populations as a whole, by complexes and individual taxonomic classes and found significant differences as well as similarities. On the surface, it appears that the NEA population is not representative of the MBA
population. There are voids and relatively small numbers in taxonomic classes that exist in the NEA when compared to the MBA population and there are some important similarities. There are, however, biases that this analysis does not address that may explain our findings.

The asteroid taxonomy classification schemas are based on visible wavelength spectra. There are ~2500 classified asteroids of which only a very small percentage have spectra in the infrared wavelength ranges. Here we demonstrate, using asteroid 1989 ML, the need for more asteroid spectra in the near-infrared wavelength range which contains much compositional information. We show that in the visible wavelengths spectra of several meteorites of very different types match the spectrum of 1989 ML.

Finally, we examine twenty-seven S and possible S Complex asteroid spectra. We find that most contain pyroxenes in the monoclinic form (clinopyroxene). Clinopyroxenes can contain calcium; however, there are some that do not. The cases of Ca-free clinopyroxenes are rare on Earth, but are readily found in the type 3 unequilibrated ordinary chondrites. Analyses of the asteroids and ordinary chondrites were conducted using the Modified Gaussian Model (MGM) and the Band Area Ratio. We also examined two terrestrial Ca-free clinopyroxenes using the MGM. From our results we conclude that the surfaces of S Complex asteroids are consistent with the type 3 unequilibrated ordinary chondrites.
This dissertation is approved for Recommendation to the Graduate Council

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ACKNOWLEDGEMENTS

I express sincere appreciation to Dr. Claud H. S. Lacy for providing me academic guidance, financial support and a listening ear to my frustrations. You allowed me the space and freedom to explore on my own, but you were there when I had questions or needed help with the solutions. I am grateful for all you have done and look forward to collaborating in the future.

I recognize Dr. Derek W. G. Sears for his efforts in this research. He has been instrumental in providing an astronomer vital lessons in the world of meteorites and geology and I am thankful.

I acknowledge Dan Ostrowski for his much appreciated assistance with spectral analysis. He has suffered through sharing a small office cubical, listening to my ramblings and rants, as well as some stimulating conversations, and still he has been a good friend.

I express thanks to my committee. Dr. Claud Lacy, Dr. Derek Sears, Dr. Julia Kennefick, Dr. Daniel Kennefick, Dr. Rick Ulrich and Dr. Lin Oliver, for their valuable comments (and yes, you counted correctly – there are six of you!)

I am grateful to everyone in the Arkansas Center for Space and Planetary Sciences at the University of Arkansas, faculty, staff and students, for making it possible for me to survive the blind leap of faith I took when I started this program. In particular, Katie Bryson, Dan Ostrowski and Kate Coleman are good friends that have helped this astronomer/physicist to muddle my way through the fields of geology and chemistry and learn.
I express thanks to Dean Patricia R. Koski for her caring and understanding that made it possible to survive past my first semester at the University of Arkansas.

I express thanks and deep appreciation to my parents, Harley and Marie Brown, my daughter, Sarah Gietzen, my daughter and son-in-law, Megan and Jason Willoughby. They have supported, encouraged and motivated me throughout the good and the bad times. In addition, I wish to thank my love, Dale Hite, who has supported me throughout and stated it best, “You took a flying blind leap and we are all here to back you up!” With back up like that, I could not fail. Thank you all.

Lastly and most importantly, I must also thank God for opening all the doors of opportunity that made this entire journey possible and giving me the strength to march on through the tough times.
DEDICATION

To my parents, my children and my love.
TABLE OF CONTENTS

Chapter 1: Introduction ............................................................................................................. 1
  1.1 Asteroid History ............................................................................................................... 1
  1.2 Asteroid Classification ................................................................................................... 3
  1.3 Main-Belt Asteroids ....................................................................................................... 12
    1.3.1 Formation of Main-Belt Asteroids ........................................................................ 12
    1.3.2 Evolution of the Primordial Main Belt ............................................................... 13
    1.3.3 Present State of the Main Belt ............................................................................. 14
  1.4 Near-Earth Asteroids .................................................................................................... 14
    1.4.1 Formation of the Near-Earth Asteroid Population ............................................ 17
    1.4.2 Evolution of the Near-Earth Asteroid Population ............................................. 18
  1.5 Missions and mitigation ............................................................................................... 18
    1.5.1 Missions ............................................................................................................... 20
    1.5.2 Asteroid Impact Mitigation .................................................................................. 25
  1.6 Present thesis ................................................................................................................. 28
  1.7 References .................................................................................................................... 30

Chapter 2: A comparison of the class distribution of asteroids in the main belt and in the near-Earth vicinity and implications for the origin and history of Near-Earth Asteroids .................................................................................. 33
  2.1 Abstract ......................................................................................................................... 33
  2.2 Introduction .................................................................................................................... 34
  2.3 Classes, Analyses, and Results .................................................................................... 36
    2.3.1 The classes ........................................................................................................... 36
    2.3.2 Statistical analyses ............................................................................................... 41
  2.4 Discussion ....................................................................................................................... 54
    2.4.1 The Q complex (Q and Sq) NEA-MBA differences ........................................... 54
    2.4.2 The S complex (Sk, Sl, Sr classes) NEA-MBA differences .................................. 60
    2.4.3 The C complex (Ch class) NEA-MBA differences ............................................. 64
    2.4.4 The O class NEA-MBA differences ..................................................................... 65
  2.5 Conclusions ................................................................................................................... 65
  2.6 References ...................................................................................................................... 67
<table>
<thead>
<tr>
<th>Chapter 3: (10302) 1989 ML: Easy to get to but hard to describe</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Abstract</td>
<td>70</td>
</tr>
<tr>
<td>3.2 Introduction</td>
<td>70</td>
</tr>
<tr>
<td>3.3 Procedure</td>
<td>71</td>
</tr>
<tr>
<td>3.4 Discussion</td>
<td>73</td>
</tr>
<tr>
<td>3.5 Conclusions</td>
<td>76</td>
</tr>
<tr>
<td>3.6 References</td>
<td>79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 4: A Resolution of the Asteroid-Meteorite Mismatch?</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Abstract</td>
<td>80</td>
</tr>
<tr>
<td>4.2 Introduction</td>
<td>81</td>
</tr>
<tr>
<td>4.3 Method Summary</td>
<td>82</td>
</tr>
<tr>
<td>4.4 Data and Results</td>
<td>83</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>83</td>
</tr>
<tr>
<td>4.6 Conclusion</td>
<td>90</td>
</tr>
<tr>
<td>4.7 References</td>
<td>93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 5: IRTF observations of S complex and other asteroids: Implications for surface compositions, the presence of clinopyroxenes, and their relationship to meteorites</th>
<th>96</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Abstract</td>
<td>96</td>
</tr>
<tr>
<td>5.2. Introduction</td>
<td>97</td>
</tr>
<tr>
<td>5.3. Method</td>
<td>99</td>
</tr>
<tr>
<td>5.4 Results</td>
<td>101</td>
</tr>
<tr>
<td>5.5 Discussion</td>
<td>103</td>
</tr>
<tr>
<td>5.5.1 Present data and the BAR plot</td>
<td>103</td>
</tr>
<tr>
<td>5.5.2 MGM results for the present data</td>
<td>111</td>
</tr>
<tr>
<td>5.5.3 Spectra of meteorites analyzed by BAR</td>
<td>116</td>
</tr>
<tr>
<td>5.5.4 Spectra of clinoenstatite (Ca-free clinopyroxene) analyzed by MGM</td>
<td>122</td>
</tr>
<tr>
<td>5.5.5 Meteorite-asteroid link</td>
<td>123</td>
</tr>
<tr>
<td>5.5.6 Concepts for meteorite parent bodies and the nature of asteroid surfaces</td>
<td>123</td>
</tr>
<tr>
<td>5.6 Conclusions</td>
<td>136</td>
</tr>
<tr>
<td>5.7 References</td>
<td>137</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 6: Conclusions and Future Work</th>
<th>143</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Conclusions</td>
<td>143</td>
</tr>
</tbody>
</table>

x
INDEX OF FIGURES ........................................................................................................ 145

INDEX OF TABLES ........................................................................................................ 153

Appendix A: Visible And Near Infrared Spectra Of Five Near Earth Asteroids 
................................................................................................................................. 154
Abstract ........................................................................................................................ 155

Appendix B: Visible And Near Infrared Spectra Of Main Belt And Near Earth 
Asteroids ...................................................................................................................... 156

Appendix C: Abundant clinopyroxene on the S asteroids and implications for 
meteorites and asteroid history and the asteroid-meteorite 
relationship .................................................................................................................. 164

Appendix D: Analysis Of Reflectance Spectra Of Ordinary Chondrites: 
Implications For Asteroids ........................................................................................ 170

Appendix E: A Comparison Of The Class Distribution Of Asteroids In The 
Main Belt And Near-Earth Vicinity ........................................................................... 177

Appendix F: Primitive Materials on Asteroids .............................................................. 181

Appendix G: Primitive Materials on Asteroids .............................................................. 183
Primitive Materials on Asteroids ................................................................................ 184
Abstract ........................................................................................................................ 184

Appendix H: Low-Calcium and Calcium-free Clinopyroxene Spectra and the 
Implications for UOC (Type 3 Ordinary Chondrite) Material on 
Asteroids ..................................................................................................................... 185
Chapter 1: Introduction

1.1 Asteroid History

Ancient cultures around the world immortalized their heroes, gods and mythical beasts in the sky as constellations. Centuries of observations allowed them to discover all the aspects of the motions of the celestial bodies. They were aware that a few of the stars moved in the sky differently than the rest, namely the planets Mercury, Venus, Mars, Jupiter and Saturn. During the renaissance period astronomy began to develop better models of the Solar System and in 1596 Johannes Kepler was the first to suggest the presence of another planet between Mars and Jupiter to explain the large gap between the two planets. He also placed one between Mercury and Venus (Serio et al., 2002). In the following centuries, the explanation for the gap was searched for by many scientists. This led Johann Titus to invoke the Titus-Bode law defining the positions of the planets and the possible positions of “missing’’ planets using a mathematical equation.

The search for the “missing planet” was such a hot and urgent topic that a group of about twenty-four European astronomers formed a society for that purpose. Each astronomer was assigned a 15° section of longitude along the zodiac with the hopes that the shared effort would produce the “missing planet” (Serio et al., 2002). The discovery of Ceres on January 1, 1801 was unexpected and occurred while Giuseppe Piazzi (who was not a member of the society) was working on his first star catalog. The aberrant motion over several nights compared to the other stars caught his attention and led him to believe that it might be the “missing planet. Piazzi’s discovery of Ceres brought him out of obscurity and made him one of the most respected astronomers of his time (Fig. 1.1). By 1807 three more asteroids, Pallas, Juno and Vesta, had been discovered.
Figure 1.1. Oil painting of Giuseppe Piazzi and Ceres. It is believed that this was painted by the Sicilian artist Giuseppe Velasco at the beginning of the nineteenth century, possibly 1803. Courtesy of the Palermo Astronomical Observatory (Serio et al., 2002).
The search for asteroids did not end with the first four, but still continues. The discovery rate for asteroids has increased dramatically over time with the advances in technology. There were only ten known asteroids by 1850 and 2031 by 1950. After 1950 the rate of discovery increased exponentially (Fig. 1.2), today there are nearly 400,000. The question that arises is why do we search for asteroids and why do we study them.

1.2 Asteroid Classification

The classification systems that have been proposed involve such criteria as continuum slope in the visible, continuum slope in the UV, mineralogic composition as deduced from the 1 µm and 2 µm bands, and albedo. (Tholen, 1989; Bus, 1999; Gaffey et al., 1993a; Bus and Binzel, 2002). Tholen’s (1989) scheme is based on a visual inspection of the visible spectra and results in 14 classes including the C-group (B, F, G, C), the S group, the X-group (M, E, P) and the individual classes (A, D, T, Q, R, and V). The Bus (1999) taxonomy makes use of a Principal Components Analysis of visible spectra which identifies the continuum slope, absorption at ~0.8 µm, and absorption in the UV as important discriminators. This results in three complexes; C, X, and S and 26 individual taxonomic classes (described in Table 1.1). The C complex asteroids (B, C, Cb, Cg, Cgh, Ch) have low albedos and essentially featureless spectra and comprise ~25% of the total asteroids classified (Bus, 1999; Gietzen et al., 2009). These are sometimes referred to as “carbonaceous” asteroids due to their dark albedos. The X complex asteroids (X, Xc, Xe, Xk) are characterized by nearly featureless and linear spectra and make up ~19% of the total asteroids classified (Bus, 1999; Gietzen et al.,
Figure 1.2. Number of known asteroids as a function of time. Note the change of scale for the last interval. Data from the NASA Data Planetary System.
<table>
<thead>
<tr>
<th>Type</th>
<th>Spectral Description</th>
<th>Examples of Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very steep to extremely steep UV slope shortward of 0.75 µm, and a moderately deep absorption feature, longward of 0.75 µm. The shape of the reflectance maximum around 0.75 µm can either be sharply peaked or can be quite broad, with the shape of the peak possibly being tied to the shape and roundness of the 1-µm feature. A subtle absorption feature is often present around 0.63 µm.</td>
<td>246, 289, 863</td>
</tr>
<tr>
<td>B</td>
<td>Linear, featureless spectrum over the interval from 0.44 to 0.92 µm, with negative (blue) to flat slope.</td>
<td>2, 24, 85</td>
</tr>
<tr>
<td>C</td>
<td>Weak to medium UV absorption shortward of 0.55 µm, generally flat to slightly red and featureless longward of 0.55 µm.</td>
<td>1, 10, 52</td>
</tr>
<tr>
<td>Cb</td>
<td>Generally linear, featureless spectrum over the interval from 0.44 to 0.92 µm, with a flat to slightly red slope.</td>
<td>150, 210, 2060</td>
</tr>
<tr>
<td>Cg</td>
<td>Strong UV absorption shortward of 0.55 µm and generally flat to slightly reddish slope longward of 0.55 µm. Occasionally a shallow absorption feature is seen longward of 0.85 µm.</td>
<td>175, 1300, 3090</td>
</tr>
<tr>
<td>Cgh</td>
<td>Similar to Cg spectrum with addition of a broad, moderately shallow absorption band centered near 0.7 µm.</td>
<td>106, 706, 776</td>
</tr>
<tr>
<td>Ch</td>
<td>Similar to C spectrum with addition of a broad, relatively shallow absorption band centered near 0.7 µm.</td>
<td>19, 48, 49</td>
</tr>
<tr>
<td>D</td>
<td>Relatively featureless spectrum with very steep red slope. A slight decrease in spectral slope (less reddened) is often seen longward of 0.75 µm.</td>
<td>1542, 2246, 4744</td>
</tr>
<tr>
<td>K</td>
<td>Moderately steep UV slope shortward of 0.75 µm, reaching a maximum relative reflectance of about 1.15. The spectral slope becomes flat to slightly negative (blue) longward of 0.75 µm, showing little or no concave-up curvature in the 1-µm absorption band.</td>
<td>221, 579, 606</td>
</tr>
<tr>
<td>L</td>
<td>Very steep UV slope shortward of 0.75 µm, becoming approximately flat, with a relative reflectance of about 1.2 longward of 0.75 µm.</td>
<td>236, 908</td>
</tr>
<tr>
<td>Ld</td>
<td>Very steep UV slope shortward of 0.7 µm, becoming essentially flat, with a relative reflectance of roughly 1.3 longward of 0.75 µm. Spectrum is generally steeper over the interval from 0.44 to 0.7 µm, and flatter from 0.75 to 0.92 µm, than is typical for D-types.</td>
<td>269, 1406, 2850</td>
</tr>
</tbody>
</table>

† Table reproduced from Bus 1999
Table 1.1 Description of classes within Bus' feature-based taxonomy

<table>
<thead>
<tr>
<th>Type</th>
<th>Spectral Description</th>
<th>Examples of Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Moderately steep UV slope from 0.44 to 0.54 µm, becoming less steep over the interval from 0.54 to 0.7 µm, and reaching peak relative reflectance of 1.05. Deep absorption feature longward of 0.75 µm.</td>
<td>3628, 4341, 5143</td>
</tr>
<tr>
<td>Q</td>
<td>Moderately steep UV slope shortward of 0.7 µm, and a deep, rounded 1-µm absorption band that reaches a minimum reflectance level of about 0.9. Reflectance maximum is relatively broad, with an average peak value of about 1.12.</td>
<td>1862, 2102, 5660</td>
</tr>
<tr>
<td>R</td>
<td>Very steep UV slope shortward of 0.7 µm, and a deep absorption feature longward of 0.75 µm. The shape of the spectrum, near maximum reflectance, is more sharply peaked than is typical for S-type spectra and is somewhat skewed due to the strength of the 1-µm absorption band that reaches a minimum at roughly 0.9 µm with a relative reflectance level of 0.9. An additional small absorption feature can be seen centered near 0.52 µm.</td>
<td>349, 1904, 5111</td>
</tr>
<tr>
<td>S</td>
<td>Moderately steep UV slope shortward of 0.7 µm and a moderate to deep absorption band longward of 0.75 µm. The shape of the spectrum, near maximum reflectance, is more sharply peaked than is typical for S-type spectra and is somewhat skewed due to the strength of the 1-µm absorption band that reaches a minimum at roughly 0.9 µm with a relative reflectance level of 0.9. An additional small absorption feature can be seen centered near 0.52 µm.</td>
<td>5, 7, 20</td>
</tr>
<tr>
<td>Sa</td>
<td>Spectrum intermediate between S- and A-types. Very steep UV slope shortward of 0.7 µm. The reflectance peak is typically broader than it is in A-type spectrum.</td>
<td>63, 244, 625</td>
</tr>
<tr>
<td>Sk</td>
<td>Intermediate between S- and K-type spectra. Absorption feature longward of 0.75 µm shows moderate concave-up curvature, as compared to the K-types, where the spectrum over this interval tends to be approximately linear. Compared with other S-types, the 0.63-µm feature can be strong.</td>
<td>3, 11, 43</td>
</tr>
<tr>
<td>Sl</td>
<td>Intermediate between S- and L-type spectra. Absorption feature longward of 0.75 µm is shallow to moderately deep, as compared to L-types, where this spectral interval is essentially flat.</td>
<td>151, 192, 354</td>
</tr>
<tr>
<td>Sq</td>
<td>Spectrum intermediate between S- and Q-types. Compared with other S-types, these spectra can contain a relatively strong 0.63-µm feature.</td>
<td>33, 720, 1483</td>
</tr>
<tr>
<td>Sr</td>
<td>Intermediate between S- and R-type spectra. Very steep UV slope shortward of 0.7 µm and a deep absorption feature longward of 0.75 µm. Reflectance peak is broader and more symmetric in shape than it is in R-type spectra.</td>
<td>984, 1494, 2956</td>
</tr>
</tbody>
</table>

† Table reproduced from Bus 1999
Table 1.1 Description of classes within Bus’ feature-based taxonomy

<table>
<thead>
<tr>
<th>Type</th>
<th>Spectral Description</th>
<th>Examples of Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Moderately steep UV slope shortward of 0.75 µm, becoming flat with a relative reflectance between 1.15 and 1.2 longward of 0.85 µm. The change in spectral slope occurs very gradually.</td>
<td>96, 596, 3317</td>
</tr>
<tr>
<td>V</td>
<td>Moderate to very steep UV slope shortward of 0.7 µm with a sharp, extremely deep absorption band longward of 0.75 µm that usually reaches a minimum relative reflectance level between 0.7 and 0.8. The spectral slope between 0.44 and 0.55 µm is usually steeper than that over the interval from 0.55 to 0.7 µm. An additional small absorption feature, centered near 0.52 µm, is occasionally seen. The largest member, 4 Vesta, is anomalous in that its slope and band depth is less extreme than for other members of this class.</td>
<td>4, 1929, 2912</td>
</tr>
<tr>
<td>X</td>
<td>A generally featureless spectrum, with slight to moderately reddish slope. A subtle UV absorption feature, shortward of 0.55 µm, can be present, as well as an occasional shallow absorption feature longward of 0.85 µm.</td>
<td>22, 55, 69</td>
</tr>
<tr>
<td>Xc</td>
<td>A slightly reddish spectrum, generally featureless except for a gentle convex curvature over the middle and red portions of the spectrum.</td>
<td>65, 131, 209</td>
</tr>
<tr>
<td>Xe</td>
<td>Overall slope that is slightly to moderately red, with a series of subtle absorption features. The most dominant feature is an absorption band shortward of 0.55 µm. This feature exhibits a concave-up curvature, most visible in the spectrum of 64 Angelina, where the band center is located at about 0.49 µm. Often a very shallow absorption feature is also seen centered near 0.6 µm. In addition, a decrease in spectral slope (becoming less red or even bluish) is usually seen longward of 0.75 µm.</td>
<td>64, 77, 434</td>
</tr>
<tr>
<td>Xk</td>
<td>Moderately red slope, shortward of about 0.75 µm, and generally flat longward of 0.75 µm with a peak relative reflectance of roughly 1.1, the change in slope occurring very gradually. Similar in spectral shape to Xc, but redder in overall slope.</td>
<td>21, 99, 114</td>
</tr>
</tbody>
</table>

†Table reproduced from Bus 1999
The S complex asteroids (A, K, L, Q, R, S, Sa, Sk, Sl, Sq, Sr) are noted for their high albedos and deep absorption bands. These asteroids are commonly referred to as the “stony” asteroids due to their bright albedos and silicate compositions. They are the largest complex of asteroids, being ~47% of the total classified asteroid population (Bus, 1999; Gietzen et al., 2009). Within the S complex, the S-type asteroids (S, Sa, Sk, Sl, Sq, Sr) are the largest group at ~40% of the total population. The complexes are displayed in Table 1.2.

There are five taxonomic classes that do not fall into any of the three defined complexes; D, T, Ld, O and V (Bus, 1999). The T and D classes plot on the periphery between the X and S complex with the T asteroids in close proximity to the Xk class and the D asteroids in proximity with the L class. The Ld asteroids are outliers that have spectral properties most like the L class asteroids, but do have steeper slopes similar to the D class. The two remaining taxonomic classes—the O and V classes—plot on the opposite side of the principal component plot. Both of these taxonomic classes plot nearer to the S complex with the single O asteroid plotting nearly on the boundary between the S and C complexes. The V asteroids are present at the far periphery of the S complex (Fig. 1.3).

Focusing more on the mineralogical interpretations of reflectance spectra, rather than a statistical analysis for discriminators, Gaffey et al. (1993a) proposed subdivision of the S asteroids into seven sub-types, S(I) through S(VII). These authors note the lack of good matches between the ordinary chondrites and the majority of S asteroids, identifying the ordinary chondrites as one of several possibilities for equivalents of the
Table 1.2. Asteroid complexes and their proportions.

<table>
<thead>
<tr>
<th>Class</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>C Complex: 25.3%</td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Cb</td>
<td></td>
</tr>
<tr>
<td>Cg</td>
<td></td>
</tr>
<tr>
<td>Cgh</td>
<td></td>
</tr>
<tr>
<td>Ch</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>S Complex: 47.2%</td>
</tr>
<tr>
<td>S</td>
<td></td>
</tr>
<tr>
<td>Sa</td>
<td></td>
</tr>
<tr>
<td>Sk</td>
<td></td>
</tr>
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<td>Sl</td>
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<td>Sr</td>
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<td>Sq</td>
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<td>K</td>
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<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td></td>
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<tr>
<td>R</td>
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</tr>
<tr>
<td>X</td>
<td>X Complex: 18.8%</td>
</tr>
<tr>
<td>Xc</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td></td>
</tr>
<tr>
<td>Xk</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2.4%</td>
</tr>
<tr>
<td>Ld</td>
<td>1.1%</td>
</tr>
<tr>
<td>O</td>
<td>0.3%</td>
</tr>
<tr>
<td>T</td>
<td>2%</td>
</tr>
<tr>
<td>V</td>
<td>2.9%</td>
</tr>
</tbody>
</table>
Figure 1.3. Component Space plot from Bus 1999 showing the three complexes and the outlier T, D, Ld, O and V taxonomic classes. Lines inserted by this author indicating the approximate boundaries between the complexes.
S(IV) asteroids. For the remaining S groups, Gaffey et al. (1993a) identify the presence of minerals characteristic of melts and partial melts, such as calcium-rich clinopyroxene (Sunshine et al., 2004), and pose the question of where are the missing melts or partial melts among the terrestrial meteorite collection (Gaffey, 2007).

While the S-type asteroids are the most common asteroids and the ordinary chondrites are the most common meteorites, and there are certain first-order similarities in their reflectance spectra, a perpetual problem in asteroid astronomy is the persistent differences in their spectra, such as steeper (redder) slope of the asteroid spectra. This was once referred to as the S asteroid paradox, why are asteroid spectra resembling ordinary chondrites so rare and why do so many S asteroids have no match among the meteorite collection (Chapman, 1976; Wetherill and Chapman, 1988; Chapman, 1996). A number of ideas for resolving this paradox have been discussed (Gaffey, 1993; 1995), such as space weathering (Clark et al., 2002), preferential delivery from a few atypical meteorites conveniently located near orbital resonances with Jupiter (Wisdom, 1985; Scholl and Froeschlé, 1991) or easily moved to the resonances by Yarkovsky effects (Vokrouhlický and Farinella, 2000), delivery of ordinary chondrites from cometary sources directly into the near-Earth region (Campins and Swindle, 1998), and most ordinary chondrite parent bodies being covered with shock-blackened material (Britt and Pieters, 1994).

A wide range of petrographic and mineralogic changes are associated with metamorphism, which reflects a move towards equilibrium for rocks that start as an assemblage of highly heterogeneous and highly diverse components (Huss et al., 2006). Thus the type 3 ordinary chondrites are often referred to as “unequilibrated” ordinary
chondrites (or UOC), while the types 4-6 are referred to as “equilibrated” ordinary chondrites, or EOC. Compared to the EOC, UOC are extremely rare, and when the term “ordinary chondrite” is used in an unqualified way, it is invariably the EOC that are being referred to. Pyroxene is one of the two major rock-forming minerals present in ordinary chondrites, the other being olivine. In the UOC, pyroxene is in the monoclinic crystallographic form usually called clinopyroxene, while heating type 4-6 levels of metamorphism converts this to the orthorhombic form, usually called orthopyroxene (Dodd et al., 1967). Unlike the clinopyroxene commonly discussed in connection with asteroid spectra, and assumed to be Ca-rich (Sunshine et al., 2004), most of the clinopyroxene in UOC is very low in calcium (Dodd et al., 1967)

1.3 Main-Belt Asteroids

Asteroids are ancient interplanetary bodies believed to be remnants of Solar System formation and therefore are important in deducing the origin and history of the Solar System. Determining their structure and mineralogical composition can give a glimpse of the early Solar System conditions and an insight to its evolution. As such, their formation, distribution, physical properties and evolution are essential to our understanding of planet building in the Solar System.

1.3.1 Formation of Main-Belt Asteroids

The Main-Belt Asteroids (MBA) are located between the orbits of Jupiter and Mars and are the largest reservoir of asteroids in the Solar System. The processes responsible for the current properties of the main belt are thought to be linked to the formation of the terrestrial planets and to Jupiter in particular (Bottke et al., 2002). Planet formation in the
inner solar system occurs by the accretion of many small bodies. The perturbations between Moon-to-Mars sized planet embryos and Jupiter caused collisions, mergers and excitations of small-body populations that kept them from being accreted into a protoplanet and constrained these bodies to the area of the main belt (Bottke et al., 2002).

1.3.2. Evolution of the Primordial Main Belt

The location and timing of the formation of Jupiter had a significant role in the evolution of the primordial main belt. Jupiter was in part responsible for a large mass depletion in the primordial main belt. Currently it contains only \( \sim 5 \times 10^{-4} \text{ M}_\oplus \), of material, a very small portion of the \( 2 - 10 \text{ M}_\oplus \) material it contained originally. Jupiter also created strong dynamical excitations within the belt. During the formation of the solar system and the main belt, the eccentricities and inclinations of the asteroid orbits in the main belt were small enough to allow accretion to occur due to gravitational perturbations by Jupiter. The current eccentricities and inclinations are large enough that when collisions occur within the main belt, the bodies fracture and fragment instead of accreting. The final effect Jupiter had on the early evolution of the main belt was radial mixing of the asteroid types (Bottke et al., 2002). Asteroids in the outer portion of the main belt should be more primitive than the inner belt asteroids that have been heated or exposed to other processes. This trend is observed in the distribution of the taxonomic classes of the main belt asteroids. The outer belt is dominated by the D and P type asteroids, the central belt is populated mainly by C type asteroids and the inner belt contains primarily S type asteroids.
1.3.3 Present State of the Main Belt

The evolution described above occurred early in the history of the Solar System and the main belt asteroids. These processes of numerous impacts, thermal processing and dynamical upheaval all occurred over a short time, ~100 million years. Once these processes had run their course, the evolution of the remaining population occurred at a much slower pace. In the current main belt there are still collisions, but they occur much less frequently and there are several dynamical mechanisms that are capable of modifying orbits of asteroids over time.

1.4 Near-Earth Asteroids

Generally, the Near-Earth Asteroids (NEA) are defined as the asteroids that have perihelion distances \( q \leq 1.3 \) AU or aphelion distances \( Q \geq 0.983 \) AU. The population is further divided into three subpopulations: (1) the Apollos \((a \geq 1.0 \) AU, \( q \leq 1.0167 \) AU), (2) the Atens \((a < 1.0 \) AU, \( Q \geq 0.983 \) AU), which are Earth-crossing orbits and (3) the Amors \((a \geq 1.0 \) AU, \( 1.0167 < q \leq 1.3 \) AU) which are Earth-approaching orbits, where \( a \) is the semimajor axis. All NEAs have short lifetimes of \( \sim 10^6 – 10^7 \) years (Morias and Morbidelli, 2002), and are quickly lost to collision with one of the inner planets or the Sun (Morbidelli et al., 2002). Thus the NEA population must be continually resupplied, and what we see is a snapshot in time.

