Linkage of Asteroids and Meteorites by the Study of Terrestrial Analogs

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LINKAGE OF ASTEROIDS AND METEORITES BY THE STUDY OF TERRESTRIAL ANALOGS
LINKAGE OF ASTEROIDS AND METEORITES BY THE STUDY OF
TERRESTRIAL ANALOGS

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

By

Daniel R. Ostrowski
Carroll College
Bachelor of Science in Chemistry, 2006

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ABSTRACT

Asteroids are one group of the bodies that can provide insights into the origin and early history of the solar system. Asteroids are considered to be fairly pristine, with alterations only occurring to their surface from the space environment. Studying them provides opportunities to learn about the primordial solar system, its materials, and processes and how it evolved into the current condition. Many asteroids have been discovered, but few have their surface compositions determined. The C and X complexes provide a difficulty in determination because their near infrared spectrum is featureless.

The C asteroids have been long associated with the carbonaceous chondrites because of similar albedos and matching spectra. The carbonaceous chondrites do not look like the major minerals that compose their matrix. Phyllosilicates are the primary mineral in the matrix and evaporites are also in high quantity. Heat treatment investigation has been conducted on terrestrial analogs to simulate heat implanted into the surface of asteroids by micrometeorite impacts.

The mineralogical interesting region of the spectrum is the near infrared region. The featureless spectrum of the C and X asteroids and carbonaceous chondrites in this region require the use of continuum slopes to compare the three groups to one another. For investigation, the continuum slope is broken down into two regions and plotted against each other. The short wavelength region is 1.0-1.75µm and the long wavelength region is 1.8-2.5µm. The break at 1.75µm is the result of a discontinuity in the spectrum of the phyllosilicates. The meteorites and asteroids plot in small fields that overlap each other showing that they are related. The phyllosilicates and
phyllosilicate-evaporite mixtures plot in a large field below the asteroids, suggesting no connection. Heating the phyllosilicates and phyllosilicate-evaporite mixtures causes the resulting data to plot among the asteroids, giving an insight to the surface composition of C and X asteroids. The surface is likely composed of a decomposed mixture of 40wt% phyllosilicate–60wt% evaporite. It is plausible that when opaque materials are taken into account that the serpentine in the mixtures would still retain its structural water, but still provide a spectrum similar to the C asteroids.
This dissertation is approved for
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DEDICATION

I dedicate this to my parents, my brothers and the rest of my family.
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we quantify the main features of these spectra using “continuum slopes”
over the two arbitrarily selected wavelength intervals, 1.0 to 1.75 µm and
1.8 to 2.5 µm. For the purposes of determining slopes, the spectra are
normalized to 0.875 µm.

Figure. 4.2 (a) Numerical spectra mixing for the phyllosilicate serpentine and the
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changes made in 10% increments. (b) From the numerical spectral mixing
a mixture of 40 wt% serpentine – 60 wt% epsomite is the smoothest of the
spectra, but a strong decreasing slope remains. Of the mixtures of these
two minerals this is the ratio that produces the most C asteroid like
spectra. In the 40 wt% serpentine – 60 wt% epsomite spectral mixture
many of the spectral features of the two mineral phases remain, but are the
weakest of all the mixtures.

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evaporite gypsum to generate the most C asteroid like spectra. The
mixtures depicted go from 100% gypsum to 100% serpentine with
changes made in 10% increments. (b) From the numerical spectral mixing
a mixture of 40 wt% serpentine – 60 wt% gypsum is the smoothest of the
spectra, but a decreasing slope remains. Of the mixtures of these two
minerals this is the ratio that produces the most C asteroid like
spectra. In the 40 wt% serpentine – 60 wt% gypsum spectral mixture many strong
spectral features of the two mineral phases remain, but many of the weak
features of the minerals are removed.

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two minerals this is the ratio that produces the most C asteroid like
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CHAPTER 1
Introduction

1.1 Asteroid Discovering History

Ancient cultures around the world gazed into the night sky, some in wonder and honor while others in study and understanding. Over the centuries these observations allowed them to discover all the aspects of the motions of the celestial bodies. In the renaissance period astronomy began to understand and develop better models of the Solar System. 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 (Serio et al., 2002). Over the course of time many scientists searched for the explanation for the gap. The search for the possible “missing planet” was one of the main goals of the Vereinigte Astronomische Gesellschaft (commonly known as the Lilienthal Society). A group of about twenty-four astronomers in the society were formed (known as Celestial Police) for the purpose of finding the “missing planet”. Each astronomer was assigned a 15° section of longitude along the zodiac with the plans to survey the zodiac down to the smallest telescopic stars (Serio et al., 2002). Ceres was discovered on January 1, 1801 by Giuseppe Piazzi (who was not a member of the society) while he was working on his star catalog. He gave the newly observed object the name Ceres after the patron goddess of Sicily. He kept calling the object a comet or new star (Piazzi, 1801). Ceres is the first discovered asteroid and later was determined to be a C-type (see taxonomy section 1.2), but in 2006 it was upgraded to a dwarf planet by the International Astronomical Union.

By 1807 three more asteroids, Pallas, Juno and Vesta, had been discovered. This led to the hypothesis of Bode (1804) that there are many small planets between Mars and
Jupiter that were formed at the same time as the other planets. The more accepted hypothesis at the time was Olbers’ theory, which suggested the newly found objects were fragments of an exploded planet (Oriani, 1802). Olbers’ theory was fueled for 40 years because it was not till 1845 that the next asteroid, Astaea, was observed. By the late 1850s Bode’s hypothesis would be the accepted one as noted by Arago (1857) when there were 50 observed asteroids.
Figure 1.1 Number of known asteroids as a function of time. There is a change of scale for the last intervals of year to show the exponential growth in the number of asteroids detected. This is the detection of all asteroids in the solar system. Data from the NASA Planetary Data System and IAU Minor Planet Center.
The search for asteroids still continues, just at a greater rate. The discovery rate for asteroids has increased dramatically over time because of the advances in technology. There were only fifty known asteroids by 1860 and 2031 by 1950. After 1950 the rate of discovery increased exponentially (Fig. 1.1); today there are just under 500,000 according to the IAU Minor Planet Center. This amount is expected to grow even more with the NASA Jet Propulsion Laboratory spacecraft WISE (Wide-field Infrared Survey Explorer). Of the near 500,000 asteroids, most are located inwards of the orbit of Jupiter (Fig 1.2).
Figure 1.2 Plot of the location of the minor objects in the inner region of the solar system. The orbits of the major planets are shown in light blue. The asteroids are indicated by green circles. Objects with perihelia within 1.3 AU are shown by red circles. Outline circles indicate objects that have observed only once. The blue clouds at 60° ahead and behind Jupiter are the Jupiter Trojans and are colored blue. Periodic comets are shown as filled light-blue squares and other comets are shown as unfilled light-blue squares. Image is obtained from the IAU Minor Planet Center <http://www.cfa.harvard.edu/iau/lists/InnerPlot.html>.
1.2 Asteroid Taxonomy

Classification systems that have been proposed involve such criteria as continuum slope in the UV, continuum slope in the visible, continuum slope in the near infrared, mineralogic composition as deduced from the 1 µm and 2 µm bands, various other absorption features in the UV to near infrared region, and albedo (Tholen, 1989; Bus, 1999; Gaffey et al., 1993a; Bus and Binzel, 2002; DeMeo et al., 2009). Tholen’s (1989) scheme consists of a visual inspection of the visible spectra that resulted 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). Bus (1999) taxonomy uses the Principal Components Analysis of visible spectra which identifies the continuum slope, absorption at ~0.8 µm, and absorption in the UV region as important discriminators. This resulted in 26 individual taxonomic classes, of which most are in three complexes; C, X, and S. 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, 2009). These are often referred to as “carbonaceous” asteroids due to their dark albedos and spectral relationship to carbonaceous chondrites. 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, 2009). 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. The S complex asteroids are commonly referred to as “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, 2009). The
percentages of the three complexes and rest of the Bus taxonomy asteroid types are displayed in Table 1.1.
### Table 1.1. 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>
<tr>
<td>Sl</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td></td>
</tr>
<tr>
<td>Sq</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</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>

*Table reproduced from Bus 1999*
The use of infrared telescopes has allowed for more detailed study of asteroids. The infrared region is useful for surface mineralogy determination of the asteroids and is becoming more used on asteroids. DeMeo et al. (2009) extended the Bus asteroid taxonomy into the near infrared region and thus uses the wavelength range of 0.45 to 2.45 \( \mu \text{m} \). This taxonomy scheme also has the ability of classify asteroid with only 0.85 to 2.45 \( \mu \text{m} \) spectral range because of the difference in spectral slope and position and strength of features, if any are present. Bus-DeMeo taxonomy is composed of 24 classes and are displayed in Fig 1.3 and described in Table 1.2. The Bus-DeMeo taxonomy eliminates the Ld, Sk and Sl classes from the Bus taxonomy and adds the Sv class. A “w” is added to some asteroid classes to denote the water features have been seen in the spectra, but it is not a distinct class (DeMeo et al., 2009).
Figure 1.3 The 24 asteroid taxonomic classes of the Bus-DeMeo taxonomy as defined over the 0.45-2.45 μm. Feature based taxonomy is displayed on the right and slope based taxonomy is displayed on the left. The slope based taxonomy is arranged by increasing slope from bottom to top. Source of image is DeMeo et al. (2009).
<table>
<thead>
<tr>
<th>Type</th>
<th>Spectral Description</th>
<th>Examples of Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Deep and extremely broad absorption band with a minimum near 1 µm, may or may not have shallow 2 µm absorption band; very highly sloped.</td>
<td>246, 289, 863</td>
</tr>
<tr>
<td>B</td>
<td>Linear, negatively sloping often with a slight round bump around 0.6 µm and/or a slightly concave up curvature in the 1 to 2 µm region.</td>
<td>2, 3200</td>
</tr>
<tr>
<td>C</td>
<td>Linear, neutral visible slope often a slight rough bump around 0.6 µm and low but positive slope after 1.3 µm. May exhibit slight feature long ward of 1 µm.</td>
<td>1, 10, 52</td>
</tr>
<tr>
<td>Cb</td>
<td>Linear with a small positive slope that begins around 1.1 µm.</td>
<td>191, 210, 785</td>
</tr>
<tr>
<td>Cg</td>
<td>Small positive slope that begins around 1.3 µm and pronounced UV drop-off</td>
<td>175</td>
</tr>
<tr>
<td>Cgh</td>
<td>Small positive slope that begins around 1 µm and pronounced UV drop-off similar to Cg includes a broad, shallow absorption band centered near 0.7 µm similar to Ch.</td>
<td>106, 706, 776</td>
</tr>
<tr>
<td>Ch</td>
<td>Small positive slope that begins around 1.1 µm and slightly pronounced UV drop-off also includes a broad, shallow absorption band centered near 0.7 µm.</td>
<td>19, 48, 49</td>
</tr>
<tr>
<td>D</td>
<td>Linear with very steep slope, some show slight curvature or gentle kink around 1.5 µm.</td>
<td>1143, 1542, 3248</td>
</tr>
<tr>
<td>K</td>
<td>Wide absorption band centered just long ward of 1 µm, the left maximum and the minimum are sharply pointed and the walls of the absorption are linear with very little curvature.</td>
<td>42, 579, 742</td>
</tr>
<tr>
<td>L</td>
<td>Steep slope in visible region leveling out abruptly around 0.7 µm. There is often a gentle concave down curvature in the infrared with a maximum around 1.5 µm. There may or may not be a 2 µm absorption feature.</td>
<td>236, 402, 606</td>
</tr>
<tr>
<td>O</td>
<td>Very rounded and deep, “bowl” absorption feature at 1 µm as well as a significant absorption feature at 2 µm.</td>
<td>3628</td>
</tr>
<tr>
<td>Q</td>
<td>Distinct 1 µm absorption feature with evidence of another feature near 1.3 µm; a 2 µm feature exists with varying depths between objects.</td>
<td>1862, 3753, 5660</td>
</tr>
<tr>
<td>R</td>
<td>Deep 1 and 2 µm features; the 1 µm feature is much narrower than a Q-type, but slightly broader than a V-type.</td>
<td>349</td>
</tr>
<tr>
<td>S</td>
<td>Moderate 1 and 2 µm features. The 2 µm feature may vary in depth between objects.</td>
<td>5, 14, 20</td>
</tr>
<tr>
<td>Sa</td>
<td>Has a deep and extremely broad absorption band at 1 µm; has similar features to A-type but is less red.</td>
<td>984, 5261</td>
</tr>
</tbody>
</table>

†Table reproduced from DeMeo et al., 2009.
<table>
<thead>
<tr>
<th>Type</th>
<th>Spectral Description</th>
<th>Examples of Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq</td>
<td>Has a wide 1 µm absorption band with evidence of a feature near 1.3 µm like the Q-type, except the 1 µm feature is more shallow for the Sq.</td>
<td>3, 11, 43</td>
</tr>
<tr>
<td>Sr</td>
<td>Has a fairly narrow 1 µm feature similar to but more shallow than an R-type as well as a 2 µm feature.</td>
<td>237, 808, 1228</td>
</tr>
<tr>
<td>Sv</td>
<td>Has a very narrow 1 µm absorption band similar to but more shallow than a V-type as well as a 2 µm feature.</td>
<td>2965, 4451</td>
</tr>
<tr>
<td>T</td>
<td>Linear with moderate to high slope and often gently concaving down.</td>
<td>96, 308, 773</td>
</tr>
<tr>
<td>V</td>
<td>Very strong and very narrow 1 µm absorption and as well as a strong 2 µm absorption feature.</td>
<td>4, 1929, 2851</td>
</tr>
<tr>
<td>X</td>
<td>Linear with medium to high slope.</td>
<td>22, 87, 153</td>
</tr>
<tr>
<td>Xc</td>
<td>Low to medium slope and slightly curved and concave downward.</td>
<td>21, 97, 739</td>
</tr>
<tr>
<td>Xe</td>
<td>Low to medium slope similar to either Xc or Xk-type, but with an absorption band feature short ward of 0.55 µm.</td>
<td>64, 77, 3103</td>
</tr>
<tr>
<td>Xk</td>
<td>Slightly curved and concave downward similar to Xc-type but with a faint feature between 0.8 to 1 µm.</td>
<td>56, 110, 337</td>
</tr>
</tbody>
</table>

†Table reproduced from DeMeo et al., 2009.
Gaffey et al. (1993) used mineralogical interpretation of reflectance spectra by proposing a subdivision of the S asteroids into seven sub-types, S(I) through S(VII). Many authors note the lack of good matches between the ordinary chondrites and the majority of S asteroids, known as the asteroid-meteorite mismatch. Gaffey et al. (1993) identified, though it had been hypothesized for many years, the ordinary chondrites as one of several possibilities similar to the S(IV) asteroids. In the other S groups, Gaffey et al. (1993) identifies the presence of minerals characteristic of melts and partial melts, such as calcium-rich clinopyroxene (Sunshine et al., 2004).

1.3 Main-Belt Asteroids

Asteroids are interplanetary bodies theorized to be remnants of Solar System formation and therefore are important in deducing the origin and history of the Solar System. Determination of the structure and mineralogical composition can give a glimpse of the early Solar System conditions and an insight to its evolution. The formation, distribution, physical properties and evolution are essential to our understanding of the life of an asteroid and some of the planet building material in the Solar System.

1.3.1 Formation of Main-Belt Asteroids

Between the orbits of Jupiter and Mars are the main-belt asteroids (MBA), which is the largest reservoir of asteroids in the Solar System. The method in which the main belt obtained its current characteristic has been suggested to be linked to the formation of the terrestrial planets and to Jupiter (Bottke et al., 2002a). Weidenschilling (2000) theorizes the sequence of planet formation in the inner solar system occurred in a four step process
starting with accumulation of dust in the solar nebula and ending with perturbations between Moon-to-Mars sized planet embryos and Jupiter caused collisions, mergers and dynamical excitations of the small-body populations that kept them from being accreted. The calcium-aluminum-rich inclusions (CAIs) in chondritic meteorites have been used to give clues to asteroid formation processes. The estimated initial formation age of asteroids with diameters greater than 10 km is \( \sim 4569 \) m.y. (Bottke et al., 2002).

### 1.3.2. Evolution of the Primordial Main Belt

The primordial main belt formation was significantly altered by the formation of Jupiter. Models by Petit et al. (2002) suggest that the main belt had between 2 – 10 \( M_\oplus \) material in it to work with, but currently it contains only \( \sim 5 \times 10^{-4} M_\oplus \). The large mass depletion is greatest in the outer main belt where Jupiter would have its greatest impact. The primordial main belt had eccentricities and inclinations to allow for accretion, but the current median values are high enough that fragmentations due to collisions occur (Petit et al., 2002). These strong dynamical excitations are theorized to be created by Jupiter. The third effect Jupiter had on the evolution of the primordial main belt is the radial mixing of the asteroid types (Bottke et al., 2002a). Thermal models state that the outer portion of the main belt should contain more primitive asteroids than the inner belt containing heated/processed asteroids (McSween et al. 2002). Petit et al. (2002) suggest that the current characteristics are the result of dynamical removal mechanism caused by Jupiter’s formation that generated resonances that could scatter the asteroids.
1.3.3 Present Condition of the Main Belt

The evolution of the main belt occurred early in the history of the Solar System and took a relatively short time, ~100 million years. The short-term alteration processes of numerous impacts, thermal processing and dynamical upheaval have run their course, but the evolution of the remaining population still occurred. The current dominant alteration process in the main belt is collisions, either by inter-asteroid collisions or by micrometeorite impacts. This alteration operates at a much slower rate in the modern geologic time frame and is mostly a geologic process. A collisional outcome depends on a few variables, but for the most part have the outcomes of surface gardening, ejecta, forming satellites, or forming asteroid families. In an orbital sense the Yarkovsky Effect can alter orbital parameters of an asteroid. As explained by Bottke et al. (2002b) small sun orbiting bodies (20 km and smaller) absorb sunlight and reradiate the thermal energy generating thermal inertia to alter the body’s spin. This process is possibly strong and or continuous to move the bodies into one of Jupiter resonances that would completely alter the asteroids’ orbit.

1.4 Near-Earth Asteroids

Near-Earth Asteroids (NEA) are a subgroup of the near-Earth object (NEO) population and are defined as the asteroids that have perihelion distances \( q \leq 1.3 \) AU and aphelion distances \( Q \geq 0.983 \) AU. There are three subcategories to the population: (1) the Apollos \( (a \geq 1.0 \text{ AU}, q \leq 1.0167 \text{ AU}) \), (2) the Atens \( (a < 1.0 \text{ AU}, Q \geq 0.983 \text{ AU}) \), which are on Earth-crossing orbits and (3) the Amors \( (a \geq 1.0 \text{ AU}, 1.0167 < q \leq 1.3 \text{ AU}) \) which are Earth-approaching orbits, where \( a \) is the semi-major axis. The NEAs in general have a short lifetime of about 10 million years (Tancredi, 1998). They are
typically lost to collision with one of the inner planets or the Sun or by a chaotic orbit becoming a hyperbolic orbit (Morais and Morbidelli, 2002). Crater record in the Earth-Moon system suggests the population has been in a steady state for 3 billion years (Grieve and Shoemaker, 1994). This means that the NEA population is being continually resupplied and that we only see a young picture.

1.4.1 Source of the Near-Earth Asteroid Population

Near-Earth asteroids have short lifetimes and with models showing the apparent steady state size of the population, thus a replacement source is required. The current theory is that the main belt is the reservoir for the NEA population. The current theories suggest that the transfer of asteroids is the result of orbital resonances with Jupiter and the $v_6$ secular resonance both of which can be aided by Yarkovsky thermal forces. (Gladman et al., 1997; Bottke et al., 2002b; Bottke et al., 2006; Brož et al., 2005).

The $v_6$ resonance is a secular resonance between the precession frequency of main belt asteroids and the precession frequency of Saturn. This occurs at the inner edge of the main belt and is about a 0.18 AU wide region (Morbidelli et al., 2002). When in the $v_6$ resonance an asteroid has its eccentricity slowly increased until it becomes a Mars-crossing orbit. This generally occurs on the scale of 0.5 – 2 million years (Morbidelli et al., 2002). Very few of the ejected asteroids become NEAs, about 80% crash into the Sun and about 12% form hyperbolic orbits (Gladman et al., 1997).

Jupiter has three mean-motion resonances with the main belt asteroids; 3:1, 5:2, and 2:1. The resonances, in name and position, are the simple integer ratios between the periods of Jupiter and the asteroids. A mean-motion resonance more specifically is the
point of conjunction where gravitational forces between the two bodies cause small oscillations in each other. The oscillations in the asteroid can increase their eccentricity and move them into a possible Earth crossing orbit. The 5:2 resonance is the fastest at turning MBAs into NEAs in about three hundred thousands years, where the 2:1 resonance is the longest at several million years (Morbidelli et al., 2002).

The Yarkovsky effect, as stated before, is a radiation force phenomenon that could alter asteroid’s orbits. Most asteroids do not live in or near the resonances. The Yarkovsky effect can move asteroids from close to the resonances to in the resonances. This allows the resonances, being the major orbital alteration force, to send asteroids towards the Earth to possible become an NEA.

1.4.2 Alteration of the Current Near-Earth Asteroid Population

The primary geologic alteration process that presently occurs in all asteroid population is collisions (Bottke et al., 2002a). The images of asteroid 433 Eros show the effects collisions from different size objects can have on an asteroid (Fig 1.4.) The impactor depending on size and composition of both bodies will cause different alterations to the body. Large impactors can blast parts off or even bust the asteroid completely apart. While on the other hand all micrometeorite size impactors can expose fresh subsurface material or inject heat capable of mineralogical alteration into the surface. Asteroids experience numerous cratering events before their final termination of a very energetic impact with a planet or the Sun. The studied remains that impact Earth provide important information about the target as well as the bombarding population.
Figure 1.4. The asteroid 433 Eros as it appeared to the NEAR-Shoemaker spacecraft. Source of image is from NASA images. 
<http://nssdc.gsfc.nasa.gov/planetary/mission/near/>
1.5 Effects of Space on Asteroid Surfaces

The space environment for an airless body is harsh and over time can result in optical changes to their surfaces. The optical changes to the surface are the result of modification by impacts, solar wind ion implantation, sputtering, or micrometeorite bombardment. These processes collectively are known as “space weathering.” Most of the information known about space weathering is from studying the moon, though the lunar environment is different than the environment on asteroids. Additional information is generated from images of asteroids from unmanned spacecraft and laboratory simulations. Understanding the effects of the space environment is important to remote sensing of asteroid surfaces.

The lunar samples have provided the ability to directly study space weathering in the laboratory. One of the main causes of alteration to the lunar surface is the implantation of nanophase iron. The nanophase iron is implanted into the regolith by solar wind sputtering as seen in Fig 1.5 (Keller et al., 1999; Pieters et al., 2000). The nanophase iron optical effects are not linear effects. For small amounts of nanophase iron it acts as a darkening agent, reducing albedo and removing spectral features causing a reddening to the spectrum. On the other hand large amounts of nanophase iron dominate the spectrum (Clark et al., 2002).
Figure 1.5 Transmission electron microscopy (TEM) image of anorthosite in lunar sample. Particles of nanophase iron are indicated in the rim of the grain. The scale bar indicates that implantation of nanophase iron only effects the uppermost region of the surface leaving the rest of the material in pristine condition. Image from Clark et al., (2002).
Space weathering effects on asteroids are dependent on the composition of the body being studied. For the S asteroids, which are mostly composed of olivine and pyroxenes, when compared to ordinary chondrites, theorized to be linked, the spectral effects are a decrease in albedo and band depth by half and a redder slope (Clark et al., 2002). On the other hand C asteroids, which are linked to carbonaceous chondrites because of similar albedos and spectra appear to not been altered, but when both are compared to terrestrial analogs of the minerals that compose the carbonaceous chondrites there is no spectral relationship. The terrestrial analogs have a non-linear slope and a higher albedo, so they have to be altered to have similar spectral properties (Ostrowski et al., 2010).

The common alteration processes that affect both the S-type and C-type asteroids are impacts and micrometeorite bombardment. Impacts entail large meteorite, asteroid and comets striking the body. The alteration they cause is either craters or breaking the asteroid apart; both result in exposing fresh subsurface material. Micrometeorite bombardment does two alterations: (1) grinds away rock material making the fine-grained material that covers the surface, and (2) the impacts implant heat into the surface. The injected heat can be hot enough to cause mineral alteration up to the point of mineral decomposition of the surface (Ostrowski et al., 2010).

1.6 Present Thesis

The main question of this thesis is: What is the surface of C and X complex asteroids composed of? This has been investigated by studying the infrared spectra of C and X asteroids, carbonaceous chondrites and terrestrial analogs. This thesis consists of a study of terrestrial phyllosilicates and thermal alterations to those phyllosilicates that are then compared to carbonaceous chondrites and C complex asteroids via continuum slopes.
of the near infrared spectrum (Chapter 2). This study’s goal is to determine the composition of the surface material for C asteroids. This work is published in Meteoritics and Planetary Science. Next is an investigation of the type of asteroids that make up the C and X complexes and how they relate to one another by continuum slopes in the near infrared spectrum to aide in the determination of their surface composition. This is described in Chapter 3, which also includes a comparison of carbonaceous chondrites to asteroids to determine possible parent type sources. This work has been submitted to Icarus for publication. Discussed in chapter 4 is continued work on the determination of C and now also X asteroids. This entails the use of continuum slopes of mixtures of phyllosilicates and evaporites of material that is known to exist in CI and CM chondrites for comparison. In the process of sample generation of the phyllosilicate-evaporite mixtures small spherical objects were generated. A visual comparison of these spherical objects to rounded phyllosilicate aggregates in CI chondrites (Chapter 5). Finally, I summarize the conclusions and make a few suggestions for future work (Chapter 6).
CHAPTER 2

An investigation of the presence and nature of phyllosilicates on the surface of C asteroids by an analysis of the continuum slopes in their near infrared spectra.

In this chapter we look at the relationship of phyllosilicates and thermally treated phyllosilicates to the surface composition of C asteroids. Dr. Claud H. S. Lacy made the asteroid observations and contributed knowledge of asteroids. Dr. Kathy Gietzen contributed knowledge and background on asteroids. Dr. Derek W. G. Sears contributed knowledge and background for the carbonaceous chondrites and their relation to the asteroids. Dr. Derek W. G. Sears also contributed the original analysis method. I generated the thermally treated phyllosilicate samples, collected and analyzed all the infrared data for the C asteroids, carbonaceous chondrites and phyllosilicates.

2.1 Abstract

In order to understand the nature of C asteroid surfaces, which are often related to phyllosilicates and C chondrites, we report near-IR spectra for a suite of phyllosilicates, heated 100-1100 °C in 100 °C intervals, and compare the results IRTF spectra for eleven C asteroids. Since C asteroids have relatively featureless spectra, we focus on “continuum plots” (1.0-1.75 µm slope against 1.8-2.5 µm slope). The use of continuum slopes is justified by several detailed arguments. We compare the continuum plots of the eleven C asteroids and our heated phyllosilicates with literature data for C chondrites. The CI, CR, CK, and CV chondrite meteorites plot in the C asteroid field, while CM chondrites plot in a close but discrete field. All are well separated from the large phyllosilicate field. Heating kaolinite and montmorillonite to \( \geq 700^\circ C \) moves their continua slopes into the C asteroid field, while chlorite and serpentine slopes move into
the CM chondrite field. Water losses during heating are generally 10-15 wt% and were associated with a 20-70% drop in albedo. Our data are consistent with surfaces of the C asteroids consisting of the alteration (dehydration) products of montmorillonite while the CM chondrites are the alteration (dehydration) products of serpentine and chlorite, in agreement with the known mineralogy of the meteorites. The presence of opaque minerals and evaporites do not provide quantitative explanations for the difference in continua slopes of the phyllosilicates and C asteroids. The CM chondrites can also be linked to the C asteroids by heating. We suggest that the CM chondrites, with their high water contents, are interior samples, the presence of a 3 µm feature in C asteroid spectra also indicates the excavation of material.

2.2 Introduction

It has been assumed for decades that the C chondrites are related to the C asteroids, but the details are unclear (Johnson and Fanale 1973; Burbine et al. 2002; Gaffey et al. 2002). The C chondrites are very rare in the terrestrial collections, presumably because of their friability, but C asteroids are very abundant in the asteroid belt so it is not clear that the few C chondrites are representative of their asteroid cousins. The reflectance spectra of both C chondrites and C asteroids show only weak absorption features, so compositional fingerprinting is difficult. C chondrites are noted for their high water contents, up to ~10 vol% for CM chondrites and up to ~20 vol% for CI chondrites (Wiik 1969; Jarosewich 1990). Maybe a half of the C asteroids contain evidence for water in the form of a 3 µm feature, but measurements are difficult because absorption by atmospheric water and weak signals. The 3.0 µm feature (actually an O-H feature) has been observed on Ceres (Lebofsky 1978), and a number of C asteroids (Lebofsky 1980;
Feierberg et al. 1985; Jones et al 1990). Vilas and Gaffey (1989) found broad features at 0.7 μm, with a depth of up to 5%, that matched similarly weak features in CM chondrites, which they ascribed to hydrated iron oxides associated with phyllosilicates. Vilas (1994) observed a correlation between the 0.7 μm feature and the 3.0 μm feature for a number of C asteroids, and finds evidence for water in about half of the 31 asteroids she considered. Fornasier et al. (1999) similarly compared CM chondrites with C asteroids and suggested that 65% of the 34 C asteroids they observed contained the 0.7 μm feature.

The meteorite classes most closely resembling the solar photosphere in composition are the CI and CM chondrites, especially the more volatile-rich CI chondrites. These meteorites are very fine-grained and the CM chondrites are inclusion and chondrule-bearing breccias displaying wide variety in the degree of aqueous alteration. Much of the fine-grained matrix in these meteorites is amorphous. Brearley (2006) recently reviewed the topic, describing the CI chondrites as complex with a dark, fine-grained matrix comprised largely of phyllosilicates (serpentine interlayered with saponite) with magnetite, sulfides, carbonates, and sulfates embedded within it (DuFresne and Anders, 1962; Böstrom and Fredriksson, 1966; Nagy, 1966; Tomeoka and Buseck, 1988). The CM chondrites are fine-grained serpentines and amorphous/nanocrystalline material, nanometer- to micrometer-sized sulfides, tochilinite [6Fe_{0.9}S 5(Fe,Mg)(OH)_{2}], intergrown the Fe^{3+}-rich serpentine, and cronstedtite (e.g., Tomeoka and Buseck, 1985). These intergrowths have commonly been called “spinach” or “poorly characterized phase (PCP)”. Given the bulk composition of the C chondrites, being high in volatile elements and water, and their apparently low formation temperatures, it seems reasonable that C asteroids should consist primarily of phyllosilicates. In fact, a number of primitive small
solar system objects such as interstellar grains, interplanetary dust particles (IDPs), and micrometeorites, are known to consist in part of phyllosilicates (Zaikowski and Knacke 1975; Rietmeijer 1991; Genge et al. 1997). So why do the spectra of C asteroids look so unlike those of phyllosilicates?

In fact, the spectra of the C chondrite meteorites bear little similarity to those of the phyllosilicates, despite frequent references to phyllosilicates in these meteorites. The spectra of C chondrites are virtually flat and featureless when compared to those of terrestrial phyllosilicates, which contain deep absorption bands attributable to a variety of water-related bonds (e.g. Hiroi and Pieters, 1993). In addition, the albedo of the C chondrites is very low (~0.06), compared to phyllosilicates (~0.4). Is it the abundance of minor phases, particularly the opaque phases, which flattens the spectra while decreasing the albedo? Or is it that silicates in these meteorites are largely dehydrated and the water in the meteorites is mostly associated with other phases, such as the abundant carbonates? Perhaps it is both the form of the silicates and the abundance of opaque phases that is responsible for the flat, featureless, low albedo spectra of C chondrites. Then we have the issue of how the phyllosilicates and the C chondrites relate to the C asteroids. Hiroi and colleagues have shown that laboratory heating experiments on CM chondrites will change the slope of their continua and make them resemble those of the C asteroids (Hiroi et al., 1993; Hiroi and Zolensky, 1999), so why is this the case and how do these data relate to phyllosilicates? The purpose of this paper is to explore these relationships.

Phyllosilicates are minerals consisting of silicate sheets, the layers being made of tetrahedral and octahedral unit cells. Depending on the number and pattern of these sheets, the phyllosilicate structures are referred to as 1:1, 2:1, and 2:1:1.
Compositionally, phyllosilicates can be quite diverse. The octahedral sheets commonly contain Fe(II), Fe(III), Al, or Mg, whereas the tetrahedral sheets contain Si, Al, and sometimes Fe(III). Their layered structure and ionic environment mean that they are capable of adsorbing variable amounts of water that can usually be removed by heating to 500 to 700°C (Grim 1968, chapter 9).

It is clear from many images of asteroid surfaces, in fact the surfaces of most airless solar system bodies, that impact, thermal processing, and regolith gardening have been important in determining the present nature of their surfaces. Thus Hiroi and his co-workers have performed laboratory heating experiments on C chondrites and suggest that CM chondrites heated to 1000°C provide a reasonable match in the shape of the continuum (including the UV wavelengths) for the spectra of five C asteroids (Hiroi et al. 1993). On the basis of analogous heating studies of five terrestrial phyllosilicates, but heating only to 600°C, Hiroi and Zolensky (1999) suggested that the phyllosilicate on C asteroid surfaces was saponite (a smectite) but were uncomfortable with this conclusion because this mineral is rare in CM chondrites.

In the present paper we report heating experiments – over the temperature range 100 to 1100°C – on five terrestrial phyllosilicates, chosen to represent a variety of compositions and structures, and we compare the results with spectra of eleven C asteroids and with C chondrites. We have obtained spectra for meteorites and terrestrial phyllosilicates from the on-line databases, and we have obtained spectra for C asteroids using the NASA Infrared Telescope Facility (IRTF) which are discussed elsewhere (Ostrowski et al., 2010). We place an emphasis on continuum slopes in our work, because we argue that they provide a new quantitative way of comparing spectra and
looking for genetic links. There is no reason to assume every C asteroid is represented in our meteorite collections, and in any event the meteorites are probably not representative of their parent asteroids. They are a random selection of the tougher ejecta. As we discuss above, meteorites are also highly complex and take some disentangling themselves to understand their history. So to improve our understanding the least we can do is take likely minerals and treat them in the laboratory in a manner likely to reproduce there some aspect of their history on an asteroid surface. Hiroi’s phyllosilicate heating experiments had an upper temperature limit was 600°C, which is too low for impact processes that result in craters, glasses, breccias etc. Our results clearly link certain phyllosilicates to certain asteroids for which meteorite data are consistent but not definitive. Preliminary reports of this project were made at several conferences (Ostrowski et al. 2008a,b; Sears et al. 2008a,b)

2.3 Experimental

The phyllosilicates we used for this work are listed in Table 2.1, with source, composition, structure, and typical terrestrial occurrence. Samples were sieved to a grain size less than 63μm using a #230 U.S. Standard Testing Sieve attached to a Humboldt MFG Co. shaker. Two-gram samples of the phyllosilicates were placed in a ceramic tube and preheated to 100°C in an oven to release adsorbed water. Samples were then heated to 300, 400, 500, 600, 700, 800, 900 for 24 hours and at 1000 and 1100°C for six hours. Two sigma uncertainties on these temperatures throughout the experiment were ~1%. Water loss was determined by difference. Samples were placed in desiccators for cooling. Most samples were heated and allowed to cool in air, but since some of the
samples changed color and albedo, we also performed a series of heating experiments on chlorite in an argon atmosphere flowing at 135 ml/min.
Table 2.1. Phyllosilicates used in the present study with relevant information.

<table>
<thead>
<tr>
<th>Sample, Catalog No.*, Location</th>
<th>Nominal Composition</th>
<th>Structure</th>
<th>Typical terrestrial occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite, 46E0995, Edgar, Florida</td>
<td>Al$_2$Si$_2$O$_5$(OH)$_4$</td>
<td>1:1</td>
<td>Weathering and decomposition of rocks containing feldspathic minerals (Kruckeberg et al. 2002; Best 2003; Evans 2004).</td>
</tr>
<tr>
<td>Serpentine, 46E7263, Eden Mills, Vermont</td>
<td>Mg$_3$Si$_2$O$_5$(OH)$_4$</td>
<td>1:1</td>
<td>Metamorphic and aqueous alteration of forsterite and pyroxene, replacement other magnesium silicates (Lagasse et al 2008)</td>
</tr>
<tr>
<td>Nontronite, 49E5108 Cheney, Washington</td>
<td>Na$_{0.3}$Fe$^{+3}$_2Si$<em>3$AlO$</em>{10}$(OH)$_2$·4(H$_2$O)</td>
<td>2:1</td>
<td>Weathering of biotite and basalts, precipitation from iron and silicon rich hydrothermal fluids (Bischoff 1972; Eggleton 1975).</td>
</tr>
<tr>
<td>Montmorillonite, 46E04 Panther Creek, Colorado</td>
<td>(Na,Ca)$_{0.3}$(Al,Mg)$_2$Si$<em>4$O$</em>{10}$(OH)$_2$(H$<em>2$O)$</em>{10}$</td>
<td>2:1</td>
<td>Aqueous alteration product of volcanic tuff and ash, pegmatite dikes, wall rocks. Alkaline conditions of poor drainage (Early et al. 1953; Deer et al. 1963; Gaines et al. 1997).</td>
</tr>
<tr>
<td>Chlorite, 46E1923, Madison Co., North Carolina</td>
<td>(Mg,Fe$^{+2}$)$_3$Al(Si$<em>3$Al)O$</em>{10}$(OH)$_8$</td>
<td>2:1:1</td>
<td>Alteration product of mafic minerals such as pyroxenes, amphiboles, and biotite, low-grade metamorphism (Hurlbut and Klein 1985).</td>
</tr>
</tbody>
</table>

* Catalog numbers of the Ward’s Natural Science.
After the heat treatments, many of the samples sintered and caked slightly, and were gently crushed a second time. They were then mounted in holders and their reflectance spectra obtained over the range 0.8 to 2.5 μm using a Nicolet 6700 FTIR in diffuse reflectance mode with an incident and emergence angle of 90°. A flowing atmosphere of dry nitrogen kept the samples dry during spectroscopy, and 150 scans were summed providing a final resolution of 2 cm⁻¹. Titanium dioxide was used as a reflectance standard. The phase angle of the phyllosilicate reflectance measurements, 90°, and much less than that used to measure the asteroids, generally 15-50°. Measurements of reflectivity as a function of phase angle for the Allende meteorite, which we assume to be typical of dark carbonaceous chondrites, have shown this effect to be insignificant at these angles (Gradie and Veverka, 1982).
Figure 2.1. (a) Representative spectra for an asteroid (45 Eugenia), meteorite (Orgueil CI chondrite), and a terrestrial phyllosilicate (serpentine), displaced on the vertical scale for clarity. Note the numerous absorption bands in the phyllosilicate and weak to absent bands in the meteorite and asteroid. (b) Illustration of way in which we determine “continuum slopes” for these spectra over the two wavelength intervals. For the purposes of determining slopes, the spectra are normalized to 0.875 µm.
We focus on the spectral range 0.8 to 2.5 µm because this is the range of the IRTF and because it is the range of most relevance to mineralogy. Representative spectra are shown in Fig. 2.1a. We quantify the curves by comparing the continuum slope between 1.0 to 1.75 µm with the continuum slope between 1.8 to 2.5 µm (Fig. 2.1b). Since the slope depends on the wavelength used for normalization, we normalized all the spectra to 0.875 µm. The difference in the reflectance at values at 1.0 to 1.75 µm were divided by 0.75 and the difference in the reflectance at values at 1.8 to 2.5 µm were divided by 0.70 to obtain the slopes in the two regions. We refer to the graphs of the 1.0 to 1.75 µm continuum slope against the 1.8 to 2.5 µm continuum slope as “continuum plots”. Based on multiple measurements of a given sample, we estimate a 5% uncertainty in both the 1.0 to 1.75 µm continuum slope and the 1.8 to 2.5 µm continuum slope. Of course the uncertainty is greater for phyllosilicates with multiple absorption features, but even here we find reproducibility for a given silicate. In fact, these bands do cause scatter in the data, and the reduction of this scatter upon heating is a diagnostic feature of the data and it can be meaningfully compared with the scatter in asteroid and meteorite data.

An approximate estimate of albedo was determined from digital photographs using the Adobe Photoshop software. Our “albedo” value refers to the grayness of the sample normalized to the grayness of an adjacent and equal area of white paper. We recognize that this is not a very sophisticated method for determining albedo but the reproducibility and scatter of the data suggest that our albedo values are reasonable to about ±0.05.
2.4 Results

2.4.1 Spectra of heated phyllosilicates

In Fig. 2.2 we show representative spectra for our heated phyllosilicates. For the sake of simplicity we do not show all the spectra, but the others can be assumed to be reasonable interpolations of those shown. We see three changes occurring to the spectra as a result of heating that are fairly common to the samples. (1) The absorption features at 1.4 and 2.3 μm weaken after heating to 300-400°C and have almost disappeared after heating to 800-900°C. (2) The long wavelength slopes (1.8 – 2.5 μm) go from negative to positive over the temperature range 600 to 1100°C. (3) The reflectance of the samples increases with heating up to about 600-800°C, and thereafter falls so that the samples heated at 1100°C are the darkest. These results are in general agreement with those of Hiroi and Zolensky (1999), although these authors limited their heating experiments on phyllosilicates to temperatures ≤600°C.
Figure 2.2. Representative spectra for five terrestrial phyllosilicates in the unheated states and after heating in air for 6-24 h at the temperatures indicated, and a sample of chlorite heated in an inert atmosphere. (a) Kaolinite, (b) serpentine, (c) nontronite, (d) montmorillonite, (e) chlorite, (f) chlorite in argon. At higher temperatures absorption features disappear, albedo changes (first increasing and then decreasing), and continuum slopes, as defined in Fig. 1b, change, sometimes increasing, sometimes decreasing. The albedo changes in the sample of chlorite heated in an inert atmosphere were greater than the sample heated in air, but otherwise the results are very similar.
While the samples have the above responses to the heat treatment in common, their behavior is not identical. Kaolinite and montmorillonite show relatively little change in reflectance, while for serpentine and nontronite there was a large change. The chlorite sample heated in argon showed greater change in reflectance than the samples heated in air.

2.4.2 Water release on heating phyllosilicates.

Our water release data are shown in Table 2.2 and Fig. 2.3. The patterns are fairly similar for the six cases, a 5-10% mass loss after heating to 100°C, and a major mass loss after heating to 500°C. The degree of the major mass loss varies from ~10% for montmorillonite, to ~15% for chlorite, chlorite in Ar and serpentine, kaolinite and nontronite. These results are very similar to those described in Grim’s (1968) textbook (see chapter 9).
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Kaolinite (wt. %)</th>
<th>Serpentine (wt. %)</th>
<th>Nontronite (wt. %)</th>
<th>Montmorillonite (wt. %)</th>
<th>Chlorite (wt. %)</th>
<th>Chlorite in Argon (wt. %)</th>
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<tr>
<td>100</td>
<td>0.28</td>
<td>0.99</td>
<td>7.50</td>
<td>8.46</td>
<td>0.50</td>
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</tr>
<tr>
<td>300</td>
<td>0.50</td>
<td>2.49</td>
<td>2.50</td>
<td>3.54</td>
<td>1.99</td>
<td>1.99</td>
</tr>
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<td>13.86</td>
<td>13.00</td>
<td>9.45</td>
<td>12.44</td>
<td>12.38</td>
</tr>
<tr>
<td>1000</td>
<td>14.50</td>
<td>13.93</td>
<td>12.38</td>
<td>9.50</td>
<td>12.12</td>
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<td>14.43</td>
<td>10.45</td>
<td>9.00</td>
<td>14.00</td>
<td>13.93</td>
</tr>
</tbody>
</table>

* The wt% figures refer to weight loss relative to original weight. Heating times were 24 h for all but 1000 and 1100°C, which were heated for 6 h. Separate samples were used at each temperature, so these are not stepwise heating experiments. There is a 0.4% uncertainty in the weight percent calculations.

** The uncertainty in the temperature measurements is ±1% of the reported value.

# The kaolinite 300°C sample was actually heated to 350°C.
Figure 2.3. Mass loss as a result of heating the present terrestrial phyllosilicates for 6-24 h. These are not step-wise heating experiments, but individual experiments in which independent samples were heated in the manner indicated. Thus the apparent mass gain occasionally observed reflects sample heterogeneity and, in the case of the low-temperature step (100°C), variations in the amount of surface adsorbed water, which depend on the nature of adsorption (number of molecular layers, silicate morphology, etc.). The amount of surface adsorbed water is typically ~5% by mass. After heating to temperatures above 500°C, chemically bound water is lost and this water amounts to 10-15% by mass.
2.4.3 Albedo changes on heating.

With the exception of kaolinite all samples of terrestrial phyllosilicate experienced a lowering of albedo after these heating treatments (Fig. 2.4). The decrease in albedo for montmorillonite was 1.0 to 0.8, while for serpentine and chlorite the decrease was from 0.8-0.9 to 0.5-0.6. The decrease was greatest for nontronite, where a decrease from ~0.9 to ~0.3 was observed. These values are not as low as observed for C chondrites, but they are certainly significant decreases. The argon atmosphere in the chlorite sample seems to have made little difference to the albedo change, suggesting that it is not related to an oxidation process.
Figure 2.4. Albedo plotted against heating temperature for five phyllosilicates. For this purpose, albedo was determined by dividing the grayness of the sample by the grayness of an adjacent sheet of white paper measured under the same conditions and quantified using digital images and Photoshop software. Heating was performed in air, but for chlorite an additional heating series was performed with the samples in an inert atmosphere. Experimental uncertainties can be judged from the scatter and are typically $\pm 0.05$ (one sigma). There is little or no change for the kaolinite samples, but for montmorillonite and serpentine there is a drop of $\sim 20\%$. For chlorite and nontronite the decrease in albedo is greater, for chlorite (regardless of the heating atmosphere) decrease is $\sim 40\%$ while for nontronite the decrease seems to be $\sim 60\%$, ending albedos being $\sim 0.3$. 
2.5 Discussion

We are primarily interested in determining the surface composition of the C asteroids and will discuss our data with this in mind. This is based on the spectral similarities the C asteroids have the C chondrites. Both do not spectrally look similar to the phyllosilicates that are the major mineral phase in the C chondrites. We will first discuss the continuum plots for terrestrial phyllosilicates, and we will compare these with similar data for C asteroids we obtained and discuss the C chondrite data from the literature. We then discuss our data for the heated phyllosilicates samples and the extent to which heated phyllosilicates resemble the C asteroids and can explain their surface compositions. We conclude with a discussion of the C chondrites and remaining challenges in understanding the spectra and surface composition of C asteroids.

2.5.1 The value and limitations of continuum slopes and absorption features

We are not the first researchers to consider continuum slope in the analysis of asteroid spectra, although we are probably the first to focus on this property. 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. DeMeo at al. (2009) extend the Bus scheme into the near-IR, continuing to rely strongly on slope. Similarly, Hiroi et al. (1993; 1996) performs spectral matching between heated phyllosilicates, C chondrites, and C asteroids that are generally featureless so that his method amounts to slope comparison.
While continuum slopes are implicit in major asteroid spectra studies, some authors remain skeptical about its use. For example Bus and Binzel (2002, page 147) state that, “It (taxonomy) should be based only on spectral (absorption) features, as these are the most reliable indicators of an asteroid's underlying composition”, but an anonymous reviewer of our paper adds “Studying slope variations is resorted to when absorption features are not present”. In fact, most of the C, X and similar classes described by DeMeo et al. (2009) are defined by slope (see their Table 5). Absorption features are generally weak or absent in C asteroids, and even papers ostensibly based on absorption features, such as Hiroi and Zolensky (1999) repeatedly rely on slopes. The 3 µm absorption feature has long been used to demonstrate the presence of water on asteroid surfaces, although this observation requires careful correction for atmospheric water (Lebofsky 1980; Lebofsky et al. 1990; Jones et al. 1990). Vilas (1994) has shown that an absorption feature at 0.7 µm, also observed in C chondrites (Vilas and Gaffey 1989), and which correlates with the 3 µm feature, could also be used to deduce the presence of water. The similarity of this feature in C chondrites and C asteroids suggests the presence of Fe-rich phyllosilicates on the asteroids. The strength of the UV absorption correlates with the strength of the 3 µm band and indicates that this too provides an indication of the presence of water on the asteroids (Hiroi et al. 1996b). None of these features were observed in the present study, and a maximum absorption intensity of approximately 5% was observed by Vilas and Gaffey (1989) for the 0.7 µm band, most were considerably weaker.