The rate of discovery of near-Earth asteroids has reached very high levels in the last few years (Fig. 1.4) due to the creation of a number of programs aimed at detecting all asteroids larger than 1 km (Table 1.3). These programs utilize a number of new technologies, some made available to the scientific community following the end of the cold war.
Figure 1.4. Because of current support by NSF and other agencies, near-Earth asteroids are being discovered at record rates. The science, exploration and impact mitigation effort all are well served by the information on surface compositions to be determined in the present work.
The large number of programs to detect NEA require support to characterize them, especially given the great compositional diversity expected.

<table>
<thead>
<tr>
<th>Program</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincoln Near-Earth Asteroid Research</td>
<td>New Mexico, GEODSS 1 m&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Near-Earth Asteroid Tracking</td>
<td>MSSS&lt;sup&gt;2&lt;/sup&gt;, Palomar</td>
</tr>
<tr>
<td>Spacewatch</td>
<td>Kitt Peak, 1.8 and 0.9 m</td>
</tr>
<tr>
<td>Lowell Observatory Near-Earth Object Search</td>
<td>Flagstaff, 0.6 m</td>
</tr>
<tr>
<td>Catalina Sky Survey</td>
<td>Mt. Bigelow, Mt. Lemmon, Siding Springs, 0.76 m, 1.5-m, 1 and 2 m</td>
</tr>
<tr>
<td>Japanese Spaceguard Association</td>
<td>Bisei, 0.5 and 1 m</td>
</tr>
<tr>
<td>Campo Imperatore Astronomical Observatory</td>
<td>Gran Sasso Mt., 0.6, 0.9, 1.8 m</td>
</tr>
</tbody>
</table>

1Ground-based Electro-Optical Deep Space Surveillance  
2Maui Space Surveillance Site
1.4.1 Formation of the Near-Earth Asteroid Population

The short lifetimes of the asteroids and the apparent steady state of the size of the NEA population requires a source to provide a supply of replacement asteroids. It is currently believed that the reservoir that supplies the NEA population is the main belt with about two-thirds coming from the inner belt, one-fourth from the central belt and the remainder being supplied by the outer belt and Jupiter family comets. Current theories suggest that this transfer of asteroids from the main belt is due to orbital resonances with Jupiter and the $\nu_6$ secular resonance both of which are sometimes aided by Yarkovsky thermal forces. (Gladman et al., 1993; Bottke et al., 2002b; Bottke et al., 2006; Brož, 2002).

In the main belt, orbital resonances with Jupiter occur when an asteroid has an orbital period that is a ratio of two small integers and the two bodies exert regular, periodic gravitational influence on each other. In most cases, this periodic tug causes an unstable interaction causing an exchange of momentum which most often ejects the asteroid from the region of resonance. This can occur over any timescale.

When the orbits of two bodies precess (precession of perihelion, ascending node or both) at the same rate, a secular resonance occurs. The $\nu_6$ resonance is a secular resonance between asteroids and Saturn. The orbit of an asteroid in secular resonance with Saturn will slowly increase in eccentricity until it becomes a Mars-crossing orbit. This generally occurs on the scale of $10^4 – 10^6$ years.

The Yarkovsky effect is a radiation force phenomenon. Insolation causes the sunward side of an asteroid to heat up and the thermal energy is then reradiated into space
as the heated side rotates away from the Sun. Momentum is carried away from the asteroid as an infrared photon. When this occurs, the net result is a push on the asteroid in the opposite direction of the photon. This can ultimately change the orbit of the asteroid. If the rotation of the asteroid is prograde, the orbit will expand and conversely, if rotation is retrograde the orbit will shrink.

1.4.2 Evolution of the Near-Earth Asteroid Population

The primary geologic process that presently occurs in the asteroid population is collisions (Bottke et al., 2002). Images of asteroids show the scars of these collisions in the form of impact craters (Fig 1.5.) These evolutionary events grind the asteroids into increasingly smaller fragments. The members of the asteroid population experience numerous cratering events before they are disrupted by a very energetic impact or collide with a planet or the Sun. When studied, these leftover records provide important information about the target as well as the bombarding population.

1.5 Missions and mitigation

Near-Earth asteroids (NEAs) are interesting because of their collisional hazard and value to solar system exploration as intermediate targets between the Moon and Mars. Since asteroids are a possible destination intermediate to the Moon and Mars in technical difficulty, obtaining data for asteroids and their nature is of value to the human exploration of space. The more that is known about them from ground-based measurements the easier and more scientifically rewarding such missions will be. In the long term, water-rich asteroids might be a resource for the space exploration program and knowing which asteroids contain this resource will be an important asset.
Figure 1.5. The asteroid Eros as it appeared to the NEAR-Shoemaker spacecraft (NASA images http://nssdc.gsfc.nasa.gov/planetary/mission/near/).
A growing number of scientists and governments are concerned about the danger of collision between an asteroid and the Earth (Gehrels et al., 1994; Belton et al., 2004), a concern shared by the general public. The geologic record shows strong evidence for major impacts having a dramatic effect on the fauna of Earth. Several workshops and books have considered means for deflecting an asteroid from an Earth-impacting trajectory and all depend on knowing the nature of the surface (Fig. 1.6; Gritzner and Kahlne, 2004). Data determining asteroid composition, velocity, orbital path, etc., is vitally needed information in order to determine a plan of action should an asteroid be on a collision course with Earth.

1.5.1 Missions

Since asteroids are considered to be fairly pristine, studying them provides opportunities to learn more about the primordial solar system, its materials, processes and history. With the exception of the handful of space missions such as Galileo and NEAR, our current knowledge of asteroids has come from reflectance spectra acquired through ground-based remote sensing. In situ data from the Galileo flybys of asteroids Gaspra and Ida as well as data from the NEAR rendezvous and landing on Eros are invaluable in gaining an understanding of these space nomads. As valuable as the in situ data is, the quality and range of the sample return data more than compensates for the limitations of the number of asteroids that can be investigated (Christou, 2003). The science of asteroids could be done with unparalleled precision, variety and accuracy (Britt et al. 2001). An asteroid rendezvous and sample return mission is the next logical step.
Figure 1.6. Knowledge of the surface composition of objects likely to collide with Earth is critical to many of the proposed methods of deflection (Sears et al., 2001). Some methods depend on the presence of volatile compounds, others depend on mechanical properties.
There are two primary considerations that play a role in selecting a target asteroid for a rendezvous and sample return mission. The science of the mission – what is there to be learned and which asteroid will provide the information; and the engineering of the mission – how will the spacecraft get to the asteroid. Ground-based remote sensing is important in providing the reconnaissance information on a target for an asteroid rendezvous and sample return mission, but it also provides general information on the properties of accessible asteroids (Christou, 2003).

As noted above, the vast majority of information available is reflectance spectra obtained by remote sensing. The spectra obtained are the basis of the current taxonomic spectral classification of asteroids and would, therefore, be one of the primary meaningful methods by which a target asteroid would be selected for sample return (Sears, 1999). There are two classes that would be considered very favorable for selection as a target asteroid: C- and S-types (Sears, 1999). Two additional types, X and V, will also be discussed.

C-type asteroids are thought to contain clays, carbon and organics on their surfaces. Spectroscopic data show a broad absorption band centered near 0.7 µm and is attributed to phyllosilicates formed by aqueous alteration processes (Bus et al., 2002). The possible presence of water makes them an excellent target for a sample return mission. What is known about these asteroids has been obtained by ground-based remote sensing, but we still know relatively little about all their characteristics. With less than 1% of all known asteroids classified, there is still a great deal about the characteristics of asteroids that is unknown and much more work remains to be done.
Spectra of S-type asteroids imply compositions of iron and magnesium bearing silicates such as pyroxenes and olivines. There are seven subclasses of S-type asteroids that range from the SI nearly monomineralic olivine assemblages to the SVII nearly monomineralic orthopyroxene assemblages (Gaffey et al., 1993). If a chondritic parent body undergoes complete differentiation, it is believed that it will produce an iron-nickel core, a thick olivine-dominated mantle and a thin plagioclase/pyroxene crust (Burbine et al., 1996). Currently, there seems to be an apparent rarity of these olivine-dominated A-type asteroids. A sample return mission to an olivine-rich SI asteroid could provide valuable insight into the early history of the solar system and a possible chondritic parent. Also of interest in the S-type asteroids would be the SIV subclass which most closely resembles the ordinary chondrites (Sears et al., 2003).

A number of scientists believe that space weathering is a major contributor to the characteristics of the asteroid surfaces. X-type asteroids have featureless spectra and therefore are poorly understood (Sears et al., 2003). The processes of space weathering are not clearly understood either, but it has been suggested that the result of these processes could be featureless spectra such as those found for the X-type asteroids. A sample return mission to an X-type asteroid could shed light on the space weathering processes and just what the extent of their effects is on an asteroid. This could provide an excellent source for new materials and data.

V-type asteroids are also scientifically important. They are basaltic in nature and are thought to all be fragments from the asteroid, Vesta (Sears, 1999). Vesta has a surface mineralogy similar to basaltic chondrites. These chondrites are physically and chemically similar to the basaltic lava flows on Earth and the Moon.
The selection of sample-return target asteroid(s) involves looking for the most dynamically favorable asteroids and obtaining the necessary information on them (Sears et al., 2003). This information is what will determine the necessary engineering for the mission, which could affect which asteroid would be selected and possibly the science. Information on the following properties (which are determined by the use of ground-based observations) is necessary in order to design a rendezvous and sample return mission (Christou, 2003, Sears et al., 2003).

- Accessibility
- Eccentricity of orbit
- Inclination of orbit
- Size
- Albedo
- Rotational properties
- Shape
- Whether the asteroid has a companion

The $\Delta V$ budget, “a function of the velocity increment needed at the point of departure to insert the spacecraft in the transfer path and the change required to cancel the relative velocity between spacecraft and target at arrival”, is one of the primary mission design criteria (Christou, 2003). This is dependent on the properties of the orbit and the physical properties of the asteroid and thus its accessibility.

Therefore, one highly important property is the accessibility of the asteroid. In order to ensure an energy-efficient transfer path, the asteroid orbit needs to be reasonably close to that of the Earth (Christou, 2003). Near-Earth asteroids with their closer orbits
are significantly more accessible than their Main Belt counterparts. This makes NEAs very attractive targets.

There is so little known about asteroids that a rendezvous and sample return mission to any asteroid could provide large quantities of new data that would greatly enhance our understanding of asteroids and the solar system in general. However, if effort and patience is put forth in the careful selection of a target asteroid for rendezvous and sample return, the return on the effort would be tremendous.

1.5.2 Asteroid Impact Mitigation

Even though the threat of an asteroid or comet impacting Earth is very low, the threat does exist. If such an impact were to occur, the potential to create public panic and local and global destruction warrants a unified approach to the science, technology and public policy concerning the hazard (Chapman et al., 2001). The extinction of the dinosaurs and ~70% of the Earth’s living species was caused by an asteroid impact sixty-five million years ago and there is evidence of other impacts of other sizes. The Barringer Meteor Crater in Arizona shown in Fig. 1.7 is just one example of the scars of asteroid impacts. Some of the expected immediate environmental consequences from an asteroid impact for three impactor sizes are described in Table 1.4. Clearly, there needs to be a global effort to address their threat.

The National Aeronautics and Space Administration (NASA) has been directed by United States law to discover, track, catalog and characterize 90% of NEOs with a diameter over 140 m (Schweickart et al., 2008). In order to be adequately prepared, an important step is to identify and characterize potential impact hazards. It is imperative
Figure 1.7 Barringer Meteor Crater, Arizona, USA – 1.2 km diameter (Schweickart et al., 2008).
### Table 1.4 Chief Environmental Consequences of Impacts*

<table>
<thead>
<tr>
<th>Category: (Impactor Diameter) Environmental Effect</th>
<th>Regional Disaster (300 m)</th>
<th>Civilization Ender (2 km)</th>
<th>K/T Extinctor (10 –15 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fires</strong> Ignited by fireball and/or re-entering ejecta</td>
<td>Localized fire at ground zone</td>
<td>Fires ignited only within hundreds of km of ground zero.</td>
<td>Fires ignited globally; global firestorm assured (Wolbach et al., 1988)</td>
</tr>
<tr>
<td><strong>Stratospheric dust</strong> obscures sunlight</td>
<td>Stratospheric dust below catastrophic levels</td>
<td>Sunlight drops to “very cloudy day” (nearly globally); global agriculture threatened by summertime freezes.</td>
<td>Global night; vision is impossible. Severe, multi-year “impact winter.”</td>
</tr>
<tr>
<td><strong>Other atmospheric effects:</strong> Sulfate aerosols, water injected into stratosphere, ozone destruction, nitric acid. Smoke, etc</td>
<td>None (except locally)</td>
<td>Sulfates and smoke augment effects of dust; ozone layer may be destroyed</td>
<td>Synergy of all factors yields decade-long winter. Approaches level that would acidify oceans (more likely by sulfuric acid than nitric acid).</td>
</tr>
<tr>
<td><strong>Earthquakes</strong></td>
<td>Local ground shaking</td>
<td>Significant damage within hundreds of km of ground zero</td>
<td>Modest to moderate damage globally</td>
</tr>
<tr>
<td><strong>Tsunamis</strong></td>
<td>Flooding of historic proportions along shores of proximate ocean</td>
<td>Shorelines of proximate ocean flooded inland tens of km</td>
<td>Primary and secondary tsunami flood most shorelines —100 km inland, inundating low-lying areas worldwide</td>
</tr>
<tr>
<td><strong>Total destruction in crater zone</strong></td>
<td>Crater zone ~5-10 km across</td>
<td>Crater zone ~50 km across</td>
<td>Crater zone Several hundred km across</td>
</tr>
</tbody>
</table>

*Chapman et al., 2001*
that this is done early enough that the proper mitigation steps can be taken. This allows for the determination of physical properties and characteristics of the asteroids such as their orbital trajectory relative to Earth, size, shape, spin rate and composition. Knowledge of the surface composition of asteroids likely to collide with Earth is critical to many of the proposed methods of deflection (Sears et al., 2001) since some methods depend on the presence of volatile compounds. Other methods depend on mechanical properties of the impactor similar to those shown in Fig. 1.6.

1.6 Present thesis

We are interested in three related questions:

- How does the composition of the NEA population compare with the composition of the Main Belt Asteroids (MBA)?

- What is the mineralogical composition of the small bodies in the vicinity of the Earth, commonly referred to as Near-Earth Asteroids?

- What are the implications of such a comparison for studies of meteorites and the early solar system, and for our understanding of the transport of small bodies around the inner solar system?

Such fundamental scientific questions also have ramifications for solar system exploration—such as the design of space missions and the availability of resources like water—and for impact mitigation. However, they cannot be answered at the moment because of inadequate data, especially considering the compositional diversity of asteroids (for example, 26 classes of MBA have been identified). It is not even clear at the moment whether marked differences in the NEA and MBA populations are real or an artifact of small numbers. There are spectra available for only a small fraction of the
5500 known NEA, especially in the mineralogically important range 0.8 – 2.5 µm. We have produced 0.8 – 2.5 µm spectra for 15 NEA by using the NASA IRTF and these have all been subjected to detailed spectral analyses (Gietzen et al., 2007a, b). We have performed a uniform mineralogical analysis of all available NEA 0.8 – 2.5 µm spectra and matched them with new and existing spectra of MBA and meteorites. This has only been done in a limited number of cases before. Several hundred NEA spectra are needed to be able to achieve acceptable statistical significance in all classes, so there is a serious need to make more observations of NEAs.

This thesis consists of a statistical comparison of the class distribution of asteroids in the main belt and in the near-Earth vicinity and implications for the origin and history of NEA (Chapter 2), which was presented at the Asteroids, Comets, Meteors meeting in Baltimore in July 2008, and has been submitted to Meteoritics and Planetary Science. Next I discuss a paper submitted to Icarus on the nature of (10302) 1989 ML which was the target for the proposed Hera mission. The emphasis of this chapter (Chapter 3) was the ambiguity of comparison of asteroids and meteorites only in the visible wavelengths and the need for more spectra in the infrared wavelengths. I then discuss a possible Resolution of the Asteroid-Meteorite Mismatch (Chapter 4). This work has been submitted to Nature, and this work is greatly expanded (Chapter 5) in a complete report and discussion of the asteroid observations we have made. Chapter 5 will be submitted to Icarus. Finally, I summarize the conclusions and make a few suggestions for future work (Chapter 6).
1.7 References


Chapter 2: A comparison of the class distribution of asteroids in the main belt and in the near-Earth vicinity and implications for the origin and history of Near-Earth Asteroids.

In this chapter we look at a statistical comparison of the two main populations of asteroids in the Solar System. After Daniel R. Ostrowski and I collected the available data from online databases, I tallied the numbers for each taxonomic class in both the Near-Earth and Main Belt asteroid populations and conducted the statistical analyses contained herein. Dr. Claud H. S. Lacy provided the statistics background and advice to properly compare the two populations. Dr. Derek W. G. Sears contributed knowledge and background for meteorites, ordinary chondrites in particular.

2.1 Abstract

In order to contribute to an understanding of the history of near-Earth asteroids and the relationships between near-Earth asteroids and asteroids in the main belt, we have performed statistical analyses of the taxonomic classes for both populations by using data obtained from the PDS, NEO-Dys and EARN databases for 2093 main belt and 351 near-Earth asteroids. The populations as a whole are different at the 0.999 level of confidence. This is due to significant differences in the size of the C and Q complexes in the two populations, specifically the Ch class in the C complex and the Q and Sq classes in the Q complex. The relative number of members in the Sk, Sl, and Sr classes in the S complex are significantly different in the NEA and MBA. Finally, there is a statistically significant excess of O class asteroids in the NEA population relative to the MBA population. These differences indicate that the NEA are not random samples of the main belt, but that either there are other sources for the NEA (like comets) or that ejection and
delivery of asteroids from the main belt is somehow selective or the snapshot changes with time. In the case of the Q and Sq classes, dynamical studies and meteorite studies suggest that much of the NEA population is fragments from the breakup of a few objects. In the case of the Ch, Sk, Sl, Sr, and O classes, the cause of the NEA-MBA difference is less clear, but may also be related to parent body breakups. There is no indication that location in the main belt determines these MBA-NEA differences.

2.2 Introduction

With the discovery of large numbers of near-Earth asteroids (NEA) in the last decade or so (Stokes et al., 2002) many new opportunities for science and exploration exist. We now have reflectance spectra for about 5300 NEA, and 25 of the 26 taxonomic classes identified statistically by Bus (1999) and coworkers are present in the NEA population (Binzel et al., 2004a). We therefore know that this is a highly diverse population compositionally. The NEA population includes an increasingly large number of asteroids with low energy requirements for missions, in fact many are energetically easier to reach than the Moon, so they are perfect exploration targets (Binzel et al., 2004b). Of course, along with the discovery of so many objects in the vicinity of the Earth, and the realization of the role of impact in Earth history, impact mitigation has also become of prime interest and a better knowledge of the properties of these objects will aid in this effort (Belton et al., 2004).

While it is widely assumed that most NEA originate in the main asteroid belt, details of the relationship between NEA and main belt asteroids and mechanisms for transport from the main belt to the near-Earth vicinity are complex and these ideas have
undergone considerable evolution in the last few decades. This is especially true since
NEA are presumably the immediate parent bodies of the meteorites (Bottke et al., 2002a; 
Morbidelli et al., 2002; Nesvorný et al., 2002; Jopek et al., 2002; Burbine et al., 2002).
The NEA population consists of the Apollo ($a \geq 1.0$ AU, $q \leq 1.0167$ AU), Aten ($a < 1.0$
AU, $Q \geq 0.983$ AU) and Amor ($a > 1$ AU, $1.017 < q \leq 1.3$ AU) asteroids, all of which
have short lifetimes, $10^6 – 10^7$ years (Morias and Morbidelli, 2002), and are quickly lost
to collision with one of the inner planets or the Sun (Morbidelli et al., 2002). Since the
population size appears to be in a steady-state, there must be a source of continuous
resupply, and the population we are observing is a snapshot in time. Current ideas are
that ~61% (H<22) come from the inner main belt, ~24% come from the central main belt,
~8% come from the outer main belt, and ~6% come from the Jupiter-family comets (JFC)
via a series of resonances, sometimes aided by Yarkovsky thermal forces (Gladman et al., 
1993; Bottke et al., 2002b; Bottke et al., 2006; Brož, 2002).

Most of the large meteorite classes show peaks in their cosmic ray exposure age
histograms, and sometimes also in their K-Ar age histograms, that suggest that they were
once part of much larger bodies that fragmented at the times indicated by these peaks
(Bogard, 1995, Eugster et al., 2006). These data have always been considered important
constraints on models for transfer of asteroids from the main belt to the near-Earth
vicinity, and the scatter on the exposure ages has recently been used as evidence for an
important role for Yarkovsky thermal processes in moving fragments to the resonances
(Vokrouhlický and Farinella, 2000).

In the present paper we conduct statistical analyses of the NEA and MBA
populations and discuss the implications for the history and origin of asteroids in the
near-Earth vicinity. This in turn should have relevance to exploration and impact mitigation.

2.3 Classes, Analyses, and Results

2.3.1 The classes

We obtained taxonomic classification information for 2093 main belt and 351 near-Earth asteroids from the NASA Planetary Data Systems (Neese, 2005), Near Earth Objects—Dynamical Site [Retrieved June 1, 2008] and European Asteroid Research Node [Retrieved June 1, 2008] databases. The classifications used in this work are based on the Bus (1999) feature-based taxonomy system, because it is widely used and a significant numbers of asteroids have been classified in this scheme. It also seems to dovetail well with other proposed schemes (Bus et al., 2002). The method is based on a Principal Components Analysis, with the principal components being related to the continuum slope in the visible region, absorption at ~0.8 µm, and absorption in the U.V. The numbers of asteroids in each class (as percentages of the total by number) are listed in Table 2.1 and the relative proportions of the classes in the two populations are shown as histograms in Fig. 2.1 and as pie charts in Fig. 2.2.

The Q complex was distinguished from the S complex by Binzel et al. (2004), since Sq and Q asteroids were so abundant in the NEA population (28%) and little-represented in the main belt population (3%). These asteroids have reflectance maxima at ~0.7 um that are broader and more rounded than typical of S asteroids and the 1 um absorption is more rounded (Bus, 1999). The Q asteroids seem to provide the best fit to the ordinary chondrites (Wetherill and Chapman, 1988; Chapman, 1976; Chapman 1996; Binzel et al., 2004; McFadden et al., 1984, 1989; Gaffey et al., 1993a, b; Gaffey and Gilbert, 1998).
Table 2.1. Asteroid classes and their populations*.

<table>
<thead>
<tr>
<th>Class</th>
<th>% by Number</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NEA</td>
<td>MBA</td>
</tr>
<tr>
<td>B</td>
<td>1.98</td>
<td>4.73</td>
</tr>
<tr>
<td>C</td>
<td>5.65</td>
<td>9.60</td>
</tr>
<tr>
<td>Cb</td>
<td>0.85</td>
<td>2.77</td>
</tr>
<tr>
<td>Cg</td>
<td>0.28</td>
<td>0.62</td>
</tr>
<tr>
<td>Cgh</td>
<td>0.00</td>
<td>0.96</td>
</tr>
<tr>
<td>Ch</td>
<td>0.28</td>
<td>9.36</td>
</tr>
<tr>
<td>S</td>
<td>21.47</td>
<td>25.51</td>
</tr>
<tr>
<td>Sa</td>
<td>0.82</td>
<td>1.77</td>
</tr>
<tr>
<td>Sk</td>
<td>3.67</td>
<td>1.29</td>
</tr>
<tr>
<td>Sl</td>
<td>1.69</td>
<td>5.83</td>
</tr>
<tr>
<td>Sr</td>
<td>3.95</td>
<td>0.81</td>
</tr>
<tr>
<td>K</td>
<td>2.26</td>
<td>2.01</td>
</tr>
<tr>
<td>L</td>
<td>1.98</td>
<td>2.72</td>
</tr>
<tr>
<td>Ld</td>
<td>0.56</td>
<td>1.15</td>
</tr>
<tr>
<td>X</td>
<td>9.32</td>
<td>10.89</td>
</tr>
<tr>
<td>Xc</td>
<td>1.98</td>
<td>3.34</td>
</tr>
<tr>
<td>Xk</td>
<td>2.82</td>
<td>2.91</td>
</tr>
<tr>
<td>Q</td>
<td>9.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Sq</td>
<td>18.64</td>
<td>3.06</td>
</tr>
<tr>
<td>A</td>
<td>0.28</td>
<td>0.91</td>
</tr>
<tr>
<td>D</td>
<td>1.13</td>
<td>2.68</td>
</tr>
<tr>
<td>O</td>
<td>1.69</td>
<td>0.05</td>
</tr>
<tr>
<td>R</td>
<td>0.85</td>
<td>0.19</td>
</tr>
<tr>
<td>T</td>
<td>1.41</td>
<td>2.10</td>
</tr>
<tr>
<td>V</td>
<td>5.08</td>
<td>2.53</td>
</tr>
<tr>
<td>Xe</td>
<td>1.41</td>
<td>2.15</td>
</tr>
</tbody>
</table>

* Data from the on-line data bases PDS, NEO-DYS, and EARN
The S complex (as redefined slightly by Binzel et al., 2004) consists of the S, Sa, Sk, Sl, Sr, K, L and Ld classes. These are asteroids with high albedos and with strong silicate absorption bands in their reflectance spectra. Like the C complex, the S complex is also larger in the main belt than the NEA, although the relative difference is smaller, 41% compared with 37%. Within the S complex, the S class has slightly higher abundance in the MBA than in the NEA populations, 25.51% and 21.47%, respectively, while Sa, Sl, L and Ld classes are more abundant in the main belt than the NEA population, and this is reversed for the Sk, and Sr types.

The X complex asteroids are noted for their essentially featureless and linear spectra. The abundance of X complex asteroids is similar in the main belt and the NEA population, 17% compared with 14%. All three classes within the X complex, X, Xc and Xk, are better represented in the MBA population than in the NEA population. (We note in passing that the E, M, and P classes, not represented in the Bus taxonomy and not included here, are members of the X complex that can only be distinguished if albedo is considered in addition to spectrum shape).

The C complex consists of asteroids with low albedos and essentially featureless reflectance spectra. We note in passing the relatively small size of the C complex, far from the 75% sometimes quoted in textbooks (Fix, 2004; Chaisson and McMillan, 2008). The C complex is larger in the main belt than the in NEA population, 28% compared with 9%. The C complex consists of classes B, C, Cb, Cg, Cgh and Ch. It is noted that Cgh is currently the only class present in the main belt that is absent from the NEA population. The C class is the largest individual class in the C complex, constituting 9.60% of the main belt and 5.65% of the NEA population. Second is the B class, which
Figure 2.1. Histogram of asteroid class populations in the main belt and near-Earth asteroids based on data in the PDS and EARN and using the taxonomy of Bus (1999). The instances of significant differences in the class population for the MBA and NEA at the 0.999 level of confidence are indicated with arrows. In three instances the classes are better represented in the MBA than NEA (Ch and Sl), while in five instances the classes are better populated in the NEA than MBA (O, Q, Sk, Sq, and Sr).
Figure 2.2. The sizes of the asteroid classes for the (a) MBA and (b) NEA represented as pie charts. There are 26 classes identified in the Bus taxonomy, and all are represented in both the NEA and MBA populations, except for Cgh for which there are 20 on the main belt and none in the NEA population (although this is not statistically significant).
is 4.73% of the main belt and 1.98% of the NEA population. A major class difference between the MBA and NEA populations is the Ch class, which is 9.36% of the main belt and only 0.28% of the near-Earth population.

Binzel et al. (2004) removed several classes from the S, C and X complexes and considered them either members of small complexes or their own complexes; these are the A, D, O, R, T, V and Xe classes. A, D, T and Xe are more abundant in the main belt, while O, R and V are more abundant in the NEA population.

2.3.2 Statistical analyses

In Table 2.1 we see that there are differences in the proportions of asteroids in the various taxonomic classes. Thus in order to quantify the compositions of the MBA and NEA populations we performed statistical analyses based on the $\chi^2$ method; this yields the level of significance that can be attached to any differences. We first address the issue of whether the NBA and NEA share a common parent population. We further seek to isolate any significant differences between the two populations in terms of the complexes. Finally, we investigate the differences in terms of the individual classes. Thus we consider the following four questions: (1) Are the NEA and MBA populations random samples of the same parent populations, based on the distribution of the individual classes? (2) Are the complexes in the MBA and the NEA from the same parent population? (3) Are the complexes in the NEA and MBA populations present in the same proportions in each population? (4) Are the classes in the NEA and MBA populations present in the same proportions in each population?
2.3.2.1 Do the NEA and MBA come from the same parent population, based on the distribution of individual classes?

We adopt the null hypothesis that the two populations are random samples of the same parent population. Observed values in both MBA and NEA were used to calculate expected values as follows, $E_i$ is the total number of asteroids of class $i$ expected in either the main-belt or the near-Earth populations:

$$E_i = \left( \frac{N_i}{N} \right) n$$

(1)

where $N_i$ is the total number of asteroids in the $i$th class for the combined NEA and MBA populations, $N$ is the total number of asteroids in the combined NEA and MBA population, and $n$ is the total number of asteroids in either population (NEA or MBA).

We calculated $\chi^2$ using

$$\chi^2 = \sum \left[ \frac{(O_i - E_i)^2}{E_i} \right]$$

(2)

where $O_i$ is the total number of asteroids of a given class $i$ observed in a given population, NEA or MBA populations: By way of example, for class A asteroids in MBA, $N_i = 20$, $N = 2444$, and $n$ (MBA) = 2093, thus $E_i$ (MBA) is 17.13, while for class A asteroids in NEA, $N_i = 20$, $N = 2444$, and $n$ (MBA) = 351, thus $E_i$ (NEA) is 2.87.

The number of degrees of freedom was determined to be 25 from the following equation

$$d.f. = (c - 1)(p - 1)$$

(3)

where $c$ is the number of taxonomic classes (26 in this case) and $p$ is the number of populations (2 in this case). The results of our analysis appear in Table 2.2. We obtained
Table 2.2. Chi-square test to answer the question as to whether the NEA and MBA come from the same parent population, based on the distribution of individual classes

<table>
<thead>
<tr>
<th>Class</th>
<th>( O_i )</th>
<th>( E_i )</th>
<th>( \frac{(O_i - E_i)^2}{E_i} )</th>
<th>Class</th>
<th>( O_i )</th>
<th>( E_i )</th>
<th>( \frac{(O_i - E_i)^2}{E_i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>19</td>
<td>17.13</td>
<td>0.20</td>
<td>A</td>
<td>1</td>
<td>2.87</td>
<td>1.22</td>
</tr>
<tr>
<td>B</td>
<td>99</td>
<td>90.78</td>
<td>0.74</td>
<td>B</td>
<td>7</td>
<td>15.22</td>
<td>4.44</td>
</tr>
<tr>
<td>C</td>
<td>201</td>
<td>189.26</td>
<td>0.73</td>
<td>C</td>
<td>20</td>
<td>31.74</td>
<td>4.34</td>
</tr>
<tr>
<td>Cb</td>
<td>58</td>
<td>52.24</td>
<td>0.64</td>
<td>Cb</td>
<td>3</td>
<td>8.76</td>
<td>3.79</td>
</tr>
<tr>
<td>Cg</td>
<td>13</td>
<td>11.99</td>
<td>0.09</td>
<td>Cg</td>
<td>1</td>
<td>2.01</td>
<td>0.51</td>
</tr>
<tr>
<td>Cgh</td>
<td>20</td>
<td>17.13</td>
<td>0.48</td>
<td>Cgh</td>
<td>0</td>
<td>2.87</td>
<td>2.87</td>
</tr>
<tr>
<td>Ch</td>
<td>196</td>
<td>168.71</td>
<td>4.42</td>
<td>Ch</td>
<td>1</td>
<td>28.29</td>
<td>26.33</td>
</tr>
<tr>
<td>D</td>
<td>56</td>
<td>51.38</td>
<td>0.41</td>
<td>D</td>
<td>4</td>
<td>8.62</td>
<td>2.47</td>
</tr>
<tr>
<td>K</td>
<td>42</td>
<td>42.82</td>
<td>0.02</td>
<td>K</td>
<td>8</td>
<td>7.18</td>
<td>0.09</td>
</tr>
<tr>
<td>L</td>
<td>57</td>
<td>54.81</td>
<td>0.09</td>
<td>L</td>
<td>7</td>
<td>9.19</td>
<td>0.52</td>
</tr>
<tr>
<td>Ld</td>
<td>24</td>
<td>22.27</td>
<td>0.14</td>
<td>Ld</td>
<td>2</td>
<td>3.73</td>
<td>0.81</td>
</tr>
<tr>
<td>O</td>
<td>1</td>
<td>5.99</td>
<td>4.16</td>
<td>O</td>
<td>6</td>
<td>1.01</td>
<td>24.81</td>
</tr>
<tr>
<td>Q</td>
<td>1</td>
<td>28.26</td>
<td>26.30</td>
<td>Q</td>
<td>32</td>
<td>4.74</td>
<td>156.80</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>5.99</td>
<td>0.66</td>
<td>R</td>
<td>3</td>
<td>1.01</td>
<td>3.96</td>
</tr>
<tr>
<td>S</td>
<td>534</td>
<td>522.39</td>
<td>0.26</td>
<td>S</td>
<td>76</td>
<td>87.61</td>
<td>1.54</td>
</tr>
<tr>
<td>Sa</td>
<td>37</td>
<td>34.26</td>
<td>0.22</td>
<td>Sa</td>
<td>3</td>
<td>5.74</td>
<td>1.31</td>
</tr>
<tr>
<td>Sk</td>
<td>27</td>
<td>34.26</td>
<td>1.54</td>
<td>Sk</td>
<td>13</td>
<td>5.74</td>
<td>9.16</td>
</tr>
<tr>
<td>Sl</td>
<td>122</td>
<td>109.62</td>
<td>1.40</td>
<td>Sl</td>
<td>6</td>
<td>18.38</td>
<td>8.34</td>
</tr>
<tr>
<td>Sq</td>
<td>64</td>
<td>111.33</td>
<td>20.12</td>
<td>Sq</td>
<td>66</td>
<td>18.67</td>
<td>119.98</td>
</tr>
<tr>
<td>Sr</td>
<td>17</td>
<td>26.55</td>
<td>3.43</td>
<td>Sr</td>
<td>14</td>
<td>4.45</td>
<td>20.48</td>
</tr>
<tr>
<td>T</td>
<td>44</td>
<td>41.96</td>
<td>0.10</td>
<td>T</td>
<td>5</td>
<td>7.04</td>
<td>0.59</td>
</tr>
<tr>
<td>V</td>
<td>53</td>
<td>60.80</td>
<td>1.00</td>
<td>V</td>
<td>18</td>
<td>10.20</td>
<td>5.97</td>
</tr>
<tr>
<td>X</td>
<td>228</td>
<td>223.52</td>
<td>0.09</td>
<td>X</td>
<td>33</td>
<td>37.48</td>
<td>0.54</td>
</tr>
<tr>
<td>Xc</td>
<td>70</td>
<td>65.94</td>
<td>0.25</td>
<td>Xc</td>
<td>7</td>
<td>11.06</td>
<td>1.49</td>
</tr>
<tr>
<td>Xe</td>
<td>45</td>
<td>42.82</td>
<td>0.11</td>
<td>Xe</td>
<td>5</td>
<td>7.18</td>
<td>0.66</td>
</tr>
<tr>
<td>Xk</td>
<td>61</td>
<td>60.80</td>
<td>0.00</td>
<td>Xk</td>
<td>10</td>
<td>10.20</td>
<td>0.00</td>
</tr>
</tbody>
</table>

\( O_i \) is the total number of asteroids of class in both the NEA and MBA populations

\( E_i \) is the expected number of asteroids calculated from equation (2).

Chi-Square: 497.83
Degrees of Freedom: 25
\( \chi^2(0.999) \): 52.62
a chi-square value of 498 while the value required for rejection of the hypothesis is any value greater than 53. In other words, we have greater than 99.9% certainty that the distribution of the taxonomic classes in the main belt and the near-Earth vicinity (shown pie chart form in Fig. 2.2) are different. Thus we now investigate the difference in terms of the complexes.

2.3.2.2 Do the NEA and MBA come from the same parent population, based on the distribution of individual complexes?

We again adopt the null hypothesis that the two populations are random samples of the same parent population, but this time the basis for comparison is the distribution of the complexes. The expected number of members $E_i$, for each complex was determined using:

$$E_i = \left( \frac{N_i}{N} \right) n$$

where $N_i$ is the sum of the MBA and NEA in the $i$th complex, and $N$ is the total combined population of the MBA and NEA, and $n$ is the total number of asteroids in either population. The number of degrees of freedom was calculated from Equation 3. For this analysis, $c$ is the number of complexes (5 in this case) and $p$ is the number of populations (2 in this case). Using Equation 1, the value of $\chi^2$ for each complex was calculated. The results of this analysis appear in Table 2.3.

The $\chi^2$ value for rejection of the hypothesis at the 0.001 level (with 4 degrees of freedom) is 18.467 which is less than our calculated value of 323.48. Therefore, we must reject the hypothesis. In other words, the relative size of these complexes in the NEA and MBA are significantly different at the 99.9% level of confidence. Pie charts showing the
Table 2.3. Chi-square test to answer the question whether the NEA and MBA come from the same parent population, based on the distribution of individual complexes *.

<table>
<thead>
<tr>
<th>Complex</th>
<th>( O_i )</th>
<th>( E_i )</th>
<th>( (O_i - E_i)^2/E_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main-Belt Asteroids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>587</td>
<td>530.10</td>
<td>6.11</td>
</tr>
<tr>
<td>S</td>
<td>860</td>
<td>846.96</td>
<td>0.20</td>
</tr>
<tr>
<td>X</td>
<td>359</td>
<td>350.26</td>
<td>0.22</td>
</tr>
<tr>
<td>Q</td>
<td>65</td>
<td>139.59</td>
<td>39.86</td>
</tr>
<tr>
<td>Other</td>
<td>222</td>
<td>226.09</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Near-Earth Asteroids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>32</td>
<td>88.90</td>
<td>36.42</td>
</tr>
<tr>
<td>S</td>
<td>129</td>
<td>142.04</td>
<td>1.20</td>
</tr>
<tr>
<td>X</td>
<td>50</td>
<td>58.74</td>
<td>1.30</td>
</tr>
<tr>
<td>Q</td>
<td>98</td>
<td>23.41</td>
<td>237.67</td>
</tr>
<tr>
<td>Other</td>
<td>42</td>
<td>37.91</td>
<td>0.44</td>
</tr>
</tbody>
</table>

\( \chi^2 \) (0.999) = 323.48, Degrees of Freedom = 4.

\( O_i \) the total number of asteroids of complex \( i \) in either the NEA or MBA population as noted.

\( E_i \) is the expected number of asteroids calculated from equation (4).
relative sizes of the complexes are shown in Fig. 2.3. We now proceed to directly compare the MBA population with the NEA population, first in terms of the complexes, and finally in terms of the individual classes, in our efforts to isolate the differences.

### 2.3.2.3. Are the complexes in the NEA and MBA populations present in the same proportions in each population?

In this case we adopt a null hypothesis that each complex in the MBA population is the same relative size as that in the NEA. Since this analysis requires a 2 x 2 table, the chi-square value for each complex was determined using:

\[ \chi^2 = \frac{N(a\overline{b} - a\overline{b})^2}{(n)N_M(N_N)} \]

where \(N\) is the total combined population of the MBA and NEA, and \(n\) is the total number of asteroids in the complex, \(\overline{n}\) is the total number of asteroids not in the complex, \(a\) is the number of MBA asteroids in the complex, \(\overline{a}\) is the number of MBA asteroids not in the complex, \(b\) is the number of NEA asteroids in the complex and \(\overline{b}\) is the number of NEA asteroids not in the complex. The number of degrees of freedom was calculated from Equation 3. For this analysis, \(c\) is the number of categories (2 in this case, in the complex or not in the complex) and \(p\) is the number of populations (2 in this case). Using Equation 5, the value of \(\chi^2\) for each complex was calculated. The results of this analysis appear in Table 2.4.

The \(\chi^2\) value for rejection of the hypothesis at the 0.001 level (with 1 degrees of freedom) is 10.827, so for the S, X and “Other” complexes, for which the chi-square values are 2.34, 1.82 and 0.57, respectively, the
Figure 2.3. Pie charts for the populations of the asteroid complexes, S, C, X, and Q for (a) MBA and (b) NEA, where complexes consist of taxonomically similar classes. The proportions of the S and X complexes are not significantly different between the MBA and NEA, but the proportions of Q and C are significantly different, the MBA consisting of a larger C complex and small Q complex while for the NEA this is reversed.
Table 2.4. Chi-square test to answer the question as to whether the complexes in the NEA and MBA populations present in the same proportions in each population.

<table>
<thead>
<tr>
<th>Complex</th>
<th>$a_{MBA}$</th>
<th>$\bar{a}_{MBA}$</th>
<th>$b_{NEA}$</th>
<th>$\bar{b}_{NEA}$</th>
<th>$\chi^2$</th>
<th>0.999 signif?</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>587</td>
<td>1506</td>
<td>32</td>
<td>319</td>
<td>56.94</td>
<td>yes</td>
</tr>
<tr>
<td>S</td>
<td>860</td>
<td>1233</td>
<td>129</td>
<td>222</td>
<td>2.34</td>
<td>no</td>
</tr>
<tr>
<td>X</td>
<td>359</td>
<td>1734</td>
<td>50</td>
<td>301</td>
<td>1.82</td>
<td>no</td>
</tr>
<tr>
<td>Q</td>
<td>65</td>
<td>2028</td>
<td>98</td>
<td>253</td>
<td>297.35</td>
<td>yes</td>
</tr>
<tr>
<td>Other</td>
<td>222</td>
<td>1871</td>
<td>42</td>
<td>309</td>
<td>0.57</td>
<td>no</td>
</tr>
</tbody>
</table>

$a$ is the number of asteroids in each complex in the MBA population.

$\bar{a}$ is the number of asteroids not in each complex in the MBA population.

$b$ is the number of asteroids in each complex in the NEA population.

$\bar{b}$ is the number of asteroids not in each complex in the NEA population.

“no” means that the difference in the size of each complex population between the NEA and MBA is not significant at the 0.999 level.

“yes” means that there is a significant difference at the 0.999 level.
hypothesis could not be rejected. In other words, these complexes in the NEA and MBA are not significantly different from each other. On the other hand, the C and Q complexes have chi square values of 56.94 and 297.35, respectively, which indicates that these complexes are significantly different at the 99.9% level of confidence. Pie charts showing the relative sizes of the complexes are shown in Fig. 2.3.

2.3.2.4. Are the classes in the NEA and MBA populations present in the same proportions in each population?

The null hypothesis we adopt in this case is that each class in the MBA population is the same relative size as that in the NEA. Since this analysis requires a 2 x 2 table, the chi-square value for each taxonomic class was determined using:

\[ \chi^2 = \frac{N(a \bar{b} - \bar{a} b)^2}{(n)(\bar{n})(N_{M})(N_{N})} \]  

where \( N \) is the total combined population of the MBA and NEA, and \( n \) is the total number of asteroids in the class, \( \bar{n} \) is the total number of asteroids not in the class, \( a \) is the number of MBA asteroids in the class, \( \bar{a} \) is the number of MBA asteroids not in the class, \( b \) is the number of NEA asteroids in the class and \( \bar{b} \) is the number of NEA asteroids not in the class. The number of degrees of freedom was calculated from Equation 3. For this analysis, \( c \) is the number of categories (2 in this case, in the class or not in the class) and \( p \) is the number of populations (2 in this case). The results of this analysis appear in Table 2.5.

The chi-square analysis of the individual taxonomic classes produced a variety of \( \chi^2 \) values, most of which were less than 10.827, the chi-square value for rejection of the
Table 2.5. Chi-square test to answer the question whether the classes in the NEA and MBA populations present in the same proportions in each population?*

<table>
<thead>
<tr>
<th>Class</th>
<th>(a) MBA</th>
<th>(\bar{a}) MBA</th>
<th>(b) NEA</th>
<th>(\bar{b}) NEA</th>
<th>(X^2)</th>
<th>0.999 signif?</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>19</td>
<td>2074</td>
<td>1</td>
<td>350</td>
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<td>no</td>
</tr>
<tr>
<td>B</td>
<td>99</td>
<td>1994</td>
<td>7</td>
<td>344</td>
<td>5.42</td>
<td>no</td>
</tr>
<tr>
<td>C</td>
<td>201</td>
<td>1892</td>
<td>20</td>
<td>331</td>
<td>5.57</td>
<td>no</td>
</tr>
<tr>
<td>Cb</td>
<td>58</td>
<td>2035</td>
<td>3</td>
<td>348</td>
<td>4.53</td>
<td>no</td>
</tr>
<tr>
<td>Cg</td>
<td>13</td>
<td>2080</td>
<td>1</td>
<td>350</td>
<td>0.59</td>
<td>no</td>
</tr>
<tr>
<td>Cgh</td>
<td>20</td>
<td>2073</td>
<td>0</td>
<td>351</td>
<td>3.38</td>
<td>no</td>
</tr>
<tr>
<td>Ch</td>
<td>196</td>
<td>1897</td>
<td>1</td>
<td>350</td>
<td>33.43</td>
<td>yes</td>
</tr>
<tr>
<td>D</td>
<td>56</td>
<td>2037</td>
<td>4</td>
<td>347</td>
<td>2.96</td>
<td>no</td>
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<tr>
<td>K</td>
<td>42</td>
<td>2051</td>
<td>8</td>
<td>343</td>
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<td>L</td>
<td>57</td>
<td>2036</td>
<td>7</td>
<td>344</td>
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<tr>
<td>Ld</td>
<td>24</td>
<td>2069</td>
<td>2</td>
<td>349</td>
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<td>no</td>
</tr>
<tr>
<td>O</td>
<td>1</td>
<td>2092</td>
<td>6</td>
<td>345</td>
<td>29.05</td>
<td>yes</td>
</tr>
<tr>
<td>Q</td>
<td>1</td>
<td>2092</td>
<td>32</td>
<td>319</td>
<td>185.60</td>
<td>yes</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>2089</td>
<td>3</td>
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</tr>
<tr>
<td>S</td>
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<tr>
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<td>2066</td>
<td>13</td>
<td>338</td>
<td>10.87</td>
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</tr>
<tr>
<td>Sk</td>
<td>122</td>
<td>1971</td>
<td>6</td>
<td>345</td>
<td>10.27</td>
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</tr>
<tr>
<td>Sq</td>
<td>64</td>
<td>2029</td>
<td>66</td>
<td>285</td>
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</tr>
<tr>
<td>Sr</td>
<td>17</td>
<td>2076</td>
<td>14</td>
<td>337</td>
<td>24.21</td>
<td>yes</td>
</tr>
<tr>
<td>T</td>
<td>44</td>
<td>2049</td>
<td>5</td>
<td>346</td>
<td>0.70</td>
<td>no</td>
</tr>
<tr>
<td>V</td>
<td>53</td>
<td>2040</td>
<td>18</td>
<td>333</td>
<td>7.18</td>
<td>no</td>
</tr>
<tr>
<td>X</td>
<td>228</td>
<td>1865</td>
<td>33</td>
<td>318</td>
<td>0.70</td>
<td>no</td>
</tr>
<tr>
<td>Xc</td>
<td>70</td>
<td>2023</td>
<td>7</td>
<td>344</td>
<td>1.79</td>
<td>no</td>
</tr>
<tr>
<td>Xe</td>
<td>45</td>
<td>2048</td>
<td>5</td>
<td>346</td>
<td>0.78</td>
<td>no</td>
</tr>
<tr>
<td>Xk</td>
<td>61</td>
<td>2032</td>
<td>10</td>
<td>341</td>
<td>0.004</td>
<td>no</td>
</tr>
</tbody>
</table>

\(a\), \(\bar{a}\), \(b\), and \(\bar{b}\) are as defined in Table 2.4.

“no” means that the difference in the size of each complex population between the NEA and MBA is not significant at the 0.999 level.

“yes” means that there is a significant difference at the 0.999 level

† Not Significant the 0.999 level, but significant at the 0.995 level.
hypothesis at the 0.001 level with 1 degree of freedom. However, there are six classes, Q ($\chi^2 = 185.60$), Sq ($\chi^2 = 147.97$), Sk ($\chi^2 = 10.87$), Sr ($\chi^2 = 24.21$), Ch ($\chi^2 = 33.43$), O ($\chi^2 = 29.05$), and for which the calculated chi-square value was greater than the rejection value at the 0.001 level. For these six classes we are able to reject the null hypothesis. In other words, we can state with 99.9% certainty that these classes are present in different proportions in the MBA and NEA samples. In addition, there is one taxonomic class that has a chi-square value less than the rejection value at the 0.001 level, but is very close to the 10.827 value. This is the Sl ($\chi^2 = 10.27$) class. We show the relative abundances of the classes that are statistically different in the two populations in Fig. 2.4 and indicate them with arrows in Fig. 2.1.

The Q complex shows the most spectacular difference in class abundance for the NEA and main belt populations, as noted by Binzel et al. (2004) (Fig. 2.4a). There are 64 Sq and one Q asteroids in the main belt, compared with 66 Sq and 32 Q asteroids in the NEA population. They plot in the lower perimeter of the S complex in Bus’ (1999) PCA treatment, and, as mentioned previously, they have often been likened to the ordinary chondrite classes.

The situation is a little different with the Sk, Sl and Sr classes (Fig. 2.4b). The relative abundance of these classes taken together is not significantly different for the NEA and MBA populations, but the relative proportions of these asteroids are significantly different. The numbers of Sk, Sl and Sr asteroids in the main belt are 27, 122, 17, respectively, while for the NEA population these numbers are 13, 6, and 14. These are all S complex classes that are intermediate in their spectral properties to the S asteroids and the K, L and R classes, respectively. The spectra of L class asteroids are
Figure 2.4. (a) Pie charts comparing the class sizes in the MBA (left column) and class sizes in the NEA populations (right column) for classes showing statistically significant differences. There is one Q asteroid among the MBAs and 32 among the NEAs. For the Sq asteroids, these numbers are 64 and 66, respectively. (b) The proportions of the three S complex classes, Sr, Sl and Sk, within their parent populations are very similar for (a) MBA and (b) NEA, (9.7% and 10.1% by number, respectively), but the relative proportions of these four classes within these parent populations is statistically significantly different (for example, 0.8% and 4.0% for the Sr class in MBA and NEA, respectively).
Figure 2.4. (c) Pie charts for the Ch class of asteroid for which the (a) MBA and (b) NEA show a statistically significant difference in abundance, the MBA containing 196 of this taxonomy and the NEA contain 1. (d) Pie charts for the O class of asteroid for which the (a) MBA and (b) NEA show a statistically significant difference in abundance, the MBA containing 1 of this taxonomy and the NEA contain 6.
similar to the K class asteroids. The UV slope in the L class is moderate to very steep and is steeper than the average K asteroids. The slope becomes generally flat beyond 0.75 \( \mu m \) with little or no upward curvature near 1 \( \mu m \). R class asteroids have a steep UV slope and a deep 1 \( \mu m \) absorption (Bus and Binzel 2002). There are 196 Ch asteroids in the main belt and only one in the NEA population (Fig. 2.4c). These are asteroids in the C complex noted for a broad 0.7 \( \mu m \) absorption feature (Bus, 1999). The O asteroids are outside the normal complexes, but on the periphery of X and C complexes, and were defined by Binzel et al (1993b) based on the unusual asteroid Božímcová (Fig. 2.4d). There is one in the main belt and six in the near-Earth population. They have been linked to the L6 and LL6 classes of ordinary chondrites.

2.4 Discussion

The lifetime of objects in the NEA region is very short, since such objects are subject to planetary perturbation and ejection from the solar system or collision with the Sun (Morais and Morbidelli, 2002; Morbidelli et al., 2002). This can be understood in terms of two scenarios. Either these asteroids were recently ejected into the NEA region from a limited number of parent objects in the main belt or, alternatively, they come from an efficient source other than the main belt asteroid belt, the most probable source being the comets. Here we will look at the asteroid groups for which these differences exist and we will look for evidence of recent ejection into the NEA region from a limited number of parent bodies or from a source other than the main asteroid belt.

2.4.1 The Q complex (Q and Sq) NEA-MBA differences.

As we have frequently mentioned, the Q complex asteroids are those that most closely resemble the ordinary chondrites, and the Fe content of the olivine seems most
similar to LL chondrites (Vernazza et al., 2008). Their refractory nature means that few if any authors identify them with comets, and there are many other lines of evidence for this. About 80% of the meteorites being seen to fall on Earth are ordinary chondrites (Sears and Dodd, 1988). They are therefore by far the most common meteorite type, and for many years it has been a concern to asteroid astronomers that good spectral matches are so rare in the main belt. Chapman (1976) referred to it as the “S asteroid paradox”. However, considerable progress has been made since then in both spectral classification of asteroids and in understanding possible dynamic evolution processes. It is now believed there are very effective means of transferring asteroids from the main belt to the Earth’s vicinity via the resonances (Nesvorný et al. 2002), which may be considered as “escape hatches”, and thermally driven Yarkovsky mechanisms have been identified for moving asteroids to the resonances (Vokrouhlický and Farinella 2000; Bottke et al., 2006).

The rather strong relationship between the Q complex and the ordinary chondrites means that we can look to the meteorite data for an explanation of the difference in Q asteroids in the Earth’s vicinity and in the main belt. Probably one of the best-known properties of the ordinary chondrites is the number of discrete peaks in the histogram of cosmic ray ages (Eugster et al., 2006; Fig. 2.5). These ages are calculated from the abundance of cosmogenic isotopes (usually isotopes of inert gases), which is divided by an estimated production rate to derive an age. Cosmic ray exposure (CRE) ages carry large uncertainties, since cosmogenic gases are easily lost, the abundance of cosmic ray isotopes is always low relative to other relevant isotopes, production rates difficult to estimate (because they require knowledge of burial depth), and there is a constant
Figure 2.5. Histograms of cosmic ray exposure ages for the three major groups of ordinary chondrites, showing that a number of discrete break up events have occurred in their histories. The H chondrite parent body underwent a single major break up event 8 million years (Ma) ago, while the L chondrites experienced many events at ~5, ~15 ~22 and 45 Ma, for instance. The LL chondrite apparently underwent a major break-up at ~17 Ma. Spread around these values could be caused by subsequent fragmentation, previous irradiation events, or analytical uncertainly in the determination of the cosmogenic isotopes used for these calculations. (Figure after Eugster et al., 2006).
possibility of multiple irradiations. What is remarkable is that despite these uncertainties
discrete peaks appear in the CRE distributions, which can only be interpreted as the time
of a disruption of the single parent object that produced all these fragments. For the H
chondrites, there is a very strong peak at ~8 Ma, for the L chondrites there are peaks at
~5, ~15 ~22 and 45 Ma, and for the LL chondrites there is a major peak at 17 Ma (Fig.
2.5). For the production of cosmic ray isotopes in a meteoroid, the object must be less
than a meter or so in size. Thus we know that the ordinary chondrite classes came from
just a few parent bodies.

The spread in CRE ages has been interpreted as evidence for Yarkovsky driven
orbital evolution of the fragments produced by these major collisions (Vokrouhlický and
Farinella, 2000). This might be so, but the large number of factors contributing to the
spread in CRE ages should be borne in mind.

There is independent evidence that most of the L chondrites are coming from one
body in the form of their distribution of K-Ar ages (Bogard, 1995). These radiogenic
ages are usually determined by a superior variant of the K-Ar method, the Ar-Ar method,
in which \(^{39}\)Ar is used to determine \(^{40}\)K in the same aliquot as \(^{40}\)Ar by neutron activation
analysis. The K-Ar histogram for L chondrites has a strong peak at 500 Ma, suggesting
that these meteorites were fragments of a single object that fragmented at that time (Fig.
2.6). Most of the meteorites in the central part of the peak are shock-blackened
chondrites, with many petrographic indications of intense shock-heating which would
have caused almost complete degassing of Ar (Heymann, 1967). The spread to higher
ages represent meteorites whose \(^{40}\)Ar was not completely lost by this event, younger ages
reflect subsequent \(^{40}\)Ar loss.
Figure 2.6. Distribution of K-Ar ages for L chondrites determined by the Ar-Ar method, the shading refers to data quality. The two peaks refer to formation (nominally ~4.5 Ga, but lowered slightly by $^{40}$Ar diffusive loss) and a major reheating event at ~0.5 Ga which caused thermally driven loss of $^{40}$Ar and a resetting of the K-Ar clock. Meteorites associated with the 0.5 Ma parent body break up event show numerous petrographic signs of shock and heating, in fact most of the meteorites were shock-blackened by the event. These data are evidence that many or most of the L chondrites were part of a single parent body prior to the event and that the ordinary chondrites are coming to Earth from a few parent asteroids. (Figure after Bogard, 1995).
Another line of evidence that we are seeing streaming of meteorites from a recently disrupted local source is the induced thermoluminescence data for H chondrites (Benoit and Sears, 1992; 1993). The data for Antarctic meteorites is quite different from the data for meteorites from the rest of the world (Fig. 2.7). The main difference between meteorites collected in the Antarctic and elsewhere, other than weathering which should not affect these data, is their terrestrial age. Antarctic meteorites typically fell ~40,000 year ago, while non-Antarctic meteorites fell in the last few thousand years or less. The relative proportions of the high temperature and low temperature phases of feldspar, this mineral being the major source of the thermoluminescence signal, govern position on these plots. The proportion of high and low temperature feldspar is determined by the cooling rate following metamorphism on the parent object. The different distributions of TL data shown in Fig. 2.7 therefore indicates that the order of delivery of the H chondrites to Earth depends on their cooling history and therefore location in the parent object.

The reason for the difference in the abundance of Q complex asteroids in the NEA vicinity and the main belt thus seems to be related to the fact that most of the ordinary chondrites are coming from a few parent bodies that happened to be able to eject their fragments to the near-Earth vicinity.

Gaffey and Gilbert (1998) have suggested that the parent body for the H chondrites (and also the geochemically-related IIE iron meteorites) is the asteroid 6 Hebe which is an S asteroid in the Bus et al. (2002) scheme and an S(IV) asteroid in the Gaffey et al. (1993) scheme. The spectrum of Hebe does not resemble that of an H chondrite, but does if the presence of considerable metallic iron is additionally present. Hebe is located close to both the 3:1 Jupiter orbital resonance and the $\nu_6$ secular resonance.
Figure 2.8 is a plot of eccentricity against semimajor axis for the 2093 main belt asteroids in the present study. The well-known mean motion resonances are easily apparent and the secular ($\nu_6$) resonance constrains the distribution in $e$ values with semimajor axis. Figure 2.8 also shows the analogous plot for the Q complex asteroids, including the position of Hebe. Gaffey et al. (1993b) suggested that S(IV) asteroids were concentrated near the 3:1 resonance, and this accounted for their abundance in the NEA population. We see no such concentration of Q and Sq asteroids near resonances that would explain their high abundance in the NEA population.