Some of the caution over the use of slopes results from the idea that there are many experimental factors that affect continuum slope, such as placement on the slit,
differential refraction, diffraction, and atmospheric variations. The asteroids and solar analogue stars in the present study were all observed no more than 15 degrees from the meridian in order to minimize differential refraction effects, which could in principle affect the continuum slope of the reduced spectrum if not carefully minimized. The spectrograph dispersion direction was normal to the slit, so when the target was kept near the meridian the atmospheric dispersion was along the slit. The entire signal along the slit was detected and combined during the reduction of the spectrograms. Automatic guiding, combined with tracking at the predicted rate and in the predicted direction, was utilized in order to keep the asteroid carefully centered on the slit. The 0.8 arcsec slit was typically slightly overfilled by the diffracted image of the asteroid or star. We corrected for atmospheric variations by using the models of Vacca et al. (2003) at the specific zenith distance of the object during the reduction of each spectrogram. We are convinced that these steps remove significant continuum slope errors in the reduced spectrograms.

Most important, we consider the clustering of slope data and the resolution of various groups of objects (C asteroids and CM chondrites, for instance), and the reproducibility of the slope data when determined by different research groups, as the most meaningful indication that these spectral continuum measurements have merit. These will be become apparent in our later discussion. Thus while we recognize the value of absorption features in studying asteroid spectra, we think that the weakness and scarcity of these peaks and the implicit use of continuum slope in prior work, means that a detailed study of heated phyllosilicate, C asteroid, and C chondrite continuum slopes is worthwhile.
2.5.2 Continuum slopes of terrestrial phyllosilicates

Figure 2.5 presents the continuum plot for terrestrial phyllosilicates for spectra in the USGS Digital Spectral Library (Clark et al. 2007). The data are not well clustered, and placement on the plot does not depend on structure or composition. There is also no correlation between the continuum slopes in the two spectral ranges. The large number of broad and intense absorptions due to OH-metal cation interactions (predominantly Fe$^{2+}$, Fe$^{3+}$, Mg$^{2+}$, Al$^{3+}$) controls the slope of the continuum at long wavelengths (Grim 1968, page 459), while the slope between 1.0 and 1.75 µm is determined by a very broad absorption effect at 1.0-1.2 µm due to charge-transfer involving Fe$^{2+}$ or Fe$^{3+}$ (Cotton and Wilkinson 1962). It is therefore reasonable that there should be no correlation between the slopes in the two regions or simple correlation with structure or composition. What is important, though, is that all of the terrestrial phyllosilicates that were examined had strong absorptions at long wavelengths and therefore negative slopes in their 1.8 to 2.5 µm continuum.
Figure 2.5. Continuum plots for nine terrestrial phyllosilicates (including the five used in the present study), with the structure indicated by symbols, and with the nominal composition indicated by formulae. We see no obvious correlation between position on this plot and structure or composition. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
2.5.3 Continuum slopes of terrestrial phyllosilicates compared with asteroids

Figure 2.6 shows the continuum plot for phyllosilicates compared with asteroids. We show the data for the eleven C asteroids obtained recently by our group (Ostrowski et al. 2009). The asteroid data plot in a relatively well-constrained field that is discrete from the phyllosilicates. This tight clustering is an indication of the value of continuum slopes in characterizing these objects. The C asteroid field has slightly positive slopes in the 1.8 to 2.5 \( \mu \)m spectral region and a narrow range of slopes in the 1.0 to 1.75 \( \mu \)m spectral region (Fig. 2.6). The tight clustering suggests similarity in the surface compositions of the asteroids and the discreteness of the fields suggests that either phyllosilicates are not important on the surfaces of asteroids or that if they were present at one time, they have undergone considerable alteration.
Figure 2.6. Continuum plot for the terrestrial phyllosilicates (reproduced from Fig. 2.5) compared with similar data for the eleven C asteroids observed by Ostrowski et al. (2009). Bounding ovals are indicated that cover the fields occupied by these two data sets. While the terrestrial phyllosilicates show considerable spread on this plot, the C asteroids occupy a relatively well-defined field with more positive slopes in the 1.8-2.5 µm region and they plot to the upper left side of the terrestrial phyllosilicate region. This suggests both the uniformity of the C asteroids and fundamental differences in the mineralogy of the C asteroids and the phyllosilicates. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
2.5.4 Continuum slopes of terrestrial phyllosilicates compared with C chondrites

Figure 2.7 compares the terrestrial phyllosilicate field, and the C asteroid field shown in Fig. 2.6, with data for C chondrites from the papers of Hiroi et al. (1993; 1996b) and Gaffey (2001). The C chondrites plot in a field more highly constrained than the phyllosilicates, but the clustering is not quite as tight as it is for the C asteroids. In fact, while the CM chondrites plot above the phyllosilicates and to the right of the C asteroids, there is overlap between the C asteroids and a variety of C chondrites which have been termed CI/CM chondrites (B-7904, Yamato-82162 and Yamato-86720), CK (Yamato-693), CV (Allende), CI (Orgueil, two samples, and Ivuna) and CR (Renazzo). Another CI (Alais) plots well outside this field and in the phyllosilicates field. This is a highly diverse group of chondrites that have little in common besides the bulk compositional parameters that define them as C chondrites.
Figure 2.7. The continuum plot shown in Fig. 2.6 with the C asteroid and phyllosilicates fields indicated as ovals, compared with similar data for C chondrites of various classes. The CM chondrites define a relatively well-constrained field within the oval labeled “CM meteorite field” while the other classes of C chondrites plot slightly to the left of the CM chondrite field and mostly in the C asteroid field. The distinction between the phyllosilicates and the C chondrites is marked, even though CM and CI chondrites are known to consist largely of phyllosilicates, the exception is the CI chondrite Alais that plots in the phyllosilicate field. It should be noted that some of the C chondrites, such as the CV and CK chondrites, do not contain phyllosilicates but plot in the C asteroid field. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot. See Ostrowski et al. (2009) for a more detailed study of C chondrites relationship to the all the asteroid types in the C complex.
The challenge, therefore, is to understand the relationship between the objects in Figs. 2.6 and 2.7 and how it is possible for the samples to navigate their way around the plot, particularly between the fields defined above. Options for moving about on the diagram are (1) the addition of minor phases, such as carbon-bearing species, sulfides, and fine sulfide-metal intergrowths, and (2) thermal treatments that in some way replicate the major alteration processes on the surfaces of asteroids. The space environment is essentially an impact environment in which heating and dehydration are the major processes. We will assume that radiation damage, microscale evaporation and condensation, and associated processes, that are collectively considered “space weathering”, are relatively minor processes that cannot explain the differences between phyllosilicates and the meteorites and asteroids shown in Fig. 2.7. We argue that the alteration processes responsible, and seen, for example, in meteorites, are macroscopic parent-body processes that are best replicated by laboratory heat treatments that can be monitored by spectral changes in the near-IR.

2.5.5 Continuum slopes of heated terrestrial phyllosilicates

Our continuum plots of heated terrestrial phyllosilicates are shown in Fig. 2.8 and 2.9. All are on the same axes to facilitate comparison, the unheated samples indicated by a larger, open symbol and the data for the heated samples labeled with the heating temperature. The fields for terrestrial phyllosilicates, C asteroids, and C chondrites (Fig. 2.7) are also shown. We will first discuss our serpentine results and compare them with similar plots derived for three serpentines that were the subject of heat treatment by Hiroi and Zolensky (1999) (Fig. 2.8) and then we will discuss each plot in Fig. 2.9 in turn.
Figure 2.8. Continuum plots for unheated and serpentine heated to 600°C, compared with the phyllosilicate, C asteroid, and CM meteorite fields. (a) Serpentine from the present study. (b) chlinochrysotile, (c) antigorite, and (d) lizardite which are various serpentine from the work of Hiroi and Zolensky (1999). The fields for the C asteroids, CM chondrites, and terrestrial phyllosilicates are as indicated in Fig. 2.7. Open diamond symbols are for unheated samples, filled diamonds are for samples heated to temperatures up to 600°C. Based on source localities, we suspect our “serpentine” is the same material as Hiroi and Zolensky’s antigorite. There is very good agreement between serpentine and antigorite data where the heating to 600°C does not significantly affect the data on this plot. The lizardite and clinochrysotile samples behave similarly on this plot, remaining in the phyllosilicate field until heating above 400-500°C at which point they move into the general region of the C asteroid and CM meteorite fields. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
2.5.5.1 Serpentine

In Fig. 2.8 we compare the data resulting from our heating experiments with those of Hiroi and Zolensky (1999) in order to assess the level of reproducibility in these data for a given mineral. We only show our data up to 600°C for ease of comparison with these authors who terminated their experiments at this point. Our serpentine sample, purchased from Wards Scientific, was said to have come from Eden Hills, Vermont, while Hiroi and Zolensky (1999) examined three serpentines, antigorite (also from Eden Hills, and probably the same as our “serpentine”), lizardite (from Cornwall, UK) and clinochrysotile (from Thetford, Quebec). The clinochrysotile and lizardite samples are displaced slightly to the right of the serpentine and antigorite samples and 500 and 600°C have left the phyllosilicate field, and moved into the CM chondrite and C asteroid fields, respectively. These data indicate that, at least to 600°C, compositionally and structurally similar phyllosilicates have similar spectra and similar response to these heat treatments, notwithstanding an occasional anomalous point. The agreement between our serpentine and Hiroi and Zolensky’s (1999) antigorite samples is particularly good.

Figure 2.9 shows our data for the present five phyllosilicates over the range 100-1100°C. We briefly discuss each mineral in turn.
Figure 2.9. Continuum plots for the present five phyllosilicates. (a) kaolinite, (b) serpentine, (c) nontronite, (d) montmorillonite, (e) chlorite, and (f) and chlorite heated in an argon atmosphere. The fields for the C asteroids, CM chondrites, and terrestrial phyllosilicates are as indicated in Fig. 2.7. In general, heating to 500-600°C moves the data on these plots but keeps them within the phyllosilicate field. Again, in general, heating above 600°C, move the samples out of the phyllosilicate field and into the C asteroid field (kaolinite and montmorillonite), or the CM chondrite field (serpentine and chlorite), or above the CM chondrite field (nontronite and chlorite in an argon atmosphere). Clearly, heat treatment is a means of moving samples from the phyllosilicates field to the other fields. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
2.5.5.2 Kaolinite

Kaolinite starts at the bottom of the terrestrial phyllosilicates field and moves directly upwards on the plot, leaving the phyllosilicates field at 500°C and plotting in the C asteroid field at temperatures above 600°C, mostly in the left half of the C asteroid field (Fig. 2.9a). During our heating experiments, kaolinite began to lose its water at 500°C and had essentially suffered complete loss by 600°C (Table 2.2, Fig. 2.3). It is the destruction of the OH-cation bonds through the loss of water that moves the data out of the phyllosilicates field and moves them into the C asteroid field. With no Fe$^{2+}$ charge transfer bands in the 1.0 μm region to be lost during heating, the continuum slope in the 1.0 to 1.75 μm region does not change significantly. We might infer from this evidence that spectra of C asteroids are consistent with their surface being dehydrated kaolinite and that temperatures experienced by the surface were ~600°C or above.

2.5.5.3 Serpentine

With heating, serpentine moves along the top of the phyllosilicates field and at 800°C moves into the CM chondrite field (Fig. 9b). The increase in continuum slope in the 1.0 to 1.75 μm region appears to be due to an increase in absorption over the interval 0.8 to 1.2 μm, and thus is not readily explained by the loss of water and the disruption of metal-OH interactions. Serpentine was one of the phyllosilicates in the present study to lose only ~12.5 % mass during our heating experiments, and most of the water was lost at ~500°C. It is therefore not clear what moved the data to the right, but it is clear that this causes the data to move into the CM field rather than the C asteroid field. Fe oxidation could cause these spectral changes, assuming there are small amounts of Fe in our serpentines, but if Fe oxidation were important it is difficult to understand our data for
chlorite (see Fig. 2.9e,f).

2.5.5.4 Nontronite

The natural nontronite sample plots in the bottom-middle of the phyllosilicates field and moves to center right of the field with heating up to 700°C (Fig. 2.9c). Above 700°C the samples make a large jump to the right of the CM chondrites field, and move leftwards at 1100°C. Again, the jump out of the phyllosilicates field coincides with the loss of long wavelength absorption features and the loss of structural water, which begins at 400°C and is complete by 700°C. There is no evidence in these data that the surface of the C asteroids consists primarily of nontronite heated by impact.

2.5.5.5 Montmorillonite

The montmorillonite trajectory on Fig. 2.9d is fairly similar to that of kaolinite, essentially an upwards movement in which the data leave the terrestrial phyllosilicates field at 600°C and then enters the C asteroid field and remains there upon further heating. Hiroi and Zolensky (1999) performed heating experiments on saponite (a member of the montmorillonite group) and the data agree well with our results although the earlier data show more scatter and their experiments terminated at 600°C. Our montmorillonite samples lose the least water in our experiments, only ~10% of their original mass, but the water is lost by 600°C when the data enter the C asteroid field. These data are also consistent with the loss of water participating in the OH-metal absorption bands at ~2.4 μm. These results would be consistent with the C asteroids having heated montmorillonite on their surface.
2.5.5.6 Chlorite

The behavior of chlorite is quite different from the previous cases since it starts on the right end of the terrestrial phyllosilicates field, then at ~500°C moves to the upper center of this field, and then moves into the CM chondrite field at 700°C (Fig. 2.9e). Hiroi and Zolensky (1999) performed heating experiments on chlorite and the data agree well with our results although the earlier data show more scatter and their experiments terminated at 600°C. The chlorite in the present work loses ~15% of its mass when heated to 600°C also suggesting that these spectral changes are related to loss of metal-OH interactions. We suggest that loss of the OH-cation interactions in the 2.4 µm region causes the leftward trend within the phyllosilicates field and loss of the Fe$^{2+}$ charge transfer bands at ~1.0-1.2 µm causes the upward trend into the C asteroid field. These data are consistent with the surfaces of the CM chondrites consisting of heated chlorite.

However, we observed that our chlorite sample underwent significant color changes during heating which we thought might reflect atmospheric oxidation of Fe$^{2+}$. Since oxidation of iron can be seen in the infrared spectra as a very broad feature between 1.0 to 1.2 µm, it would cause the slope in the 1.0-1.75 um region to increase and the data points to move to the right on the continuum plots. In fact, they move to the left inferring that oxidation of Fe is not important in determining these slopes.

2.5.5.7 Chlorite in an argon atmosphere

We therefore repeated our heating experiments under an inert atmosphere. We found that the behavior of chlorite on this plot was very similar to that of chlorite heated in air, although samples heated above 900-1100°C plotted further outside the CM chondrite field than the chlorite samples heated in air (Fig. 2.9f). In other words, the data
points move in the opposite direction to that expected if oxidation were affecting the data in Fig. 9e. In short, we do not believe the differences in Fig. 2.9e and 2.9f are significant and thus oxidation is not affecting our data.

The decrease of albedo of the heated samples does not reduce to that of the C chondrites. In general this does not affect the continuum slope much because its main effect is on week feature resolution. The higher albedo of the samples might allow for week features at the higher temperatures to still be present and if so this could lower the reflectance of parts of the continuum slope. A decrease in albedo could remove week features would cause the continuum slope in affected region, short or long, to become slightly more shallow. The effect would be to move affected sample’s data points on the continuum plot closer to 0,0 and the C asteroid field. This is not expected to be a major factor because it only affects week features which are virtually gone already when the heated samples start to match that of the C chondrites and C asteroids.

2.5.6 Continuum slopes of heated C chondrites

Figure 2.10 shows data from Hiroi et al. (1993) and Hiroi et al. (1996a) for the Murchison CM chondrite and the Ivuna CI chondrite, respectively. Murchison initially plots on the lower limit of the CM chondrite field and remains in this field until heating to 900 and 1000°C. Similarly, Ivuna is initially at or close to the lower limit of the C asteroid field and remains in the C asteroid field with heating, although the 500°C point plots close to two CI/CM chondrites (Y-82162 and B-7904, see Fig. 2.7) at the interface of the C asteroid and CM chondrite field. It is significant that the CI and CM chondrites, with their abundant water do not plot initially with the phyllosilicates. Heat treatments sufficient to dehydrate these samples, and which caused some phyllosilicates to move
into the C asteroid and CM fields, do not move CI chondrite data out of their field of origin and only when 900 and 1000°C are reached does the CM chondrite data move into the asteroid field.
Figure 2.10. Continuum plots for (a) the CM chondrite Murchison, and (b) the CI chondrite Ivuna from work of Hiroi et al. (1993) and Hiroi et al. (1996a), respectively. The fields for the C asteroids, CM chondrites, and terrestrial phyllosilicates are as indicated in Fig. 2.7. Hiroi et al. (1996a) provided data for two unheated samples of Ivuna, while for Murchison one data point is from Hiroi’s work and one is from Gaffey (2001). In the case of Murchison, heating to 800°C keeps the data in the CM chondrite field, while higher temperatures move the data into the C asteroid field. In the case of Ivuna, the data are essentially unchanged, remaining in the C asteroid field. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
2.5.7 Relationships between phyllosilicates, C asteroids, and C chondrites

2.5.7.1 Predicted primary C asteroid materials

We presume C asteroid surfaces were predominantly phyllosilicates when they formed. Thermodynamic calculations, often expressed in terms of the “condensation sequence”, assuming formation of solids in a initially hot cooling primordial solar nebula, predict that at temperatures low enough for condensed water, the silicates would be predominantly phyllosilicates with minor amounts of organics, hydrated Fe-oxides and Fe sulfides (Grossman and Larimer, 1974). In any event, the coexistence of water and silicates on the parent body would soon produce phyllosilicates (Brearley, 2006). To a reasonable approximation, this mineral assemblage is similar to that observed in CI and CM chondrites that are widely assumed to be the most “primitive” (i.e. solar like) meteorites (Brearley, 2006). There is an abundance of water in CI and CM (Wiik 1969; Jarosewich 1990), and water features are observed in about half of the C asteroids (Vilas, 1994), the CI and CM chondrites often contain phyllosilicates (Barber 1981, Zolensky and McSween 1988, Browning et al. 1996), and there are occasional spectral features in C asteroids attributed to phyllosilicates (Vilas and Gaffey, 1989).

2.5.7.2 Asteroid surface processes

Superimposed on these expectations based on thermodynamics and CI and CM chondrites, is the effect of long-term exposure to the space environment, and sometimes great impact activity (Clark et al., 2002). The surfaces of all airless bodies in the solar system examined to date are heavily cratered, often to the point of saturation. Spacecraft imagery shows the surface of asteroids to be heavily cratered (Chapman, 2002).
Our best data on the nature of surface processes on airless bodies is provided by the lunar samples. Samples returned from the Moon contain abundant evidence for heating (Taylor et al., 1991). Virtually all are breccias, diverse fragments lithified as glass, most of which show evidence for violent shocks. Impact melt spherules are common, as are agglutinates formed when melts impacted the surface prior to solidification (Symes et al., 1998). Grains in the regolith are coated with altered zones, due partly to the recondensation of elements evaporated during impact (Keller and McKay, 1993).

However, it is to be expected that there are quantitative differences between regolith processes on the Moon and asteroids (McKay et al., 1989). From models based on impact-melts in ordinary chondrites it is possible for asteroid surfaces to be collisionally heated to just over 1200°C (Rubin, 1995). It seems to us that most of the surface of the asteroids should have been drastically thermally processed, that is multiple times mostly from micrometeorite impact and up to some of the higher temperatures tested in this study, and that what is remarkable is the presence of water and hydrated phases that have been detected on the asteroid surfaces. There is also considerable gardening on asteroids, and that interior material is constantly brought to the surface. Many of these properties, a consequence of the exposure to the space environment, are referred to as “space weathering”, especially when considering the microscale processes (Clark et al., 2002).

2.5.7.3 A priori predictions

Thus, if this was all that was involved we could relate terrestrial phyllosilicates (the presumed primary phyllosilicates of asteroids) to present asteroid surfaces via Fig. 2.11. We suggest that it is possible to describe meaningful trajectories – driven by thermal
processing – that relate the phyllosilicates to the asteroids and that it might be possible to use these trajectories to make suggestions about the nature of the asteroid surfaces. For instance, the C asteroid field seems to be consistent with thermally altered kaolinite or montmorillonite, while the CM chondrite field could be interpreted as thermally altered serpentine or chlorite. On the basis of these data, there appear to be no asteroids with nontronite surfaces. Meteorites that plot in the C asteroid field, CI chondrites aside, are generally not thought of as predominantly containing phyllosilicates. The major mineralogy of the CR, CV and CO classes consists of olivines, pyroxenes, feldspars, and occasionally anhydrous refractory inclusions associated with high temperatures (Weisberg et al., 2006).
Figure 2.11. Continuum plot that summarizes the effect of heat treatment on the phyllosilicates in the present study. The symbols ΔK, ΔM, ΔS, ΔC, ΔN, refer to the locations of samples of kaolinite, montmorillonite, serpentine, chlorite and nontronite heated above 600°C. Also shown are the fields for phyllosilicates, C asteroids, and CM chondrites as indicated in Fig. 2.7. Heating kaolinite and montmorillonite produces samples in the C asteroid field, while heating chlorite and serpentine (although originally well separated on this plot) and to some extent montmorillonite produces data in the CM chondrite field. Nontronite does not produce data in the CM or C asteroid fields. We note that various authors have suggested that the CM chondrites consist of serpentine or chlorite, while some authors have suggested that the CI chondrites and certain CM chondrites consist of montmorillonite. A 5% uncertainty exist for both the x and y values for each of the points in the continuum plot.
We have not characterized the mineralogical changes produced by our heat treatments because these are well documented in textbooks such as Deer et al. (1962) and Grim (1968), and recent work in our laboratory using some of the same phyllosilicates is consistent with these observations (Gavin and Chevrier, 2009). Decomposition of the montmorillonite group occurs between 800 and 900 °C and forms spinel, quartz, or cristobolite, depending on initial composition. For the kaolinite group, decomposition occurs between 650 and 800 °C and produces metakaolinite, a highly disordered anhydrous phase, and at higher temperatures 900-1000 °C produces alumina, cristobolite, and mullite, also depending on initial compositions. Some of these phases have not been seen in the C chondrites, because most of the matrix of these meteorites is amorphous. Serpentine forms olivine at 600 °C, and variants of serpentine form olivine at slightly different temperatures. Chlorite similarly decomposes, through stages involving brucite, into olivine. While these minerals can sometimes be detected, especially at higher temperatures and even more so when melting occurs, in general after the release of chemically bound water at 600-800 °C and the collapse of the phyllosilicate structure, they produce an amorphous anhydrous material, and the purpose of the present study is to see whether the IR continuum slope is diagnostic of the precursor phyllosilicate. The sort of minerals expected from the decompositions of these phyllosilicates is very similar to the present mineralogy of the CR, CV and CO chondrites. The CR, CV, and CO chondrites are “primitive” in the sense that they have escaped the large amounts of aqueous alteration characteristic of the CI and CM chondrites, although phyllosilicates have been found in CV and CO chondrites (Rubin, 1997).
2.5.7.4 CM chondrites

What is remarkable, given our expectation about the nature of solids produced in the asteroid belt, and our understanding of the nature of the surfaces of asteroids, is that C chondrites with 10-20% water are reaching Earth (Table 2.3). Clearly, the water-rich CI and CM chondrites are samples from the interior of their parent bodies, buried too deep to be affected by surface processes, yet occasionally being capable of being excavated by major impact that would send them on their way, ultimately, to Earth. It is as if the water was introduced subsequent to the regolith dehydration processes (thus the C chondrites do not plot with the terrestrial phyllosilicates) and is now present in a form other than chemically bound within the phyllosilicate structure. It is clear that aqueous alteration has played a major part in determining the properties of at least some of the C chondrites, notably the CM chondrites (Browning et al. 1996; Brearley 2006), including the formation of opaque phases. One form in which there may be considerable water is water of crystallization associated with the evaporite minerals in these meteorites (Table 2.4).
Table 2.3. Carbon and $H_2O$ content of $C$ chondrites mentioned in the present work, where available.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Class</th>
<th>C (wt %)</th>
<th>$H_2O$ (wt %)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orgueil</td>
<td>CI</td>
<td>2.80</td>
<td>16.90</td>
<td>Fredriksson and Kerridge (1988)</td>
</tr>
<tr>
<td>Alais</td>
<td>CI</td>
<td>3.19</td>
<td>19.45</td>
<td>Wiik (1969)</td>
</tr>
<tr>
<td>Ivuna</td>
<td>CI</td>
<td>2.09</td>
<td>18.64</td>
<td>Wiik (1969)</td>
</tr>
<tr>
<td>Y-86720</td>
<td>CI/CM</td>
<td></td>
<td>6.40</td>
<td>Ikeda (1992)</td>
</tr>
<tr>
<td>B-7904</td>
<td>CI/CM</td>
<td>1.12</td>
<td>2.60</td>
<td>Shimoyama et al. (1987); Haramura et al. (1983)</td>
</tr>
<tr>
<td>Y-82162</td>
<td>CI/CM</td>
<td></td>
<td>11.95</td>
<td>Ikeda (1992)</td>
</tr>
<tr>
<td>Bells</td>
<td>CM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Bokkeveld</td>
<td>CM</td>
<td>1.30</td>
<td>15.17</td>
<td>Wiik (1969)</td>
</tr>
<tr>
<td>Mighei</td>
<td>CM</td>
<td>2.48</td>
<td>12.85</td>
<td>Wiik (1969)</td>
</tr>
<tr>
<td>ALH83100</td>
<td>CM</td>
<td>1.46</td>
<td>13.38</td>
<td>Jarosewich (1990)</td>
</tr>
<tr>
<td>Nogoya</td>
<td>CM</td>
<td>5.20</td>
<td></td>
<td>Bunch and Chang (1980)</td>
</tr>
<tr>
<td>Murchison</td>
<td>CM</td>
<td>1.85</td>
<td>10.09</td>
<td>Jarosewich (1990); Fodor et al. (1971)</td>
</tr>
<tr>
<td>Renazzo</td>
<td>CR</td>
<td>1.44</td>
<td>5.62</td>
<td>Wiik 1969</td>
</tr>
<tr>
<td>Allende</td>
<td>CV3</td>
<td>0.29</td>
<td>&lt;0.1</td>
<td>Clarke et al. (1970)</td>
</tr>
<tr>
<td>Y-693</td>
<td>CK</td>
<td></td>
<td>0.18</td>
<td>Shima et al. (1973)</td>
</tr>
</tbody>
</table>
Table 2.4. Hydrates of ionic solids in carbonaceous chondrites*.