2.4.2 The S complex (Sk, Sl, Sr classes) NEA-MBA differences.

The Sk, Sl and Sr classes, taken together, are not significantly different in the MBA and NEA populations, but the relative proportions of these three groups are significantly different, Sl are more abundant in the main belt, and Sk and Sr are more abundant in the NEA population. Gaffey et al. (1993b) “rigorously excluded” these classes as possible ordinary chondrite parent bodies because their range of mineralogy exceeded that of ordinary chondrites, and suggested connections with a variety of rare and often unique igneous meteorites. The present statistical results might suggest that these classes are coming from separate parent asteroids, Sk and Sr being nearer a resonance than Sl (Fig. 2.2.). However, it cannot be ruled out that the Sk, Sr, and Sl are from the same object, but are streaming in the manner described above for the H chondrites (Benoit and Sears, 1992; 1993). Without more positive identification with meteorites, a statistically meaningful number of related meteorites or samples from the asteroids, these issues cannot be resolved.
Figure 2.7. Left, Induced TL peak temperature vs. peak width for a suite of 31 Antarctic H chondrites (typical terrestrial age ~40,000 years). Data from Haq et al. (1988). (b) Equivalent data for 37 non-Antarctic (i.e. modern falls) H chondrites. The dashed line is a regression line through the non-Antarctic data. Note the difference in the distribution of the two sets of data, which Benoit and Sears (1992, 1993) showed was due to different post-metamorphism cooling rates.
Figure 2.8. (Top) Eccentricity against semimajor axis for the main belt asteroids illustrating the well known resonances and overall distribution. Eccentricity against semimajor axis for main belt asteroids in the Ch (middle) and Q, Sq (bottom) classes, which show statistically significant differences between the NEA and MBA populations. The Ch class is larger in the MBA and the Q, Sq class is larger in the NEA populations. Also marked on the Q, Sq plot is the asteroid Hebe which is an S asteroid in the Bus et al. (2004) scheme and an S(IV) asteroid in the Gaffey et al. (1993) scheme. Gaffey and Gilbert (1998) suggest that Hebe is the parent body for the ordinary chondrites. In both cases there is a wide spread or orbital elements for the asteroids with no particular tendency to cluster around a resonance.
Figure 2.9. Eccentricity against semimajor axis for main belt asteroids in the Sk, Sl, and Sr classes, which show statistically significant differences between the NEA and MBA populations at the 0.999 level for Sr, and at the 0.995 level for Sk and Sl. Sl are better represented in the main belt, while Sk and Sr are better represented in the NEA population. As in Fig. 2.12, there is no strong indication that the MBA and NEA population differences are being controlled by location near a resonance.
2.4.3 The C complex (Ch class) NEA-MBA differences.

The spectra of the Ch asteroids is similar to that of C asteroids with the addition of a weak absorption at 0.7 μm (Bus et al., 2002) that is associated with hydrated iron oxides (Vilas et al., 1994). There is only one Ch asteroid among the NEA population, yet 196 in the main belt. The C complex asteroids are often associated with the CI or CM chondrites, possibly with some level of dehydration (Rivkin et al., 2002). CI and CM chondrites are very rare on Earth. They are very friable, which is probably associated with their high water concentrations, which are 10-20 vol%. It is probably this friability that makes them rare on Earth because they cannot survive atmospheric passage. However, it is also possible their friability makes it difficult to survive passage from the main belt to the NEA region, or even survive ejection from their parent body. Included in the rare CI and CM chondrites on Earth are a few even rarer objects that are dehydrated and thought to have been metamorphosed (Hiroi et al., 1993; 1996). It is possible, perhaps even probable, that Ch NEAs are the parent objects of some or all of these meteorites. Because of their rarity and their intrinsic abundance of inert gases CRE and other age distributions are not available, and there is no evidence of parent body fragmentation events. In fact, it is possible that the Ch asteroids are cometary in origin. On the basis of numerical modeling of orbit evolution the latest estimates for the proportion of the NEA that are cometary is ~6±4% (Weissman et al., 2002; Bottke et al., 2002b). Several authors have suggested that asteroid classes P, D, and F are cometary on the basis of their low albedo, continuum slope, and possible presence of organics (Luu, 1993).
Figure 2.8 includes a plot of $e$ vs. $a$ for Ch asteroids in the main belt. There is no immediately obvious explanation in these data for the relative lack of Ch asteroids in the NEA population. These asteroids do not show any particular tendency to avoid resonances, other than the known clearing of the region that defines the Kirkwood gaps. In other words, the distribution is not markedly different from that of the Q complex in terms of distribution about resonances.

Figure 2.10 is a histogram for the MBA populations of Ch class and Q, Sq class asteroids. While the two show common characteristics, such as peaks in the 2.4 and 2.8 AU bins, there are differences such as the peak in the 3.2 AU bin, and the small number in the 3.3-3.5 AU bins of the Ch population and the greater number of asteroids in the 2.0, 2.2 and 2.3 AU bins for the Q, Sq populations. Thus the Ch asteroids are skewed to larger semimajor axes than the Q and Sq asteroids. The large number of Ch asteroids in the 3.2 AU bin probably explains the statistical difference between the NEA and MBA populations of this class, and might be explained by the break-up of an object at this location that was unable to eject its fragments into the near-Earth vicinity.

**2.4.4 The O class NEA-MBA differences.**

The O class asteroids are more abundant in the NEA population than in the main asteroid belt. They are few in number and there are no strong meteorite associations, so that it is difficult to make many conclusions other than the situation may be similar to the Q complex.

**2.5 Conclusions**

There are statistically significant differences in the relative abundances of several taxonomic classes of asteroids in the main belt and the near-Earth vicinity. The Q
Figure 2.10. Histograms for the MBA populations of Ch class and Q, Sq class asteroids. While the two show common characteristics, such as peaks in the 2.4 and 2.8 AU bins, there are differences such as the peak in the 3.2 bin, and the small number in the 3.3-3.5 bins of the Ch population and the greater number of asteroids in the 2.0, 2.2 and 2.3 bins for the Q, Sq populations. Thus the Q and Sq are skewed to smaller semimajor axes than the Ch asteroids.
complex (Q and Sq) and the O class are more abundant in the near-Earth vicinity while the Ch class is more abundant in the main belt. Three members of the S complex also show significant differences, but the details are more complex, Sl are more abundant in the main belt while Sk and Sr are more abundant in the NEA population. It has been suggested that a clustering of asteroids near a resonance in the main belt explains a large number of group members in the NEA. However, we see no evidence for this in the orbital elements of the main belt asteroids. The Q complex asteroids are clearly related to the ordinary chondrites. The ordinary chondrites show considerable evidence for their production by the fragmentation of a few major parent objects. We argue that all the differences in taxonomic class we observe between the asteroids in the NEA and MBA populations are due to recent fragmentation events and ease of transfer to Earth. The observed make-up of the NEA populations is therefore a snapshot in time of a continuously varying population.

2.6 References


Chapter 3: (10302) 1989 ML: Easy to get to but hard to describe

Here we look at the spectrum of asteroid (10302) 1989 ML and make comparisons with the spectra of all types of ordinary and carbonaceous chondrite meteorites. I collected available data for fifteen chondrites from online databases and conducted the spectra comparisons based on spectral shape. Dan T. Britt contributed data for five shock-blackened chondrites and Michael D. Hicks (MDH) made color magnitude observations of 1989 ML. Claud H. S. Lacy provided advice and guidance to properly normalize and compare the spectra. Larry A. Lebofsky contributed his knowledge and background for carbonaceous chondrites. Derek W. G. Sears contributed knowledge and background for meteorites, ordinary chondrites in particular.

3.1 Abstract
Here we discuss the nature of 1989 ML and its relationship to possible meteorite analogs. The spectrum matches well with one shock-blackened ordinary chondrite (Sevrukovo) and one CK chondrite (Karoonda) but not other meteorites of those types which implies no firm conclusions about its surface composition are possible at the moment.

3.2 Introduction
Asteroid 1989 ML has been and will continue to be an alluring target for asteroid sample return missions. It is one of the most easily accessible asteroids due to its low Δv, and it was the primary target for the Japanese Hayabusa mission (MUSES-C), which was later redirected to Itokawa due to launch delays. To maximize the chances of mission and science success, it is important to gather certain critical ground-based data. 1989 ML
is an Amor asteroid with an orbital period of 524.284 days, rotation period of 19 hours with an amplitude between 0.5 and 1 magnitude, perihelion of 1.099 AU, and aphelion of 1.447 AU. What is unclear is the compositional nature of the asteroid. Here we examine ground based spectral data for 1989 ML and possible meteorite analogs.

3.3 Procedure

Color magnitude observations of 1989 ML were made by MDH with the Palomar Mountain/NEAT 1.2-m Schmidt telescope equipped with a charge-coupled device (CCD). The spectral data for 1989 ML were obtained from the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) database at MIT for observations made in March and May 1999 in the visible wavelengths using the 5-m (200-inch) telescope at Palomar Mountain Observatory equipped with the Double Spectrograph (Binzel et al., 2001). Meteorite data were obtained from NASA’s Planetary Data System (PDS) and the Keck/NASA Reflectance Experiment Laboratory (RELAB) databases.

The meteorite spectra were truncated to use only the visible wavelengths up through 975 nm for comparison with the asteroid data. All spectra were normalized to 1.0 at 550 nm. Comparisons of the meteorite spectra with 1989 ML’s spectrum were made by plotting them together on the same graph. Since the color indices indicate that 1989 ML falls within the realm of the C-type asteroids (Fig. 3.1), we made our first comparison to the spectra of Alais (CI), Cold Bokkeveld (CM2), Felix (CO3), Coolidge (C4), Allende (CV3) and Karoonda (CK5). Observing a good match only for Karoonda, a CK5 chondrite, further comparisons were made to CK meteorites EET 92002 (CK4 – Elephant Moraine), EET 87526 (CK5 – Elephant Moraine) and LEW 87009 (CK6 – Lewis Cliff). The plots of all the C chondrites along with 1989 ML are shown in Fig. 3.2a.
Figure 3.1. $V$-$B$ vs. $V$-$I$ and $V$-$R$ vs. $V$-$I$ color indices plots of 1989 ML with C-, D-, and S-type asteroids. In each case, 1989 ML falls within the plot of C-type asteroids.
Binzel et al. (2001) have pointed out that Sevrukovo, a shock-blackened ordinary chondrite, is a close match to 1989 ML. We therefore obtained spectra of further shock-blackened L5 chondrites, Arapaho, Farmington, Harvard, Taiban and Wickenberg, and we obtained some unshocked L chondrites for comparison, Mezo-Madaras (L3), Bald Mountain (L4), Elenovka (L5) and Bruderheim (L6). The results are shown in Fig. 3.2b.

### 3.4 Discussion

Chondrites are the most abundant class of meteorites found. Roughly 85% of all meteorite falls are chondrites with 80% being ordinary chondrites and the other 5% carbonaceous chondrites. Carbonaceous chondrites match the chemistry of the Sun more closely than any other meteorites and are therefore thought to be relatively unaltered material from the early Solar System. Carbonaceous chondrites are noted for containing water-bearing minerals and carbonaceous compounds and minerals such as olivines, pyroxenes, plagioclase and nickel-iron alloys. There are six main classes of carbonaceous chondrite; CI, CM, CR, CO, CV and CK.

Of the C chondrites we considered, Allende (CV3) and Karoonda (CK5) were the best matches for 1989 ML, although Allende did not fit in the UV and IR (Fig.3.2a). None of the other CK chondrites, including another CK5 (EET87526 – Elephant Moraine), were good matches for 1989 ML. At this point our analysis turned to the ordinary chondrites.

Ordinary chondrites are the most common meteorites found. They consist mainly of olivines and orthopyroxenes. Based on the amount of iron content of the olivines, they
Figure 3.2a. Plot of 1989 ML with C chondrites: a-Alais CI, b-Cold Bokkeveld CM2, c-1989 ML, d-Felix CO3, e-Coolidge C4, f-Allende CV3, g-Karoonda CK5, h-EET92002 CK4, i-EET87526 CK5, j-LEW87009 CK6
are divided into three classes: H (high metallic iron), L (low metallic iron), and LL (little or no metallic iron).

Comparisons were made to the H chondrites Tieschitz (H3), Grueneberg (H4), Allegan (H5), and Lancon (H6) with no matches found. As shown in Fig. 3.2b, the spectra of the L chondrites chosen did not produce any matches. Considering the fact that Karoonda is considerably shocked, we made comparisons of 1989 ML to the five shock blackened L5 chondrites. Two of the shock blackened chondrites (Arapaho and Harvard) were a much better fit than the other three; however, they did not match well in the UV wavelengths.

3.5 Conclusions

In Binzel et al. (2001), it was shown that the spectrum of Sevrukovo, a shock blackened L5 chondrite, was a very good match for 1989 ML. In Fig. 3.3, we have plotted the spectra of 1989 ML, Karoonda and Sevrukovo which shows that both meteorite spectra are very good matches for the spectrum of 1989 ML. In fact the spectra of the two meteorites match each other well. From the comparisons of the spectrum of 1989 ML to the spectra of the various types of chondrites, we conclude that the asteroid 1989 ML does not match any particular type of chondrite. It also does not, in general, match shock blackened chondrites. Rather, it seems that its spectrum matches some individual shocked chondrites of more than one type. The factor that produces this effect may not be the composition of the asteroid, but instead that the spectra depend on the precise degree of shock that has occurred.
Figure 3.3. Plot of 1989 ML with chondrites Karoonda CK5 and Sevrukovo L5.
What does this say about 1989 ML? One possibility may be that it is a shocked asteroid. This conclusion begs the question, how do you shock an entire asteroid? Is it impossible that 1989 ML underwent a massive collision event that shocked the entire surface of the asteroid? Possibly the event occurred at the time of the asteroid’s formation. Continued observations are needed in order to answer this question.
3.6 References


Chapter 4: A Resolution of the Asteroid-Meteorite Mismatch?

In this chapter we discuss the relationship between common stony asteroids, S asteroids, and common stony meteorites, ordinary chondrites. Comparisons of the asteroid spectra were made using infrared data (collected by Dr. Claud H. S. Lacy) utilizing the NASA IRFT. After collecting the available visible wavelength data from online databases, I coupled them with our infrared wavelengths, normalized the spectral data, and conducted an MGM analysis for each asteroid. I also collected ordinary chondrite spectral data from online databases and Daniel R. Ostrowski conducted MGM analysis for each meteorite. Dr. Claud H. S. Lacy performed the data reduction and provided assistance and advice to properly compare the two populations. Dr. Derek W. G. Sears contributed to the project conception, planning, and interpretation efforts as well as knowledge and background for meteorites, ordinary chondrites in particular.

4.1 Abstract

Meteorites and their presumed parent bodies, the asteroids, hold the potential to provide considerable information on the nature and history of the early solar system (Bottke et al., 2002; Lauretta and McSween, 2006). While laboratory measurements of meteorites provide an enormous array of highly precise data (Lauretta and McSween, 2006), linking them to asteroids is problematic. This is because, despite some initial success with relatively rare meteorites (McCord, et al., 1970), the most common meteorites (the equilibrated ordinary chondrites) only rarely have matches among the largest class of asteroids, the S asteroids (Gaffey et al., 1993). Here we show that many
S asteroids apparently have surfaces resembling unequilibrated ordinary chondrites. One issue in connecting ordinary chondrites with S asteroids concerns the major rock-forming mineral pyroxene, which is in the monoclinic form on S asteroids and in the orthorhombic form in equilibrated ordinary chondrites (Gaffey et al., 2007; Dodd et al., 1967). We recently obtained spectra for eight S asteroids and found that in all but one case their spectra have important similarities to those of unequilibrated ordinary chondrites, which contain pyroxene in the monoclinic form. The more common equilibrated ordinary chondrites show ample evidence for a history involving a small number of major break-up events and apparently came from the interiors of a few parent asteroids (Marti and Graf, 1992; Bogard 1995). Thus it is not surprising that astronomers rarely observe them on the surfaces of asteroids. Implications for this discovery are that there is a strong linkage between the largest asteroid class and the largest meteorite class, that the surfaces of asteroids are not the same as their interiors, that much of the small body population of the inner solar system is chondritic, and that the wealth of data provided by meteorites can be put in an asteroid context. These new insights into the nature of asteroids have relevance to models for early solar system evolution and the formation of planets, to the planning of the scientific exploration of the solar system, and to the development of techniques for mitigating asteroid impact on Earth.

4.2 Introduction

The two major silicate rock-forming minerals are olivine and pyroxene whose reflectance spectra have absorption bands in the 1 and 2 μm regions, but detailed positions depend on composition and structure (Cloutis and Gaffey, 1991; Sunshine and Pieters, 1993, 1998; Sunshine et al., 2004). Pyroxene in the orthorhombic form (orthopyroxene) has features at ~0.91 μm and ~1.83 μm in its spectrum, while
monoclinic pyroxene (clinopyroxene) has prominent spectral features at \( \sim 1.01 \ \mu m \) and \( \sim 2.27 \ \mu m \), regardless of composition (Gietzen et al., 2009). Sample spectra are shown in Fig. 4.1. The orthopyroxene in the sample spectrum in Fig 4.1a contains no clinopyroxene, and the clinopyroxene sample in Fig. 4.1b seems relatively pure. The validity of these assignments and our ability to extract quantitative information has been demonstrated through measurements on synthetic pyroxenes (Cloutis and Gaffey, 1991; Sunshine and Pieters, 1993). These absorption bands are associated with electronic transitions in \( \text{Fe}^{2+} \) located in the M1 octahedral sites of the pyroxene. A number of weaker absorptions are associated with charge-transfer, forbidden transitions, other cations, and other sites in the mineral, and may vary from pyroxene to pyroxene. Olivine absorption at \( \sim 1 \ \mu m \) is difficult to use in quantitative astronomical applications (Sunshine and Pieters, 1998). The many other minerals potentially present are either too minor or do not produce useable features.

4.3 Method Summary

We obtained spectra in the range 0.8 – 2.5 \( \mu m \) for eight S-type asteroids by using the NASA Infrared Telescope Facility equipped with the SpeX infrared spectrometer (Rayner et al., 2003). In order to obtain a more complete spectrum, data in 0.4 – 0.9 \( \mu m \) range were taken from the literature (Bus and Binzel, 2002). A published curve fitting technique, called the modified Gaussian model (MGM) (Sunshine et al., 1990), was used to isolate individual absorption bands in the spectra and identify the minerals present. The MGM analysis identifies the absorption bands as a number of inverted Gaussian curves. The residuals (differences between the sums of the Gaussian curves plus continuum and the spectrum) are essentially zero but displaced upward on our spectra for clarity. This method will be used extensively in the next section.
4.4 Data and Results

Table 4.1 lists the eight asteroids we observed with their spectral classifications according to two popular schemes (Bus and Binzel, 2002; Gaffey et al., 1993). Figure 4.2a shows representative spectra for one of our asteroids. With one exception, the spectra for all the S asteroids we observed contained absorption bands indicating the presence of both clinopyroxene and orthopyroxene. The exception is an olivine-rich asteroid, 354 Eleonora that will not be discussed here. Using the laboratory calibrations mentioned above (Sunshine and Pieters, 1998; Bus and Binzel, 2002), we estimate that the volumetric amounts of clinopyroxene present on the surface of these asteroids are ~40 – 70% with the remainder being orthopyroxene (Table 4.1). Previous investigators have assumed the clinopyroxene being detected on the surfaces of S asteroids is calcium-rich and have assumed an association with igneous rocks such as the basalts, or other melts or partial melts (Gaffey et al., 1993; Gaffey, 2007; Sunshine et al., 2004). This has lead to an unsuccessful search for such materials among the meteorites (Gaffey, 2007).

4.5 Discussion

Clinopyroxene is present in certain ordinary chondrites, namely those that have escaped significant alteration by parent body metamorphism, alteration in the solid state by elevated temperatures (Dodd et al., 1967). The ordinary chondrites are subdivided into types 3-6 with the level of metamorphic alteration increasing gradationally along the type 3-4-5-6 series (van Schmus and Wood, 1967). The type 3 ordinary chondrites have received considerable attention because, while they show a wide range in metamorphic alteration (leading to the subdivision into types 3.0 to 3.9 (Hutcheson and Hutchison, 1989)), some of them are almost completely unaltered, and therefore primary
Figure 4.1. Visible/near-Infrared reflectivity spectra for terrestrial pyroxenes (Gietzen et al., 2009). (a) Orthopyroxene from Webster, North Carolina, (actually enstatite, MgSiO₃), (b) a clinopyroxene from an Hawaiian volcanic bomb. The spectra are indicated by a series of (+) symbols. Also shown are gaussian curves fitted to the spectra using the MGM software (Sunshine and Pieters 1993), the continuum, and the residuals. Orthopyroxene has absorption bands at ~0.9 µm and ~1.8 µm, while clinopyroxene has bands at ~1.0 µm and ~2.3 µm. Olivine [(Fe,Mg)Si₂O₆], the second major rock-forming mineral on asteroids, has a major absorption band at ~1.0 µm that often cannot be resolved from the pyroxene bands. The smaller bands are attributed to a variety of absorption mechanisms and mineral sites that vary from sample to sample. Such laboratory data indicate the potential of the technique to identify certain key major minerals on the asteroid surface.
### Table 4.1. S class asteroids and ordinary chondrites in this study.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Class</th>
<th>% CPX 1 µm</th>
<th>% CPX 2µm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asteroids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 - Hebe</td>
<td>$S^{(2)}$</td>
<td>56±2</td>
<td>44±4</td>
</tr>
<tr>
<td>18 - Melpomene</td>
<td>$S^{(2)}$, $S(VI)^{(3)}$</td>
<td>65±3</td>
<td>61±3</td>
</tr>
<tr>
<td>63 - Ausonia</td>
<td>$Sa^{(2)}$</td>
<td>81±2</td>
<td>48±6</td>
</tr>
<tr>
<td>167 - Urda</td>
<td>$Sk^{(2)}$</td>
<td>45±3</td>
<td>42±6</td>
</tr>
<tr>
<td>354 – Eleonora</td>
<td>$Si^{(3)}$, $Si^{(3)}$</td>
<td>Olivine-rich$^{(4)}$</td>
<td></td>
</tr>
<tr>
<td>1036 - Ganymed</td>
<td>$S^{(2)}$, $S(V)^{(3)}$</td>
<td>45±2</td>
<td>39±4</td>
</tr>
<tr>
<td>22771 - 1999 CU3</td>
<td>$S^{(2)}$, $S(V)^{(3)}$</td>
<td>65±3</td>
<td>68±8</td>
</tr>
<tr>
<td>1999 JV3</td>
<td>$S^{(2)}$</td>
<td>58±6</td>
<td>59±3</td>
</tr>
<tr>
<td><strong>Type 3 Ordinary Chondrites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bishunpur</td>
<td>LL3.1</td>
<td>78±5</td>
<td>73±5</td>
</tr>
<tr>
<td>Parnallee</td>
<td>LL3.3</td>
<td>77±2</td>
<td>64±1</td>
</tr>
<tr>
<td>Hedjaz</td>
<td>L3.7</td>
<td>66±6</td>
<td>44±5</td>
</tr>
<tr>
<td>Dhajala</td>
<td>H3.8</td>
<td>84±7</td>
<td>63±4</td>
</tr>
<tr>
<td><strong>Type 6 Ordinary Chondrites</strong>$^{(1)}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manbloom</td>
<td>LL6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Colby (Wisconsin)</td>
<td>L6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Brudenheim</td>
<td>L6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

1. n.d., no clinopyroxene (CPX) detected
2. Class assignments from Sunshine and Pieters, 1993
3. Class assignments from Sears et al., 1980
4. Traces of pyroxene detected
Figure 4.2a. Visible/near-Infrared reflectivity spectra for an S asteroid (number 18, Melpomene). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite the absorption band at ~1.9 µm indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1)
Figure 4.2b. Visible/near-Infrared reflectivity spectra for a type 3 (unequilibrated) ordinary chondrite (Parnallee, LL class). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite the absorption band at ~1.9 µm indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1)
Figure 4.2c. Visible/near-Infrared reflectivity spectra for a type 6 (equilibrated) ordinary chondrite (Colby, Wisconsin, L class). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite the absorption band at ~1.9 μm indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1). In contrast, the equilibrated ordinary chondrite shows no evidence for clinopyroxene. These meteorite spectra are consistent with their known mineralogy and suggest that instead of having a surface of melts and partial melts, as usually inferred from the presence of clinopyroxene, the surfaces actually resemble the unequilibrated ordinary chondrites.
nebular material (Dodd et al., 1967; van Schmus and Wood, 1967; Sears et al., 1980). A characteristic feature of the type 3 ordinary chondrites is the lack of equilibration between the components, and they are therefore also referred to as the unequilibrated ordinary chondrites. In contrast, type 4-6 are equilibrated ordinary chondrites. When meteoriticists and astronomers refer to ordinary chondrites they are usually referring to the numerically dominant equilibrated ordinary chondrites.

Besides their lack of equilibration, the major discriminator between the unequilibrated and equilibrated ordinary chondrites is the presence of clinopyroxenes in the former (Dodd et al., 1967). In the least metamorphosed ordinary chondrites the pyroxene is mostly in the clinorhombic form, regardless of its other properties such as the amount of Ca in the mineral. With increasing metamorphism, the small Ca-rich clinopyroxene grains coarsen but remain as Ca-rich clinopyroxene. However, with metamorphism the dominant form of pyroxene, Ca-poor pyroxene, converts from the clinorhombic to the orthorhombic form. In going from type 3.0 to 3.9, the ratio of Ca-poor orthopyroxene to clinopyroxene increases with metamorphism until by type 4 it is all in the orthorhombic form. In the type 5 and 6 ordinary chondrites, both forms of the pyroxene continue to grow in grain size until easily observable.

We have performed a spectral analysis for four unequilibrated and three equilibrated ordinary chondrites, using data from NASA’s Planetary Data System (Fig. 4.2, Table 4.1). Using the same spectral analysis procedures that we used for our asteroid data, we find that ~40% to ~75% of the pyroxene in the unequilibrated ordinary chondrites is clinopyroxene, while as expected we found no indication of clinopyroxene in the equilibrated ordinary chondrites. This indicates a strong link between the surfaces of these S asteroids and the unequilibrated ordinary chondrites. The possibility that the
surface of certain S asteroids consists of material similar to unmetamorphosed ordinary chondrites, rather than some form of igneous material, has important implications for our understandings of the nature of S asteroids, the internal structure of these asteroids, and identity of the asteroid parent bodies for ordinary chondrites.

4.6 Conclusion

For many decades there was a major issue in identifying the heat source that caused the differentiation or metamorphism within parent bodies. With the discovery of $^{26}\text{Mg}$ in certain minerals in meteorites (Lee and Wasserburg, 1976), including those in ordinary chondrites (Hutcheson and Hutchison, 1989), it became clear that $^{26}\text{Al}$ was once abundant in these meteorites. $^{26}\text{Al}$ is a rapidly decaying isotope (half-life 0.76 million years) of a relatively abundant element that would have been an important heat source, but it would have died off rapidly. Objects that formed early would have ample $^{26}\text{Al}$ and therefore sufficient heat to differentiate their interiors and produce iron meteorites, basaltic meteorites, and stony iron meteorites (Fig. 4.3a). Judging by the variety of igneous stony meteorites, iron meteorites, and stony-iron meteorites, there are probably many such bodies (Burbine et al., 2002). Objects that formed later, say a few million years after the first-formed solids, would have interiors that underwent metamorphism but whose surfaces were unchanged, producing an onionskin structure with layers that increased in metamorphic type with increasing depth (Fig. 4.3b). This has been a long-favored model for meteoriticists as it explains many meteorite properties, such as the correlations between petrographic type and cooling rate (Kleine et al., 2008). Several authors have described thermal profiles to be expected of such objects (Akridge et al., 1998; McSween and Bennett, 1996). Objects that formed even later, say 10-20 million years, would remain essentially unaltered since the $^{26}\text{Al}$ will have decayed to insignificant levels when
they formed (Fig. 4.3c). Disruption and reaccumulation of such objects could produce Itokawa-like rubble piles (Fig. 4.3d) (Fujiwara et al., 2006). The scenarios depicted in Figs 4.3b and 4.3c would be consistent with the present results, so would the scenario in Fig. 4.3d if the object originally resembled that in Fig. 4.3c.

The ordinary chondrites coming to Earth show evidence for formation through a number of relatively recent disruption events. Many of the L chondrites, the largest of the chemical subclasses of ordinary chondrite, have K-Ar ages clustered around 500 million years, suggesting that they were once part of the same parent object that underwent a violent collision at that time (Bogard, 1995). All three of the chemical subclasses of ordinary chondrite, the others being the H and LL classes, show evidence for similar but less intense break-ups in the form of their relatively short cosmic ray exposure ages (Marti and Graf, 1992). It seems that all the H, L, and LL classes were part of a few parent objects that produced meter-sized fragments through a few recent collisional events and previously were located in the interiors of their parent asteroids. Thus it is not surprising if astronomers do not observe equilibrated material by their remote sensing techniques.

In addition to the scientific implications of our work, the linkage between asteroids and meteorites, the internal structures of asteroids, and the prevalence of chondritic materials in the asteroid belt, the present work provides new data to help in the sensible scientific choice of asteroid targets for scientific exploration of the solar system (Farquhar et al., 2002), and to the development of techniques for mitigating the impact of an asteroid on a collision course with Earth (Belton et al., 2004).
Figure 4.3. Schematic diagrams illustrating possible internal structures for asteroids and meteorite parent bodies. (a) Parent bodies forming while $^{26}$Al was abundant would completely melt and when fragmented would deliver objects to Earth resembling the many igneous stony meteorites, iron meteorites, and stony-iron meteorites. (b) Parent bodies forming a few million years later, would have sufficient heat from $^{26}$Al decay to heat but not melt the interior while the surface is unaltered. Onion-skin thermal zoning would reflect metamorphic alteration and the petrographic types 3-6. (c) Parent bodies forming later 10-20 million years later would contain no $^{26}$Al and would remain unaltered throughout. (d) Later fragmentation and reassembly would bring a mixture to the surfaces, depending on prior internal structure. While many objects resembling (a) exist, such as Vesta, the source of many basaltic meteorites, the present data are consistent with (b) and (c), and with (d) if the fragmented object originally resembled (c).
4.7 References


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this paper, and to Jeff Grossman (USGS) and Alan Rubin (University of California, Los Angeles) for discussions concerning the pyroxenes of unequilibrated ordinary chondrites.
Chapter 5: IRTF observations of S complex and other asteroids: Implications for surface compositions, the presence of clinopyroxenes, and their relationship to meteorites

This chapter is a culmination of the work in the previous chapters. We fully report on the composition of S asteroids and their relationship to ordinary chondrites. Using our infrared wavelength data coupled with visible wavelength data from online databases, I conducted an MGM analysis for each asteroid, calculated the Band Area Ratios and Band Center for each asteroid and meteorite. I collected ordinary chondrite spectral data from online databases and Daniel R. Ostrowski conducted MGM analysis for each meteorite as well assisting in the determination of the band centers. Dr. Claud H. S. Lacy provided guidance and advice to properly analyze and compare the asteroids and meteorites. Dr. Derek W. G. Sears contributed knowledge and background for meteorites; ordinary chondrites in particular

5.1 Abstract

In order to investigate the nature of the surfaces of S complex asteroids and their relationship to meteorites, we have obtained infrared spectra of 29 asteroids by using NASA’s Infrared Telescope Facility in Hawaii. We supplement these data with spectra in the visible range taken from the literature and on-line databases. We compare these data with the S(I)-S(VII) classes defined by Gaffey and his colleagues and with the taxonomic classes defined by Tholen, Bus, and their colleagues. We have also analyzed the spectra by using the Modified Gaussian Method of Sunshine and her colleagues and compare the results with similar data for meteorites and terrestrial low-calcium clinopyroxenes. The asteroids we have observed cover many or most of the Gaffey, Tholen, and Bus classes, and all of the asteroids to which these methods can be applied
(21 out of 26) appear to contain pyroxene in the monoclinic form (clinopyroxene). The amount of pyroxene that is in the clinopyroxene form tends to be \( \sim 50 \pm 10\% \) and \( 65 \pm 10\% \) in the 1- and 2-\( \mu \)m regions, respectively, with no obvious association with classification.

The rare and little metamorphosed ordinary chondrites (type 3 or unequilibrated ordinary chondrites, UOC) contain low-calcium clinopyroxene and their reflectance spectra are consistent with this composition. Eight out of ten type 3 ordinary chondrites plot in the S(IV) asteroid field on the band center vs. band area ratio plot of Gaffey et al., (1993) the field in which these authors include ordinary chondrites. In contrast to the UOC, the abundant metamorphosed ordinary chondrites (the type 4-6 or equilibrated ordinary chondrites) contain only orthopyroxene. They also plot in the S(IV) field. A popular model for the interior of ordinary chondrite parent bodies is an object internally heated by \(^{26}\text{Al}\) so that the petrologic type decreases from six at the center to three on the surface. Thermal models predict a large abundance of type 6 and small amounts of type 3, as observed in chondrite fall statistics. The isotopic ages for chondrites (K-Ar age in the case of L chondrites and cosmic ray exposure age in the case of H, L and LL chondrites), indicate that most ordinary chondrites come from the interiors of relatively few parent asteroids, and that the distribution of these ages for type 3 ordinary chondrites is significantly different and suggests additional independent parent body sources for the type 3s. While it is the location and history of just a few of these asteroids that provides the abundant type 4-6 ordinary chondrites, many of the S(IV) asteroids could be covered with type 3 ordinary chondrite material and are providing these meteorites to Earth.

5.2. Introduction

Asteroids are clearly the remnants of the materials from which the planets formed (Bottke et al., 2002). Yet they are highly diverse, reflecting a variety of nebular and early
solar system processes (Hilton, 2002; Bus et al., 2002; Gaffey et al., 2002). While considerable insights into their history and present nature have been provided by missions (Belton et al., 1992; 1994; Sullivan et al., 1996; Thomas et al., 1999; Robinson et al., 2002; Thomas et al., 2002), an explanation for this diversity still eludes us. Of special interest are the near-Earth asteroids, which are presumably the immediate parent bodies for meteorites (Burbine et al., 2002). They are also likely targets for missions of intermediate complexity between the moon and Mars (Farquhar et al., 2002), and they are the population among which impact hazards exist (Belton et al., 2004).

In the absence of returned samples, the primary source for compositional data for asteroids is reflectance spectra obtained by remote sensing, mostly by ground-based observations. Spectra in the visible wavelength range (0.4 – 0.9 µm) have been available for some time and most classification systems are based on these data (e.g., Tholen, 1989; Bus and Binzel, 2002). However, a great deal of the mineralogic information is contained in the near-infrared wavelengths (0.8 – 2.5 µm), which are becoming increasingly important with the availability of the NASA Infrared Telescope Facility. This provides additional scope for classification (Gaffey et al., 1993a). However, it is still the case that of the over 5,000 known NEAs, spectral data exist for only ~6% of them, and spectral data in the mineralogically valuable 0.8 – 2.5 µm range exist for only ~1.5%.

The present study began as an attempt to increase the number of NEA for which we had IR spectra and taxonomy, although inevitably we observed almost as many main belt asteroids. We soon realized that many or most of the asteroids, even those in the S(IV) field that might be linked to ordinary chondrites, contained clinopyroxene on their surfaces. The chondrites are divided into chemical classes (H, L, and LL) on the basis of
their metal and Fe contents (van Schmus and Wood, 1967), and into “petrographic types” on the basis of the level of solid state heating (metamorphism) on their parent bodies. Type 3 ordinary chondrites reflect the lowest levels of alteration, while type 6 reflect the highest levels of alteration, with 4 and 5 being intermediate.

We have therefore performed a multiyear study of the reflectance spectra of S asteroids, low-Ca clinopyroxene, and type 3 ordinary chondrites. Progress reports of this work have appeared as conference abstracts (Gietzen et al., 2006, 2007a, 2007b, 2008, 2009; Sears et al., 2008). The present paper is a synthesis of our data and ideas, and supersedes these abstracts.

5.3. Method

Our data were obtained by using the NASA IRTF telescope on Mauna Kea, HI between 2004 August 6 and 2008 April 18. The SpeX infrared spectrometer (Rayner et al., 2003) was used in the low-resolution prism mode, which could yield usable spectra for asteroids as faint as magnitude 17.5. The spectra covered the range 0.8 to 2.5 µm with a resolution element of 5 nm. The raw data were reduced using IRAF and IDL software. Data reduction included elimination of instrumental and atmospheric artifacts, normalization to solar analogue spectra, and production of 1-dimensional wavelength-calibrated spectra having a resolution element of 5 nm. Our spectra are available at the project web site (http://www.uark.edu/misc/clacy/SpeX_site/index.htm/).

While mineralogically important information is contained within the near-infrared (NIR) spectra, in order to perform a complete analysis using the Modified Gaussian Model (MGM) (Sunshine et al., 1990) visible spectral data were necessary. Available visible wavelength (~0.4 – 0.9 µm) data was downloaded from the Small Main Belt
Asteroid Spectroscopic Survey database (http://smass.mit.edu/smass.html) and spliced onto our IR spectra. We analyzed the spectra of each asteroid by using MGM, an asymmetric curve-fitting program that identifies absorption features as a number of inverted gaussian curves. The residuals (differences between the sums of the Gaussian curves plus continuum and the spectrum) were essentially zero.

We were particularly interested in using MGM to determine the proportion of clinopyroxene to orthopyroxene. The uncertainty in these determinations was estimated by running the MGM analysis for multiple simulated spectra in which data were allowed to fluctuate randomly within a one-sigma range indicated by counting statistics. The uncertainty was assumed to be the standard deviation shown by the clinopyroxene estimated by the MGM software using these multiple simulated spectra. This was done for nine independent asteroids, after which it became clear that our one-sigma uncertainties were typically 7% of the value estimated from a single spectrum. This value can be assumed for all the clinopyroxene estimates we report. For our meteorites, where we took the data from the literature, we performed uncertainty estimates using the same procedure for each meteorite.

The band area for each spectrum was calculated by using the ORIGIN analysis software (by OriginLab Corp.). For the 1-µm absorption band, the software used integration to determine the area under the spectral curve between the relative maxima at 0.7 and in the 1.4 – 1.7 µm region. A continuum line was then drawn between the two maxima and integration was applied to determine the total area under the continuum line. The area under the spectrum was subtracted from the continuum area, obtaining the absorption band area. The same procedure was applied to the 2-µm absorption feature
between the relative maximum in the 1.4 – 1.7 µm region and at 2.4 µm. 2.4 µm was used as the cutoff on all spectra in order to be consistent. Beyond this point the spectrum often becomes noisy.

Band centers for the 1-µm absorption feature were determined by first finding the slope of the linear continuum produced as above, finding the equation of the line, and then calculating the reflectance value for each wavelength observed in each spectrum. The continuum line was then divided out of the spectral curve and an \( N^{th} \) (\( N = 3 – 8 \)) order polynomial was fitted to the result to produce a smooth fit (Gaffey et al., 1993). The band center was then determined to be the center of the polynomial at one-third of the reflectance from the band minimum to the maximum at 1.4 – 1.7 µm.

5.4 Results

The list of asteroids we were able to observe is listed in Table 5.1, along with the date of observation, classification according to three schemes, and the amount of clinopyroxene as determined by an empirical calibration (Sunshine and Pieters, 1993). A wide variety of the various classes are represented in our data set. Many of our asteroids had not previously been classified, so we have indicated our proposed classifications.
Table 5.1.  List of asteroids observed and relevant information*.

<table>
<thead>
<tr>
<th>Asteroid number</th>
<th>Asteroid name</th>
<th>Dates obs</th>
<th>Taxonomy††</th>
<th>%CPX‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gaffey</td>
<td>Tholen</td>
</tr>
<tr>
<td>6</td>
<td>Hebe</td>
<td>4/14/05</td>
<td>S(IV)</td>
<td>S</td>
</tr>
<tr>
<td>18</td>
<td>Melpomene</td>
<td>4/14/05</td>
<td>S(V)</td>
<td>S</td>
</tr>
<tr>
<td>42</td>
<td>Isis</td>
<td>4/18/08</td>
<td>S(I)</td>
<td>S</td>
</tr>
<tr>
<td>63</td>
<td>Ausonia</td>
<td>5/30/06</td>
<td>S(II-III)</td>
<td>S</td>
</tr>
<tr>
<td>167</td>
<td>Urda</td>
<td>4/14/05</td>
<td>S(VI)†</td>
<td>S</td>
</tr>
<tr>
<td>180</td>
<td>Garumna</td>
<td>1/22/08</td>
<td>S(VI)†</td>
<td>S</td>
</tr>
<tr>
<td>234</td>
<td>Barbara</td>
<td>4/27/07</td>
<td>--</td>
<td>S</td>
</tr>
<tr>
<td>246</td>
<td>Asporina</td>
<td>1/22/08</td>
<td>S(I) †</td>
<td>A</td>
</tr>
<tr>
<td>269</td>
<td>Justitia</td>
<td>4/14/05</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>349</td>
<td>Dembowska</td>
<td>1/22/08</td>
<td>S(V) †</td>
<td>R</td>
</tr>
<tr>
<td>354</td>
<td>Eleonora</td>
<td>5/30/06</td>
<td>S(I)</td>
<td>S</td>
</tr>
<tr>
<td>1036.1</td>
<td>Ganymed</td>
<td>5/30/06</td>
<td>S(VI-VII)</td>
<td>S</td>
</tr>
<tr>
<td>1036.2</td>
<td>Ganymed</td>
<td>5/30/06</td>
<td>S(VI-VII)</td>
<td>S</td>
</tr>
<tr>
<td>1620</td>
<td>Geographos</td>
<td>1/22/08</td>
<td>S(IV)†</td>
<td>S</td>
</tr>
<tr>
<td>1980</td>
<td>Tezcatlipoca</td>
<td>12/29/06</td>
<td>S(IV)†</td>
<td>SU</td>
</tr>
<tr>
<td>2212</td>
<td>Hephaistos</td>
<td>12/29/06</td>
<td>S(IV)†</td>
<td>SG</td>
</tr>
<tr>
<td>3288</td>
<td>Seleucus</td>
<td>1/22/08</td>
<td>S(IV)†</td>
<td>S</td>
</tr>
<tr>
<td>3908</td>
<td>Nix</td>
<td>12/3/04</td>
<td>--</td>
<td>V</td>
</tr>
<tr>
<td>4450</td>
<td>Pan</td>
<td>1/22/08</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4954</td>
<td>Eric</td>
<td>1/22/08</td>
<td>S(VI)†</td>
<td>--</td>
</tr>
<tr>
<td>22771</td>
<td>1999 CU3</td>
<td>10/14/05</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>68950</td>
<td>2002 QF15</td>
<td>5/30/06</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>152895</td>
<td>2000 CQ101</td>
<td>4/27/07</td>
<td>S(V)†</td>
<td>--</td>
</tr>
<tr>
<td>170891</td>
<td>2004 TY16</td>
<td>1/22/08</td>
<td>S(V)†</td>
<td>--</td>
</tr>
<tr>
<td>152756</td>
<td>1999 JV3</td>
<td>5/30/06</td>
<td>S(IV)†</td>
<td>--</td>
</tr>
<tr>
<td>143947</td>
<td>2003 YQ117</td>
<td>5/30/06</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2005 NB7</td>
<td>2005 NB7</td>
<td>4/18/08</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

* “--” data not available; “na” method not applicable.
† Assignments based on present work.
†† Literature assignments: Gaffey, Gaffey et al. (1993a); Bus, Bus and Binzel (2002); Tholen, Tholen (1980).
‡ Estimated clinopyroxene (CPX) using the MGM software (Sunshine and Pieters, 1993). Uncertainties by the manner described in the text are typically 7%
We detected considerable clinopyroxene in all of the asteroids we observed, except the three S(I) asteroids which are olivine-rich, the Ld asteroid Justitia that has a steep and almost featureless spectrum, and Ausonia which is an S(II-III). The raw spectra for the asteroids we observed are shown in Fig. 5.1a-c, with the spectrum extended into the visible by using the SMASS database. In some instances the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) spectra overlapped with the IRTF spectra and both are shown. Typical S spectra have a deep 1 µm band and a shallower 2 µm band, and transition gradationally into spectra with the steep slopes and weaker features of, say, the L asteroid 269 Justitia. At the other extreme, the V asteroids have strong absorptions at 1 and 2 µm which are approximately equal in strength. On this basis, we suggest that the previously unclassified asteroid 143947 is a Vestoid. We do not classify asteroids 4450, Pan 2005 NB7, and 6950 2002 QF15 for lack of spectra in the visible range.

5.5 Discussion

Our discussion will focus on the determination of the mineralogy of the surfaces of our asteroids by using the BAR plot, determination of the amount of clinopyroxene by using spectrum analysis through the MGM procedure, and then a comparison of these results to data for meteorites and terrestrial low-Ca clinopyroxenes. Finally, we will discuss the implications of these results for our understanding of the links between meteorites and asteroids and possible structures of the asteroids and meteorite parent bodies.

5.5.1 Present data and the BAR plot

Figure 5.2a shows a schematic diagram of the plot of the centroid of Band I against the ratio of the area of Band II over the area of Band I and the
Figure 5.1a. Twelve raw spectra for eleven S complex asteroids reported in this paper. The data over the 0.8 – 2.5 µm range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range were not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids.
Figure 5.1b. Raw spectra for five S complex asteroids reported in this paper. The data over the 0.8 – 2.5 μm range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range were not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids.
Figure 5.1c. Raw spectra for ten S complex asteroids reported in this paper. The data over the 0.8 – 2.5 μm range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range we not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids.
Figure 5.2a Wavelength of the center of the $\sim 1 \mu m$ absorption band (Band I) against the ratio of the area under the 2 $\mu m$ band (Band II) to the area under area under the 1 $\mu m$ band (the “BAR plot”) which Gaffey et al., (1993a) used to define six groups of S complex asteroids, S(I) to S(VII). The position of the basaltic achondrites (BA), also known as the HED meteorites and which are linked to Vesta, are also indicated. A line passing through the fields is an olivine-pyroxene mixing line. Olivine rich objects plot at the left of the trend (Ol), pyroxene rich asteroids plot at the right end of the trend, ordinary chondrites (OC), which are mixtures of olivine and pyroxene, plot in the middle. Surrounding this trend are fields representing various classes including the basaltic achondrites.
Figure 5.2b Distribution of the twelve of present asteroids on this plot are identified by asteroid number. The remaining asteroids are not plotted because the method is not applicable or because we lack data in the visible range needed to characterize Band I. With the exception of asteroid 42, the asteroids plot in one of the Gaffey et al. (1993a) classes and can be assigned the classifications indicated in Table 5.1.
Figure 5.2c Distribution of twelve of the present asteroids on this plot identified by their Bus and Binzel (2002) classifications. The A and L classes plot in or close to the S(l) class and the V asteroids plot near or in the BA field. However, there appears to be no simple correlation between the remaining Bus classes and the Gaffey classes.
regions defined by Gaffey et al., (1993a) in their subdivision of the S asteroids. We refer to this as the Band Area Ratio, or BAR, plot. Running through the diagram is a heavy curve that connects olivine rich objects (S(I)) with orthopyroxene-rich objects (S(VII)). Along this “mixing line” are the classes S(IV) and S(VI). The classes S(II) and S(VI) lie above the mixing line, class S(III) straddles the mixing line. Above the orthopyroxene rich end of the mixing line are the basaltic achondrites, which contain abundant Ca-rich clinopyroxene.

We add the present asteroids to the Gaffey et al. (1993) BAR plot in Fig. 5.2b. We omit asteroids for which we have no spectral data in the visible region and thus cannot accurately determine centroid positions and band area ratios. These are asteroids 2212, 4450, 14397, 66251, 68950, 152895, and 2005 NB7. Our present suite of asteroids plot across the whole diagram, from the olivine-rich S(I) asteroids 42, 246, and 354, to the V asteroid 3908. A large fraction of our asteroids (6, 1036, 1620, 3288, and 152756) plot in the S(IV) ordinary chondrite field, while we have three S(V) asteroids (18, 349, 170881) and three S(VI) asteroids (167, 180, and 4954). Within the limits of the statistics of small numbers, this distribution of S asteroids over the seven subclasses is consistent with that of Gaffey et al. (1993a).

Figure 5.2c identifies the asteroids on the BAR plot in terms of their Bus and Tholen classifications. See also Table 5.1. In this way we compare the taxonomies based on visible spectra to those based on near IR spectra. Since both Bus and Tholen schemes are based on spectral shapes, and Bus et al. (2002) attempted to absorb the Tholen classes into their scheme, it is not surprising to see a broad level of agreement. The S(I) asteroids and their Tholen, Bus taxonomies (-- indicates no classification has been assigned) are
42 (S,L), 246 (A,A), 354 (S, Sl). There are no S(II) or S(III) asteroids in the present database. The S(IV) asteroids are 6 (S,S), 1620 (S,S), 1980 (SU, Sl), 2212 (SG,--), 3288 (S, K), and 152756 (--, S). The S(V) asteroids are 18 (S,S), 349 (R,R), 152895 (--,--), while the S(VI) asteroids are 167 (S, Sk), and 180 (S and Sq). Asteroid 1036 is classified as S(VI-VII) and is classified as (S,S). In short, there appears to be little correlation between the Gaffey classes and the classes based on visible spectra. We note that the Sq classification of S(VI) asteroid 180 is often likened to ordinary chondrites, which Gaffey et al. (1993a) associate with type S(IV). DeMeo et al. (2008) have suggested minor changes to the Bus scheme to reflect incorporation on the IR portions of the spectra into the scheme.

### 5.5.2 MGM results for the present data

A spectral analysis by the MGM method was performed on all spectra for which we could locate data in the visible region, and which had measurable bands in the 1 µm region (olivine) or both the 1 µm and 2 µm regions (pyroxene). Fig. 5.3 shows the spectra of three asteroids, one from each end of the mixing line and one from the middle, illustrating the results of the curve fitting. The mineralogical differences in the surfaces of these asteroids are readily apparent from these results. Olivine has major bands that MGM can locate at ~0.88 µm, 1.06 µm, and 1.25 µm, depending on Fe content. In the absence of pyroxene these dominate the spectra of S(I) asteroids like asteroid 42 (Fig. 5.3a). Ca-rich clinopyroxenes have seven bands that MGM can locate, the largest of which are at ~1.01 µm and ~2.27 µm, which are intense absorptions in the spectra of V asteroids like asteroid 3908 (Fig. 5.3c). Olivine and clinopyroxene are apparent in the combination of absorption bands in asteroid 3288 (Fig. 5.3b).
Results of MGM analysis of asteroid 42 Isis which plots at the olivine-rich end of the olivine-pyroxene mixing line in Fig. 5.2. The ~2 µm pyroxene band (Band II) is weak or absent in the 42 Isis spectrum, while it is the very strong in the spectrum of 3908 Nyx. The intermediate case, asteroid 3288 Seleucus, shows both Band I and Band II reflecting the presence of both olivine and pyroxene. The spectra are shown as a series of plus signs with the results of deconvolution appearing as inverted approximately gaussian curves. The continuum is shown as a broken line. The sum of the modified Gaussian curves and the continuum is shown as a smooth line passing through the spectra generally indistinguishable from it. The residuals (difference between the sum and the spectrum data points) are displaced upwards 10%
Figure 5.3b Results of MGM analysis of asteroid 3288 Seleucus that plot in the middle of the mixing line. The ~2 μm pyroxene band (Band II) is weak or absent in the 42 Isis spectrum, while it is the very strong in the spectrum of 3908 Nyx. The intermediate case, asteroid 3288 Seleucus, shows both Band I and Band II reflecting the presence of both olivine and pyroxene. The spectra are shown as a series of plus signs with the results of deconvolution appearing as inverted approximately gaussian curves. The continuum is shown as a broken line. The sum of the modified Gaussian curves and the continuum is shown as a smooth line passing through the spectra generally indistinguishable from it. The residuals (difference between the sum and the spectrum data points) are displaced upwards 10%.
Figure 5.3c  Results of MGM analysis of asteroid 3908 Nyx which plots at the pyroxene end of the mixing line. The \(~2 \mu m\) pyroxene band (Band II) is weak or absent in the 42 Isis spectrum, while it is the very strong in the spectrum of 3908 Nyx. The intermediate case, asteroid 3288 Seleucus, shows both Band I and Band II reflecting the presence of both olivine and pyroxene. The spectra are shown as a series of plus signs with the results of deconvolution appearing as inverted approximately gaussian curves. The continuum is shown as a broken line. The sum of the modified Gaussian curves and the continuum is shown as a smooth line passing through the spectra generally indistinguishable from it. The residuals (difference between the sum and the spectrum data points) are displaced upwards 10%.
Figure 5.4. Comparison of the estimate for the amount of clinopyroxene in the pyroxene as determined by the 1 µm band and the 2 µm band. While there is scatter caused by the presence of other minerals, there is a suggestion of bimodality in the clinopyroxene abundance, a cluster at 50% and another at 70%. The data points identified by asteroid number are S(IV) asteroids that appear in both clusters. The diagonal is a unity line. While to the first order, there is agreement between the two clinopyroxene estimates, five of the asteroids plot more than two-sigma from the diagonal. These are asteroids 180, 349, 1620, 3908, and 3288, which represent a variety of classes.
Estimates for the relative amounts of clinopyroxene and orthopyroxene based on the ~1 µm and 2 µm bands appear in Table 5.1 and are plotted in Fig. 5.4. While the data scatter due to the presence of other mineral phases, there is reasonable agreement with the estimates based on the 1 µm band and the 2 µm band with a suggestion of clustering at ~50% and ~70%. There is no readily apparent relationship between position on the plot and asteroid class.

5.5.3 Spectra of meteorites analyzed by BAR

As Gaffey et al. (1993a) showed, the ordinary chondrites plot within the area of the BAR plot described as class S(IV). The chemical classes of ordinary chondrite, the H, L, and LL classes (Gastineau-Lyons et al., 2002), are resolvable within this field because their difference in oxidation state is reflected in a difference in the olivine-pyroxene ratio (Sears et al., 1996). H chondrites are concentrated at the bottom of the field, then L chondrites, and the LL chondrites—which show a wide range in their oxidation state (Sears and Axon, 1978)—are spread widely through the rest of the field. Indicated in Fig. 5.5 are the locations of ten unequilibrated ordinary chondrites. Eight of the UOC plot among the equilibrated chondrites and the S(IV) asteroids.

Figure 5.6 shows examples of near-IR spectra for an unequilibrated (Fig. 5.6a) and an equilibrated ordinary chondrite (Fig. 5.6c), which can be compared with the spectra of clinopyroxene (Fig. 5.6b) and orthopyroxene (Fig. 5.6d), which are discussed below. There are major differences in the spectra of these two meteorites. The unequilibrated ordinary chondrite Parnallee (Fig. 5.6a) shows absorption bands due to olivine, orthopyroxene, and clinopyroxene, while the equilibrated ordinary chondrite Colby (Wisconsin) shows only dips due to olivine and orthopyroxene. When quantitative MGM
Figure 5.5. The BAR plot of Gaffey et al. (1993a) on which data for ten type 3 ordinary chondrites (also known as unequilibrated ordinary chondrites, or UOC) from the Planetary Data System (Gaffey et al., 1972) have been plotted. All but two plot in the $S(IV)$ field in which equilibrated ordinary chondrites (EOC) plot. The meteorites are identified by their first three letters, Bishunpur, Dimmitt, Hedjaz, Krymka, Tieschitz, Dhajala, Chainpur, Parnalle, Mező-Madaras, and Gorlovka.
Figure 5.6. Results of MGM analysis of (a) a type 3 (UOC) meteorite, (b) a terrestrial clinopyroxene, (c) a type 6 (EOC) meteorite, and (d) a terrestrial orthopyroxene (taken from Sunshine and Pieters, 1993). See caption to Fig. 5.3 for an explanation of the details. Several decades of mineralogical and petrographic investigation have shown that much of the pyroxene in unequilibrated ordinary chondrites is entirely in the monoclinic form (clinopyroxene) while in equilibrated ordinary chondrites the pyroxene is in the orthorhombic form (orthopyroxene). These known mineralogical differences between UOC and EOU are readily apparent in their reflectance spectra. Our clinoenstatite sample was slightly weathered and water features were observed, but these were successfully removed during MGM analysis.
Table 5.2. Results of MGM analysis of meteorites

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Class</th>
<th>% CPX‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 µm</td>
</tr>
<tr>
<td><strong>Type 3 Ordinary Chondrites</strong></td>
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<td></td>
</tr>
<tr>
<td>Bishunpur</td>
<td>LL3.1</td>
<td>78±5</td>
</tr>
<tr>
<td>Parnallee</td>
<td>LL3.3</td>
<td>77±2</td>
</tr>
<tr>
<td>Hedjaz</td>
<td>L3.7</td>
<td>66±6</td>
</tr>
<tr>
<td>Dhajala</td>
<td>H3.8</td>
<td>84±7</td>
</tr>
<tr>
<td><strong>Type 6 Ordinary Chondrites</strong>(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manbloom</td>
<td>LL6</td>
<td>n.d.</td>
</tr>
<tr>
<td>Colby (Wisconsin)</td>
<td>L6</td>
<td>n.d.</td>
</tr>
<tr>
<td>Brudenheim</td>
<td>L6</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

‡ Estimated using the MGM software (Sunshine and Pieters, 1993). Uncertainties were estimated for each spectrum using the methods described in the text.
results for the unequilibrated ordinary chondrites are empirically calibrated using terrestrial mineral mixtures in the manner described by Sunshine and Pieters (1993), the amount of clinopyroxene found to be in the unequilibrated ordinary chondrites is as shown in Table 5.2. The amounts of clinopyroxene observed in the unequilibrated ordinary chondrites are comparable with the amounts observed in the asteroids, especially the upper “cluster” in Fig. 5.4.

The structural form of the pyroxene is a major discriminator in separating equilibrated from unequilibrated ordinary chondrites. High-Ca pyroxenes in the monoclinic form occur in ordinary chondrites, regardless of petrographic type. However, the more abundant low-Ca pyroxenes are in the monoclinic form in the type 3 but convert to the orthorhombic form in the types 4-6. There are thus important issues to resolve here, and they relate to the decades old issue of why equilibrated ordinary chondrites are so abundant on Earth yet rare in the asteroid belt but convert to the orthorhombic form in the types 4-6. (Chapman, 1976; Wetherill and Chapman, 1988; Gaffey, 1992, 1995; Chapman, 1996). Virtually all S asteroids contain clinopyroxene, while most ordinary chondrites (the equilibrated ordinary chondrites) contain mostly orthopyroxene. Could it be that the surfaces of the S asteroids, particularly the S(IV) asteroids, are more closely related to the unequilibrated ordinary chondrites than the far more numerous equilibrated ordinary chondrites?

In Fig. 5.7 we show the BAR plot with a line running parallel to the orthopyroxene-olivine mixing line, but originating in the basaltic achondrite box, the V asteroids, and terminating in the olivine field. Basaltic achondrites, a not-altogether correct term for the Howardite-Eucrite-Diogenite meteorites related to Vesta and the V asteroids (McCord et al., 1970; Frierberg and Drake, 1980; Drake, 2001; Cochran et al., 2004), contain
Figure 5.7. The BAR plot with two mixing lines indicated. The solid line is the line suggested by Gaffey et al. (1993a) and thought to represent the mixing of olivine and orthopyroxene. The broken line is the same line pinned at olivine end and adjusted upwards at the pyroxene end to pass through the BA field in which the pyroxene is known to be in the monoclinic form. It would be tempting to suggest that this upper line refers to the olivine-clinopyroxene mixing. However, all the asteroids in the present study and the UOC that plot in the S(IV) field contain a mixture of orthopyroxene and clinopyroxene, so the lower line reflects the presence of orthopyroxene rather than being pure orthopyroxene. This would suggest the upper line represents olivine-Ca-rich pyroxene mixing and the lower represents olivine-Ca-free pyroxene mixing.
abundant high Ca clinopyroxene (Duke and Silver, 1967; Buchanan and Reid, 1996; Mayne et al., 2009). This hypothetical mixing line, drawn simply by displacing the existing line upwards, passes through the S(II), S(III), and S(V) fields. It is commonly assumed that Ca-rich clinopyroxenes are always associated with volcanism, or at least melts or partial melts, and that classes S(II), S(III), and S(V) represent igneous assemblages not observed among the meteorite population or the common terrestrial igneous rocks (Sunshine et al., 2004). Now we observe that Ca-poor clinopyroxenes of the sort commonly observed in the unequilibrated ordinary chondrites are abundant in the S(IV), chondrite-like, asteroids. There is a laboratory test that can be applied to this suggestion, which is to obtain the near-IR spectra of the terrestrial low calcium clinopyroxene, clinoenstatite.