<table>
<thead>
<tr>
<th>Hydrate</th>
<th>Formula</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulfates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blodite</td>
<td>Na$_2$Mg(SO$_4$)$_2$.4$H_2$O</td>
<td>CI</td>
</tr>
<tr>
<td>Epsomite</td>
<td>MgSO$_4$.7$H_2$O</td>
<td>CI</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO$_4$.2$H_2$O</td>
<td>CI</td>
</tr>
<tr>
<td>Hexahydrite</td>
<td>MgSO$_4$.6$H_2$O</td>
<td>CI</td>
</tr>
<tr>
<td><strong>Oxalates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whewellite</td>
<td>CaC$_2$O$_4$.H$_2$O</td>
<td>CM</td>
</tr>
</tbody>
</table>

* From the compilation of Rubin (1997)
2.5.7.5 Evaporites

Evaporites are abundant in CI chondrites and present in CM chondrites, and sometimes appear as thick macroscopic veins passing through CI chondrites. Water introduced into the asteroid surfaces from the interior of the asteroid would almost certainly have been mineral-rich, and these liquids would have been quickly evaporated to produce crystals with considerable water of crystallization (for instance, MgSO\(_4\).7H\(_2\)O; Dufresne and Anders 1962). Assuming that the 1.7-2.2 wt% S (Wiik 1968; Jarosewich 1990) in these meteorites is in the MgSO\(_4\).7H\(_2\)O, then 6.7-8.6 wt %, (about half) of the water in these meteorites is in the evaporites and not in the phyllosilicates. Of course, there is considerable uncertainty in this calculation, because there are other phases to host sulfur and there are other inorganic solids to host the water, but it is reasonable that much of the water in the CI and CM meteorites and by implication the C asteroids, is not associated with the phyllosilicates. Figure 2.12 compares the spectra of serpentine and epsomite (MgSO\(_4\).7H\(_2\)O) and a numerical sum resulting from a 40% epsomite and 60% serpentine mixture. This is the mixture that produces the most featureless spectrum. We can calculate the expected proportions of these phases in a CI chondrite from the bulk composition of Orgueil and assuming S is distributed between FeS or (Fe,Ni)S and epsomite and Mg is distributed between epsomite and serpentine. The values are 17-27 wt% epsomite in the meteorites and 30-26 wt % serpentine, the range depending on the amount of Ni assumed to be in the sulfide. Thus our mixture in Fig. 12 is reasonable and we can see that this mixture will cause the loss of several strong absorption features but it retains a negative slope (Ostrowski et al. 2010). So the co-existence of serpentine and
epsomite-like minerals would explain some of the featureless nature of the C chondrite spectra, but not the zero slopes of their spectra.
Figure 2.12. Spectra for serpentine and epsomite, normalized at 0.875 µm, with continuum slopes as defined in Fig. 2.1b superimposed. While both samples show absorptions due to water in various locations in the solid phases, the slopes are complimentary and form a trapezium suggesting that a mixture of the two phases would produce a relatively featureless spectrum with a negative slope.
2.5.7.6 Opaques and albedo

As summarized in the Introduction, the matrix of the C chondrites is complex, fine-grained, often amorphous, highly heterogeneous with a mixture of components, and requires TEM to characterize. This is a highly localized technique that only occasionally locates unambiguous characteristics of a readily identifiable phyllosilicate. Much of the fine-grained material is a complicated mixture of Fe-rich phyllosilicates produced by aqueous alteration of metal and sulfides, tochilinite, $\text{Fe}^{2+}_{5.6}(\text{Mg,Fe}^{2+})_{5}[(\text{OH})_{10}\text{S}_{6}]$, montmorillonite, or cronstedite (Barber et al. 1983; Mackinnon and Zolensky 1984; Tomeoka and Buseck, 1985) Thus there are a great many nano-scale opaque minerals, finely integrated with the silicates, that can have a profound effect on the spectra of these materials.

Several workers have suggested that the effect of these opaque phases on the spectra of phyllosilicates can be investigated by the addition of carbon black, or other opaque phases such as ilmenite (Clark, 1983; Cloutis et al., 1990; Milliken and Mustard, 2007). Of course, while meteorites can contain up to 4 wt% C, it is virtually all in the form of organics (mostly an insoluble polymer, but some as volatile colorless compounds), so free carbon is essentially absent, but it is assumed that the carbon black can reproduce most of the physical effects of any finely dispersed opaque phase. However, it remains clear from these studies that the primary effect of opaque phases is to weaken the features and decrease albedo. It is not clear that opaque phases on their own are sufficient to obliterate absorption features (Cloutis et al., 1990), but they can reduce albedo to values approaching those of C asteroids. On the other hand, dehydrated phyllosilicate products can have albedos one-half to one-third those of their hydrated
equivalents (Fig. 4), so if asteroid surfaces contain heat-alteration products this too would contribute to their low albedos.
Figure 2.13. Continuum plot for samples of montmorillonite to which various amounts of carbon black have been added. Also shown are the previously described fields for the C asteroids, CM chondrites, and terrestrial phyllosilicates. The addition of carbon black affects both the short and long wavelengths of the spectra, with a greater effect on the long wavelength region. In fact, as the amount of carbon increases, the data show a negative linear trend in which at short wavelengths the slope decreases from 0.0 to −0.1, while the slope at long wavelengths increases −0.6 to −0.1. This is in contrast to the effect of heating on terrestrial phyllosilicates in which the trends on this plot are essentially positive (chlorite excepted).
So what is the effect of the addition of opaque phases on the continuum slopes? The data from two research groups is presented in Fig. 2.13 (Clark, 1983; Milliken and Mustard, 2007). The data from these authors is in good agreement. Coating the surface of the grains with a black material causes the data to move up and left on the diagram (the slope at shorter wavelengths decreasing while the slope at longer wavelengths increases) in a fairly linear fashion. Thus we can argue that the presence of opaque phases could move only nontronite and chlorite into the asteroid fields (Fig. 2.11); however these are not reasonable candidates for the phyllosilicates on asteroids. While many asteroid astronomers believe carbon black is a reasonable proxy for the opaque phases on asteroids, it has been suggested that certain opaque phases (maybe organics, metals, and sulfides) might produce slightly reddened spectra, especially if fine grained and well dispersed (Pieters and McFadden, 1994). This effect has yet to be explored.

Britt and Pieters (1994) have also shown that ordinary chondrites can have flat and relatively featureless reflectance spectra when they have been severely shocked. During such intense events the metal and sulfide melts and is finely disseminated throughout the rock making it appear black. The gas-rich ordinary chondrite regolith breccias are also known for the darkness of their matrix, which encloses normal ordinary chondrite clasts. (This is often referred to as the light-dark structure). The origin of the dark matrix involves shock blackening, and the introduction of C and inert gases by the adsorption of solar wind. It should therefore be borne in mind that some C or X asteroids could be related to such ordinary chondrite material, but they are anhydrous and will not be further discussed here.
While grain size seems to affect the continuum slope at the shorter wavelengths, there is little or no effect on the continuum slope at the longer wavelengths. The finer grain fractions (<63 and <125 μm) plot in the CM chondrite field while the coarser fraction (<200 μm) plot in the C asteroid field.

Figure 2.14. Continuum plot for samples of the Murchison CM chondrite compared with the previously described fields for C asteroids and CM chondrites. The Murchison bulk data point is from Hiroi et al. (1993; 1996) while the grain size fractions are from spectra acquired by Mike Gaffey, Tahi Hiroi, and Carle Pieters at the NASA RELAB Laboratory at Brown University.
2.5.7.7 Grain size effects

Grain size affects the reflectance spectra of these bodies. As grain size decreases, the absolute reflectance of the material increases and the ability to resolve absorption features decreases (Milliken and Mustard, 2007b). The Murchison CM chondrite has been the subject of study in a variety of contexts by several research groups. Figure 2.14 shows a compilation of the data for Murchison grain size separates. We first note that for samples of similar grain size, the data obtained by the different groups are very similar, suggesting that continuum slopes are reproducible. Second, the smaller grain size fractions plot within the CM chondrite field and it is only when especially large grain size fractions are involved that the data move into the C asteroid field. This would imply that if the C asteroids are mineralogically similar to CM chondrites, their surfaces are covered with coarser grains, a reasonable conclusion if one assumes that the finer material would be lost to space under the microgravity conditions on the asteroid. This of course is only based on infrared spectra. The grain size of the phyllosilicates in the C chondrites is much smaller, on the order of micron to submicron, than the grain size of the phyllosilicates used in this study, but what matters is not the size of individual grains but the size of particles on the surface, which will be grain aggregates. It has been calculated that asteroid 253 Mathide has a surface regolith grain size of less than 150 μm (Clark et al., 1999), at the coarser end of the size range in Fig. 14. The meteorite measurements shown in Fig. 2.7 were not made on sorted powders and were in most respects similar, so we doubt that grain size is relevant in determining the location of meteorites in the continuum plot.
2.5.7.8 C chondrites and C asteroids

It seems equally clear that there is no evidence that C chondrites of any class came from the surface of their asteroid parent bodies. There are no impact regolith breccias among the C chondrites, although several ordinary chondrites contain small clasts of dehydrated CM-like material suggesting that CM chondrites are abundant impactors (Bischoff et al. 2006). In addition, the regolith diffusion and desorption rates for water - even from phyllosilicates - are fast at near-Earth asteroid surface temperatures (Bryson et al. 2008; Chevrier et al. 2008; Zent et al. 2001). The fact that water features have been observed in spectra from asteroid surfaces suggests that gardening of material from the interior is important. This suggestion is plausible because over the life of the asteroids the vacuum and impact environment would have dehydrated the surface of the asteroids (e.g. Kiefer and Simonds, 1980).

We conclude that the surfaces of the C asteroids are serpentine or chlorite (CM field) or montmorillonite or kaolinite (CI chondrites field) that have been dehydrated by heating above ~600°C. It is clear that the C chondrites we now observe have never been heated above 800°C because they are water-rich. However, as we argued earlier, this implies aqueous alteration as a secondary process. In other words, we argue that (1) surface dehydration processes moved the data from the terrestrial phyllosilicates field and into the CM chondrites field, whereupon (2) the meteorites were buried and water was introduced as a secondary process. Finally, (3) major impact excavated this material and sent it to Earth.
2.5.7.9 Implications for asteroid history

Table 2.1 includes a summary of the sort of environment in which these phyllosilicates are found on Earth. Of course conditions in the early solar system and on an asteroid are very different from these terrestrial environments, but the chemical constraints will be common to both bodies; i.e. whether on Earth or on asteroids, the right bulk compositions must be present and not all phyllosilicates can be produced from chondritic precursors. Serpentine and chlorite are metamorphic and aqueous alteration products of mafic minerals, the mafic minerals being predicted by cosmic abundances and found in ordinary chondrites. They are therefore reasonable phyllosilicates to be found in meteorites (Table 2.5) and on asteroids. Nontronite and montmorillonite are aqueous alteration products of basaltic materials, expected for differentiated bodies, such as V asteroids. Kaolinite is an aqueous alteration product of feldspar, which—while found in ordinary chondrites at the 5% level—again would be expected to be a major component only in differentiated bodies like the lunar uplands. In summary, the trajectories and the associations suggested in Fig. 2.11 are reasonable, excluding kaolinite, nontronite, and possibly montmorillonite although it has been observed by TEM studies.
<table>
<thead>
<tr>
<th>Silicate</th>
<th>Formula</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chlorite group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamosite</td>
<td>(Fe$^{2+}$,Mg,Fe$^{3+}$)$_5$Al(Si$<em>3$Al)O$</em>{10}$(OH,O)$_8$</td>
<td>CM, CI</td>
</tr>
<tr>
<td>Clinochlore</td>
<td>(Mg,Fe$^{2+}$)$_5$Al(Si$<em>3$Al)O$</em>{10}$(OH)$_8$</td>
<td>CM, CV, CO</td>
</tr>
<tr>
<td><strong>Serpentine group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amesite</td>
<td>Mg$_2$Al(SiAl)O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Antigorite</td>
<td>Mg$_3$Si$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Berthierine</td>
<td>(Fe$^{2+}$,Fe$^{3+}$,Mg)$_2$·(Si,Al)$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Chrysotile</td>
<td>Mg$_3$Si$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Cronstedtite</td>
<td>Fe$^{2+}$Fe$^{3+}$(SiFe$^{3+}$)O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Ferroan Antigorite</td>
<td>(Mg,Fe,Mn)$_3$(Si, Al)$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Greenalite</td>
<td>(Fe$^{2+}$,Fe$^{3+}$)$_2$·Si$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td>Lizardite</td>
<td>Mg$_3$Si$_2$O$_5$(OH)$_4$</td>
<td>CM</td>
</tr>
<tr>
<td><strong>Smectite group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saponite</td>
<td>(Ca,Na)$_{0.3}$(Mg, Fe$^{2+}$)$_3$(Si, Al)$<em>4$O$</em>{10}$(OH)$_2$.4H$_2$O</td>
<td>CM, CV</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>(Na, Ca)$_{0.3}$(Al, Mg)$_2$Si$<em>3$O$</em>{10}$(OH)$_2$.nH$_2$O</td>
<td>CI, CV</td>
</tr>
<tr>
<td>Sobotkite</td>
<td>(K, Ca)$_{0.3}$(Mg$_2$Al)(Si$<em>3$Al)O$</em>{10}$(OH)$_2$.5H$_2$O</td>
<td>CM</td>
</tr>
<tr>
<td><strong>Mica</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clintonite</td>
<td>Ca(Mg,Al)$_3$(Al, Si)$<em>4$O$</em>{10}$(OH,F)$_2$</td>
<td>CV</td>
</tr>
<tr>
<td>Margarite</td>
<td>CaAl$_2$(Si$_2$Al$<em>2$)O$</em>{10}$(OH)$_2$</td>
<td>CV</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium-phlogopite</td>
<td>(Na,K)Mg$_3$(Si$<em>3$Al)O$</em>{10}$(F,OH)$_2$</td>
<td>CV</td>
</tr>
<tr>
<td>Talc</td>
<td>Mg$_3$(Si$<em>4$O$</em>{10}$)(OH)$_2$</td>
<td>CM</td>
</tr>
</tbody>
</table>

* From the compilation of Rubin (1997).
2.6 Conclusion

We have obtained reflectance spectra of eleven C asteroids using NASA’s IRTF and conducted heating experiments on a suite of terrestrial phyllosilicates. Further, since C asteroid and C chondrite spectra are essentially featureless, it is appropriate to discuss their spectra in terms of “continuum plots”, plots of the continuum between 1.0 and 1.75 µm against the continuum between 1.8 to 2.5 µm. The use of continuum slopes is implicit in existing asteroid taxonomies (Bus and Binzel, 2002). The use of continuum slopes is also implicit in several studies that interpret asteroid spectra by spectrum matching (e.g. Hiroi et al., 1993). We acknowledge that the continua of spectra are affected by a number of instrumental factors, but argue these are minor. We point out that the existence of discrete and well-defined clusters of C asteroids and C meteorites on the continuum plot and the reproducibility of measurements on the Murchison CM chondrite suggest that this method of spectral characterization is meaningful.

In confirmation of earlier studies (Hiroi and Zolensky, 1999) we have found that heating five phyllosilicates of diverse composition and structure causes features in their IR to weaken and disappear and, with one exception, their albedo to decrease by as much as 70%. These responses are associated with water loss and mineralogical changes.

Terrestrial phyllosilicates of a variety of structures and compositions have a wide range of continuum slopes and there is no systematic relationship between these parameters and location in the continuum plot. However, they are discrete from the C asteroids and C meteorites because of the large negative slopes at long wavelengths reflecting the presence of considerable structural water.
The C chondrites of CI, CV, CK and CR classes plot in a discrete field on the continuum plot that overlaps the C asteroid field. The CM chondrites also plot in a tight, discrete field, well separated from the terrestrial phyllosilicates, but also discrete from the C asteroid/C chondrite field. A group of meteorites identified as CI/CM chondrites plot on the interface between the C chondrite and the CM chondrite fields.

Heat treatments on five terrestrial phyllosilicates (also chosen to bracket compositions and structures of meteorites) cause the positions of the samples to move on the continuum plot. Heating to temperatures below 700°C causes the samples to move within the terrestrial phyllosilicate field. Heating to temperatures above 700°C moves montmorillonite and kaolinite into the region occupied by the C asteroids and C chondrites, while heating serpentine and chlorite >700°C moves their data into the CM chondrite field. Heating nontronite >700°C moves the data away from the C asteroid/C chondrite and CM chondrite fields. We observed that the chemically bound water is lost between 500 and 700°C and undoubtedly it is the loss of this water and collapse of the phyllosilicate structure that explains the spectral changes we observe. The data are consistent with the surfaces of the C asteroids being composed of dehydrated phyllosilicates, serpentine or montmorillonite. These phyllosilicates have been observed in C chondrites.

The data are also consistent with CM chondrites containing heated serpentine and chlorite, and again these minerals have been reported in CM chondrites. Literature data show that CM chondrites can be moved into the C asteroid field on the continuum plot by heating >800 °C (Hiroi et al., 1993; 1996a; 1996b). CM chondrites are also water-rich suggesting that these meteorites were excavated from the interior of the asteroid since
exposure for prolonged times on the surface would have caused them to become dehydrated. The presence of 3 µm absorption features on many C asteroids infers that excavation of interior material occurs.

Our data provide insights into the nature of asteroid surfaces and the relationship between the C asteroids and phyllosilicates. Dehydration causes the albedos to decrease to values almost as low as observed for the C asteroids, the presence of opaques would lower the albedo further and the presence of hydrated ionic solids would help remove absorption bands, although it does not affect slope. In summary, while we think opaques and hydrated ionic solids play a part in explaining the spectra of asteroids, most of their properties can be understood in terms of the dehydrated phyllosilicates montmorillonite and kaolinite.

2.7 Acknowledgements

We are grateful to Vincent Chevrier for providing the samples used in this work, NASA for funding, and Ed Cloutis, Ralph Milliken, Taki Hiroi and an anonymous reviewer that helped us clarify the text. This research utilizes spectra acquired by Mike Gaffey, Taki Hiroi, and Carle Pieters at the NASA RELAB Laboratory at Brown University.
CHAPTER 3

IRTF spectra for 17 asteroids from the C and X complexes: A discussion of continuum slopes and their relationships to C chondrites and phyllosilicates

Here we look at the continuum slopes of the individual classes that comprise the C and X complexes and how the classes relate to one another. The classes are compared to phyllosilicates and to carbonaceous chondrites to suggest possible parent bodies. Dr. Claud H. S. Lacy made the asteroid observations and contributed knowledge of asteroids. Dr. Kathy Gietzen contributed knowledge and background on asteroids. Dr. Derek W. G. Sears contributed knowledge and background for the carbonaceous chondrites and their relation to the asteroids. I collected and analyzed all the infrared data for the C asteroids, X asteroids, carbonaceous chondrites and terrestrial phyllosilicates.

3.1 Abstract

In order to gain further insight into their relationships with asteroids and their surface compositions, we have obtained spectra for seventeen C and X complex asteroids using NASA’s Infrared Telescope facility and SpeX infrared spectrometer. We augment these spectra with data in the visible region taken from the on-line databases. We searched the spectra for three spectral features often discussed, the UV slope, a 0.7 µm feature and a 3 µm feature. We found all of these in four of the present asteroids, and none of the features in only one. Asteroids can also be characterized by the slopes of their spectral continua and DeMeo et al. (2009), whose classification scheme we use here, showed that 88% of the variance in asteroid spectra is explained by continuum slope. We quantify the spectral slopes by plotting the slope between 1.8 to 2.5 µm against slope between 1.0 to 1.75 µm, the break at ~1.8 µm chosen since phyllosilicates show numerous water-related features beyond this wavelength. On such plots, the C complex
fields match those of phyllosilicates kaolinite and montmorillonite that have been heated to about 700°C, while the X complex fields match the fields for phyllosilicates montmorillonite and serpentine that have been similarly heated. On the basis of overlapping in fields on these plots we suggest that the CI chondrites are linked with the Cgh asteroids, individual CV and CR chondrites are linked with Xc asteroids, and a CK chondrite is linked with the Ch or Cgh asteroids. A number of unusual CI/CM meteorites are linked with C asteroids, while the CM chondrites are linked with the Xk asteroids. We suggest that the surface of the slope C complex asteroids consist of decomposition products of kaolinite or montmorillonite while for the X complex we suggest that surfaces consist of decomposition products of montmorillonite or serpentine. The associations are in reasonable agreement chondrite mineralogy and albedo data. Thus while previous characterization efforts for asteroids have focused on spectral features, we suggest that continuum slopes should have a role in our understanding of these asteroids.