5.5.4 Spectra of clinoenstatite (Ca-free clinopyroxene) analyzed by MGM

We obtained a Ca-free clinoenstatite from Napouli, New Caledonia (Smithonian Institution catalog number NMNH 163346), similar to the clinopyroxene found in type 3 ordinary chondrites and obtained its near-IR spectra using equipment in our own laboratory and the RELAB facility at Brown University. We analyzed the spectra using the MGM software. Representative results are shown in Fig. 5.6, along with an orthopyroxene spectrum taken from Sunshine and Pieters (1993). The similarity of the Parnellee and clinoenstatite spectra is apparent, both having fairly strong dips at ~2.0 and ~2.4 μm, as well as dips at ~1.0 μm. Both the Colby and orthopyroxene samples share the properties of a dominant band at ~2.0 μm relative to the band at ~2.4 μm, and both have a 1 μm dip. These observations are consistent with the known mineralogy of the meteorites, and with prior observations of the properties of these terrestrial pyroxenes (Cloutis and Gaffey, 1991; Sunshine and Pieters, 1993).
5.5.5 Meteorite-asteroid link

All the type 3 ordinary chondrites plot with the ordinary chondrites in the S(IV) field of the BAR plot, consistent with a similar mineralogy. However, all of the type 3 ordinary chondrites, by definition, contain pyroxene in the monoclinic form, which is Ca free and spectra for terrestrial clinopyroxenes are consistent with this composition. Additionally, all the S asteroids we have examined that plot in the S(IV) field contain clinopyroxene characteristic of type 3 ordinary chondrites. It therefore appears that all of the S asteroids in the S(IV) field have material on their surfaces resembling type 3 ordinary chondrites.

No chondritic meteorites, equilibrated or unequilibrated, plot in the S(II), S(III), S(V) fields, and there is no evidence for a relationship between these asteroids and ordinary chondrite meteorites. The S(II), S(III), S(V) asteroids plot on the Ca-rich clinopyroxene – olivine mixing line, suggesting that they contain calcic clinopyroxene and may have an origin as melts or partial melts, as advocated by Gaffey et al. (1993a, Sunshine et al. (2004), and Gaffey (2007).

5.5.6 Concepts for meteorite parent bodies and the nature of asteroid surfaces

The abundance of differentiated meteorites, the achondrites, the irons, and the stony irons, now known to be the product of a wide variety of igneous processes (Chabot and Haack, 2006; McCoy et al., 2006), was for many years perplexing, given that the only known source for heating such bodies were the long-lived isotopes of U, Th and K (Wood, 1967a, b). Only objects larger than 800 km could build up enough heat to differentiate such objects. However, with the discovery of $^{26}$Mg excesses in the Al-rich, Mg-poor phases of meteorites, it became clear that now extinct $^{26}$Al was once present in the solar system (Lee et al., 1976). With its high relative abundance (Al is the 13th most
abundant element in cosmic abundance), and its geologically rapid rate of decay (its half life is 0.76 Ma), $^{26}\text{Al}$ must have been the major heat source in the early solar system, capable of melting every asteroid greater than 5 km if the highest inferred values of $^{26}\text{Al}/^{27}\text{Al}$ were commonplace (Lee et al., 1976). However, the effectiveness of $^{26}\text{Al}$ in heating objects depends not just on their size, but on their accretion times, so objects accreting two half-lives later would incorporate only one-fourth of the isotope. Thus we have the scenarios described in Fig. 5.8. Early formed or larger objects would differentiate to produce a variety of igneous rocks, lunar-like and Vesta-like anorthosites and basalts on their surfaces, metallic objects at their cores, and pallasite (stony iron) meteorites at the core-mantle interface (Fig. 5.8a). Variations on this theme, magma chambers ejecting materials to higher layers, and impact mixing (with or without melting), would produce a wide variety of objects similar to those seen in the meteorite collection and inferred from the asteroid spectroscopy.

Smaller objects, or objects forming later, would be heated in their interiors and unheated at their surfaces, and produce concentric (onion skin) zones of increasing metamorphism that decrease from the interiors to their surfaces (Fig. 5.8b). Several authors have performed calculations to determine thermal profiles, and most predict a large interior volume of heavily heated material and smaller amounts of the less altered material towards their surface (McSween and Bennett, 1996; Ackridge et al., 1998). The main factor determining the thermal profile is the assumed thermal conductivity, which depends mostly on the nature and thickness of unconsolidated surface layers.
Figure 5.8. Models for the interiors of S complex asteroids. (a) Objects that form when $^{26}\text{Al}$ is still present in the solar system and which are large enough will melt and differentiate to form a core, mantle and crust. Meteorites are known that appear to represent these objects, such as iron meteorites from cores, stony-iron meteorites from the interface, and various differentiated meteorites that represent mantle and crust of their parent asteroids. (b) Objects that formed later or were too small to retain enough heat for complete melting will have a heated interior and unheated surface with concentric zoning of metamorphic alteration that increases with depth. The thickness of the layers will depend on composition, amount of $^{26}\text{Al}$, and—most importantly—the thermal properties of the layers. However all models predict a volumetrically large amount of type 6 material and relatively smaller amounts of the outer layers, consistent with the observed ordinary chondrite flux to Earth. (c) Asteroids forming after decay of $^{26}\text{Al}$, or too small for significant heating by $^{26}\text{Al}$, will resemble type 3 material throughout. Astronomical spectroscopy seems to be detecting asteroids with surfaces resembling the first three models, the scarcity of ordinary chondrites without clinopyroxene implies that few are exposing their interiors, the notable exceptions being the Q asteroids that closely resemble the equilibrated ordinary chondrites. (d) After formation impact could disrupt the object and allow mixing, so the surface would reflect the prior internal nature of the asteroid.
Even smaller objects, or objects forming even later, would experience little or no internal heating and remain unaltered throughout (Fig. 5.8c). Their composition and structure would depend on the nature of the material in the solar nebula prior to accretion and the processes that accompanied accretion. In the outer asteroid belt, or among the later formed asteroids that capture no $^{26}$Al, these would resemble the C chondrites and the C and X asteroids (Lunine, 2006). In the inner asteroid belt, or among the objects that were otherwise too warm to accrete ices (perhaps they contained traces of $^{26}$Al), asteroids resembling the type 3 ordinary chondrites were formed.

The final episode of asteroid evolution, at least among some asteroids, was probably fragmentation and reassembly to produce the rubble piles that are often discussed (Michel et al., 2001) and that have been directly observed in the case asteroid Itokawa (Fujiwara et al., 2006). The nature the surfaces of such objects will depend on the nature of the precursor asteroid. Forming a rubble pile of an initially uniform object would not change its surface composition. Disruption of fully differentiated objects or internally metamorphosed objects would bring very different kinds of material to the surface. This of course, would be consistent with the wide variety of asteroid surfaces inferred from spectroscopy (Gaffey et al., 1993b).

It is tempting to relate the classes of S asteroid described in Fig. 5.2a to the scenarios described in Fig. 5.8. Gaffey et al. (1993a) effectively did this by identifying the mineralogy of the surfaces through reflectance spectroscopy. Thus the upper mixing line in Fig. 5.7 might represent a variety of objects from differentiated bodies described by Fig. 5.8a. Olivine cumulates that would form at the bottom of magma chambers, plot at one end, and basalts that would be associated with various stages of volcanism at the other. Variations in these processes produce asteroid classes in between. Along this line
plot the meteorites such as the HED, the lodranites, winonites, ureilites and pallasites which appear to be mixtures of olivine and clinopyroxene.

The lower mixing line in Fig. 5.7 was identified by Gaffey et al. (1993a) mixtures of orthopyroxene and olivine such as observed in the lodranites, mesosiderites, ordinary chondrites and pallasites. Except for the ordinary chondrites, these meteorite classes are the result of igneous processes, probably related to impact in the case of mesosiderites, and would also be associated with a differentiated parent body. Ordinary chondrites came from a parent body in which only metamorphism occurred (Figs. 5.8b and 5.8c), and being a mixture of olivine and orthopyroxene, it comes as no surprise that the equilibrated ordinary chondrites plot on this line among the S(IV) asteroids.

The major effect of space weathering (i.e., the results of exposure to the space environment) on the Moon, for which it has been well studied, is the formation of nanophase iron phases that redden the spectrum (McKay et al., 1991). It is usually assumed that the same reddening will occur on asteroids as a result of the exposure of their surfaces to the space environment (Chapman, 1996; Binzel et al., 2004b), and experiments involving laser irradiation and ion bombardment have reproduced this process in the laboratory (Brunetto and Strazzulla, 2005; Sasaki et al., 2002). However, there are major differences in the composition and impact environment of the Moon and asteroids (McKay et al., 1991).

Probably the best experimental data on asteroid fragmentation history are the ages of meteorites, in particular the K-Ar ages (in the case of L chondrites, Bogard, 1995) and the cosmic ray exposure ages (in the case of all the ordinary chondrites, Eugster et al., 2006). The L chondrites show an often-discussed peak in the K-Ar ages at ~0.5 Ma and the meteorites most clearly showing this age are the shock-blackened ordinary chondrites.
Apparently at this time the L chondrite parent object underwent a major break-up, so that most suffered a complete loss of $^{40}$Ar and resetting of their K-Ar ages. Others not as much affected by the heat, maybe those closer to the surface or further from the point of impact, may have suffered less or little, to give a dispersion in apparent ages. These effects can be disentangled to some degree by the Ar-Ar method, which determines the degree of gas loss and identifies those for which a reliable age can be calculated. Fig. 5.9 shows the ages determined this way. These data indicate that the majority and probably all of the L chondrites were produced from the breakup of a single parent object. Of course, if other similar L chondrite asteroids were in the solar system now, they will not visible by terrestrial techniques looking at their surfaces.

Cosmic ray exposure ages reflect the time at which the bodies became meter sized and penetrable by cosmic radiation. Prior to that we must assume the bodies were shielded inside larger bodies. It is therefore highly significant that cosmic ray exposure ages for ordinary chondrites are very short, generally less than 100 Ma, again implying that the majority of meteorites came from the interior of bodies recently disrupted. There is also clustering of ages that appear as peaks in the cosmic age distributions. The peak at 8 Ma for the H chondrites, 17 Ma for the LL chondrites, and possibly several peaks at 4, 20 and 50 Ma in the L chondrites have been frequently discussed (Eugster et al., 2006). It is therefore no surprise that astronomical observations should not see material resembling the chondrites on Earth.

If ordinary chondrites are coming from metamorphically zoned asteroids similar to those in Fig. 5.8b, then one might expect the type 3 chondrites to be coming from any number of asteroids, released by moderately sized impacts. These impacts need not be large enough to disrupt the body, and could be quite gentle. Therefore they would not
Figure 5.9. The distribution of K-Ar age (determined by the Ar-Ar method) for L chondrites shows a large proportion of members with 0.5 Ga ages, suggesting that until that time these meteorites were part of the same parent object. Consistent with a major and violent break-up event, most of the L chondrites in the 0.5 Ga peak are shock blackened. The shading refers to meteorites that have plateau in their Ar release patterns, and that have been undisturbed since the event that reset their K-Ar clock. Such data indicates that most or probably all of these meteorites came from the interior of their parent asteroid and would not be observed by astronomical techniques. This diagram is a simplified version of a figure in Bogard, 1996.
be expected to show the same cosmic ray exposure age distribution as the equilibrated ordinary chondrites that required major disruption events, particularly the L chondrites.

Figure 5.10 shows the cosmic ray age histograms for the H3, L3 and LL3 chondrites in comparison with the equilibrated ordinary chondrites, \(^{21}\text{Ne}\) data taken from the compilation of Schultz and Frank (2004) averaging data for a single meteorite and assuming a production rate or \(0.3 \times 10^{-8} \text{ cc/g/Ma}\) (Leya et al., 2000). For each of the chemical classes, H, L and LL, there are significant differences between the age distribution of the equilibrated and unequilibrated ordinary chondrites. In the case of the H3 chondrites, the peak at 8 Ma that dominates the equilibrated chondrites is still apparent in the unequilibrated ordinary chondrites, but so is a major peak at ~25 Ma which is absent in the equilibrated chondrites (Fig. 5.10a). For the L3 chondrites there is a major peak at ~2 Ma, which is absent in the equilibrated chondrites (Fig. 5.10b). For the LL3 chondrites the 17 Ma peak is absent but there is a peak at ~5 Ma that is absent in the equilibrated ordinary chondrites (Fig. 5.10c).

Since many of these meteorites are finds from highly productive field areas, like the Allan Hills of Antarctica, it is possible that peaks in the relatively small type 3 populations could be the result of unrecognized pairing. Pairing is the term used to describe fragments of a meteorite that fragmented in the atmosphere and strew pieces over a large region. These are common among observed falls, and readily recognizable as such, but among the finds of Antarctica or the deserts the abundance of meteorites and their movement by wind and ice flow make it difficult to identify paired fragments and this is a constant issue for statistical studies. We therefore list in Table 5.3 the meteorites
Figure 5.10a Cosmic ray exposure ages for ordinary chondrites calculated from $^{21}\text{Ne}$ concentrations obtained from the compilation by Schultz and Frank (2004) assuming a production rate of $0.3 \times 10^{-8}$ cm$^3$ STP/(gGa) (Leya et al., 2000). Multiple determinations for a single meteorite have been averaged. For each of the chemical classes, H, L and LL, the type 3 (unequilibrated) and type 4-6 (equilibrated) ordinary chondrites are shown. The presence of peaks in these histograms suggests meteorite formation by fragmentation of a single parent object. All three chemical classes show differences in the distribution for type 3 compared with type 4-6 suggesting that some fraction came from separate parent objects. Examples are the $\sim$25 Ma peak for the H chondrites, the $\sim$2 Ma peak for the L chondrites and the $\sim$5 Ma peak for the LL chondrites. Conversely, peaks are sometimes present in the type 4-6 distributions that are absent from the type 3 distributions, such as 52-55 Ma peak for L4-6 chondrites and the $\sim$38 Ma peak for LL4-6. The $\sim$2 Ma peak for the L3 chondrites may be due to pairing, a large number of meteorite fragments being unrecognized fragments of the same meteorite, but for the H and LL ordinary chondrites there appear to be genuinely different distributions for the type 3 and type 4-6 ordinary chondrites that suggest origins for some fraction of the type 3s on different parent bodies.
Figure 5.10b. Cosmic ray exposure ages for ordinary chondrites calculated from $^{21}$Ne concentrations obtained from the compilation by Schultz and Frank (2004) assuming a production rate of $0.3 \times 10^{-8} \text{ cm}^3 \text{ STP/(gGa)}$ (Leya et al., 2000). Multiple determinations for a single meteorite have been averaged. For each of the chemical classes, H, L and LL, the type 3 (unequilibrated) and type 4-6 (equilibrated) ordinary chondrites are shown. The presence of peaks in these histograms suggests meteorite formation by fragmentation of a single parent object. All three chemical classes show differences in the distribution for type 3 compared with type 4-6 suggesting that some fraction came from separate parent objects. Examples are the ~25 Ma peak for the H chondrites, the ~2 Ma peak for the L chondrites and the ~5 Ma peak for the LL chondrites. Conversely, peaks are sometimes present in the type 4-6 distributions that are absent from the type 3 distributions, such as 52-55 Ma peak for L4-6 chondrites and the ~38 Ma peak for LL4-6. The ~2 Ma peak for the L3 chondrites may be due to pairing, a large number of meteorite fragments being unrecognized fragments of the same meteorite, but for the H and LL ordinary chondrites there appear to be genuinely different distributions for the type 3 and type 4-6 ordinary chondrites that suggest origins for some fraction of the type 3s on different parent bodies.
Figure 5.10c. Cosmic ray exposure ages for ordinary chondrites calculated from $^{21}$Ne concentrations obtained from the compilation by Schultz and Frank (2004) assuming a production rate of $0.3 \times 10^{-8} \text{ cm}^3 \text{ STP/(gGa)}$ (Leya et al., 2000). Multiple determinations for a single meteorite have been averaged. For each of the chemical classes, H, L and LL, the type 3 (unequilibrated) and type 4-6 (equilibrated) ordinary chondrites are shown. The presence of peaks in these histograms suggests meteorite formation by fragmentation of a single parent object. All three chemical classes show differences in the distribution for type 3 compared with type 4-6 suggesting that some fraction came from separate parent objects. Examples are the ~25 Ma peak for the H chondrites, the ~2 Ma peak for the L chondrites and the ~5 Ma peak for the LL chondrites. Conversely, peaks are sometimes present in the type 4-6 distributions that are absent from the type 3 distributions, such as 52-55 Ma peak for L4-6 chondrites and the ~38 Ma peak for LL4-6. The ~2 Ma peak for the L3 chondrites may be due to pairing, a large number of meteorite fragments being unrecognized fragments of the same meteorite, but for the H and LL ordinary chondrites there appear to be genuinely different distributions for the type 3 and type 4-6 ordinary chondrites that suggest origins for some fraction of the type 3s on different parent bodies.
Table 5.3. Type 3 ordinary chondrites occupying peaks in the cosmic ray exposure age distributions where those peaks are weak or absent in the type 4-6 distributions*.

<table>
<thead>
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<th>Meteorite</th>
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<th>Meteorite</th>
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<th>Meteorite</th>
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<td>Adzhibogdo</td>
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<td>ALH77214</td>
<td>L3.4</td>
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<td>Yamato 2133</td>
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</table>

* ALH refers to Allan Hills.
populating the peaks in the histograms for the type 3 ordinary chondrites that are weak or absent among the peaks in the histograms of type 4-6 ordinary chondrites. For the ~25 Ma H3 chondrite peaks, there are several Acfer meteorites and one from the nearby Hammadah al Hamra that could conceivably be paired, but the others are sufficiently disperse in time and place of fall and properties that this possibility can be eliminated. Even assuming maximum pairing, the difference between the type 3 and the type 4-6 histograms remains. This is not true of the L chondrite histograms, where large number of Allan Hill meteorites of type ~3.4 are present that could be paired. Like the H chondrite case, the LL chondrite ~5 Ma peak in the histogram type 3 does not appear to be the result of pairing, the meteorites being too separate in time and place of fall and petrographic properties. Most are observed falls.

There are also peaks present in the histograms for type 4-6 chondrites that are absent in the histograms for type 3 chondrites, such as the 38 Ma peak in the LL4-6 chondrites and the 52-55 Ma peak in the L4-6 chondrites. Overall, there is reasonable evidence that many of the type 3 ordinary chondrites are not sharing the fragmentation history of their type 4-6 equivalents.

The case is even stronger when one considers that the absence of a peak in the cosmic ray age distributions cannot be interpreted. Many factors affect cosmic ray exposure age determination, production rate variations due to shielding and target composition, and errors and uncertainties in the measurement, for example. But a peak is significant and difficult or impossible to create artificially, and must mean a common disruption effect. Similarly, the differences in the distributions of ages for type 3 and type 4-6 in Fig. 5.10 are greater than indicated, because of uncertainties in classification, both chemical class and petrographic type. These uncertainties tend to smooth out
differences. It seems very likely on the basis of Fig. 5.10 that the type 3 ordinary chondrites are not necessarily coming from the same parent objects that produced the much more common equilibrated ordinary chondrites.

5.6 Conclusions

The twenty-one asteroids we observed were spread over the classes of Gaffey et al. (1993) and Bus and colleagues, and included five in the S(IV) class associated with ordinary chondrites, along with lodranites, certain urielites, winonites and IAB irons. All of the asteroids we observed contain clinopyroxene on their surfaces, consistent with previous work, including the S(IV) asteroids. We conclude that many, perhaps most, of the S(IV) asteroids are type 3 ordinary chondrites, otherwise known as unequilibrated ordinary chondrites (UOC). These are relatively rare types of ordinary chondrite terrestrially, the far more common ordinary chondrites being type 4-6 (or equilibrated ordinary chondrites, EOC). Type 4-6 ordinary chondrites do not contain clinopyroxene because parent body metamorphism has converted it to orthopyroxene. We conclude that the surfaces of many asteroids resemble type 3 ordinary chondrites in composition, the higher types coming from the metamorphosed interiors of their asteroid parents where they are not visible to astronomical observation. The majority of ordinary chondrites on Earth came from the breakup of a few asteroids located in the asteroid belt in manner favoring their transport to Earth. Isotopic dating of ordinary chondrite break-up events is consistent with this.
5.7 References


140


Chapter 6: Conclusions and Future Work

6.1 Conclusions

This research has examined the properties and relationships between the Near-Earth and Main Belt asteroid populations. Delving into the populations, the properties, compositions and relationships of the taxonomic classes (S Complex asteroids in particular) were studied. These properties were used to make a comparison and ultimately a link between them and meteorites, in particular the ordinary chondrites.

Since the lifetimes of Near-Earth asteroids are relatively short ($10^6 – 10^7$ yrs), it is thought that the NEA population is being continually resupplied by the Main Belt asteroids. In our statistical examination of the relationships between the two populations, we found that the NEA population is not a representative random sample of the MBA population. The relative abundances of several taxonomic classes displayed significant differences. The Q, Sq and O taxonomic classes were found to be statistically more abundant in the NEA population while the Ch taxonomic class is more abundant in the MBA population. The Sq class in particular has been linked to the ordinary chondrites which are the most abundant meteorites found on Earth. We see no evidence in the orbital elements of the main belt asteroids of a clustering of asteroids near a resonance that explains a large number of group members in the NEA.

Most asteroid taxonomies are based on information in the visible wavelengths of asteroid spectra. As a result, we find significant ambiguity in these asteroid classification schema. The available spectrum for asteroid 1989 ML is only in the visible range of wavelengths. We show that this spectrum can be matched to a number of meteorites from different meteorite types. When the spectra is extended into the near-infrared
wavelengths, much more information is available and provides a much clearer picture of an asteroid’s nature and composition. Recently, there have been ventures into developing taxonomies (Bus-DeMeo) that utilize the rich infrared area of the spectra.

We observed twenty-seven S and possible S Complex asteroids that were determined to be spread over the classes of Gaffey et al. (1993) and Bus and colleagues, which included five in the S(IV) class associated with ordinary chondrites, along with lodranites, certain urielites, winonites and IAB irons. We found all of the asteroids contain clinopyroxene on their surfaces. Since clinopyroxene (Ca-free) is found in the type 3 ordinary chondrites, we show evidence for a connection with the S asteroids. We conclude that many, perhaps most, of the S(IV) asteroids are type 3 ordinary chondrites, otherwise known as unequilibrated ordinary chondrites.

6.2 Future Work

Spectral data collected using the NASA Infrared Telescope Facility represent a very small percentage of the S asteroids. Extraction of existing data from the available database would allow for a more thorough examination of the mineralogy of the S asteroids and their connections with meteorites. Future work could also investigate the proposition based on models that asteroids that incur a collision with a hypervelocity impactor are completely disrupted. The pieces then recoalesce into a homogeneous asteroid. This would explain the lack of significant differences in the spectra of members within a family of asteroids since the core, mantle and surface materials are expected to be different compositions. This research would involve combining the spectra of meteorites, ordinary chondrites in the case of S asteroid families in different proportions in order to obtain spectra matching that of the family asteroids.
INDEX OF FIGURES

Figure 1.1. Oil painting of Giuseppe Piazzi and Ceres. It is believed that this was painted by the Sicilian artist Giuseppe Velasco at the beginning of the nineteenth century, possibly 1803. Courtesy of the Palermo Astronomical Observatory (Serio et al., 2002) ................................................................. 2

Figure 1.2. Number of known asteroids as a function of time. Note the change of scale for the last interval. Data from the NASA Data Planetary System. ................................. 4

Figure 1.3. Component Space plot from Bus 1999 showing the three complexes and the outlier T, D, Ld, O and V taxonomic classes. Lines inserted by this author indicating the approximate boundaries between the complexes .............................. 9

Figure 1.4. Because of current support by NSF and other agencies, near-Earth asteroids are being discovered at record rates. This science, exploration and impact mitigation efforts, all of which are well served by the information on surface compositions to be determined in the present work ......................................................... 14

Figure 1.5. The asteroid Eros as it appeared to the NEAR-Shoemaker spacecraft ........ 17

Figure 1.6. Knowledge of the surface composition of objects likely to collide with Earth is critical to many of the proposed methods of deflection (Sears et al., 2001). Some methods depend on the presence of volatile compounds, others depend on mechanical properties ................................................................. 19

Figure 1.7 Barringer Meteor Crater, Arizona, USA – 1.2 km diameter (Schweickart et al., 2008). ................................................................................................................... 24

Figure 2.1. Histogram of asteroid class populations in the main belt and near-Earth asteroids based on data in the PDS and EARN and using the taxonomy of Bus (1999). The instances of significant differences in the class population for the MBA and NEA at the 0.999 level of confidence are indicated with arrows. In three instances the classes are better represented in the MBA than NEA (Ch and Sl), while in five instances the classes are better populated in the NEA than MBA (O, Q, Sk, Sq, and Sr) ................................................................................................................. 37

Figure 2.2. The sizes of the asteroid classes for the (a) MBA and (b) NEA represented as pie charts. There are 26 classes identified in the Bus taxonomy, and all are represented in both the NEA and MBA populations, except for Cgh for which there are 20 on the main belt and none in the NEA population (although this is not statistically significant) .......................................................................................... 38

Figure 2.3. Pie charts for the populations of the asteroid complexes, S, C, X, and Q for (a) MBA and (b) NEA, where complexes consist of taxonomically similar classes. The proportions of the S and X complexes are not significantly different between the MBA and NEA, but the proportions of Q and C are significantly different, the MBA consisting of a larger C complex and small Q complex while for the NEA this is reversed .......................................................................................................................... 45
Figure 2.4. (a) Pie charts comparing the class sizes in the MBA (left column) and class sizes in the NEA populations (left column) for classes showing statistically significant differences. There is one Q asteroid among the MBAs and 32 among the NEAs. For the Sq asteroids, these numbers are 64 and 66, respectively. (b) The proportions of the three S complex classes, Sr, Sl and Sk, within their parent populations are very similar for (a) MBA and (b) NEA, (9.7% and 10.1% by number, respectively), but the relative proportions of these four classes within these parent populations is statistically significantly different (for example, 0.8% and 4.0% for the Sr class in MBA and NEA, respectively). ................................ 50

Figure 2.4. (c) Pie charts for the Ch class of asteroid for which the (a) MBA and (b) NEA show a statistically significant difference in abundance, the MBA containing 196 of this taxonomy and the NEA contain 1. (d) Pie charts for the O class of asteroid for which the (a) MBA and (b) NEA show a statistically significant difference in abundance, the MBA containing 1 of this taxonomy and the NEA contain 6. .............................................................................................................. 51

Figure 2.5. Histograms of cosmic ray exposure ages for the three major groups of ordinary chondrites, showing that a number of discrete break up events have occurred in their histories. The H chondrite parent body underwent a single major break up event 8 Ma ago, while the L chondrites experienced many events at ~5, ~15 ~22 and 45 Ma, for instance. The LL chondrite apparently underwent a major break-up at ~17 Ma. Spread around these values could be caused by subsequent fragmentation, previous irradiation events, or analytical uncertainly in the determination of the cosmogenic isotopes used for these calculations. (Figure after Eugster et al., 2006). .................................................................................... 54

Figure 2.6. Distribution of K-Ar ages for L chondrites determined by the Ar-Ar method, the shading refers to data quality. The two peaks refer to formation (nominally ~4.5 Ga, but lowered slight by $^{40}$Ar diffusive loss) and a major reheating event at ~0.5 Ga which caused thermally driven loss of $^{40}$Ar and a resetting of the K-Ar clock. Meteorites associated with the 0.5 Ma parent body break up event show numerous petrographic signs of shock and heating, in fact most of the meteorites were shock-blackened by the event. These data are evidence that many or most of the L chondrites were part of a single parent body prior to the event and that the ordinary chondrites are coming to Earth from a few parent asteroids. (Figure after Bogard, 1995). ............................................................................................. 56

Figure 2.7. Left, Induced TL peak temperature vs. peak width for a suite of 31 Antarctic H chondrites (typical terrestrial age ~40,000 years). Data from Haq et al. (1988). (b) Equivalent data for 37 non-Antarctic (i.e. modern falls) H chondrites. The dashed line is a regression line through the non-Antrctic data. Note the difference in the distribution of the two sets of data, which Benoit and Sears (1992, 1993) showed was due to different post-metamorphism cooling rates .... 59
**Figure 2.8.** (Top) Eccentricity against semimajor axis for the main belt asteroids illustrating the well known resonances and overall distribution. Eccentricity against semimajor axis for main belt asteroids in the Ch (middle) and Q,Sq (bottom) classes, which show statistically significant differences between the NEA and MBA populations. The Ch class is larger in the MBA and the Q,Sq class is larger in the NEA populations. Also marked on the Q,Sq plot is the asteroid Hebe which is an S asteroid in the Bus et al. (2004) scheme and an S(IV) asteroid in the Gaffey et al. (1993) scheme. Gaffey and Gilbert (1998) suggest that Hebe is the parent body for the ordinary chondrites. In both cases there is a wide spread or orbital elements for the asteroids with no particular tendency to cluster around a resonance ................................................................. 60

**Figure 2.9.** Eccentricity against semimajor axis for main belt asteroids in the Sk, Sl, and Sr classes, which show statistically significant differences between the NEA and MBA populations at the 0.999 level for Sr, and at the 0.995 level for Sk and Sl. Sl are better represented in the main belt, while Sk and Sr are better represented in the NEA population. As in Fig. 2.12, there is no strong indication that the MBA and NEA population differences are being controlled by location near a resonance ............................................................................................................. 61

**Figure 2.10.** Histograms for the MBA populations of Ch class and Q,Sq class asteroids. While the two show common characteristics, such as peaks in the 2.4 and 2.8 AU bins, there are differences such as the peak in the 3.2 bin, and the small number in the 3.3-3.5 bins of the Ch population and the greater number of asteroids in the 2.0, 2.2 and 2.3 bins for the Q, Sq populations. Thus the Q and Sq are skewed to smaller semimajor axes than the Ch asteroids................................................. 64

**Figure 3.1.** V-B vs. V-I and V-R and V-R vs. V-I color magnitude plots of 1989 ML with C-, D-, and S-type asteroids. In each case, 1989 ML falls within the plot of C-type asteroids ............................................................................................................................................ 71

**Figure 3.2a.** Plot of 1989 ML with C chondrites: a-Alais CI, b-Cold Bokkeveld CM2, c-1989 ML, d-Felix CO3, e-Coolidge C4, f-Allende CV3, g-Karooonda CK5, h-EET92002 CK4, i-EET87526 CK5, j-LEW87009 CK6 ......................................................... 72

**Figure 3.2b.** Plot of 1989 ML with L chondrites: a-Wickenberg L6, b-Taiban L,5 c-Harvard L5, d-Farmington L5, e-Arapaho L5, f-1989 ML, g-Mezo-Madaras L3, h-Bald Mountain L4, i-Elenovka L5, j-Brudenheim L6. Plots are offset for clarity. ......73

**Figure 3.3.** Plot of 1989 ML with chondrites Karoonda CK5 and Sevrukovo L5............. 75

**Figure 4.1.** Visible/near-Infrared reflectivity spectra for terrestrial pyroxenes(Gietzen et al., 2009). (a) Orthopyroxene from Webster, North Carolina, (actually enstatite, MgSiO3), (b) a clinopyroxene from an Hawaii volcanic bomb. The spectra are indicated by a series of (+) symbols. Also shown are gaussian curves fitted to the spectra using the MGM software (Sunshine and Pieters 1993), the continuum, and the residuals. Orthopyroxene has absorption bands at ~0.9 µm and ~1.8 µm, while clinopyroxene has bands at ~1.0 µm and ~2.3 µm. Olivine [(Fe,Mg)Si2O6], the second major rock-forming mineral on asteroids, has a major absorption band at ~1.0 µm that often cannot be resolved from the pyroxene bands. The smaller bands are attributed to a variety of absorption mechanisms and mineral sites that vary from sample to sample. Such laboratory data indicate the potential of the technique to identify certain key major minerals on the asteroid surface......... 82
Figure 4.2a. Visible/near-Infrared reflectivity spectra for an S asteroid (number 18, Melpomene). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite, the absorption band at ~1.9 \( \mu m \) indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1). 84

Figure 4.2b. Visible/near-Infrared reflectivity spectra for a type 3 (unequilibrated) ordinary chondrite (Parnallee, LL class). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite, the absorption band at ~1.9 \( \mu m \) indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1). 85

Figure 4.2c. Visible/near-Infrared reflectivity spectra for a type 6 (equilibrated) ordinary chondrite (Colby, Wisconsin, L class). The symbols and labels are as in the Fig. 4.1, but the fitted curve is a solid line and the spectra are plus symbols. In both the asteroid and the unequilibrated ordinary chondrite, the absorption band at ~1.9 \( \mu m \) indicates the coexistence of orthopyroxene and clinopyroxene and laboratory calibration enables a volumetric ratio to be determined (Table 4.1). In contrast, the equilibrated ordinary chondrite shows no evidence for clinopyroxene. These meteorite spectra are consistent with their known mineralogy and suggest that instead of having a surface of melts and partial melts, as usually inferred from the presence of clinopyroxene, the surfaces actually resemble the unequilibrated ordinary chondrites. 86

Figure 4.3. Schematic diagrams illustrating possible internal structures for asteroids and meteorite parent bodies.
(a) Parent bodies forming while \(^{26}\)Al was abundant would completely melt and when fragmented would deliver to objects to Earth resembling the many igneous stony meteorites, iron meteorites, and stony-iron meteorites. (b) Parent bodies forming a few million years later would have sufficient heat from \(^{26}\)Al decay to heat but not melt the interior while the surface is unaltered. Onion-skin thermal zoning would reflect metamorphic alteration and the petrographic types 3-6. (c) Parent bodies forming later 10-20 million years later would contain no \(^{26}\)Al and would remain unaltered throughout. (d) Later fragmentation and reassembled would bring mixture to the surfaces, depending on prior internal structure. While many objects resembling (a) exist, such as Vesta, the source of many basaltic meteorites, the present data are consistent with (b) and (c), and with (d) if the fragmented object originally resembled (c). 90

Figure 5.1a. Twelve raw spectra for eleven S complex asteroids reported in this paper. The data over the 0.8 – 2.5 \( \mu m \) range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range were not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids. 102
**Figure 5.1b.** Raw spectra for five S complex asteroids reported in this paper. The data over the 0.8 – 2.5 \( \mu \text{m} \) range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range we not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids. .............................................. 103

**Figure 5.1c.** Raw spectra for ten S complex asteroids reported in this paper. The data over the 0.8 – 2.5 \( \mu \text{m} \) range were obtained by the authors using NASA’s IRTF and SPEX spectrometer. Spectra over the visible range were obtained from the literature (Xu et al., 1995; Bus and Binzel, 2002; Binzel et al., 2001; 2004a; 2004b). In a few cases, spectra over the visible region were not available, and in some instances there was overlap in the present and literature data and both are shown. For analysis by the BAR and MGM methods asteroids without data in the visible range we not included and in cases of overlap the present data were used. The data obtained during the present campaign cover the full range of spectral types observed for S complex asteroids. .............................................. 104

**Figure 5.2b** Distribution of the twelve of present asteroids on this plot are identified by asteroid number. The remaining asteroids are not plotted because the method is not applicable or because we lack data in the visible range needed to characterize Band I. With the exception of asteroid 42, the asteroids plot in one of the Gaffey et al., (1993a) classes and can be assigned the classifications indicated in Table 5.1 ..................................................................................................................... 107

**Figure 5.3a** Results of MGM analysis of asteroid 42 Isis which plots at the olivine-rich end of the olivine-pyroxene mixing line in Fig. 5.2. The \(~2\) um pyroxene band (Band II) is weak or absent in the 42 Isis spectrum, while it is the very strong in the spectrum of 3908 Nyx. The intermediate case, asteroid 3288 Seleucus, shows both Band I and Band II reflecting the presence of both olivine and pyroxene. The spectra are shown as a series of plus signs with the results of deconvolution appearing as inverted approximately gaussian curves. The continuum is shown as a broken line. The sum of the modified Gaussian curves and the continuum is shown as a smooth line passing through the spectra generally indistinguishable from it. The residuals (difference between the sum and the spectrum data points) are displaced upwards 10%. ...................................................................................................... 112

**Figure 5.3b** Results of MGM analysis of asteroid 3288 Seleucus that plot in the middle of the mixing line. The \(~2\) um pyroxene band (Band II) is weak or absent in the 42 Isis spectrum, while it is the very strong in the spectrum of 3908 Nyx. The intermediate case, asteroid 3288 Seleucus, shows both Band I and Band II reflecting the presence of both olivine and pyroxene. The spectra are shown as a series of plus signs with the results of deconvolution appearing as inverted approximately gaussian curves. The continuum is shown as a broken line. The sum of the modified Gaussian curves and the continuum is shown as a smooth line passing through the spectra generally indistinguishable from it. The residuals (difference between the sum and the spectrum data points) are displaced upwards 10%................................. 115
Figure 5.5. The BAR plot of Gaffey et al., (1993a) on which data for ten type 3 ordinary chondrites (also known as unequilibrated ordinary chondrites, or UOC) from the Planetary Data System (Gaffey et al., 1972) have been plotted. All but two plot in the S(IV) field in which equilibrated ordinary chondrites (EOC) plot. The meteorites are identified by their first three letters, Bishunpur, Dimmitt, Hedjaz, Krymka, Tieschitz, Dhajala, Chainpur, Parnallee, Mezö-Madaras, and Gorlovka.

Figure 5.6. Results of MGM analysis of (a) a type 3 (UOC) meteorite, (b) a terrestrial clinopyroxene, (c) a type 6 (EOC) meteorite, and (d) a terrestrial orthopyroxene (taken from Sunshine and Pieters, 1993). See caption to Fig. 5.3 for an explanation of the details. Several decades of mineralogical and petrographic investigation have shown that much of the pyroxene in unequilibrated ordinary chondrites is entirely in the monoclinic form (clinopyroxene) while in equilibrated ordinary chondrites the pyroxene is in the orthorhombic form (orthopyroxene). These known mineralogical differences between UOC and EOC are readily apparent in their reflectance spectra. Our clinoenstatite sample was slightly weathered and water features were observed, but these were successfully removed during MGM analysis.

Figure 5.7. The BAR plot with two mixing lines indicated. The solid line is the line suggested by Gaffey et al., (1993a) and thought to represent the mixing of olivine and orthopyroxene. The broken line is the same line pinned at olivine end and adjusted upwards at the pyroxene end to pass through the BA field in which the pyroxene is known to be in the clinorhombic form. It would be tempting to suggest that this upper line refers to the olivine-clinopyroxene mixing. However, all the asteroids in the present study and the UOC that plot in the S(IV) field contain a mixture of orthopyroxene and clinopyroxene, so the lower line reflects the presence of orthopyroxene rather than being pure orthopyroxene.

Figure 5.8. Models for the interiors of S complex asteroids. (a) Objects that form when $^{26}$Al is still present in the solar system and which are large enough will melt and differentiate to form a core, mantle and crust. Meteorites are known that appear to represent these objects, such as iron meteorites from cores, stony-iron meteorites from the interface, and various differentiated meteorites that represent mantle and crust of their parent asteroids. (b) Objects that formed later or were too small to retain enough heat for complete melting will have a heated interior and unheated surface with concentric zoning of metamorphic alteration that increases with depth. The thickness of the layers will depend on composition, amount of $^{26}$Al, and – most importantly – the thermal properties of the layers. However all models predict a volumetrically large amount of type 6 material and relatively smaller amounts of the outer layers, consistent with the observed ordinary chondrite flux to Earth. (c) Asteroids forming after decay of $^{26}$Al, or too small for significant heating by $^{26}$Al, will resemble type 3 material throughout. Astronomical spectroscopy seems to be detecting asteroids with surfaces resembling the first three models, the scarcity of ordinary chondrites without clinopyroxene implies that few are exposing their interiors, the notable exceptions being the Q asteroids that closely resemble the equilibrated ordinary chondrites. (d) After formation impact could disrupt the object and allow mixing, so the surface would reflect the prior internal nature of the asteroid.
The distribution of K-Ar age (determined by the Ar-Ar method) for L chondrites shows a large proportion of members with 0.5 Ga ages, suggesting that until that time these meteorites were part of the same parent object. Consistent with a major and violent break-up event, most of the L chondrites in the 0.5 Ga peak are shock blackened. The shading refers to meteorites that have plateau in their Ar release patterns, and that have been undisturbed since the event that reset their K-Ar clock. Such data indicates that most or probably all of these meteorites came from the interior of their parent asteroid and would not be observed by astronomical techniques. This diagram is a simplified version of a figure in Bogard, 1996.

Figure 5.10a Cosmic ray exposure ages for ordinary chondrites calculated from $^{21}$Ne concentrations obtained from the compilation by Schultz and Frank (2004) assuming a production rate of $0.3 \times 10^{-8} \text{ cm}^3 \text{ STP/(g Ga)}$ (Leya et al., 2000). Multiple determinations for a single meteorite have been averaged. For each of the chemical classes, H, L and LL, the type 3 (unequilibrated) and type 4-6 (equilibrated) ordinary chondrites are shown. The presence of peaks in these histograms suggests meteorite formation by fragmentation of a single parent object. All three chemical classes show differences in the distribution for type 3 compared with type 4-6 suggesting that some fraction came from separate parent objects. Examples are the $\sim 25$ Ma peak for the H chondrites, the $\sim 2$ Ma peak for the L chondrites and the $\sim 5$ Ma peak for the LL chondrites. Conversely, peaks are sometimes present in the type 4-6 distributions that are absent from the type 3 distributions, such as $52-55$ Ma peak for L4-6 chondrites and the $\sim 38$ Ma peak for LL4-6. The $\sim 2$ Ma peak for the L3 chondrites may be due to pairing, a large number of meteorite fragments being unrecognized fragments of the same meteorite, but for the H and LL ordinary chondrites there appear to be genuinely different distributions for the type 3 and type 4-6 ordinary chondrites that suggest origins for some fraction of the type 3s on different parent bodies.
Figure 5.10c. Cosmic ray exposure ages for ordinary chondrites calculated from $^{21}\text{Ne}$ concentrations obtained from the compilation by Schultz and Frank (2004) assuming a production rate of $0.3 \times 10^{-8} \text{ cm}^3 \text{ STP/(gGa)}$ (Leya et al., 2000). Multiple determinations for a single meteorite have been averaged. For each of the chemical classes, H, L and LL, the type 3 (unequilibrated) and type 4-6 (equilibrated) ordinary chondrites are shown. The presence of peaks in these histograms suggests meteorite formation by fragmentation of a single parent object. All three chemical classes show differences in the distribution for type 3 compared with type 4-6 suggesting that some fraction came from separate parent objects. Examples are the ~25 Ma peak for the H chondrites, the ~2 Ma peak for the L chondrites and the ~5 Ma peak for the LL chondrites. Conversely, peaks are sometimes present in the type 4-6 distributions that are absent from the type 3 distributions, such as 52-55 Ma peak for L4-6 chondrites and the ~38 Ma peak for LL4-6. The ~2 Ma peak for the L3 chondrites may be due to pairing, a large number of meteorite fragments being unrecognized fragments of the same meteorite, but for the H and LL ordinary chondrites there appear to be genuinely different distributions for the type 3 and type 4-6 ordinary chondrites that suggest origins for some fraction of the type 3s on different parent bodies. .................. 131
INDEX OF TABLES

Table 1.1 Description of classes within Bus’ feature-based taxonomy†, ................................. 5
Table 1.3. The large number of programs to detect NEA require support to characterize them, especially given the great compositional diversity expected., ................................. 15
Table 1.4 Chief Environmental Consequences of Impacts*, ................................................ 25
Table 2.1. Asteroid classes and their populations*, ............................................................. 36
Table 2.2. Chi-square test to answer the question as to whether the NEA and MBA come from the same parent population, based on the distribution of individual classes, ................................................................. 41
Table 2.3. Chi-square test to answer the question whether the NEA and MBA come from the same parent population, based on the distribution of individual complexes *, ................................. 43
Table 2.4. Chi-square test to answer the question as to whether the complexes in the NEA and MBA populations present in the same proportions in each population, ................................. 46
Table 2.5. Chi-square test to answer the question whether the classes in the NEA and MBA populations present in the same proportions in each population?, ................................. 48
Table 4.1. S class asteroids and ordinary chondrites in this study(1), ................................... 83
Table 5.1. List of asteroids observed and relevant information*, ...................................... 100
Table 5.2. Results of MGM analysis of meteorites, ........................................................... 117
Table 5.3. Type 3 ordinary chondrites occupying peaks in the cosmic ray exposure age distributions where those peaks are weak or absent in the type 4-6 distributions*. ................................. 132
Appendix A: Visible And Near Infrared Spectra Of Five Near Earth Asteroids
Visible and Near-Infrared Spectra of Five Near-Earth Asteroids

Gietzen, K. M., Lacy, C. J. Rivkin, A. S

Abstract

Reflectance spectra of five near earth asteroids (3908, 7753, 22771, 54509 and 66251) were obtained in the near infrared (.8 - 2.5 µm) using the NASA IRTF equipped with the SpEX infrared spectrometer at Mauna Kea in 2004 and 2005. The data obtained was coupled with spectral data in the visible wavelengths from the SMASS database [2, 3, 4, and 5] and analyzed using the Modified Gaussian Model (MGM). The expected absorption bands at 1 and 2 µm for olivines and pyroxenes were observed in a number of the asteroid spectra. However, we also found that there were asteroid reflectance spectra that were very featureless and the absorption bands that were present (if any) were very weak. Space weathering has been given by others [1] as a possible explanation for the lack of absorption features in the spectra of asteroids. This space weathering has been described to be the possible result of the processes of sputtering erosion as a result of the impacts and implantations, radiation and cosmic ray effects. Asteroid 1989 ML (10302) was also studied using SMASS observation data in the visible wavelengths. The reflectance spectra was compared to the spectra of various types of meteorites in an attempt find a match that would aid in the classification of 1989 ML References: [1] B. Hapke (2001) J. Geophys. Res. 106, 10039-10073; [2] J.T. Rayner et al. (2003) PASP 115, 362; [3] R.P. Binzel et al. (2004) Icarus 170, 259-294; [4] R.P. Binzel et al. (2004) Meteoritics and Planetary Science 39, 354-366; [5] T.H. Burbine et al. (2002) Icarus 159, 468-499
Appendix B: Visible And Near Infrared Spectra Of Main Belt And Near Earth Asteroids
VISIBLE AND NEAR INFRARED SPECTRA OF MAIN BELT AND NEAR EARTH ASTEROIDS

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Introduction: Asteroids provide unique insights into the origin and early history of the solar system. Near-Earth asteroids (NEAs) are also interesting because of the collisional hazard and value to solar system exploration as intermediate targets between the Moon and Mars. Reflectance spectra of twenty-five main belt and NEAs (Table 1) have been obtained in the near infrared (0.8 – 2.5 μm). Here we present a progress report of these studies.

Experimentation: The main belt asteroids in this study were chosen to provide a range of asteroid types while the NEAs were chosen on the basis of observability. Our spectra were obtained at Mount Keck between 2004 and 2006 using the NASA IRTF equipped with the SpEX infrared spectrometer. The data were reduced by IRAF and other commonly used methods. The data were then coupled with spectral data in the visible wavelengths (0.4 – 0.9 μm) from the MIT SMASS [2, 3, 4, 6, 7, 8, 9, 10] database to provide a spectrum covering the visible to near infrared. The spectra were analyzed using the Modified Gaussian Model (MGM) [11] and will soon be analyzed by other methods.

Results: Our spectra are shown in Fig. 1. The spectra of the asteroids were grouped by visual inspection. We began by placing the spectra which had absorption features in the 1 and 2 μm region together and arranging them according to the relative strengths of the two features. These were further divided according to the strength of the 1μm feature and the relative strength of the 2 μm feature. The remainder of the spectra were separated based on the presence and strength of a 1 μm feature and the basic shape of the spectra. We found seven distinct groups consistent with published taxonomies.

Discussion: The largest of these seven groups contains nine asteroids eight of which are all classified as an S, S1, Sa or Sk in Bus and Binzel's [10] taxonomy. The ninth asteroid 54509, has not previously been classified in this way because of the lack of a visible spectrum. The second group contains 3908, a V type asteroid, and two other as yet unclassified asteroids. Group three contains three asteroids that are classified as C or CB asteroids. The fourth group contains one Ch and one S1 asteroid. Group five is comprised of four asteroids classified as Ld, X and C. The sixth group contains an Xk and a Ch classified asteroid and the last group also has two asteroids both classified as X. Classifications we have assigned to previously unclassified asteroids are indicated in Table 1.

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<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
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<td>--------</td>
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*Present work. 1Near-Earth Objects – Dynamic Site [12]. 1Planetary Data System [13]

In pyroxene-bearing asteroids (the first two groups in Fig. 1), there are two or three individual absorption bands that combine to make up the characteristic 1 μm and 2 μm bands which MGM can separate. The component band strength ratio (CBSR) was calculated for both the 1 and 2 μm regions using the methods of Shu and Pieters [11]. From this the percentage of clinopyroxenes relative to the total pyroxenes was determined for these asteroids (Table 1). In general there is agreement (within uncertainties) in the amount of %CPX calculated from each band, although asteroids 63, 354 and 3908 are exceptions. Asteroid 63, an Sa type has a spectra that is intermediate between the S type and the olivine-rich A type based on their UV slope [10]. This could indicate that asteroid 63 contains more olivine than is typical.
of S asteroids. The apparent absence of olivine-rich asteroids has concerned researchers [5], so this asteroid may have considerable significance. Asteroid 3908 is a V type (Tholen classification — no SMAS-II classification) asteroid and contains considerable plagioclase neglected in the CBRS calculation. Asteroid 354 is an S1 type asteroid whose spectrum suggests an olivine-rich (A type) asteroid, with strong ultraviolet and 1 μm absorption bands [5]. Again abundant olivine would upset the CBRS calculation and is of considerable interest for the reasons discussed above.

Our study includes four previously unclassified asteroids, 2003 YQ117, 54509, 66251 and 68950 to which we assign classifications in Table 1. Except for the recent work of Abell, et al. [1], there was no visible data for these asteroids. Of the nine NEAs observed, one-third are currently classified as S type asteroids with the possibility of one or two more (54509 and 66251). Including 2003 YQ117, 68950 and 54509, it is possible for nearly half to be V type asteroids.

Future work on this project will refine this study by continuing with MGM while also looking at adding other analysis methods.

Figure 1: Spectra of twenty-five asteroids placed into seven groups by spectral shape. The range of the x-axis is 0.2 – 2.8 μm on all spectra. The near-infrared spectrum of asteroid 66251 appears to fit best into group one which would indicate a classification of S type. The spectrum of asteroid 54509 is also grouped into the first group. Even though there is quite a bit of scatter, there are some definite features apparent. The 1 μm feature is very strong compared to the other asteroids in group 1 (indicating a possible classification of V type), however, the 2 μm feature is not as strong relative to the 1μm feature (indicating a possible classification of S type). Both 2003 YQ117 and 68950 have a strong 1 μm feature and a 2 μm that is relatively strong compared to the 1μm feature and could be classified as a V type asteroid.

Visible and Near Infrared Spectra of Main Belt and Near Earth Asteroids

Katherine M. Getzien and Claud H. Sandberg Lacy
Arkansas Center for Space & Planetary Sciences
Lunar & Planetary Science Conference
March 13, 2007

Introduction
- Asteroids are important in deducing the origin and history of the Solar System
- NEAs are of significant importance as potential impactors
- Primary source of compositional data are reflectance spectra
- Visible spectra are widely available, but are greatly enhanced by extension into the infrared

Visible Spectra of Asteroid 1989 ML, a Shock-blackened Ordinary Chondrite and a CK5 Chondrite

Extension of Spectra into Infrared
New Infrared Spectra

- Infrared data acquired for 25 asteroids
  - 16 Main Belt
  - 9 Near-Earth
  - 0.8 – 2.5 μm
- Coupled with visible data
  - 0.4 – 0.9 μm
- Small Main-Belt Asteroid Spectroscopic Survey (SMASS) database at MIT and others

Analysis

- Modified Gaussian Model (MGM)
- Component Band Strength Ratio (CBSR)
  - 1 μm and 2 μm absorptions
  - Ratios of Orthopyroxene/Clinopyroxene (OPX/CPX)
- % CPX
- Sorted by visual inspection, strength of 1 μm band, ratio of 1 and 2 μm band, and continuum slope into 7 groups

Results

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Type</th>
<th>% CPX 1 μm</th>
<th>Mean Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1236 - Genghis</td>
<td>S</td>
<td>0.11</td>
<td>0.28</td>
</tr>
<tr>
<td>3005 - Nuns</td>
<td>V</td>
<td>0.36</td>
<td>0.23</td>
</tr>
<tr>
<td>7713 - 1998 KB</td>
<td>S</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>1966 JX5</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>2003 YQ17</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>22771 - 1998 QU3</td>
<td>SI</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>45409 - 2000 PH1</td>
<td>S</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>86261 - 1999 QJ2</td>
<td>S</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>86010 - 2001 DE3</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Type</th>
<th>% CPX 2 μm</th>
<th>Mean Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1296 - Genghis</td>
<td>S</td>
<td>0.11</td>
<td>0.28</td>
</tr>
<tr>
<td>3005 - Nuns</td>
<td>V</td>
<td>0.36</td>
<td>0.23</td>
</tr>
<tr>
<td>7713 - 1998 KB</td>
<td>S</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>1966 JX5</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>2003 YQ17</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>22771 - 1998 QU3</td>
<td>SI</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>45409 - 2000 PH1</td>
<td>S</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>86261 - 1999 QJ2</td>
<td>S</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>86010 - 2001 DE3</td>
<td>V</td>
<td>0.16</td>
<td>0.28</td>
</tr>
</tbody>
</table>
63 - Ausonia

- Sa type asteroid
- Spectrum intermediate between S and olivine-rich A type asteroids (Bus & Binzel 2002)
- Maybe contains more olivine
- Less than 20 known A-type asteroids
354 - Eleonora

- SI type asteroid
- SI spectra are intermediate between S and L asteroids
- Spectrum suggests olivine-rich composition
- S1 asteroids plot in the olivine-rich area on the Band Center vs. Band Area Ratio plot (Gaffey et al. 1993)

3908 - Nyx

- V-type Near-Earth Asteroid
- Basaltic and probably contains considerable plagioclase
Previously Unclassified Asteroids

- 4 previously unclassified
  - 66251
  - 54509
  - 2003 YQ117
  - 68950

Conclusions

- Able to determine %CPX in 8 asteroids
- Disagreement with CBSR in 3 asteroids indicates possible presence of other minerals
- Possible new V type asteroids would increase known V-type NEA population from 4 to 6
Appendix C: Abundant clinopyroxene on the S asteroids and implications for meteorites and asteroid history and the asteroid-meteorite relationship
Abundant clinopyroxene on the S asteroids and implications for meteorites and asteroid history and the asteroid-meteorite relationship

K. M. Gietzen¹, C. H. S. Lacy¹,², and D. W. G. Sears¹,³. ¹Arkansas Center for Space and Planetary Sciences, ²Department of Physics and Astronomy Sciences. ³Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Ar 72701, USA. (kgietze@uark.edu)

Abstract

We have obtained spectra for 25 asteroids in the range 0.8 – 2.5 µm using the NASA IRTF, of which eight were S asteroids. Analysis of their spectra using the Modified Gaussian Model of Sunshine and Pieters (1993) suggests that six of the eight contain significant amounts of pyroxene in the clinorhombic form (CPX), as opposed to the more common orthopyroxene, (OPX). Our pyroxene-rich targets were Hebe (%CPX = 50%), Melpomene (63%), Urda (43%), Ganymed (41%), 1999 JV3 (55%), 1999 CU3 (61%). Clinopyroxene is the low temperature form of pyroxene and is an important diagnostic feature of the primitive (least metamorphosed) ordinary chondrites. Clinopyroxene is also the form of pyroxene associated with igneous meteorites and two V asteroids in our database also contain considerable clinopyroxenes 2003 YQ 117 (50%) and 2002 QF15 (55%). Primitive and igneous meteorites are well-known and widely studied, but numerically they are very rare. The presence of this mineral phase on the
surfaces of asteroids therefore has major implications for both asteroid history and
the asteroid-meteorite connection.

First, the abundance of CPX on the surface of S asteroids implies either that (1) they are covered with unmetamorphosed material, consistent with an onion skin model in which metamorphism is caused by internal heating and the level of metamorphism experienced by the asteroid decreases with increasing distance from the center, or (2) they are covered with igneous material. Second, the abundance of CPX on the surface of S asteroids is consistent with them not being related to ordinary chondrites, most of which are highly metamorphosed and contain only orthopyroxene (OPX). Space weathering is therefore not the reason for the spectral mismatch between S asteroids and ordinary chondrites.
ABUNDANT CLINOPYROXENE ON THE S ASTEROIDS AND IMPLICATIONS FOR METEORITES AND ASTEROID HISTORY AND THE ASTEROID–METEORITE RELATIONSHIP

Katherine M. Gietzen, Claud H. Sandberg Lacy and Derek W. G. Sears
Arkansas Center for Space and Planetary Sciences
University of Arkansas
Fayetteville, Arkansas
DPS Meeting – October 10, 2007

Introduction
- Asteroids are important in deducing the origin and history of the solar system
- Asteroids as meteorite parent bodies
- Reflectance spectra can provide mineralogical and compositional information

Infrared Spectra
- Infrared data acquired for 30 asteroids
  - 19 Main Belt
  - 11 Near–Earth
  - 0.8 – 2.5 μm
- Coupled with visible data
  - 0.4 – 0.9 μm
  - Small Main–Belt Asteroid Spectroscopic Survey (SMASS) database at MIT and others

S asteroids
Analysis

- Modified Gaussian Model (MGM)
- Component Band Strength Ratio (CBSR)
  - 1 μm and 2μm absorptions
  - Ratios of Orthopyroxene/Clinopyroxene (OPX/CPX)
  - % CPX

Results

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Class</th>
<th>% CPX</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 - Hebe</td>
<td>S(1)</td>
<td>51</td>
</tr>
<tr>
<td>6 - Melpomene</td>
<td>S(1)S(VI)(2)</td>
<td>61</td>
</tr>
<tr>
<td>63 - Asania</td>
<td>S(3)</td>
<td>68</td>
</tr>
<tr>
<td>167 - Urda</td>
<td>S(1)</td>
<td>45</td>
</tr>
<tr>
<td>1036 - Ganymed</td>
<td>S(1)S(VI)(2)</td>
<td>41</td>
</tr>
<tr>
<td>1999 JV3</td>
<td>S(1)</td>
<td>56</td>
</tr>
<tr>
<td>22771 - 1999 CU3</td>
<td>S(1)S(VI)(2)</td>
<td>61</td>
</tr>
</tbody>
</table>

1. Class assignments from Bin and Binnew (2002b).
2. Class assignments from Gaffey et al. (1997).

Clinopyroxene in Meteorites

Type 3 ordinary chondrites

Basilic meteorites
What does this mean?