3.2 Introduction

As part of a project to characterize the surface of asteroids and the asteroid-meteorite linkage, especially for potential mission targets (Sears et al., 2004), we launched a program of obtaining near-IR spectra for near-Earth and main belt asteroids using NASA’s Infrared Telescope Facility in Hawaii and the SpeX spectrometer (0.8-2.5 μm). Here we report data for seventeen C and X complex asteroids. Elsewhere we report data for S and V asteroids (Geitzen et al., 2010).

The C, X and related classes were originally defined by Bus and Binzel (2002), using visible spectra, as an outgrowth of the Tholen (1989) scheme. The basis of their approach is a Principal Component Analysis that identified absorption in the UV,
absorption around 0.9 µm, and the continuum slope as the most significant factors in characterizing asteroid spectra. In addition, a 0.7 µm feature that correlates with a much stronger water-related absorption feature at 3 µm, which has been seen in about half of the C complex asteroids, is also used in taxonomy (Lebofsky, 1978; 1980; Feierberg et al., 1985; Vilas and Gaffey, 1989; Vilas, 1994; Jones et al 1990; Fornasier et al., 1999). Rivkin et al. (2002) published a review of water-related spectral features for asteroids. DeMeo et al. (2009) recently added near infrared data to the taxonomy scheme and introduced a few modifications. Their scheme will be used throughout this paper.

Because of their low albedos, relatively featureless spectra, and occasional evidence for water-related features, the C asteroids have frequently been linked to carbonaceous chondrites, specifically CI and CM (Vilas and Gaffey, 1989; Vilas et al., 1993; Vilas, 1994). The CI chondrites were originally linked to C asteroids by Gaffey and McCord (1978), while the CM chondrites have been linked with the Fortuna Ch asteroid by Burbine (1998). More recently, Carvano et al. (2003) linked the CM chondrites to any asteroid that had a 0.7 µm band. The CI and CM chondrites are the meteorites that are closest to the solar photosphere in composition and they contain abundant water, up to 10 vol % for the CM chondrites and up to 20 vol % for the CI chondrites (Wiik 1969; Jarosewich 1990).

In addition to the water-rich CI and CM chondrites, other C chondrite classes include the anhydrous CO and CV chondrites, the anhydrous metal-rich CH chondrites, and several others. The CO and CV chondrites have been linked to K asteroids by Bell (1988). The small CR class was linked to C asteroids by Hiroi et al. (1996) and equally small CK chondrite and was linked to C asteroids by Gaffey and McCord (1978). The
CH chondrites have been linked to C or M asteroids by Burbine et al. (2002). Carvano et al. (2003) linked the CK chondrites to B asteroids (that are included in the C asteroid complex).

It is very difficult to characterize the mineralogy of CI and CM chondrites since they seem to consist largely of an amorphous silicate phases intermixed with microscopic sulfide and metal grains. This mixed phase was once called “PCP” (for “poorly characterized phase”), but is now termed tochilonite (Barber et al., 1983; Mackinnon and Zolensky, 1984; Tomeoka and Buseck, 1985; Brearley, 2006). It is sometimes possible to find fine-scale regions of a recognizable phyllosilicate phase, such as serpentine and chlorite (Brearley, 2006), and indirect inferences based on bulk chemistry have been used to characterize the phyllosilicate phase in meteorites (McSween and Richardson, 1977). Vilas and Gaffey (1989) suggested serpentine and chlorite as possible phyllosilicates on the surface of low albedo asteroids. In their review spectroscopic information on the nature of the surface of C and X complex asteroids, Rivkin et al., (2002) inferred the presence of hydrated phases including phyllosilicates. Rivkin (1997) and Rivkin et al. (2006) suggested that the surface of C asteroid Ceres contained an ammoniated smectite, such as ammoniated cronstedtite.

The surface of asteroids is heavily altered as a result of exposure to the space environment. Radiation damage by solar wind and solar energetic particles, micrometeorite bombardment, and major meteorite impacts will have affected the surface. The surfaces of all asteroids visited by spacecraft to date are heavily impacted, and are thus covered with unconsolidated regolith (e.g. Sullivan et al., 2002). Thus Hiroi and Zolensky (1999) performed heat treatments on terrestrial phyllosilicates, three
members of the serpentine group (antigorite, lizardite, clinochrysotile), chlorite, and saponite. They considered albedo, UV absorption, the 0.7 \(\mu\)m band, and the 3.0 \(\mu\)m band and they compared their heated phyllosilicate spectra with those of the asteroids. Hiroi and Zolensky (1999) concluded that the best fit for the phyllosilicate on the asteroid surfaces was saponite, but were concerned that this mineral had not been observed in meteorites.

Ostrowski et al (2010) recently reported data for a series of heated phyllosilicates that covered and extended the range of samples examined by Hiroi and his colleagues and took the experiments to higher temperatures where more complete destruction of the phyllosilicates occurs. In this paper we report results of a detailed comparison of spectra for asteroids, meteorites, and heated phyllosilicates and discuss implications for asteroid-meteorite linkage and asteroid surface composition. Preliminary reports have been made at various conferences (Ostrowski et al., 2008a,b; 2009a,b; Sears et al., 2008a,b), but the data and conclusions reported here supersede them.

3.3 Methods

Our spectra were obtained using the NASA InfraRed Telescope Facility on Mauna Kea, Hawaii, and the SpeX infrared spectrometer in low-resolution prism mode over 0.8 to 2.5 \(\mu\)m (Rayner et al. 2003), between 2004 August 6 and 2008 April 18 (Table 3.1). Asteroids as faint as magnitude 17.5 produced usable spectra. The raw data were reduced by 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.
Table 3.1. Observational details for the present asteroids*.

<table>
<thead>
<tr>
<th>Asteroid number</th>
<th>Asteroid name</th>
<th>UT Date</th>
<th>Exposure (s)</th>
<th>Air mass</th>
<th>Visual magnitude</th>
<th>Sky conditions</th>
<th>Analog Stars</th>
<th>Solar elongation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Themis</td>
<td>4/18/2008</td>
<td>300(10)</td>
<td>1.019</td>
<td>12.3</td>
<td>c, m</td>
<td>5, 6, 8</td>
<td>-92.9</td>
</tr>
<tr>
<td>34</td>
<td>Circe</td>
<td>4/14/2005</td>
<td>720(6)</td>
<td>1.222</td>
<td>12.4</td>
<td>8, 9, 11</td>
<td>144.7</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Eugenia</td>
<td>4/14/2005</td>
<td>320(4)</td>
<td>1.185</td>
<td>11.3</td>
<td>8, 9, 11</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Nemausa</td>
<td>10/14/2005</td>
<td>200(4)</td>
<td>1.071</td>
<td>10.8</td>
<td>2, 3, 13</td>
<td>-166.7</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Europa</td>
<td>5/30/2006</td>
<td>160(4)</td>
<td>1.106</td>
<td>11.3</td>
<td>7,8,9, 11</td>
<td>-148.3</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>Frigga</td>
<td>1/22/2008</td>
<td>720(6)</td>
<td>1.113</td>
<td>12.8</td>
<td>m</td>
<td>2, 3, 5, 7</td>
<td>133.5</td>
</tr>
<tr>
<td>87</td>
<td>Sylvia</td>
<td>10/14/2005</td>
<td>400(8)</td>
<td>1.004</td>
<td>12.1</td>
<td>2, 3, 13</td>
<td>139.4</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>Thisbe</td>
<td>10/14/2005</td>
<td>240(8)</td>
<td>1.006</td>
<td>11.3</td>
<td>2, 3, 13</td>
<td>145.5</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>Minerva</td>
<td>10/14/2005</td>
<td>400(8)</td>
<td>1.025</td>
<td>12.8</td>
<td>2, 3, 13</td>
<td>123.2</td>
<td></td>
</tr>
<tr>
<td>129</td>
<td>Antigone</td>
<td>4/14/2005</td>
<td>240(8)</td>
<td>1.055</td>
<td>10.2</td>
<td>8, 9, 11</td>
<td>148.3</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>Siwa</td>
<td>12/29/2006</td>
<td>480(4)</td>
<td>1.004</td>
<td>13.4</td>
<td>3, 4, 5</td>
<td>164.2</td>
<td></td>
</tr>
<tr>
<td>181</td>
<td>Eucharis</td>
<td>5/30/2006</td>
<td>480(4)</td>
<td>1.007</td>
<td>13.3</td>
<td>7,8,9, 11</td>
<td>-128.4</td>
<td></td>
</tr>
<tr>
<td>191</td>
<td>Kolga</td>
<td>4/14/2005</td>
<td>960(8)</td>
<td>1.135</td>
<td>13.9</td>
<td>8, 9, 11</td>
<td>127.7</td>
<td></td>
</tr>
<tr>
<td>213</td>
<td>Lilaea</td>
<td>12/29/2006</td>
<td>160(4)</td>
<td>1</td>
<td>13.3</td>
<td>3, 4, 5</td>
<td>-171.6</td>
<td></td>
</tr>
<tr>
<td>3691</td>
<td>Bede</td>
<td>1/22/2008</td>
<td>960(8)</td>
<td>1.033</td>
<td>16.9</td>
<td>m</td>
<td>2, 3, 5, 7</td>
<td>111.3</td>
</tr>
<tr>
<td>7753</td>
<td>1988 XB</td>
<td>12/3/2004</td>
<td>3600(30)</td>
<td>1.021</td>
<td>15.1</td>
<td>1, 2, 5, 6</td>
<td>131.2</td>
<td></td>
</tr>
<tr>
<td>153591</td>
<td>2001 SN263</td>
<td>1/22/2008</td>
<td>1560(13)</td>
<td>1.165</td>
<td>14.2</td>
<td>m</td>
<td>2, 3, 5, 7</td>
<td>-122.9</td>
</tr>
<tr>
<td>153591(b)</td>
<td>2001 SN263</td>
<td>4/18/2008</td>
<td>1920(16)</td>
<td>1.408</td>
<td>15.6</td>
<td>c, m</td>
<td>5, 6, 8</td>
<td>-148.6</td>
</tr>
</tbody>
</table>

* Digital files of the spectra can be found at the following web site (http://www.uark.edu/misc/clacy/SpecX_site/index.htm)

- **Exposure**: The total exposure time, in seconds, followed by the number of CCD images (in parentheses) that were combined to produce the total exposure time.
- **Air mass**: Mean air mass of the observations, calculated from the air mass values recorded at the start of each exposure.
- **Visual magnitude**: Calculated visual (V-band) magnitude of the asteroid at the time of the observation.
- **Sky conditions**: Sky conditions at the time of the observation, where c is for cloudy, roughly defined as the presence of clouds that led to erratic variations (greater than 5%) in the observed flux of either the solar-analog star or the asteroid, h is for a relative humidity greater than 70%, and m is for moonlight, where the lunar illumination is greater than 50%, and the moon’s altitude above the horizon is greater than 20°.
- **Solar Elongation**: The angle between the Sun and the asteroid at the time of observation.
Much of our discussion below will relate to the slope of the spectral continuum. There is much precedence for using slope in studies of asteroid spectra. In extending the Bus and Binzel (2002) scheme into the IR, DeMeo et al (2009) found that 88% of the variance in asteroid spectra is explained by continuum slope variations and a description of slope appears in the descriptions of most C and X classes. Hiroi et al. (1993; 1996) performed spectral matching between heated phyllosilicates, C chondrites, and C asteroids that are generally featureless so that his method amounts to slope comparison. A recent paper by Clark et al. (2010) also emphasizes continuum slope of B asteroids in an effort to find meteorite analogs.

We will quantify the overall shape of the spectra in the near-IR region by dividing the spectra into two more-or-less equal halves (1.0-1.75 µm and 1.8-2.5 µm), as shown in Fig. 3.1. We make the break at 1.8 µm because it is beyond 1.8 µm that a number of large water features are present in phyllosilicates (e.g. Ostrowski et al., 2010). A plot of the longer wavelength interval against the shorter wavelength interval we call the “continuum plot” (Ostrowski et al., 2010).
Figure 3.1. (a) Representative spectra for three asteroids; 153591 2001 SN263 (B), 52 Europa (C), and 129 Antigone (Xk), displaced on the vertical scale for clarity. Note the lack of major absorption features in the spectra. (b) Explanation for the manner in which we quantify the main features of these spectra using “continuum slopes” over the two wavelength intervals, 1.0 to 1.75 µm and 1.8 to 2.5 µm. The break at 1.8 µm was selected because of a frequent change in slope observed for terrestrial phyllosilicates at the wavelength due to the large number of water-related bands possible in the longer wavelength interval. For the purposes of determining slopes, the spectra are normalized to 0.875 µm.
Many experimental factors have the potential to affect continuum slope, such as placement on the slit, differential refraction, diffraction, and atmospheric variations. The asteroids and solar analogue stars in the present study were within 15 degrees of the meridian so as to minimize the effects of differential refraction. Dispersion was normal to the slit so when the target was kept near the meridian the atmospheric dispersion was along the slit and the entire signal along the slit was included in the data reduction. Automatic tracking and guidance kept the asteroid centered on the slit so the diffracted image overfilled it, manual corrections being used when necessary, and the infrared slit-viewing camera continuously monitored the object’s position on the 0.8 arcsec slit. We corrected for atmospheric variations using the models of Vacca et al. (2003) at the specific zenith distance of the object. The clustering of slope data and resolution of various groups of objects (C and X asteroids and CM chondrites, for instance), and the reproducibility of the slope data when determined by different research groups, are indications that these continuum measurements are not dominated by these sources of scatter.

3.4 Results

The spectra for the asteroids we observed are shown in Fig. 3.2a. Digital files of these spectra are available at the web site (http://www.uark.edu/misc/clacy/SpeX_site/index.htm). The spectra of asteroid 7753 and the two observations of asteroid 153591 show an increase in intensity at the long wavelengths due to the presence of thermal emission. This effect has been removed from the data using the method of Rivkin et al. (2005) and the results are shown in Fig. 3.2b.
This method uses a model that includes the effects of albedo and "beaming" along with the phase angle of observation.
Figure 3.2. (a) Raw spectra of asteroids from the B, C and X complexes observed in this study, displaced on a vertical scale for clarity. Taxonomy is based on the system of DeMeo et al. (2009). Most of the observed asteroids are relatively flat and featureless and the slope of their continua seems the major discriminator between them and is adopted as a basis for comparison in the present paper. (The small feature at ~1.35 μm and the anomalous features at longer wavelengths are due to terrestrial atmospheric water). (b) Asteroids 153591 and 7753 show evidence for thermal emission at long wavelengths, which was removed prior to analysis using the method of Rivkin et al. (2005).
In general the near-IR spectra we obtained are flat and featureless. Most show positive continuum slopes although for 213 Lilea it is negative. A few show a notable change in slope, for example 51 Nemausa has an inflection at ~1.5 µm, and 87 Sylvia and 129 Antigone have slope changes at ~1.25 µm. The data and the continuum plot for the present asteroids appear in Table 3.2 and are plotted in Fig. 3.3. The distinction between C and X asteroids is readily apparent in Fig. 3.3. The two diagonal lines are naked-eye estimates of the trends for the C and X complex asteroids. In fact, this plot is a quantitative and visual summary of the class descriptions in Table 3.3, where the asteroid classes are defined and where C complex asteroids are said to have a “slightly positive” slope and the X complex asteroids have a “slight to moderate” slope. The anomalous asteroid, 51 Nemausa (Cgh), is noted for its positive slope at the shorter wavelengths (see Fig. 3.2) and for its water-related absorption features discussed below. This is an indication that asteroids with water-related features in their spectra might not follow the trends otherwise observed in continuum plots.
Table 3.2. Continuum slope and albedo data for the present asteroids.

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Short $\lambda$ slope</th>
<th>Long $\lambda$ slope</th>
<th>Albedo#</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 Themis</td>
<td>0.175±0.014</td>
<td>0.197±0.017</td>
<td>0.067</td>
</tr>
<tr>
<td>34 Circe</td>
<td>0.009±0.001</td>
<td>0.003±0.001</td>
<td>0.0541</td>
</tr>
<tr>
<td>45 Eugenia</td>
<td>0.127±0.004</td>
<td>0.169±0.001</td>
<td>0.0398</td>
</tr>
<tr>
<td>51 Nemaesa</td>
<td>0.235±0.004</td>
<td>-0.036±0.007</td>
<td>0.0928</td>
</tr>
<tr>
<td>52 Europa</td>
<td>0.135±0.002</td>
<td>0.224±0.006</td>
<td>0.0578</td>
</tr>
<tr>
<td>77 Frigga</td>
<td>0.213±0.009</td>
<td>0.091±0.005</td>
<td>0.144</td>
</tr>
<tr>
<td>87 Sylvia</td>
<td>0.189±0.002</td>
<td>0.176±0.004</td>
<td>0.0435</td>
</tr>
<tr>
<td>88 Thisbe</td>
<td>0.092±0.001</td>
<td>0.113±0.001</td>
<td>0.0671</td>
</tr>
<tr>
<td>93 Minerva</td>
<td>0.080±0.002</td>
<td>0.106±0.006</td>
<td>0.0733</td>
</tr>
<tr>
<td>129 Antigone</td>
<td>0.167±0.003</td>
<td>0.139±0.005</td>
<td>0.164</td>
</tr>
<tr>
<td>140 Siwa</td>
<td>0.164±0.003</td>
<td>-0.014±0.007</td>
<td>0.0676</td>
</tr>
<tr>
<td>181 Eucharis</td>
<td>0.156±0.003</td>
<td>0.073±0.001</td>
<td>0.1135</td>
</tr>
<tr>
<td>191 Kolga</td>
<td>0.165±0.008</td>
<td>0.204±0.005</td>
<td>0.0408</td>
</tr>
<tr>
<td>213 Lilaea</td>
<td>-0.059±0.004</td>
<td>-0.061±0.006</td>
<td>0.0897</td>
</tr>
<tr>
<td>3691 Bede</td>
<td>0.114±0.011</td>
<td>-0.089±0.012</td>
<td></td>
</tr>
<tr>
<td>7753 1988 XB</td>
<td>0.025±0.001</td>
<td>0.034±0.001</td>
<td></td>
</tr>
<tr>
<td>153591 2001 SN263*</td>
<td>-0.002±0.002</td>
<td>0.020±0.006</td>
<td></td>
</tr>
<tr>
<td>153591 2001 SN263**</td>
<td>-0.033±0.005</td>
<td>0.064±0.004</td>
<td></td>
</tr>
</tbody>
</table>

# Albedo data from Zellner et al. (1985)
* Corrected for thermal radiation
$ Duplicate observation
Table 3.3. Classification of the asteroids observed in the present study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Themis</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>34</td>
<td>Circe</td>
<td>C</td>
<td>Ch</td>
<td>Ch</td>
</tr>
<tr>
<td>45</td>
<td>Eugenia</td>
<td>FC</td>
<td>C</td>
<td>C*</td>
</tr>
<tr>
<td>51</td>
<td>Nemausa</td>
<td>CU</td>
<td>Ch</td>
<td>Cgh</td>
</tr>
<tr>
<td>52</td>
<td>Europa</td>
<td>CF</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>77</td>
<td>Frigga</td>
<td>MU</td>
<td>Xe</td>
<td>Xe</td>
</tr>
<tr>
<td>87</td>
<td>Sylvia</td>
<td>P</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>88</td>
<td>Thisbe</td>
<td>CF</td>
<td>B</td>
<td>Cb*</td>
</tr>
<tr>
<td>93</td>
<td>Minerva</td>
<td>CU</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>129</td>
<td>Antigone</td>
<td>M</td>
<td>X</td>
<td>Xk*</td>
</tr>
<tr>
<td>140</td>
<td>Siwa</td>
<td>P</td>
<td>Xc</td>
<td>Xc*</td>
</tr>
<tr>
<td>181</td>
<td>Eucharis</td>
<td>S</td>
<td>Xk</td>
<td>Xk</td>
</tr>
<tr>
<td>191</td>
<td>Kolga</td>
<td>XC</td>
<td>Cb</td>
<td>Cb</td>
</tr>
<tr>
<td>213</td>
<td>Lilaea</td>
<td>F</td>
<td>B</td>
<td>B*</td>
</tr>
<tr>
<td>3691</td>
<td>Bede</td>
<td>Xc</td>
<td>Xc*</td>
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<tr>
<td>7753</td>
<td>1988 XB</td>
<td>B</td>
<td>C*</td>
<td></td>
</tr>
<tr>
<td>153591</td>
<td>2001 SN263</td>
<td></td>
<td></td>
<td>B*</td>
</tr>
</tbody>
</table>

* Classifications determined by applying the DeMeo et al. (2009) software (available at http://smass.mit.edu/cgi-bin/busdemeoclass-cgi) to the present spectra.
Figure 3.3. A continuum plot for C and X complex asteroids observed in the present study. Two possible trend lines are indicated, one passing through the C asteroids and one passing through the X asteroids. The anomalous Cgh asteroid, 51 Nemausa, is noteworthy for an unusual change in slope in its spectrum at ~1.5 mm.
The only absorption features we observed in our spectra are weak bands at 1.35 µm, which appear in 12 of our 18 spectra. However, these are clearly due to telluric water since several display spectral reversals (e.g. 88 Thisbe, 34 Chicago, 52 Europa). Gaffey (2003) discussed this issue. The features seen in the long wavelength region for asteroids 88 (Cb), 213 (B) and 140 (Xc) are also telluric water features that have not been completely removed by our correction procedures. These features do not seem to have affected their continuum slopes (judging by the similarity of the slopes with asteroids of the same class), so we have decided to retain these spectra in our study.

3.5 Discussion

We will first discuss taxonomy of the present asteroids, which will lead us to stress the importance of continuum slopes in both asteroid taxonomy and characterization. We will then present our data in the form of continuum plots, looking at individual C complex asteroids, individual X complex asteroids, and then comparing the C and X fields. We will then discuss the terrestrial phyllosilicate data reported by Ostrowski et al. (2010), and the C chondrites, suggesting asteroid linkages where possible. Finally we offer some thoughts on the nature of C and X complex asteroids.

3.5.1 Taxonomy of the present asteroids and the importance of continuum slope

The classifications of the present asteroids are shown in Table 3.3. In general, we have taken these classes assignments from the literature but where indicated we used the DeMeo et al. (2009) on-line software (http://smass.mit.edu/cgi-bin/busdemeoclass-cgi). The Tholen (1989) and Bus and Binzel (2002) schemes are based solely on visible spectra. A Principal Components Analysis found that continuum slope, absorption at
~0.8 mm, and absorption in the UV were the major factors cause of variation. A summary of the DeMeo et al. (2009) description of the asteroid classes of interest here is shown in Table 3.4. For five of the nine classes an absorption feature is part of the class description, but for all nine continuum slope is also part of the class description with slope increasing along the B-C-X series. The evolution in taxonomy between the first two schemes in Table 3.3 is significant, but only five of our asteroids (numbers 24, 51, 88, 129 and 7753) needed reclassification on the basis of the additional near-IR data.
Table 3.4. Description of the classes with respect to slope and water-related features for the present asteroids (after DeMeo et al., 2009).