- Could imply S asteroid surfaces are covered with type 3 ordinary chondrite material
  - Petrologic types ranging from 3 – 6
  - Type 3 (rare, little metamorphism), type 6 (abundant, much metamorphism)
  - Onion skin model (type 6 center, type 3 surface)
  - Could explain asteroid–meteorite mismatch

- Could imply S asteroids are covered with igneous materials
  - V asteroids
  - Could explain asteroid–meteorite mismatch

Conclusion

- Surface of many (most) S asteroids contains clinopyroxene which links them with type 3 ordinary chondrites and igneous meteorites
- This distinguishes them from the majority of meteorites falling on Earth
- This would mean that space weathering is not the cause of the asteroid–meteorite mismatch
Appendix D: Analysis Of Reflectance Spectra Of Ordinary Chondrites: Implications For Asteroids.
ANALYSIS OF REFLECTANCE SPECTRA OF ORDINARY CHONDRITES: IMPLICATIONS FOR ASTEROIDS. K. M. Gietzen\(^1\) <kgietze@uark.edu>, C. H. S. Lacy\(^2\), D. R. Ostrowski\(^1\), D. W. G. Sears\(^1\).

\(^1\)Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, AR 72701, \(^2\)Department of Physics and Astronomy, University of Arkansas, Fayetteville, AR 72701

Introduction: Chondritic meteorites have a composition very similar to that of the photosphere of the Sun. They are classified into one or more groups based on subtle variations in bulk phase and mineral compositions. The most abundant of these are the ordinary chondrites, which comprise ~55% of all meteorite falls and make up three of the chondrite classifications, namely H, L, and LL. They are additionally sorted into petrographic types 3, 4, 5 and 6 according to the degree of metamorphism. The pyroxene structures convert from clinoenstatite (CPX) to orthorhombic (OPX) form with metamorphism.

In the search for parent bodies for meteorites, asteroids have always seemed the logical solution. In particular, the S asteroid population has long been the center of the search for a connection with the ordinary chondrites due to their relative abundance to the asteroid population and the seemingly similar composition. The subtle spectral variations in the S asteroids and the ordinary chondrites and in the asteroids themselves have made this connection difficult to make. Recent work has found the clinoenstatite form of pyroxene on surfaces of S asteroids which may be able to aid in the connection of these two groups of solar system bodies [1].

Experimentation: Reflectance spectra (3 – 2.5 \(\mu m\)) for seven ordinary chondrites (Table 1) were obtained through the NASA Planetary Data Systems database [2]. The spectra were analyzed using the Modified Gaussian Model (MGM) [3] as were the asteroids in our earlier work.

Results: Our analysis indicated that there are absorption features in both the 1 and 2 \(\mu m\) regions present in all seven chondrites. This would suggest the presence of pyroxenes in all. However, there is an indication that the structure of the pyroxene is different in the type 3 chondrites compared to the type 6 chondrites. As shown in the upper plot in Fig. 1, there is an additional absorption feature in the 2 \(\mu m\) region of the type 3 chondrites that is not present in the spectra of the type 6 (Fig. 1 lower plot). This additional feature represents the presence of clinoenstatite pyroxenes (CPX).

Discussion: There are two or three individual absorption bands that combine to make up the 1 \(\mu m\) and 2 \(\mu m\) bands characteristic to pyroxenes which MGM can separate. The component band strength ratio (CBSR) was calculated for both the 1 and 2 \(\mu m\) regions using the methods of Sunshine and Pieters [3]. The CBSR allowed us to determine the percentages of clinoenstatite relative to total pyroxenes for each chondrite (Table 1).

Table 1. Type 3 and 6 ordinary chondrites analyzed in the present study, their class and the percent clinoenstatite determined by spectral analysis\(^1\).

<table>
<thead>
<tr>
<th>Meteorites</th>
<th>Class</th>
<th>% CPX 1 (\mu m)</th>
<th>% CPX 2 (\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 3 Ordinary Chondrites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dushanbe</td>
<td>L3.1</td>
<td>78±5</td>
<td>73±5</td>
</tr>
<tr>
<td>Parmalee</td>
<td>L3.3</td>
<td>77±2</td>
<td>84±1</td>
</tr>
<tr>
<td>Haddo</td>
<td>L3.7</td>
<td>66±6</td>
<td>44±5</td>
</tr>
<tr>
<td>Dhajala</td>
<td>L3.8</td>
<td>64±7</td>
<td>63±4</td>
</tr>
<tr>
<td>Type 6 Ordinary Chondrites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mabroon</td>
<td>L6</td>
<td>84±2</td>
<td>n.d.</td>
</tr>
<tr>
<td>Colby (Wisconsin)</td>
<td>L6</td>
<td>79±2</td>
<td>n.d.</td>
</tr>
<tr>
<td>Bruderholm</td>
<td>L5</td>
<td>76±2</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

1. n.d., not detected

In the 2 \(\mu m\) region, we found CPX percentages to range from 44 – 73% for the type 3 chondrites and found no evidence of CPX for the type 6 chondrites. The CBSR also shows percentages for CPX in the 1 \(\mu m\) region for all the type 3 chondrites. In general, the 1 \(\mu m\) percentages are greater than those for the 2 \(\mu m\) for type 3. The type 6 chondrites show no indication of CPX. Other minerals such as plagioclase and olivine have absorption features in the 1 \(\mu m\) region in the same range as the clinoenstatite pyroxenes that are responsible for these numbers. These minerals do not, however, have a 2 \(\mu m\) feature.

Gietzen, et al. [1] found abundant clinoenstatite pyroxenes in seven of eight S asteroids ranging from 42 – 61%, similar results to what is found for the type 3 ordinary chondrites in this work. This would suggest that the surfaces of S asteroids are type 3 ordinary chondrite material and provides an explanation of the asteroid-meteorite mismatch. We are not, however, the first to observe abundant clinoenstatite in S asteroids. Gaffey et al. [4] reported finding calcic pyroxene in many of their S asteroid subclasses. They attributed it to being igneous in origin which further muddles the meteorite-asteroid connection since there is not a large
representation in the terrestrial meteorite collection [5]. However, if the pyroxenes were not calcic, but still clinopyroxene in structure, there may be a connection with the S asteroids.

![Normalized natural log reflectance](image)

**Fig. 1.** Application of our data reduction methods to CPX-bearing type 3 chondrites and CPX-free type 6 chondrites confirms our interpretation of the S asteroid spectra contain evidence for clinopyroxene on the surfaces.

The lower petrographic unequilibrated ordinary chondrites (UOC) are known to contain calcium-free CPX which converts to OPX with metamorphism. The UOC are rare, but the equilibrated ordinary chondrites (EOC) are much more common. The division of the ordinary chondrites into types 3 – 6 is based on the degree of metamorphic alteration, with type 3, (unequilibrated or unequilibrated chondrites) gradational to type 6, (metamorphosed and equilibrated) chondrites. $^{26}$Mg was discovered in high aluminum-low magnesium minerals in meteorites, including ordinary chondrites indicating that $^{26}$Al was once present in these meteorites [7-10]. The presence of $^{26}$Al would have been an important source for internal heating of early solar system bodies that could cause the metamorphism of the meteorite parent bodies. Objects that formed in the early solar system would have onion-skin structures with metamorphosed interiors and increasingly less metamorphosed materials toward their surfaces. Thermal models have indicated that the relative proportion of types 3, 4, 5, and 6 produced this way (Fig 2) are in agreement with statistics for terrestrial meteorite falls [11].

![Diagram](image)

**Fig. 2.** Recent model for the interior of an ordinary chondrite parent body, in this case the H chondrites. The numbers (3, 4, 5, 6) refer to the temperatures experienced as a result of internal heating, the level of metamorphism caused by the heating increasing along the series 3, 4, 5, and 6.

**Conclusions:** The implications of our findings suggest that there is a strong relationship between the S asteroids and ordinary chondrites. The meteorite-asteroid mismatch between these two groups may not be due to space weathering or other suggested processes. The onion-skin models such as that of Akridge et al. [11] shown in Fig. 2 can account for the rarity of the type 3 ordinary chondrites and the abundance of type 6 ordinary chondrites implying their parent bodies experienced internal heating and are spherically zoned. The meteorite-asteroid mismatch can be largely explained by the fact that the meteorites are a sampling of the interiors of asteroids and astronomical spectroscopy is sampling their surface. This would imply that the S asteroids would be good candidates as ordinary chondrite parent bodies.

ANALYSIS OF REFLECTANCE SPECTRA OF ORDINARY CHONDrites: IMPLICATIONS FOR ASTEROIDS

Katherine M. Gietzen, Claud H. Sandberg Lacy, Daniel R. Ostrowski, Derek W. G. Sears
Arkansas Center for Space and Planetary Sciences
Lunar and Planetary Science Conference
March 10, 2008

Introduction
- A link between ordinary chondrites and S asteroids has been sought for several decades
- Presence of pyroxenes in the clinorhombic form on S asteroids was used to link to igneous meteorites
- Unequilibrated ordinary chondrites also contain abundant clinopyroxenes
- We show here a clear connection between the S asteroids and ordinary chondritic meteorites

Pyroxenes in Meteorites
- Ordinary chondrites (H, L, LL)
  - Most abundant meteorite falls
  - Four petrologic types ranging from 3 - 6
    - Type 3 (rare, little metamorphism)
    - Type 6 (abundant, much metamorphism)
- Metamorphism causes pyroxene structures to convert from clinorhombic (CPX) to orthorhombic (OPX)

Meteorite Spectra
- Data acquired for seven ordinary chondrites
  - Four type 3
    - Bishunpur LL3.1
    - Pamelia LL3.3
    - H52: H3.7
    - Dhajala H3.8
  - Three type 6
    - Marbloom L1.6
    - Colby (Wisconsin) L6
    - Bruderheim L6
  - 0.3 - 2.5 μm
  - NASA Planetary Data Systems
Analysis

- Modified Gaussian Model (MGM)
- Component Band Strength Ratio (CBSR)
  - 1 \(\mu\)m and 2 \(\mu\)m absorptions
  - Ratios of OPX/CPX
  - %CPX

<table>
<thead>
<tr>
<th>Meteorites</th>
<th>Class</th>
<th>% CPX 1 (\mu)m</th>
<th>% CPX 2 (\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishunpur</td>
<td>LL3.1</td>
<td>78±5</td>
<td>73±5</td>
</tr>
<tr>
<td>Parnallese</td>
<td>LL3.3</td>
<td>77±2</td>
<td>64±1</td>
</tr>
<tr>
<td>Hedjaz</td>
<td>L3.7</td>
<td>66±6</td>
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<td>H3.8</td>
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<td>63±4</td>
</tr>
<tr>
<td>Type 6 Ordinary Chondrites</td>
<td></td>
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</tr>
<tr>
<td>Mambool</td>
<td>LL6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
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<td>Colby (Wisconsin)</td>
<td>L6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Brudenheim</td>
<td>L6</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

n.d. - not detected
**Meteorite Parent Body Onion Skin Model**
- Thermal metamorphism of parent bodies would produce an onion-skin internal structure
- $^{26}$Al would provide the necessary heat source
- Relative proportions of types 3, 4, 5 and 6 from this model agree with those found in ordinary chondrites

**S Asteroid Spectra**
- Infrared data for eight asteroids
  - Previously classified as S type
  - 0.8 – 2.5 μm
- Coupled with visible data
  - 0.4 – 0.9 μm
- Small Main-Belt Spectroscopic Survey (SMASS) database at MIT and others

**Asteroid Results**

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Class</th>
<th>% CPX 1 μm</th>
<th>% CPX 2 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 - Hebe</td>
<td>S$^{(1)}$</td>
<td>51</td>
<td>47</td>
</tr>
<tr>
<td>18 - Melpomene</td>
<td>S$^{(1)}$S(VD)$^{(2)}$</td>
<td>61</td>
<td>65</td>
</tr>
<tr>
<td>63 - Astonia</td>
<td>S$^{(1)}$</td>
<td>68</td>
<td>42</td>
</tr>
<tr>
<td>167 - Urdia</td>
<td>Sk$^{(1)}$</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>354 – Eleonora</td>
<td>S$^{(1)}$S$^{(2)}$</td>
<td>Olivine-rich$^{(3)}$</td>
<td></td>
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<tr>
<td>1035 - Ganymed</td>
<td>S$^{(1)}$S(V)$^{(2)}$</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>1999 JV3</td>
<td>S$^{(1)}$</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>22771 - 1999 CU3</td>
<td>S$^{(1)}$S(V)$^{(2)}$</td>
<td>61</td>
<td>61</td>
</tr>
</tbody>
</table>

1. Class assignments from Bu and Binzel (2002)
2. Class assignments from Gaffey et al. (1990)
3. Small amounts of pyroxene appear to be orthorhombic
Conclusions

- Strong relationship between the S asteroids and ordinary chondrites
- S asteroid surfaces are covered with unequilibrated material similar to the rare unequilibrated type 3 ordinary chondrites
- The meteorite-asteroid mismatch can be explained
  - Meteorites sample the interiors of asteroids
  - Astronomical spectroscopy samples their surfaces.
Appendix E: A Comparison Of The Class Distribution Of Asteroids In The Main Belt And Near-Earth Vicinity
A COMPARISON OF THE CLASS DISTRIBUTION OF ASTEROIDS IN THE MAIN BELT AND NEAR-EARTH VICINITY. K. M. Gietzen, C. H. S. Lacy, D. R. Ostrowski, and D. W. G. Sears. 1Arkansas Center for Space and Planetary Sciences, 2Department of Physics and Astronomy Sciences. 3Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Ar 72701, USA. (kgietze@uark.edu)

Introduction: The asteroid population in the solar system consists of the Main Belt Asteroids (MBAs) located at 2 – 4 AU and the Near-Earth Objects (NEOs) located at <1 – 1.3 AU. It has long been thought that the NEOs are a subset of the main belt asteroids, but with the discovery of large numbers of new NEA this conclusion should be frequently revisited. Here we compare the two populations using their taxonomic classes as the basis for comparison (Fig. 1).

Background: Within the NEO population, Apollos (a > 1.0 AU, q < 1.0167 AU), Atens (a < 1.0 AU, Q > 0.983 AU) and Amors (a > 1 AU, 1.017 < q < 1.3 AU) at the time of writing stands at ~5300. Lifetimes for objects in these orbits are short, 10^6 – 10^7 years [1, 2], which indicates that the population must be continually resupplied. Potential sources are short period comets, such as Halley and the Jupiter-family comets [3, 4], and the main belt asteroids. Models of the collisional history of asteroids in the main belt suggest that most NEAs probably originate in the main belt [5].

Experimental: We obtained taxonomy classification information for the main belt and near-Earth asteroids from the NASA Planetary Data Systems [6] and Near Earth Objects – Dynamical Site [7] databases. The results appear in Fig. 2. While there are important similarities, most striking, is the similar abundance of S asteroids in each population, but also the A, B, Cb, D, Sk, Sl and T groups seem similar. Some groups are too small to call. However, more striking are the number of major disagreements indicated by arrows in Fig. 2.

We performed a chi square analysis of the MBA and NEA class distributions to see if they came from the same major population. There are ~1800 well classified MBA and ~300 NEA. We adopted the null hypothesis that the two populations are identical and obtained a chi squared value of 399, greater than 38 which is the chi squared value for rejection of the hypothesis at the 0.05 level. In other words, we must rejected our null hypothesis and conclude that at the 5% level of confidence that the two

![Fig. 1](https://via.placeholder.com/150)

**Fig. 1** Grouping of the classifications for the MBAs. There is considerable compositional heterogeneity among these oldest relics of the solar system.

![Fig. 2](https://via.placeholder.com/150)

**Fig. 2** Comparison of the MBA and NEA populations based on taxonomic class. Note the variance in the abundances of the classes between the populations (indicated by arrows).

We performed a chi square analysis of the MBA and NEA class distributions to see if they came from the same major population. There are ~1800 well classified MBA and ~300 NEA. We adopted the null hypothesis that the two populations are identical and obtained a chi squared value of 399, greater than 38 which is the chi squared value for rejection of the hypothesis at the 0.05 level. In other words, we must rejected our null hypothesis and conclude that at the 5% level of confidence that the two
populations are different. The NEA are not representative of the main belt. Either a different source is involved, or different sources are being sampled differently, for example a few major MBA impacts are feeding the NEA population. Cosmic ray exposures ages of chondrite meteorites suggest this might be the case since they show that a few major events disrupted the parent bodies of these major classes [6].

Comparison of the Class Distribution of Asteroids in the Main Belt and Near-Earth Vicinity

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Introduction
- Asteroid Populations
  - Main Belt Asteroids
    - 2 - 4 AU
  - Near-Earth Objects
    - <1 - 1.3 AU
- Are the NEOs a subset of the Main Belt asteroids?

Background
- ~3000 in NEO population
- Atens
  - \( \sigma \leq 1.0 \text{ AU} \)
  - \( Q > 0.983 \text{ AU} \)
- Apollos
  - \( \sigma \geq 1.0 \text{ AU} \)
  - \( q \leq 1.0167 \text{ AU} \)
- Amors
  - \( \sigma \geq 1 \text{ AU} \)
  - \( 1.017 < q \leq 1.3 \text{ AU} \)
  - \( 10^6 - 10^7 \text{ year lifetimes} \)
- Potential sources of resupply
  - Short period comets
  - Halley’s comet
  - Jupiter-family comets
  - Main belt asteroids

Experimental
- Taxonomy classifications
  - NASA Planetary Data Systems
  - Near Earth Objects - Dynamical Site
  - JPL Small Body Database
- Compared classifications of the two populations
- Performed a chi squared analysis of the MBA and NEA class distributions

Conclusions
- Similar abundances in each population
  - S, A, B, Cb, D, S, SI and T classes
- Striking number of disagreements
- ~1800 MBA and ~300 NEA that are well classified
- Chi squared value of 300 was obtained
  - Strongly rejects hypothesis at 5% level of confidence
  - Compared to the expected value of 28
- The NEA are not representative of the Main Belt

References
Appendix F: Primitive Materials on Asteroids
PRIMITIVE MATERIALS ON ASTEROIDS.


Introduction: The linkage between asteroids and meteorites is critical if we are to fully understand the origin and evolution of the primitive materials of the solar system [1]. Usually, astronomical spectra are obtained and meteorite matches are sought. We are reversing this, and searching for what we perceive to be likely primitive materials among the asteroid spectra, emphasizing NEA [2-4]. We are focusing on type 3 ordinary chondrites and terrestrial phyllosilicates, not relying on the rare C chondrite observed falls as a point of comparison because of selection effects of the atmosphere. To add to the database of published spectra, we also run our own program of IRTF observations.

Type 3 (unequilibrated) ordinary chondrites (UOC): To date we have located IR spectra of six UOC, run the MGM spectral analysis program [5,6] and plotted the data on the Gaffey plot [7]. Few if any of the UOC plot in the ordinary chondrite fields of the Gaffey plot, but when analyzed by MGM all have absorption dips at ~2 μm normally associated with calcic pyroxene. This band is almost certainly due to monoclinic pyroxene a major phase in UOC [2,3]. The question thus arises whether any of the asteroids for which calcic pyroxene has been reported are actually the source objects for UOC. The discovery of asteroids whose surfaces are uniformly covered with UOC material would suggest that those objects are internally heated monoliths, with equilibrated ordinary chondrites coming from the interiors during fragmentation. The presence of UOC material on one side of the asteroid would indicate fragmentation, whereas patchy occurrences of UOC material, only observable with spacecraft resolution, would indicate rubble piles.

Phyllosilicates: While some authors have focused on finding bands of hydrated minerals or water on asteroids [8,9], others have used continuum slope as a basis for comparison [10]. We find that the slope of the continuum of phyllosilicate IR spectra depends on composition and structure, and does not overlap with similar data for the C asteroids unless the phyllosilicates are heated in the laboratory to temperatures ~900°C [4]. This suggests that the surfaces of C asteroids are covered with hydrated phyllosilicates, presumably dehydrated by the heat of micrometeorite impact. We are optimistic that further analysis will make it possible to constrain the nature of the phyllosilicates and the degree of heating.

Appendix G: Primitive Materials on Asteroids
Primitive Materials on Asteroids

Sears, Derek W. G.; Gietzen, K.; Ostrowski, D.; Lacy, C; Chevrier, V

Abstract

The linkage between asteroids and meteorites is critical if we are to fully understand both. We are searching for evidence of likely primitive materials among asteroid spectra, looking for unequilibrated ordinary chondrite (UOC) material on S asteroids and material similar to terrestrial phyllosilicates on C asteroids. We do not rely on the rare C chondrites as a point of comparison with C asteroids because of selection effects in their passage to Earth.

Few if any of the UOC plot in the ordinary chondrite field of the Gaffey plot, but all have absorption bands at 2 μm normally associated with calcic clinopyroxene. In the UOC this band is almost certainly due to Ca-free monoclinic pyroxene, a major phase in these meteorites. The question thus arises whether any of the asteroids for which calcic pyroxene has been reported are actually the source objects for UOC. The presence of asteroids with UOC-like surfaces would suggest that those objects are internally heated monoliths, with the equilibrated ordinary chondrites, which are more abundant in terrestrial falls, coming from the interiors. The presence of UOC material irregularly dispersed on the surface would suggest that the asteroids are rubble piles, but spacecraft observations would be required to see this.

The slope of the continuum of phyllosilicate IR spectra depends on composition and structure, and does not overlap with similar data for the C asteroids unless the phyllosilicates are heated in the laboratory to temperatures in excess of 900°C. This suggests that the surfaces of C asteroids are covered with phyllosilicates that were dehydrated during regolith working, as others have reported. We are optimistic that further analysis will make it possible to constrain the nature of the phyllosilicates and the degree of heating.
Appendix H: Low-Calcium and Calcium-free Clinopyroxene Spectra and the Implications for UOC (Type 3 Ordinary Chondrite) Material on Asteroids
LOW-CALCIUM AND CALCIUM-FREE CLINOPYROXENE SPECTRA AND THE IMPLICATIONS FOR UOC MATERIAL ON ASTEROIDS. K. M. Gietzen, C. H. S. Lacy1,2, D. R. Ostrowski, and D. W. G. Sears1,3. 1Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, Arkansas 72701, 2Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701, 3Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701 (kgietze@uark.edu)

Introduction: While some authors suggest that S asteroids have a similar mineral assemblage to ordinary chondrites, altered by space weathering and with small amounts of unknown admixtures [e.g. 1], others have argued that – based on comparison with terrestrial minerals – most of the S asteroids are a wide variety of materials, many of which are igneous assemblages unknown on Earth [e.g. 2]. In a recent study of eleven S asteroids we have observed by NASA’s IRTF all but one contained evidence for clinopyroxene when analyzed by the MGM method [3-5]. Since Ca-free clinopyroxene is a major component in the unequilibrated ordinary chondrites (UOC, also referred to as type 3 ordinary chondrites), and is absent in more populous equilibrated ordinary chondrites (EOC, type 4-6) where the pyroxene is in the orthorhombic form, we have argued that many or perhaps even most of the S asteroids have UOC material on their surfaces.

Experimental: Five low calcium or calcium-free terrestrial clinopyroxene samples were identified from their descriptions in ref. [8] and obtained from the Smithsonian Institution (Table 1). The samples were crushed and ground using a pestle and mortar and infrared spectra obtained over the range 0.8 – 2.5 μm, the range best suited to mineral identification and the range of our IRTF observations. The spectra were then analyzed using the Modified Gaussian Model (MGM) [6].

An issue in this proposal is that the MGM method is calibrated on the clinopyroxenes commonly encountered on Earth which are Ca-rich and normally have igneous associations [6,7]. The clinopyroxene in UOC is an unusual Ca-free variety, and it is not clear that this would have the same spectral properties as the Ca-rich forms. Most critical is the presence of an absorption band at ~2.3 μm, which is present in the Ca-rich clinopyroxenes but absent in the orthorhombic forms characteristic of most ordinary chondrites. We have therefore obtained near-IR spectra for calcium-free or calcium-poor clinopyroxenes. Here we report the results.

Results: While the whole spectrum is considered in mineral identification, the absorption band for Ca-rich clinopyroxene is located at ~2.3 μm, the exact position depending slightly on grain size, Fe content, and other factors. All five of

<table>
<thead>
<tr>
<th>Sample and Number</th>
<th>Location</th>
<th>Formula</th>
</tr>
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<tr>
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<td>NaFe3+(Si:O6)</td>
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<td>Napoui, New Caledonia.</td>
<td>MgSiO3</td>
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<td>Ravensworth, New South Wales, Australia</td>
<td>FeSiO3</td>
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<tr>
<td>Jadeite 113778</td>
<td>Clear Creek, California</td>
<td>NaAl(Si:O6)</td>
</tr>
<tr>
<td>Spodumene R3068</td>
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</tr>
</tbody>
</table>

Table 1. Low-Ca and Ca-free clinopyroxenes used in the present work.*

Fig. 1. Spectrum for a low-Ca clinopyroxene (purple dots) analyzed by the MGM method. The clinopyroxene absorption is indicated. Like Ca-rich clinopyroxenes, low-Ca clinopyroxenes have an absorption band at ~2.3 μm.

our terrestrial low-Ca clinopyroxenes showed an absorption feature at ~2.3 μm. As an example, we show one of the spectra and the results of MGM analysis in Fig. 1. We plot the locations of the ~2.3 μm absorption bands in Fig. 2.
Discussion: The majority of ordinary chondrites, are the highly metamorphosed EOCs. Relatively rare are the UOC some which are thought to be close in physical form to the material that accreted from the primordial solar nebula and of special importance in deciphering early solar system history. While rare on Earth, low-Ca clinopyroxene is abundant in the UOC, maybe 25 vol% of the meteorite [9]. Thermal metamorphism to temperatures of greater than ~700°C produces a wide variety of mineralogical, chemical, and physical changes in the meteorites including the conversion of clinopyroxene to orthopyroxene. Thus the great majority of ordinary chondrites contain orthopyroxene and this goes some way in explaining the mismatch between ordinary chondrites and S asteroids since orthopyroxene does not display the ~2.3 μm absorption (Fig. 3). Thus it is possible that many, perhaps most, of the S asteroids have surfaces consisting of UOC or UOC-like materials.

Fig. 2. All low-Ca clinopyroxenes studied here display an absorption at ~2.3 μm which is similar to that of UOC, S asteroids, and calcic clinopyroxenes, and which distinguishes them from the common ordinary chondrites (the EOC).

If we are correct, then there are major ramifications for meteorite genesis and asteroid structure. UOC are rare on Earth, yet would seem abundant on asteroids, consistent with several lines of data that suggest stochastic events dominate in determining the nature of the ordinary chondrite flux to Earth. The ordinary chondrites came from very large objects (~100km) whose fragmentation is documented by clusterings in the cosmic ray exposure ages (8 Ma for the H chondrites, 17 Ma for the LL chondrites) and K-Ar ages (500 Ma for the L chondrites). These were huge events that must have largely exposed interior and highly metamorphosed materials [10]. Several authors have published thermal models for the interior of asteroids, and assuming modest levels of internal heating by 26Al, much of the asteroid is expected to be highly metamorphosed. In fact, only the outer 5% or so of a typical asteroid experienced UOC levels of alteration according to such models [e.g. 11]. Thus an onion skin (concentrically zoned) structure would be inferred and much of the surface would be UOC and most of the interior would be EOC material. Alternatively, if the bodies formed late and did not acquire the rapidly decaying 26Al, then the entire body would be UOC and these asteroids could be rubble piles.

Fig. 3. Spectra for an (a) S asteroid 18, (b) UOC Tieschitz, (c) EOC Colby. The asteroid and the UOC contains spectroscopic evidence
for clinopyroxene, the EOC does not. This is consistent with the S asteroids have UOC or UOC-like material on their surfaces.

Low-Calcium and Calcium-free Clinopyroxene Spectra and the Implications for UOC (Type 3 Ordinary Chondrite) Material on Asteroids

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<td>Eta mine, South Dakota</td>
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</table>

Introduction

- Two possibilities for S asteroids
- Mineralogy similar to ordinary chondrites but altered by space weathering [1].
- Wide variety of mineralogy - many are igneous assemblages [2, 6, 7].
- Our previous studies find evidence of clinopyroxene (CPX) in the spectra for ten of eleven S asteroids [3-5].

Ca-free CPX is a major component in type 3 ordinary chondrites and CPX is absent in type 4 – 6. We have proposed type 3 material is common on S asteroids [3-5].

While calcium CPX has been well studied [6], little spectroscopic data exists on Ca poor CPX. We here report data for five Ca poor clinopyroxenes.

Procedures

- Five low-Ca or Ca-free terrestrial CPX samples identified using [8] were obtained from the Smithsonian Institution (Table 1).
- Infrared spectra over the range 0.8 – 2.5 μm were obtained, and analyzed using the Modified Gaussian Model (MGM) [7].

Fig. 1. Near Infrared MGM analysis of Ca-free clinopyroxene spectra.

Results

- All Ca-free clinopyroxene spectra displayed an absorption band ~2.2 μm (Fig. 1 and 2).
- Ca-free UOC S asteroids and Ca-rich clinopyroxenes displayed an absorption feature ~2.2 μm as well (Fig. 2).

Conclusions

- CPX that is Ca-free contains an absorption feature near 2.2 μm like the calcic CPX (Fig. 1 and 2).
- Type 3 ordinary chondrites are rich in Ca-free CPX and display an absorption near 2.2 μm [4,5].
- S asteroid spectra also contain the 2.2 μm feature [3].
- It is probable that the surfaces of many, perhaps most, S asteroids contain UOC material.

References