<table>
<thead>
<tr>
<th>Slope</th>
<th>Water-related features*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UV</td>
</tr>
<tr>
<td>B Linear, negative, bump 0.6 µm, dip 1-2 µm</td>
<td>NA</td>
</tr>
<tr>
<td>C Linear, flat, bump 0.6, positive &gt;1.3 um</td>
<td>NA</td>
</tr>
<tr>
<td>Ch Slight positive &gt;1.1 µm</td>
<td>UV drop off</td>
</tr>
<tr>
<td>Cgh Slight positive &gt;1 µm</td>
<td>Pronounced UV drop off</td>
</tr>
<tr>
<td>Cb Linear, slight positive &gt;1.1 µm</td>
<td>NA</td>
</tr>
<tr>
<td>X Linear, medium to high</td>
<td>NA</td>
</tr>
<tr>
<td>Xc Low to medium, slightly curved concave downward</td>
<td>NA</td>
</tr>
<tr>
<td>Xe Low to medium, like Xc</td>
<td>NA</td>
</tr>
<tr>
<td>Xk Like Xc</td>
<td>NA</td>
</tr>
</tbody>
</table>

* NA, not applicable, means that the feature is absent or not relevant to the definition of the class.
3.5.2 Existing data for absorption features in the spectra of there asteroids

Given that absorption features have the potential to provide compositional information, in Table 3.5 we report our search for spectral features in the present asteroids using literature data. We have calculated parameters for UV absorption, the depth of absorption at 0.7 µm, and the depth of absorption at 3 µm. As with previous workers (Vilas, 1994; Hiroi et al., 1996; Hiroi and Zolensky, 1999; Fornasier et al., 1999), we measure these absorptions with three φ parameters, φ<sub>UV</sub>, (UV absorption strength), φ<sub>0.7</sub> (0.7 µm band strength) and φ<sub>3</sub> (3 µm band strength), which are defined by:

\[
φ_{UV} = \ln R_{0.337} - \ln R_{0.550}
\]

\[
φ_{0.7} = \ln R_{0.701} - \frac{0.152 \ln R_{0.550} + 0.151 \ln R_{0.853}}{0.303}
\]

\[
φ_{3} = \ln R_{3.0} - \ln R_{2.4}
\]

where R refers to spectral reflectance and the subscripts refer to wavelength in µm.
Table 3.5. Spectra data on the present asteroids and water-related features*.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Absorption/bands calculated value</th>
<th>Evidence for water?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>UV (φ_{UV})‡</td>
<td>0.7 µm (φ_{0.7})‡</td>
</tr>
<tr>
<td>24</td>
<td>Themis</td>
<td>-0.2220</td>
<td>-0.0071</td>
</tr>
<tr>
<td>34</td>
<td>Circe</td>
<td>-0.2303</td>
<td>-0.0259</td>
</tr>
<tr>
<td>45</td>
<td>Eugenia</td>
<td>-0.0953</td>
<td>0.0138</td>
</tr>
<tr>
<td>51</td>
<td>Nemausa</td>
<td>-0.4664</td>
<td>-0.0213</td>
</tr>
<tr>
<td>52</td>
<td>Europa</td>
<td>-0.1262</td>
<td>0.0265</td>
</tr>
<tr>
<td>77</td>
<td>Frigga</td>
<td>-0.1253</td>
<td>0.0298</td>
</tr>
<tr>
<td>87</td>
<td>Sylvia</td>
<td>-0.0712</td>
<td>-0.0017</td>
</tr>
<tr>
<td>88</td>
<td>Thisbe</td>
<td>-0.1299</td>
<td>-0.0085</td>
</tr>
<tr>
<td>93</td>
<td>Minerva</td>
<td>-0.1874</td>
<td>0.0037</td>
</tr>
<tr>
<td>129</td>
<td>Antigone</td>
<td>-0.0249</td>
<td>0.0275</td>
</tr>
<tr>
<td>140</td>
<td>Siwa</td>
<td>-0.0839</td>
<td>0.0292</td>
</tr>
<tr>
<td>181</td>
<td>Eucharis</td>
<td>-0.0231</td>
<td>0.0435</td>
</tr>
<tr>
<td>191</td>
<td>Kolga</td>
<td>0.0213</td>
<td>-0.4869</td>
</tr>
<tr>
<td>213</td>
<td>Lilaea</td>
<td>-0.0083</td>
<td>-0.0060</td>
</tr>
<tr>
<td>3691</td>
<td>Bede</td>
<td>-0.1656</td>
<td>0.0234</td>
</tr>
</tbody>
</table>

* Excluded are asteroids 7753 (1988 XB) and 153591 (2001 SN263) for which there are no data at these wavelengths. “N” indicates no, “Y” indicates yes, “nd” indicates no data for these features.


† Slopes and band strengths (φ values) defined as follows:

\[
\phi_{UV} = \ln R_{0.337} - \ln R_{0.550}
\]

\[
\phi_{0.7} = \ln R_{0.701} - [0.152 \ln R_{0.350} + 0.151 \ln R_{0.853}] / 0.303
\]

\[
\phi_{3} = \ln R_{3.0} - \ln R_{2.4}
\]

where R is spectral reflectance and the subscripts refer to wavelength (µm).

‡ Water is assumed to be present if the UV slope smaller than –0.3, if the 0.7 µm band is less than 0.01, and if the 3 µm band is smaller than –0.02 (see text for explanation).
Judging from the plots of Hiroi et al. (1996; their Fig. 4) and the spread in positive values in Table 3.5, we take the presence of a water-related feature to be positive if $\phi_{UV} < -0.3$, if $\phi_{0.7} < 0.01$ (assuming this feature is water-related, Vilas, 1994), and if $\phi_3 = -0.02$. These criteria are similar to those used by other workers. It needs to be noted that results using ECAS data and SMASS data may result in a different outcome for the 0.7 μm feature because of the higher resolution for the SMASS spectra. We find evidence for water related features in all but one of the spectra of the present asteroids, the exception being Eucharis. On the other hand, all three features are present in the spectra of only three of the present asteroids, namely 24 Themis, 34 Circe, and 51 Nemausa.

Asteroids 24 Themis, 34 Circe, and 51 Nemausa are classes C, Ch, and Cgh, respectively. The “h” in the Cgh and Ch classifications signifies the presence of a 0.7 μm feature. Vilas (1994) found that 47.7 % of C asteroids showed evidence for hydration and 33.0% of B asteroids showed evidence for hydration and 5.6% of X asteroids. We find that eight out of the 15 for which we have data show an absorption feature at 0.7 mm. Four of the present asteroids were included in the Vilas (1994) study, 51 Nemausa, 52 Europa, 87 Sylvia, and 88 Thisbe. Vilas found 0.7 μm and 3.0 μm for 51 Nemausa, and none for 52 Europa, in agreement with our results, whereas she found neither band in 87 Sylvia we find a 0.7 μm band. In other words, while there is a high degree of agreement over the objects as a whole, there are differences at the individual object level.

Features seen at <0.55 μm (in the Xe class) and 0.8-1.0 μm (in the Xk class) are diagnostic of their classes and might be associated with hydration features (Rivkin et al.,
and while the absorption band >1 µm sometimes seen in class Xk could be associated with olivine and pyroxene (Sunshine and Pieters, 1993).

### 3.5.3 Continuum plots for individual C complex asteroids

Figure 3.4 shows continuum plots for the C complex asteroids in our study with literature data where available (Table 3.6). It should first be noted that there are many instances of good-to-excellent agreement between separate observations in well-populated classes. This suggests that continua slopes can be reproducibly determined and that this method of quantifying the data is meaningful. Second, the B class plots to the left of the C classes, and the C class generally plots higher than the other classes. Second, the C, Cb and Ch classes display positive correlations between the long-wavelength slope and short-wavelength slope (with slopes on this plot of 1.0, 1.1, 0.6, respectively). The B and Cgh class produce either horizontal slightly negative trends. The Cb and Cg classes, with four or less members, are not well defined. We will now discuss each class in turn.
Table 3.6. Literature data for continuum slopes and albedos for C and X asteroids

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Class</th>
<th>Short $\lambda$ slope</th>
<th>Long $\lambda$ slope</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Psyche</td>
<td>Xk</td>
<td>0.192±0.002</td>
<td>0.167±0.009</td>
<td>0.1203</td>
</tr>
<tr>
<td>19 Fortuna</td>
<td>Ch</td>
<td>0.135±0.003</td>
<td>0.030±0.007</td>
<td>0.037</td>
</tr>
<tr>
<td>19 Fortuna $</td>
<td>$</td>
<td>Ch</td>
<td>0.227±0.003</td>
<td>0.111±0.008</td>
</tr>
<tr>
<td>21 Lutetia</td>
<td>Xc</td>
<td>0.115±0.007</td>
<td>0.022±0.001</td>
<td>0.2212</td>
</tr>
<tr>
<td>22 Kalliope</td>
<td>X</td>
<td>0.281±0.005</td>
<td>0.177±0.006</td>
<td>0.1419</td>
</tr>
<tr>
<td>24 Themis</td>
<td>C</td>
<td>0.054±0.002</td>
<td>0.169±0.005</td>
<td>0.067</td>
</tr>
<tr>
<td>41 Daphne</td>
<td>Ch</td>
<td>0.131±0.003</td>
<td>0.039±0.004</td>
<td>0.0828</td>
</tr>
<tr>
<td>48 Doris</td>
<td>Ch</td>
<td>0.056±0.001</td>
<td>-0.002±0.007</td>
<td>0.0624</td>
</tr>
<tr>
<td>52 Europa</td>
<td>C</td>
<td>0.168±0.003</td>
<td>0.223±0.007</td>
<td>0.0578</td>
</tr>
<tr>
<td>55 Pandora</td>
<td>Xk</td>
<td>0.285±0.005</td>
<td>0.228±0.006</td>
<td>0.3013</td>
</tr>
<tr>
<td>55 Pandora $</td>
<td>$</td>
<td>Xk</td>
<td>0.267±0.012</td>
<td>0.207±0.01</td>
</tr>
<tr>
<td>66 Maja</td>
<td>Ch</td>
<td>0.042±0.002</td>
<td>0.013±0.002</td>
<td>0.0618</td>
</tr>
<tr>
<td>66 Maja $</td>
<td>$</td>
<td>Ch</td>
<td>0.109±0.003</td>
<td>0.071±0.009</td>
</tr>
<tr>
<td>69 Hesperia</td>
<td>Xk</td>
<td>0.293±0.003</td>
<td>0.219±0.006</td>
<td>0.1402</td>
</tr>
<tr>
<td>76 Freia</td>
<td>C</td>
<td>0.253±0.004</td>
<td>0.247±0.007</td>
<td>0.0362</td>
</tr>
<tr>
<td>77 Frigga</td>
<td>Xe</td>
<td>0.167±0.001</td>
<td>0.056±0.003</td>
<td>0.144</td>
</tr>
<tr>
<td>78 Diana</td>
<td>Ch</td>
<td>0.135±0.006</td>
<td>0.069±0.006</td>
<td>0.0706</td>
</tr>
<tr>
<td>87 Sylvia</td>
<td>X</td>
<td>0.248±0.004</td>
<td>0.250±0.007</td>
<td>0.0435</td>
</tr>
<tr>
<td>90 Antiope</td>
<td>C</td>
<td>0.212±0.006</td>
<td>0.270±0.006</td>
<td>0.0603</td>
</tr>
<tr>
<td>99 Dike</td>
<td>Xk</td>
<td>0.099±0.006</td>
<td>0.004±0.005</td>
<td>0.0627</td>
</tr>
<tr>
<td>110 Lydia</td>
<td>Xk</td>
<td>0.270±0.002</td>
<td>0.213±0.004</td>
<td>0.1808</td>
</tr>
<tr>
<td>114 Kassandra</td>
<td></td>
<td>0.248±0.004</td>
<td>0.113±0.001</td>
<td>0.0884</td>
</tr>
<tr>
<td>132 Aethra</td>
<td>Xe</td>
<td>0.121±0.004</td>
<td>0.017±0.006</td>
<td>0.199</td>
</tr>
<tr>
<td>153 Hilda</td>
<td>X</td>
<td>0.261±0.006</td>
<td>0.187±0.006</td>
<td>0.0618</td>
</tr>
<tr>
<td>175 Andromache</td>
<td>Cg</td>
<td>0.146±0.005</td>
<td>0.111±0.004</td>
<td>0.0819</td>
</tr>
<tr>
<td>191 Kolga</td>
<td>Ch</td>
<td>0.177±0.002</td>
<td>0.201±0.003</td>
<td>0.0408</td>
</tr>
<tr>
<td>210 Isabella</td>
<td>Cb</td>
<td>0.132±0.001</td>
<td>0.113±0.002</td>
<td>0.0436</td>
</tr>
<tr>
<td>261 Prymno</td>
<td>Xk</td>
<td>0.187±0.003</td>
<td>0.137±0.006</td>
<td>0.1141</td>
</tr>
<tr>
<td>266 Aline</td>
<td>Ch</td>
<td>0.147±0.001</td>
<td>0.042±0.004</td>
<td>0.0448</td>
</tr>
<tr>
<td>345 Tercidima</td>
<td>Ch</td>
<td>0.187±0.002</td>
<td>0.097±0.006</td>
<td>0.0654</td>
</tr>
<tr>
<td>706 Hirundo</td>
<td>Cgh</td>
<td>0.319±0.003</td>
<td>-0.020±0.008</td>
<td>0.1721</td>
</tr>
<tr>
<td>706 Hirundo $</td>
<td>$</td>
<td>Cgh</td>
<td>0.293±0.005</td>
<td>-0.041±0.009</td>
</tr>
<tr>
<td>776 Berbereria</td>
<td>Cgh</td>
<td>0.085±0.002</td>
<td>0.010±0.005</td>
<td>0.0655</td>
</tr>
<tr>
<td>1300 Marcelle</td>
<td>Cgh</td>
<td>0.129±0.007</td>
<td>-0.070±0.007</td>
<td>0.0995</td>
</tr>
<tr>
<td>1300 Marcelle $</td>
<td>$</td>
<td>Cgh</td>
<td>0.145±0.008</td>
<td>-0.031±0.003</td>
</tr>
<tr>
<td>2099 Opik</td>
<td>Ch</td>
<td>0.144±0.005</td>
<td>0.161±0.003</td>
<td></td>
</tr>
<tr>
<td>2378 Pannekoek</td>
<td>Cgh</td>
<td>0.072±0.004</td>
<td>0.079±0.006</td>
<td>0.0891</td>
</tr>
<tr>
<td>3200 Phaethon</td>
<td>B</td>
<td>-0.165±0.008</td>
<td>0.007±0.009</td>
<td>0.1066</td>
</tr>
<tr>
<td>3691 Bede</td>
<td>Xc</td>
<td>0.143±0.005</td>
<td>-0.016±0.004</td>
<td></td>
</tr>
<tr>
<td>4744 1988 RF5</td>
<td></td>
<td>0.760±0.023</td>
<td>0.493±0.006</td>
<td></td>
</tr>
<tr>
<td>53319 1999JM8*</td>
<td>X</td>
<td>0.156±0.009</td>
<td>0.164±0.007</td>
<td></td>
</tr>
<tr>
<td>137170 1999 HF1</td>
<td>B</td>
<td>-0.001±0.004</td>
<td>-0.034±0.009</td>
<td></td>
</tr>
</tbody>
</table>

# Albedo data from Zellner et al. (1985).
* Corrected for thermal radiation.
$ $ Duplicate observation.
Figure 3.4. Continuum plots for asteroids in the C complex, separated by asteroid class. Data from the present study have been combined with data from the literature, present data in bold type, literature data in normal type. In most cases, the class members define fairly narrow fields on this plot, usually with a positive trend, especially where the number of observations is four or greater. Note that where there are two observations by different research groups, in general the agreement between groups is very good. The literature data is taken from SMAS-S Small Main-Belt Asteroid Spectroscopic Survey, Binzel et al. (2004) and MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance.
There are five members of the B class in Fig. 3.4a, with duplicate observations for one that are in reasonable agreement. One of the asteroids at the lower end of the range is 3200 Phaethon, which is thought to be the parent of the Geminid meteor stream and an extinct cometary nucleus (Ohtsuka et al., 2006). Asteroid 137170 1999 HF1 shows a second periodicity in the light curve indicating that it is a binary object (Polishook and Brosch, 2008). Asteroid 153591 is a near-Earth asteroid that is actually a triple system, the first reported among the NEA (Nolan et al. 2008).

There are nine members of the C class (Fig. 3.4b) and we have two independent observations 24 Themis and 52 Europa. The duplicate data for 52 Europa are in good agreement, but the short wavelength slopes of the two spectra for 24 Themis spread across the ellipse in weak agreement. Asteroid 90 Antiope is a double asteroid in the Themis family (Descamps et al. 2007) and plots near the upper end of the range. Asteroid 93 Minerva is a large main belt asteroid that plots at the lower in the range. Of the C asteroids that were observed for this study, 24 Themis, 45 Eugenia, 52 Europa, and 93 Minerva, none have significant absorption features according to the criteria in Table 3.5.

The field for the Cb class (Fig. 3.4c) includes 191 Kolga, 88 Thisbe and 210 Isabell. The two independent observations of 191 Kolga are in good agreement. Using the criteria in Table 5, neither of the present asteroids (191 Kolga and 88 Thisbe) have detectable absorption features. Asteroid 191 Kolga has a fairly strong 0.7 \( \mu \text{m} \) feature, which would normally be indicative of Ch or Cgh asteroids. However, the continuum slopes support the Cb classification (compare Fig. 3.4c with Figs. 3.4e and 3.4f).
For the Cg asteroids (Fig. 3.4d) we have only one object (175 Andromache) and can say little, other than observe that it provides some indication of the location of the field. For the Cgh class (Fig. 3.4e), we have seven observations including duplicates for 706 Hirundo and 1300 Marcelle. There is excellent agreement between the observations of the duplicates. The other members of the group are 51 Nemausa, 776 Berbericia, and 2378 Pannekoek. Asteroid 51 Nemausa was mentioned above since it appears anomalous on Fig. 3.3. This is related to its unusual spectrum in which a large positive slope change abruptly at ~1.5 \( \mu m \) to a shallow or negative slope (Fig. 3.1). The clustering in Fig. 3.4e suggests that this behavior is typical of the class. Asteroid 51 Nemausa has rotational spectral variations suggesting a non-uniform surface composition (Sawyer, 1991), and that its surface contains a “red spot” (Kristensen, 1991). Asteroid 51 Nemausa does not have a 0.7\( \mu m \) feature in our spectrum, but as mentioned above does show strong UV absorption and 3 \( \mu m \) feature (Table 3.5). This is in agreement with Hiroi et al. (1996) who found a positive correlation between the UV absorption and 3 \( \mu m \) features. Apparently, 51 Nemausa has water in some form on its surface.

The Ch asteroid field is well populated with 11 members and a fairly well defined ellipse (Fig. 3.4f). Asteroid 2099 Opik stands slightly apart from the others because its near-infrared spectrum is a steadily increasing continuum, whereas other Ch asteroids level off at longer wavelengths. Maybe the classification of 2099 Opik should be reconsidered. The Ch class is defined by having members with a 0.7 \( \mu m \) feature, but the only Ch asteroid we observed, 34 Circe, has 0.7 \( \mu m \) feature and no UV absorption (Table 3.5). The two literature samples of asteroid 19 Fortuna have weak agreement in the short and long wavelength slopes because of about a 0.7 separation on both axes.
3.5.4 Continuum plots for individual X complex asteroids

Figure 3.5 shows the present and literature data for the four classes in the X complex represented by X, Xc, Xe and Xk in the present study. Again we first note the many cases of very good agreement between duplicate observations of the same asteroid: 87 Sylvia, 3691 Bede, 77 Frigga, and 55 Pandora, which are classes X, Xc, Xe and Xk, respectively. In general, the two observations are within ~0.07 on each axis. Second, the trends on these plots are positive, an exception being the Xc class for which there are few objects. The slopes of the trend lines in Fig. 3.5 are 0.6, 0.8 and 1.1 for the X, Xe and Xk classes, respectively, similar to the values mentioned above. We will now discuss each class individually.
Figure 3.5. Continuum plots for asteroids in the X complex. Details as in Fig. 3.4. Again there is fairly tight clustering, positive slopes, and good agreement between observers.
There are four members of the X class (Fig. 3.5a), 153 Hilda, 53319 1999 JM8, 22 Kaliaope and 87 Sylvia. Our spectrum for 87 Sylvia contained no water-related spectral features (Table 3.5). The three members of the Xc class, 3691 Bede, 140 Siwa, and 21 Lutetia, plot closely on Fig. 3.5b. 3691 Bede is a tumbling asteroid (Pravec et al. 2005), which might explain the small differences in the two observations. According to our criteria there are no water-related features in the spectra of Xc asteroids 140 Siwa and 3691 Bede (Table 3.5). The Rosetta spacecraft will flyby Lutetia in 2010 and Lazzarin et al. (2004) have observed features attributed to aqueous alteration in. The two members of the Xe class (Fig. 3.5c) plot closely. Asteroid 77 Frigga does not appear to have UV absorption or 0.7 μm and 3 μm features (Table 3.5). The Xe asteroid 132 Aethra is noted for its relatively flat spectrum, especially in the long wavelengths. Finally, the eight members of the Xk class form a reasonably tight cluster with steep continuum at both the short and long wavelengths (Fig. 3.5d). Asteroids 129 and 181 Eucharis do not to have a 0.7 μm feature and UV absorption according to our criteria, but a weak 3 μm feature is present in the spectra of 129 Antigone.
Figure 3.6. Summary of the fields identified in Figs. 3.5 and 3.6. The prevalence of positive slopes and the difference between the C and X complexes in overall slope on these plots (as observed in our own data, Fig. 3.3) are apparent. Most particularly, the X complex classes are displaced to the right relative to the C complexes. These plots provide a means of comparing asteroid spectral reflectivity data with that of other similar samples, such as heated phyllosilicates and C chondrites.
3.5.5 Comparison of C and X fields

Figure 3.6 compares the ellipses drawn around the data in Figs. 3.4 and 3.5. Three points can be stressed, some of which were mentioned above and have been noted by others. First, in general, the X complex classes are displaced to the right on Fig. 3.6 relative to the C complex classes and the B asteroids are displaced to the left. In other words, the (1) members of the X complex tend to have similar continua in the long wavelength range but steeper continua in the short wavelength range compared to the C complex, and (2) B asteroids have smaller (negative) slopes at short wavelengths but among the shallower slopes at long wavelengths compared to the rest of the C complex and the X complex asteroids. The major exception is that the Cgh class overlaps with the X complex. Second, while slopes of the X complex classes are very similar (notwithstanding the small number and clustering of the Xc class), the C complex classes show a wide range of behavior with some classes having similar trend slopes to the X complex classes.

While there is some overlap of the fields shown by the various asteroid classes, it is clearly not close to 100%. In fact, the overlap of one class with its closest neighbor is usually <50%. Thus the classes recognized on the basis of spectra in the visible and infrared range are reflected in these continua plots lending an additional indication that such continuum plots are meaningful. We now wish to compare our astronomical data with data obtained in the laboratory for meteorites and phyllosilicates. Before doing so, we must consider some complications that must be borne in mind.
3.5.6 Considerations when comparing laboratory measurements with astronomical measurements

In comparing laboratory measurements with astronomical measurements we are concerned with three primary effects. (1) The similarity of the standard light sources for the laboratory and astronomical measurements. In the case of the laboratory spectrometer, the reference light source is a halogen lamp whereas for the astronomical measurements the reference light source is a number of solar-like stars. (2) The effect of grain size on the measurements and how the grains used for laboratory measurements compare with grains sizes on the asteroids. (3) Laboratory measurements are made on freshly ground interior samples, while astronomical measurements are made on a surface that has been exposed to space. In space, there will have been a number of alteration processes that are collectively referred to as “space weathering”.

In response to point (1), our laboratory light source is normalized to a white spectral-standard material (TiO$_2$). The stellar reference sources may not be perfectly white, but they are close, and any error caused by slight differences is well within our experimental uncertainties. It should also be kept in mind that the range of slopes we observe in the asteroid, meteorite, and mineral spectra are very large. Of course, these issues are not relevant to our measurement of absorption strengths that are calculated with respect to the continuum.

Figure 3.7 shows the continuum plot for samples of Murchison of three sieve fractions (data of Gaffey, Hiroi, and Pieters taken from the RELAB on-line database). The range of slopes in the short wavelength interval is considerable, with data ranging from –0.1 to 0.5 on the horizontal axis with slope decreasing with coarsening grain size.
On the other hand, the range slopes in the longer wavelength interval is small or negligible.
Figure 3.7. Continuum plot for bulk and grain separates of samples of the Murchison CM chondrite. The Murchison bulk data point is from Hiroi et al. (1993; 1996) while the grain size fractions are from spectra acquired by Mike Gaffey, Taki Hiroi, and Carle Pieters at the NASA RELAB Laboratory at Brown University. While grain size seems to affect the continuum slope at the shorter wavelengths, there is little or no effect on the continuum slope at the longer wavelengths. The finer grain fractions (<63 and <125 µm) plot in the CM chondrite field while the coarser fraction (<200 µm) plot in the C asteroid field.
The data shown in Fig. 3.7 are surprising, since, in general, data for a given meteorite or meteorite class tends to be very reproducible, regardless of grain size. Figure 3.8 shows the continuum plot for meteorites for which near-IR spectra have been published. The data appear in Table 3.7. Five CM chondrites plot in the same general region of the continuum plot, having relatively steep positive slopes in the 1.0 to 1.75 μm region, and no overlap with the remaining meteorites. In fact, three CM chondrites (Cold Bokkeveld, Murray and Murchison) are the same within experimental limits. Three CI/CM chondrites have similar slopes to the CM chondrites in the 1.8-2.5 μm region, but significantly shallower slopes in the 1.0 to 1.75 μm region. Three C remaining chondrites, CV, CR, and CK chondrites, have 1.0-1.75 μm slopes of 0.05-0.20 but negative slopes in the long wavelength region. In other words, the continuum plot is separating these three types of C chondrite. This suggests that these data are not being dominated by grain size effects and can be compared with asteroid data.
Table 3.7. Continuum slopes and albedos of carbonaceous chondrites.

<table>
<thead>
<tr>
<th>Meteorite Class</th>
<th>Meteorite Name</th>
<th>Short λ slope</th>
<th>Long λ slope</th>
<th>Albedo*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI/CM</td>
<td>Y-86720</td>
<td>0.004±0.0002</td>
<td>0.090±0.005</td>
<td></td>
</tr>
<tr>
<td>CI/CM</td>
<td>B-7904</td>
<td>0.141±0.007</td>
<td>0.128±0.006</td>
<td></td>
</tr>
<tr>
<td>CI/CM</td>
<td>Y-82162</td>
<td>0.150±0.007</td>
<td>0.129±0.006</td>
<td></td>
</tr>
<tr>
<td>CK</td>
<td>Y-693</td>
<td>0.038±0.002</td>
<td>-0.040±0.002</td>
<td></td>
</tr>
<tr>
<td>CV</td>
<td>Allende</td>
<td>0.153±0.008</td>
<td>0.006±0.0003</td>
<td>0.102</td>
</tr>
<tr>
<td>CR</td>
<td>Renazzo</td>
<td>0.168±0.008</td>
<td>-0.060±0.003</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>Ivuna #1</td>
<td>0.044±0.002</td>
<td>-0.017±0.0008</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>Ivuna #2</td>
<td>-0.018±0.0009</td>
<td>-0.080±0.004</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>Orgueil (Hiroi)</td>
<td>0.193±0.010</td>
<td>-0.104±0.005</td>
<td>0.072</td>
</tr>
<tr>
<td>CI</td>
<td>Orgueil (Gaffey)</td>
<td>0.052±0.002</td>
<td>-0.069±0.003</td>
<td>0.072</td>
</tr>
<tr>
<td>CM</td>
<td>Mighei</td>
<td>0.316±0.003</td>
<td>0.199±0.008</td>
<td>0.051</td>
</tr>
<tr>
<td>CM</td>
<td>Cold Bokkeveld</td>
<td>0.259±0.001</td>
<td>0.115±0.005</td>
<td></td>
</tr>
<tr>
<td>CM</td>
<td>Murray</td>
<td>0.268±0.001</td>
<td>0.103±0.005</td>
<td></td>
</tr>
<tr>
<td>CM</td>
<td>Murchison</td>
<td>0.263±0.004</td>
<td>0.094±0.007</td>
<td>0.061</td>
</tr>
<tr>
<td>CM</td>
<td>Nogoya</td>
<td>0.335±0.006</td>
<td>0.071±0.004</td>
<td>0.051</td>
</tr>
</tbody>
</table>

* Zellner et al. (1977)
Figure 3.8. Continuum plot for 15 C chondrites. The chondrites plot in the same general vicinity of the plot as the C and X asteroids (Fig. 3.6), but with significant differences in detail. CM chondrites plot in the upper right of this diagram, CI/CM chondrites in the upper middle, and the remainder (CI, CV, CR and CK) plot in the middle lower region of the plot. This suggests that continuum slopes have taxonomic (genetic) value, and are a basis of comparison with terrestrial minerals and asteroids.
An exception is the CI chondrites where there is evidence of considerable variation in the slopes of their continua. There is poor agreement for in the Orgueil spectra obtained by Gaffey and Hiroi and there is poor agreement between the two splits of Ivuna run by Hiroi. Nevertheless, they still plot in a region discrete from the CM and CI/CM chondrites with shallow 1.8-2.5 \text{um} slopes. The reason for the poor agreement between splits is the very likely due to the large amount of water in these meteorites that can easily be lost during handling.

Spacecraft observations of different surfaces on asteroids tend to give very similar spectra regardless of texture also suggesting that grain size is not driving spectral slopes. For example, the Eros “ponds” are very fine grained and the remainder of the surface is very rough, yet their spectral slope differences are less 4\% (McFadden et al., 2001). Similarly, the Muses Sea on Itokawa shows a \sim 10 \% differences in albedo and band depth compared to the surrounding much rougher regions, but the slope shows little or no change (Abe et al., 2006). Eros and Itokawa are S complex asteroids, where one might expect grain size effects because of their expected petrologic complexity. The C complex asteroids, if they are similar to the C chondrites, are fine grained and relative homogeneous, and one would not expect major effects due to grain size.

The term “space weathering” includes all of the many processes that alter the surface of an airless body in the space environment. Most information comes from detailed investigations of lunar samples where the chief cause of changes is impact (e.g. McKay et al., 1991). On the largest scales, impact causes heating, melting, lithification, brecciation, and gardening. On the smallest scale, micrometeorite impact causes impact
pits, volatilization, and glass formation, and in the process of dispersal the glass becomes agglutinates (Keller et al., 1999; Pieters et al., 2000). At the same time, solar wind exposure causes the implantation of ions and surface radiation damage (Nichols et al., 1994). The effects are therefore numerous and complicated, and extrapolation from the Moon to the asteroids is not a trivial exercise (McKay et al., 1991).

Gas-rich breccia meteorites, the equivalent of lunar regolith and breccias, have a few similarities and many differences from their lunar equivalents (Keil, 1982). To some extent we can bridge the gap with laboratory experiments using lasers and charged particles (Sasaki et al., 2002; Dukes et al., 1999), observations on gas-rich regolith breccia chondrites (Britt and Pieters, 1994), and spacecraft observations of asteroids (Chapman, 1996). Clark et al. (2002) recently reviewed the overall effects of space weathering on asteroid reflectance spectra, pointing out that reddening and neutral darkening will happen, but that the degree of reddening is much less than for lunar samples.

Space weathering always has to be borne in mind when comparing astronomical and laboratory data, but it seems to us that the effects will be small compared to the class-to-class variations for asteroids and meteorites. In any event, if the major process distinguishing certain classes, say the S-R-Q sequence, as advocated by Binzel et al. (1996), is space weathering, then by studying these classes we are implicitly investigating space weathering.
3.5.7 Comparison of C and X fields with terrestrial phyllosilicate fields

It is frequently assumed, based on mineralogical studies of meteorites, that the surfaces of C asteroids consist of phyllosilicates (e.g. Rivkin et al., 2002). There are several spectral features that are consistent with this, such as the presence of water features at 3 μm and other wavelengths and a feature at 0.7μm attributed to Fe$^{2+}$ to Fe$^{3+}$ charge transfer, which usually occurs in a hydrated environment (Vilas and Gaffey, 1989). However, these features are very weak, certainly much weaker than observed in terrestrial phyllosilicates in the laboratory. The reason for the almost featureless spectra of asteroids must be associated with their space environment, exposure to the vacuum of space, solar irradiation effects, micrometeorite and meteorite impact effects. Thus the immediate surface has seen a high temperature history and dehydrated surfaces are to be expected. Thus Hiroi and Zolensky (1999) and Ostrowski et al. (2010) have compared the spectra of asteroids to those of phyllosilicates heated in the laboratory. The effects are particularly apparent in the heating experiments of Ostrowski et al. (2010), where temperatures in excess of 700°C were employed.
Figure 3.9. Continuum plot comparing terrestrial phyllosilicates with fields for heated phyllosilicates, and the C and X complex asteroids. Phyllosilicate data from Ostrowski et al. (2010), asteroid complex fields summarize the data in Fig 6. The phyllosilicates are plotted as crossed-circles, from which arrows originate and point to the area of the diagram at which the phyllosilicates plot after heating between 700 and 1100°C. On the basis of this plot we infer that the C complex contains portions of the heated kaolinite and heated montmorillonite and the X complex asteroids contain heated montmorillonite and possibly serpentine.
Figure 3.9 is a continuum plot that compares the present C and X asteroid complexes with terrestrial phyllosilicates that have been heated to >700°C (Ostrowski et al. 2010). Data for five terrestrial phyllosilicates are shown, representing the range of structures and compositions found in terrestrial phyllosilicates. They include the phyllosilicates previously observed in the meteorites. Upon heating, absorption bands weaken and eventually disappear while continua increase in slope, especially at longer wavelengths where a number of major water-related absorption bands occur (Ostrowski et al., 2010). At ~700°C chemically bound water is lost and the phyllosilicate lattice collapses. The decomposition products depend on the phyllosilicate, and consist of identifiable minerals in a mostly amorphous matrix, but there is little overlap in the long wavelength continua.

The fields for the asteroid complexes overlap with the fields for heated kaolinite, montmorillonite, and serpentine. Nontronite and chlorite occupy regions of Fig. 3.9 with steeper long wavelength continuum slopes. This is especially interesting in the case of chlorite, which has occasionally been observed in C chondrites. On the basis of Fig. 3.9 we suggest that the prominent minerals in the surface material of C complex asteroids resemble the decomposition products of heated kaolinite and montmorillonite. Montmorillonite has been observed in C chondrites, but kaolinite is a surprise. In terrestrial occurrences kaolinite is an aqueous alteration product of feldspar, which is found in small amounts in ordinary chondrites but not in carbonaceous chondrites. Perhaps some of these asteroids were once feldspar- and water-rich. Montmorillonite is
formed by aqueous alteration of olivine and pyroxene, common meteorite-forming minerals, in alkaline aqueous conditions.

The X complex overlaps the heated montmorillonite field and touches the field for heated serpentine (Fig 3.9). As mentioned above, the past presence of montmorillonite on an asteroid surface seems reasonable, as does the presence of serpentine. Serpentine has frequently been observed in carbonaceous chondrites.

3.5.8 Comparison with meteorites

The C chondrite classes considered here plot in the same general region of the continuum plot as the C and X complex asteroids (Fig. 3.10). However, we see several details that appear to be significant.
Figure 3.10. Continuum plot comparing the C chondrites (data from the NASA PDS database; Gaffey, 2001) with the asteroid fields. (a) C chondrites compared with C complex asteroids (b) the C chondrites compared with X complex asteroids. Based on these figures and other data arguments discussed in the text we suggest associations between the C chondrites and the asteroid classes as listed in Table 3.8.
First, the CM chondrites do not fall into any of the C complex fields and while they are close to several X fields they also fall to the right of the X classes.

Second, the CI chondrites do not plot in any of the X fields but plot in the same general area of the diagram as B, Ch, and Cgh fields.

Third, the CR, CV, and CK chondrites are close to the Ch field but plot in the Cgh field. Allende also plots on the Xc field.

Finally, the three CI/CM chondrites plot close to several C asteroid fields (i.e. Cg, Cb, Ch, and C), and two CI/CM chondrites plot close to the X and Xc classes. However, all three CI/CM chondrites plot in the C asteroid field. A relationship with the Ch class can be ruled out because Y-86720, Y-82162 and B-7904 have been determined not to have a 0.7 µm feature (Hiroi et al., 1996).

Based on the low albedo and essentially featureless spectra with occasional 0.7 µm and 3 µm features, that CM chondrites have been linked to C complex asteroids, the Ch asteroids especially (Fornasier et al. 1999, Burbine 1998, Burbine et al 2002). However, the continuum plot suggests a closer affinity for CM chondrites to the X complex asteroids than the C complex asteroids. This is illustrated with the spectra in Fig. 3.11. Below 0.9 µm there is good match between the spectra of the meteorite and the asteroids. However, at longer wavelengths there are significant differences between the spectra for the two C asteroids, 19 Fortuna (Ch) and 175 Andromache, and the CM chondrite Cold Bokkeveld. In contrast, the spectra for two X complex asteroids 110 Lydia (Xk), and 153 Hilda (X) match closely the spectrum for Cold Bokkeveld, the only discrepancy being a slight negative slope short of 0.85 µm for Cold Bokkeveld.
Figure 3.11. Comparison of the spectra of (a) two C asteroids and the CM chondrite Cold Bokkeveld, and (b) two X asteroids and the Overlay of C asteroids and CM and X asteroids and CM chondrite Cold Bokkeveld. These spectra illustrate the differences in slope that have been described earlier in this paper and cause us to link, as an example, the CM chondrites with the Xk asteroids rather than any of the C asteroid classes.
Table 3.8. Meteorites considered in the present study and proposed asteroid class associations.

<table>
<thead>
<tr>
<th>Meteorite Name</th>
<th>Meteorite</th>
<th>Asteroid Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-82162</td>
<td>CI/CM</td>
<td>C</td>
</tr>
<tr>
<td>B-7904</td>
<td>CI/CM</td>
<td>C</td>
</tr>
<tr>
<td>Y-86720</td>
<td>CI/CM</td>
<td>C</td>
</tr>
<tr>
<td>Y-693</td>
<td>CK</td>
<td>Ch or Cgh</td>
</tr>
<tr>
<td>Ivuna #1</td>
<td>CI</td>
<td>Cgh</td>
</tr>
<tr>
<td>Ivuna #2</td>
<td>CI</td>
<td>Cgh</td>
</tr>
<tr>
<td>Orgueil (Gaffey)</td>
<td>CI</td>
<td>Cgh</td>
</tr>
<tr>
<td>Orgueil (Hiroi)</td>
<td>CI</td>
<td>Cgh</td>
</tr>
<tr>
<td>Allende</td>
<td>CV</td>
<td>Xc</td>
</tr>
<tr>
<td>Renazzo</td>
<td>CR</td>
<td>Xc</td>
</tr>
<tr>
<td>Cold Bokkeveld</td>
<td>CM</td>
<td>Xk</td>
</tr>
<tr>
<td>Murray</td>
<td>CM</td>
<td>Xk</td>
</tr>
<tr>
<td>Murchison</td>
<td>CM</td>
<td>Xk</td>
</tr>
<tr>
<td>Mighei</td>
<td>CM</td>
<td>Xk</td>
</tr>
<tr>
<td>Nogoya</td>
<td>CM</td>
<td>Xk</td>
</tr>
</tbody>
</table>
In Table 3.8 we list the meteorite-asteroid associations we would propose on the basis of the continua in the near IR. Two of the three meteorites classified as CI/CM plot in or near the Cb, Cg, and C fields, while the third plots between the C and B fields. If we assume that all three CI/CM chondrites should come from the same parent source, then we would favor the C class as it is equally suited to all three chondrites. Y-693 is placed to be equally associated with the Ch and Cgh classes. The two chips of the Ivuna CI chondrite could be linked with the B, Ch, or Cgh asteroid classes, while the two chips of the Orgueil CI chondrite are closest to the Cgh asteroid field. If we use the argument members of a single class should be linked with the same asteroid then we would have to link all the CI chondrites with the Cgh class. Renazzo also plots in the Cgh field, so a linkage with the CI chondrites might be implied, but it also plots with the Xc field, which is an equally likely match that would separate it from the CI chondrites. There are many petrographic and compositional differences between Renazzo and the CI chondrites. Allende also plots with the Cgh and Xc asteroids, but it lacks any similarity with CI chondrites and has been linked with the CV chondrites, which makes a linkage with Xc asteroids likely. The CM chondrites were discussed above. While they do not plot in any of the asteroid fields they are closest to Xk and if we assume all CM chondrites came from one body it would have to be an Xk asteroid. Hiroi et al. (1993) pointed out that the CM chondrites needed to be heated to make their spectra match those of C asteroids.

In addition to matching meteorite and asteroid spectra, we can compare albedos. Asteroid albedos are listed in Table 3.6 and the few chondrite albedos available are listed in Table 3.6. Asteroid classes C, Cb, and Ch have albedos of 0.04-0.07, while B, and Cg asteroids have albedos around 0.1. The Cgh asteroids show a wide range of albedos, 0.05
to 0.17, which is similar to the range shown by X asteroids and slightly less than the Xc (0.07-0.22) and Xk (0.06-0.30) asteroids. Xe asteroids generally have higher albedos, 0.14 to 0.19. In comparison, CI and CM chondrites have albedos 0.05-0.07 while CV chondrites have albedos of about 0.1. In short, in view of the variety of albedos within a given asteroid class, and the small number of asteroids and chondrites for which we have albedo data, we see no problem with the proposed matches listed in Table 3.8.

We now compare the mineralogies derived from reflectance spectra as summarized in Fig. 3.9 with the mineralogy of the C chondrite classes determined by laboratory methods. The matrix of the C chondrites is complex and fine-grained, and requires TEM, which is a highly localized technique to characterize. Current suggestions for the mineral composition of C chondrites have been summarized by Rubin (1997) and include phyllosilicates as their primary mineral. It should be stressed that much of the fine-grained material in carbonaceous chondrites appears to be a complicated mixture of Fe-rich phyllosilicates produced by aqueous alteration of metal and sulfides (described as tochilinite, $\text{Fe}^{2+}_{5.6}(\text{Mg,Fe}^{2+})_{5}[(\text{OH})_{10}\text{S}_{6}]$) once referred to as PCP, “poorly characterized phase” (Barber et al. 1983; Mackinnon and Zolensky 1984; Tomeoka and Buseck, 1985) and it is only occasionally that this phase takes on the unambiguous characteristics of a readily identifiable phyllosilicate. The matrix of CI chondrites has also been described as serpentine or montmorillonite and that the matrix of CM chondrites is serpentine, montmorillonite, or chlorite with most minerals containing measurable Fe. Montmorillonite and serpentine are known to be present in CV classes (Rubin, 1997). We earlier postulated that C complex asteroids have surfaces containing kaolinite and
montmorillonite while the X complex asteroids have surfaces rich in montmorillonite and serpentine.

In addition to these major phases, there are a host of minor phases that affect the reflectivity spectra of meteorites and presumably asteroids. These are the opaque phases, finely dispersed metal and sulfide, organics (possibly), and others. Traditionally, the effects of opaque phases are modeled by adding carbon black to the silicates and are found to lower albedo and weaken bands (Clark, 1983; Milliken and Mustard, 2007). The presence of opaque phases would lower the albedo of heated phyllosilicates in our laboratory experiments and bring them into line with the albedos of C asteroids and CI and CM chondrites (Ostrowski et al., 2010). The effect on continuum plots is shown in Fig. 3.12. The data of Clark (1983) and Milliken and Mustard (2007) are in good agreement and show that the addition of opaque phases causes a relatively small decrease in the slope in the 1.0 to 1.75 um region and only slightly greater increase in the slope in the 1.8 to 2.5 um region. However, the changes are not only minor, they generally go in the wrong direction in relating terrestrial phyllosilicates to the asteroids and meteorites. We do not think that the presence of opaques is playing an important part of explaining the difference in the continuum slopes of asteroids and meteorites compared to terrestrial phyllosilicates.
Figure 3.12. Continuum plot for samples of montmorillonite to which various amounts of carbon black have been added. The addition of carbon black affects both the short and long wavelengths of the spectra, with a greater effect on the long wavelength region. In fact, the amount of carbon increases, the data show a negative linear trend in which at short wavelengths decreases from 0.0 to −0.1 while the slope at long wavelengths increases −0.6 to −0.1. This is contrast to the effect of heating on terrestrial phyllosilicates in which the trends on this plot are essentially positive (chlorite excepted).
3.5.9 On the nature of C and X complex asteroids

Phyllosilicates are highly diverse in composition and are associated with a number of discrete environments on Earth (Table 3.9). The weathering of feldspar-rich rock types produces kaolinite. Metamorphic and aqueous alteration of olivines and pyroxenes, typical chondritic minerals, results in serpentine, while in the presence of an Al source, such as micas, produces chlorite. In alkaline conditions and poor drainage, aqueous alteration of olivine and pyroxene rich rocks produces montmorillonite.
Table 3.9. Phyllosilicates discussed here with typical terrestrial occurrence.

<table>
<thead>
<tr>
<th>Terrestrial phyllosilicate</th>
<th>Typical terrestrial occurrence</th>
</tr>
</thead>
</table>
| **Kaolinite**
\[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \] | Weathering and decomposition of rocks containing feldspathic minerals (Kruckeberg 2002; Best 2003; Evans 2004). |
| **Serpentine**
\[ \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 \] | Metamorphic and aqueous alteration of forsterite and pyroxene, replacement other magnesium silicates (Lagasse et al 2008) |
| **Nontronite**
\[ \text{Na}_{0.3}\text{Fe}^{+3}_2\text{Si}_3\text{AlO}_10(\text{OH})_2\cdot 4(\text{H}_2\text{O}) \] | Weathering of biotite and basalts, precipitation from iron and silicon rich hydrothermal fluids (Bischoff 1972; Eggleton 1975). |
| **Montmorillonite**
\[ (\text{Na,Ca})_{0.3}(\text{Al,Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2(\text{H}_2\text{O})_{10} \] | Aqueous alteration product of volcanic tuff and ash, pegmatite dikes, wall rocks. Alkaline conditions of poor drainage (Early et al. 1953; Deer et al. 1963; Gaines et al. 1997). |
| **Chlorite**
\[ (\text{Mg,Fe}^{+2})_5\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_8 \] | Alteration product of mafic minerals such as pyroxenes, amphiboles, and biotite, low-grade metamorphism (Hurlbut and Klein 1985). |
Asteroids with interiors resembling CI or CM chondrites may contain serpentine and chlorite from the aqueous alteration of olivines and pyroxenes, and we identify these meteorites with Cgh and Xk asteroids, respectively. Asteroids with drier interiors, through accretion at higher temperatures or small amounts of internal heating, may have CV-like interiors and would undergo aqueous alteration to produce montmorillonite, and we identify these as Xc asteroids. If kaolinite is present on the surfaces of B asteroids, as suggested by the present results, we identify no known meteorite class with them. Indeed, no meteorite class has been reported to contain kaolinite. To create the bulk composition needed to produce kaolinite, the parent asteroid would have to be differentiated, with a core, mantle and crust. Gaffey et al. (1993) have discussed this situation at length. These authors suggest that while many asteroids have melts or partial melts on their surfaces, corresponding meteorites are missing. The mineralogy of the CI/CM chondrites appears to be complex intergrowths of fine phases produced by bouts of aqueous alteration and metamorphism, with serpentine as a possible phyllosilicate, which we here identify with C asteroids.

3.6 Conclusions

We report near IR spectra for seventeen asteroids that belong to the C and X complexes. In order to determine possible surface composition, we collected literature data for these asteroids in the visible and looked for spectral features suggestive of the water and water related components on the asteroids (the UV slope, the 0.7 μm absorption and the 3 μm absorption). Using fairly conservative criteria, we find such evidence in only three of the present 17 asteroids, 24 Themis, 34 Circe, and 51 Nemausa have all three features. We have assigned classes to these asteroids using literature or on-
line facilities and for all 17 asteroids the spectra are consistent with the properties of the published classes. Asteroid 191 Kolga has a 0.7 \( \mu \text{m} \) feature and while this is not required for its Cb classification according to DeMeo et al. (2009), Vilas (1994) observes that half the C asteroids have this feature.

Of the nine classes represented in the present data, DeMeo et al. (2009) characterize seven by the slopes of their continua in their classification scheme and slope is an important characteristic in the others. In fact, 88\% of the variance in C and X asteroid spectra can be explained by continua slope. We thus examined the spectra of the present asteroids in terms of the continuum slopes, plotting the slope between 1.0 to 1.75 \( \mu \text{m} \) against the slope between 1.8 to 2.5 \( \mu \text{m} \) and call this the continuum plot. We made the break at ~1.8 \( \mu \text{m} \) because water features in phyllosilicates (a strong candidate for surface materials on these asteroids) occurs beyond 1.8 \( \mu \text{m} \). Meteorite classes, asteroid classes, terrestrial phyllosilicates, and heated terrestrial phyllosilicates usually plot in discrete and separate fields on these plots, confirming the value of this approach.

On the basis of overlapping in fields on the continuum plots we made associations between asteroid classes and meteorite classes and summarize our suggestions in Table 3.8. The CI chondrites are linked with the Cgh asteroids, individual CV and CR chondrites are linked with Xc asteroids, and a CK chondrite is linked with the Ch or Cgh asteroids. A number of unusual CI/CM meteorites are linked with C asteroids, while the CM chondrites are linked with the Xk asteroids. Previous authors have linked the CM chondrites to the Ch asteroids because of the presence of a weak 0.7 \( \mu \text{m} \) feature, however their continuum slopes are very different. We argue that continuum slopes are easily and
accurately measured, and are sufficiently diagnostic of the various meteorite and asteroid classes to provide important information on asteroid-meteorite linkage.

Most authors agree that the surfaces of the C asteroids are probably in major part phyllosilicates whose spectra are weakened by the presence of opaques and space weathering. We find that the presence of opaques is not alone sufficient to weaken features to the observed degree as stated in Cloutis et al. (1990), and cause the observed continuum slope trends. Neither do we find the grain size variations a likely explanation for the asteroid-to-asteroid spectral differences, although grain size does affect laboratory spectra. Instead, we suggest that the slope difference are the result of asteroid surfaces consisting in large part of the decomposition products of heated various phyllosilicates and in this case can make suggestions as the likely precursor phyllosilicate (and therefore surface composition) on the asteroids. Thus we suggest that for the C complex kaolinite and montmorillonite are possible precursor phyllosilicates, although we rule out kaolinite because it suggests a nonchondritic precursor and has never been observed in chondrites. For the X complex we suggest that precursor phyllosilicates were montmorillonite or serpentines, these minerals have been observed in CM chondrites.

3.7 Acknowledgements

We are grateful to Bobby Bus and NASA/NSF for access to the IRTF, Andy Rivkin for help with the correction of spectra for thermal emission, Hazel Sears for reviewing and proofing the manuscript, Beth Clark and anonymous reviewer for very helpful comments, and NASA for grant support. We utilized both the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance and the Bus-DeMeo Taxonomy Classification Web
tool and are grateful to the responsible researchers and their funding sources. This research utilizes spectra acquired by Mike Gaffey, Takahiro Hiroi, and Carle Pieters at the NASA RELAB Laboratory at Brown University.
CHAPTER 4

Examination of phyllosilicate-evaporite mixtures: An analysis of continuum slopes in the near infrared spectra for analysis of possible nature of the surfaces of C and X asteroids

In this chapter we investigate the thermally treated phyllosilicate-evaporite mixtures as the composition of the surface of C and X asteroids. Dr. Claud H. S. Lacy contributed knowledge and background on asteroids. Dr. Kathy Gietzen contributed knowledge and background on asteroids. Dr. Derek W. G. Sears contributed knowledge and background for the carbonaceous chondrites and their relation to the asteroids. I determined the weight ratios of the phyllosilicate-evaporite mixtures. I also generated the heated phyllosilicate-evaporite mixtures and collected and analyzed all the infrared data for the C asteroids, X asteroids, carbonaceous chondrites and heated phyllosilicate-evaporite mixtures.

4.1 Abstract

To understand the nature of C and X asteroid surfaces, which are often related to phyllosilicates and C chondrites, we report near-IR spectra for mixtures of phyllosilicates and evaporites heated at various temperatures up to ~1150 °C. The results are compared to the near-infrared spectra of C chondrites, the C asteroid complex, and the X asteroid complex. Since C and X asteroids have relatively featureless spectra in the near-infrared region, continuum plots (1.0-1.75 μm slope against 1.8-2.5 μm slope) are used to make comparisons. The use of continuum slopes has been used many times to match carbonaceous chondrites to C asteroids and even used to determine the taxonomy of C and X asteroids. Numerical spectral mixing was conducted first to determine the most asteroid like spectra for laboratory heating study. This resulted in a mixture of 40 wt%
phylllosilicate – 60 wt% evaporite for all four mixtures. Results of 40 wt% serpentine – 60 wt% epsomite heated above 1000 °C matches the continuum data of the X asteroids, and the small high albedo population of this group. This implies that the surface of X asteroids is composed of a mixture of decomposed serpentine and epsomite. When trace amounts of opaques are taken into account, which also help in albedo matching, the mixture of 40 wt% serpentine – 60 wt% gypsum which was heated to 400 °C matches the continuum data of the C complex asteroids. At 400 °C gypsum decomposes and serpentine retains its structural water. This could explain the hydration features seen in the C asteroids. This heated mixture also matches the continuum data of the CI chondrites Ivuna and Orgueil, which allows for a mineralogical match. This implies that the surface of the C asteroids is composed of a mixture of serpentine with only structural water, decomposed gypsum, and trace amounts of opaques.

4.2 Introduction

For decades the carbonaceous chondrites have been linked to the C asteroid complex (Johnson and Fanale 1973; Burbine et al. 2002; Gaffey et al. 2002). The large population of C asteroids and small population of C chondrites would tend not to support this connection, however this can be easily explained by the friability of the chondrites. The connection has been made on the general matching of the UV, visible and near-infrared spectrum of the meteorites and asteroids. Compositional fingerprinting is difficult because, for the most part, the C asteroids have a featureless spectrum. The main spectral feature that is seen in the C asteroids is the 3.0 μm water feature, which to be precise, is for the O-H bond. This feature was first observed on Ceres (Lebofksy 1978). At first, the measurement of this feature was difficult because of the spectral
absorption of atmospheric water, but modern observing techniques have aided in correcting this problem. Since then many C asteroids have shown the 3.0 µm feature (Lebofsky 1980; Feierberg et al. 1985; Jones et al. 1990). The other major feature observed in the Ch and Cgh asteroids is the weak and broad 0.7 µm band. In the CM chondrites, the 0.7 µm spectral feature is attributed to hydrated iron oxides associated with phyllosilicates (Vilas and Gaffey, 1989). The 0.7 µm feature is common in C asteroids, as shown by Fornasier et al. (1999) who found that 65% of the C asteroids contained the feature. A correlation between the 0.7 µm and the 3.0 µm features has been found for about half of the 31 C asteroids observed by Vilas (1994). The spectral features in C asteroids are weak and hard to see and most of the classes in the complex do not contain diagnostic features. The class is governed by its low albedo, most have albedos less than 0.065 (Bowell and Lumme 1979; Zellner 1979; Gradie and Tedesco 1982), but some have been seen as high as 0.100 (Fornasier et al. 1999). The C complex is also determined by its flat to slight red spectral slope (DeMeo et al. 2009). Ignoring the albedo differences, the X asteroid complex is sometimes associated with the C asteroids for both being dark and having near featureless spectra. Over half of the X asteroids have an albedo of less than 0.10 and over 90% have albedo of less than 0.30 (Clark et al. 2004). Some features are seen in visible spectral region of the X asteroid complex as described in the subdivisions by Bus and Binzel (2002), specifically an absorption feature shortward of 0.55 µm in the Xe type. These features were reconfirmed along with the near infrared spectrum being examined to show that there are no features by DeMeo et al. (2009). A diverse selection of meteorites has been suggested as mineralogy matches to the X asteroids. The suggestion of matches shows an evolution of
understanding of the asteroids. The range of meteorites are nickel-iron metal, aubrites, enstatite chondrites, carbonaceous chondrites, and CH and CB chondrites (Zellner and Gradie 1976; Gaffey et al. 1989; Cloutis et al. 1990a, Pieters and McFadden 1994; Hardersen et al. 2003).

Carbonaceous chondrites are the most primitive class of meteorites. This includes the CI and CM chondrites, which are the classes closest to the solar photosphere in composition. The CI and CM chondrites are rich in water with CI’s containing more, approaching 20 vol % (Wiik 1969; Jarosewich 1990). Carbonaceous chondrites have a fine-grained texture that adds to their complexity, making it difficult to identify the mineral phases present. This is on top of the matrix generally being amorphous. The CI and CM chondrite mineralogy displays evidence of an aqueous alteration past, along with the CR, CV and CO chondrites showing some stages of aqueous alteration. In the review by Brearley (2006), the matrix of CI chondrites are dark and fine-grained composed of mostly phyllosilicates, primarily serpentine interlayered with saponite. The CM chondrites are also well known for their phyllosilicate material. The transmission electron microscope (TEM) analysis of CMs shows that the meteorites are dominated by fine grained serpentines of different morphologies and compositions (Barber 1981; Zolensky et al. 1993; Lauretta et al, 2000; Zega and Buseck 2003; Zega et al, 2003). These meteorites are mostly composed of phyllosilicates, but do contain other alteration products such as sulfates, carbonates, sulfides, oxides, halides, and oxyhydroxides (Brearley, 2006). Rubin (1997) summarized all the specific different alteration products found in the carbonaceous chondrites. The most common phyllosilicates found in the C chondrites are serpentine and chlorite, especially in the CMs. Epsomite and gypsum are
the two most common sulfates discovered in the CI chondrites. Epsomite, seen as white sulfate veins, is the earliest sulfate to be observed in the CI chondrites (DuFresne and Anders, 1962; Mason, 1962; Boström and Fredriksson, 1966; Richardson, 1978). The CI chondrites contain nearly all the sulfates that are in carbonaceous chondrites, but the CMs do contain some gypsum (Brearley, 2006; Rubin, 1997). It has been argued by Gounelle and Zolensky (2001) that the sulfate veins are a result of remobilization and reprecipitation of the sulfate as a result of the meteorites interaction with water in the atmosphere after time spent on Earth. This would only increase the amount of sulfates in the meteorites meaning that they still originated in the meteorite and are of an extraterrestrial origin.

The terrestrial phyllosilicates are minerals consisting of silicate sheets, the layers being made of tetrahedral and octahedral unit cells. The number, 2, 3 or 4 sheets and pattern of these sheets in the phyllosilicate structures are referred to as 1:1, 2:1, and 2:1:1. Phyllosilicates can be rather compositionally diverse. The octahedral sheets commonly contain Fe(II), Fe(III), Al, or Mg, whereas the tetrahedral sheets contain Si, Al, and sometimes Fe(III). Between the layered structure and ionic environment, phyllosilicates are capable of adsorbing variable amounts of water that can usually be removed by heating to 500 to 700°C (Grim 1968, chapter 9).

Terrestrial evaporites make up more than 80 known minerals. Sulfates are one of the more common evaporites that are also in the meteorites. The structure of sulfates varies just like the cation chemistry that produces the different types. For example gypsum has a monoclinic structure, while epsomite has an orthorhombic structure. For
the hydrated sulfates the water is weakly bonded and most the water is completely gone by 350°C (Klein 2002, chapter 10).

Images of many asteroid surfaces and as seen on the surfaces of most airless solar system bodies that impact, thermal processing, and regolith gardening have been important in understanding the present nature of asteroid surfaces. Laboratory heating experiments on the CM chondrite Murchison have been preformed and the data suggests heated samples to 600°C have spectra matches for the UV region and the overall spectra when samples are heated 1000°C provide a reasonable match in the shape of the continuum for the spectra of five C asteroids and 5 G asteroids (Tholen taxonomy) (Hiroi et al. 1993). On the basis of analogous heating studies of five terrestrial phyllosilicates, but heating only to 600°C, Hiroi and Zolensky (1999) suggested that the phyllosilicate on C asteroid surfaces was saponite, but this mineral is rare in CM chondrites. Ostrowski et al. (2010a) presented heating experiments on five terrestrial phyllosilicates over the temperature range 100 to 1100°C and we compare the results with C asteroids and C chondrites by continuum slope analysis. They showed that the spectra of kaolinite and montmorillonite samples heated to ≥700°C matches C asteroids while the spectra of chlorite and serpentine samples heated to ≥700°C matches CM chondrites.

In the present paper we report heating experiments on phyllosilicate-evaporite mixtures of serpentine, chlorite, epsomite, and gypsum. The results are compared with the spectra of C and X complex asteroids and with C chondrites. We have obtained spectra for meteorites from the online databases and have obtained our own asteroid spectra using the NASA Infrared Telescope Facility (IRTF) and have supplemented
asteroid spectra from literature sources. Preliminary reports of this project have been made by Ostrowski et al. (2010b).

4.3 Methods

The phyllosilicates and evaporites, with their chemistry, used for this work are listed in Table 4.1. Infrared spectra for serpentine, chlorite, epsomite, and gypsum have been obtained from the USGS online spectral database (Clark et al. 2007). Numerical mixing of the reflectance spectra of the phyllosilicates and the evaporites is conducted to determine the weight percent of each mineral phase to be used to create laboratory samples to be studied. The spectrum of one phyllosilicate is mixed with one evaporite, starting at 100% phyllosilicate and adding the evaporite in 10 % increments to 100 % evaporite. The desired mixture is to generate the most asteroidal like spectra.
### Table 4.1. Phyllosilicates and Evaporites used in mineral mixtures.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Meteorite Occurrence&lt;sup&gt;◊&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epsomite</td>
<td>MgSO₄•7H₂O</td>
<td>CI</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄•2H₂O</td>
<td>CI, CM</td>
</tr>
<tr>
<td>Chlorite</td>
<td>Mg₃Si₂O₅(OH)₄</td>
<td>CI, CM, CV, CO</td>
</tr>
<tr>
<td>Serpentine</td>
<td>(Mg,Fe²⁺)₅Al(Si₃Al)O₁₀(OH)₈</td>
<td>CI&lt;sup&gt;†&lt;/sup&gt;, CM</td>
</tr>
</tbody>
</table>

◊ Rubin (1997)
* Lee (1993), in the non-hydrate form
† Tomeoka and Buseck (1988)
Mineral samples were crushed and then sieved to a grain size less than 63µm using a #230 U.S. Standard Testing Sieve attached to a Humboldt MFG. Co shaker. Two-gram samples of mixtures are created as 40 weight percent phyllosilicate and 60 weight percent evaporite. See the results section for the weight percent determination. Independent samples of the phyllosilicate-evaporite mixtures were then heated from 100 to ~1150±1%°C in 200°C intervals, rather than step-wise heating. The heating durations for the 200 to 800°C treatments were 24 hours, and for the highest temperature samples the heating duration was six hours. All samples were heated in an air atmosphere and allowed to cool to room temperature in a desiccator.

After the heat treatments, the samples mixed with epsomite were crushed again since they formed hollow cakes. The powder samples of unheated and heated phyllosilicate-evaporite mixtures were mounted in holders and their reflectance spectra obtained over the range 0.8 to 2.5µm using a Nicolet 6700 FTIR in diffuse reflectance mode with an incident and emergence angle of 90°. The spectra were obtained in a flowing dry nitrogen atmosphere, 150 scans being summed, providing a final resolution of 2 cm⁻¹. Titanium dioxide was used as a standard.
Figure 4.1. Representative spectra for an asteroid (45 Eugenia), meteorite (Orgueil CI chondrite), terrestrial phyllosilicate (serpentine), and evaporite (epsomite) displaced on the vertical scale for clarity. Note the numerous absorption bands in the phyllosilicate and evaporite, which are weak to absent bands in the meteorite and asteroid. Illustration of way in which we quantify the main features of these spectra using “continuum slopes” over the two arbitrarily selected wavelength intervals, 1.0 to 1.75 µm and 1.8 to 2.5 µm. For the purposes of determining slopes, the spectra are normalized to 0.875 µm.
The spectral range 0.8 to 2.5 µm is focused on because this is the range of the IRTF and because it is the range of most relevance to mineralogy of the phyllosilicates and evaporites. Representative spectra are shown in Fig. 4.1. The curves are quantified by comparing the continuum slope between 1.0 to 1.75 µm with the continuum slope between 1.8 to 2.5 µm (Fig. 4.1). Since the slope depends on the wavelength used for normalization, we normalized all the spectra to 0.875 µm. The difference in the reflectance at values at 1.0 to 1.75 µm were divided by 0.75 and the difference in the reflectance at values at 1.8 to 2.5 µm were divided by 0.70 to obtain the slopes in the two regions. We refer to the graphs of the 1.0 to 1.75 µm continuum slope against the 1.8 to 2.5 µm continuum slope as “continuum plots”.

4.4 Results

4.4.1 Spectra of numerical phyllosilicate-evaporite mixtures
Figure 4.2. (a) Numerical spectra mixing for the phyllosilicate serpentine and the evaporite epsomite to generate the most C asteroid like spectra. The mixtures depicted go from 100% epsomite to 100% serpentine with changes made in 10% increments. (b) From the numerical spectral mixing a mixture of 40 wt% serpentine – 60 wt% epsomite is the smoothest of the spectra, but a strong decreasing slope remains. Of the mixtures of these two minerals this is the ratio that produces the most C asteroid like spectra. In the 40 wt% serpentine – 60 wt% epsomite spectral mixture many of the spectral features of the two mineral phases remain, but are the weakest of all the mixtures.
In Fig. 4.2a are the spectra of serpentine, epsomite, and numerical mixtures of the spectra of the two. For the sake of simplicity we plot all the spectra on their own x,y axis, only 10% increment changes, but the others can be assumed to be reasonable interpolations of those shown. The epsomite spectra have a sharp drop off of reflectance between 1.0 and 1.4µm and then roughly flattens out with a broad feature at ~1.95µm. The Serpentine spectrum is mostly flat with one sharp feature at 1.4µm until 1.8µm the slope starts to decrease with a couple of features. As the numerical mixing of the two spectra approaches a 50:50 mix the features become more muted out. The mixture of 40 wt% serpentine and 60 wt% epsomite, as seen enlarged in Fig. 4.2b, is the mixture that produces the most featureless spectra. This is the ratio mixture that has muted the strong 1.4 µm feature in serpentine and broad ~1.45 µm the best. The mixture still has a strong decreasing slope, but because of the combination of two spectra that have decreasing reflectance at different wavelengths, the deceasing slope is continuous from 0.8 to 2.5 µm.
Figure 4.3. (a) Numerical spectra mixing for the phyllosilicate serpentine and the evaporite gypsum to generate the most C asteroid like spectra. The mixtures depicted go from 100% gypsum to 100% serpentine with changes made in 10% increments. (b) From the numerical spectral mixing a mixture of 40 wt% serpentine – 60 wt% gypsum is the smoothest of the spectra, but a decreasing slope remains. Of the mixtures of these two minerals this is the ratio that produces the most C asteroid like spectra. In the 40 wt% serpentine – 60 wt% gypsum spectral mixture many strong spectral features of the two mineral phases remain, but many of the weak features of the minerals are removed.
Figure 4.3a is the spectra of serpentine, gypsum and the numerical mixtures of the two minerals. The gypsum has a gradual decreasing slope until ~2.4 µm and then drops off to a metal-OH interaction between 2.4-2.5 µm leading into the strong broad 3.0 µm hydroxide feature. The spectrum of gypsum also has two strong features at 1.4 µm, broad feature, and at 1.95 µm. The dominant features in both gypsum and serpentine are roughly at the same wavelengths, which makes removal of the features impossible via spectral mixing. The primary features do change in both broadness and strength based on which mineral’s spectrum is the dominant one. An overall decreasing slope is present in all of the mixtures, but they are more flat and near featureless. The one major feature and no minor features of the short wavelength region of serpentine effectively weakens and or removes the small features short of 1.4 µm in gypsum. On the other hand, gypsum’s broad feature at 2.2 µm weakens or cover-ups the 2.1 µm feature in serpentine. The removal of minor features as described results in the 40 wt% serpentine and 60 wt% gypsum, as seen in Fig. 4.3b, being the closest to a featureless spectrum. As seen in Fig 4.3b, not all the minor features of the two mixed minerals are removed, but the ones that do remain are very shallow like the 1.2 µm gypsum feature. The two main features of 1.4 and 1.9 µm still remain, but appear weaker than the same features in gypsum and broader than the same features in serpentine. The 40 wt% serpentine - 60 wt% gypsum mixture has a slope of -0.41, which is much shallower than the steep slope of -0.53 of 40 wt% serpentine – 60 wt% epsomite.
Figure 4.4. (a) Numerical spectra mixing for the phyllosilicate chlorite and the evaporite epsomite to generate the most C asteroid like spectra. The mixtures depicted go from 100% epsomite to 100% chlorite with changes made in 10% increments. (b) From the numerical spectral mixing a mixture of 40 wt% chlorite – 60 wt% epsomite is the smoothest of the spectra, but a slight decreasing slope remains. Of the mixtures of these two minerals this is the ratio that produces the most C asteroid like spectra. In the 40 wt% chlorite – 60 wt% epsomite spectral mixture many of the strong characteristic spectral features of the two mineral phases remain, but are the weakest of all the mixtures.
Figure 4.4a displays the spectra of chlorite, epsomite, and the numerical mixtures of the two minerals. Chlorite has two distinct features beyond 1.8 µm, which are a broad 2.0 µm feature and a sharp and strong 2.3 µm feature. The 2.3 µm feature is from the metal-OH interaction. Chlorite has a strong increasing slope in the 1.0 to 1.75 µm region. This increasing slope counters the strong decreasing slope of epsomite to flatten out the spectra of both minerals when mathematically combined. In Fig 4.4a the flattest mixture spectrum is of 40 wt% chlorite and 60 wt% epsomite. This spectrum is enlarged and shown in Fig. 4.4b and depicts that all of the features of the combined minerals remain. Combining the minerals at the 40 wt% chlorite – 60 wt% epsomite ratio does weaken the depth of the features. At 40 wt% chlorite there is an increase in reflectance from 1.4 to 2.1 µm, but not enough to eliminate an overall slight decreasing slope of -0.22.
Figure 4.5. (a) Numerical spectra mixing for the phyllosilicate chlorite and the evaporite gypsum to generate the most C asteroid like spectra. The mixtures depicted go from 100% gypsum to 100% chlorite with changes made in 10% increments. All mixtures that have greater than or equal to 30 wt% chlorite have a strong increase in reflectance between 1.6 to 2.2 µm, which gives different continuum slope values for the short and long wavelength regions compared to the overall slope. (b) From the numerical spectral mixing a mixture of 40 wt% chlorite – 60 wt% gypsum is the smoothest of the spectra, but a slight decreasing slope over the full wavelength range remains. Of the mixtures of these two minerals this is the ratio that produces the most C asteroid like spectra. In the 40 wt% chlorite – 60 wt% gypsum spectral mixture few of the spectral features of the two mineral phases remain, but the ones that remain are the weakest of all the mixtures.
Figure 4.5a is the spectrum of chlorite, gypsum and the numerical mixtures of the two minerals. The high normalized reflectance in the long wavelengths of chlorite caused by the large increasing slope that dominates most of the mixtures. The 30 wt% chlorite – 70 wt% gypsum and 40 wt% chlorite – 60 wt% gypsum are the mixture spectra with the flattest slopes. The 30 wt% chlorite – 70 wt% gypsum mixture has a slight increase in reflectance at 1.6 µm, but a decreasing slope past 2.1 µm drops the overall slope past a straight line. The 40 wt% chlorite – 60 wt% gypsum mixture has a slight increase in reflectance between 1.6 to 2.1 µm, but it is slightly greater than the increase for the 30 wt% chlorite mixture. The decrease in slope past 2.1 µm for the 40 wt% mixture is about the same as the decrease in the 30 wt% mixture, but since the drop in the slope for the 40 wt% mixture starts slightly higher, it creates a more flat overall slope. The spectrum for the numerical mixture of 40 wt% chlorite – 60 wt% gypsum (Fig 4.5b) is the flattest, slope of -0.12, and the closest to featureless of all the chlorite – gypsum mixtures. The minor features of gypsum, at 1.0 and 1.2 µm, have been removed and the major features of both chlorite and gypsum have had their reflectance reduced compared to the pure minerals.

4.4.2 Spectra of heated phyllosilicate-evaporite mixtures

Figure 4.6 displays the near-infrared spectra of the four phyllosilicate-evaporite mixtures and the results of heating the mixtures up to about 1150 °C. In general, for all the mixtures, as the temperature increases the spectral features are removed. By 1000 °C all the features have been removed in all the samples, except for the 40 wt% serpentine – 60 wt% epsomite sample heated to 1150 °C (Fig 4.6a). For the mixtures with 60 wt% gypsum the features become weaker as the temperature increases. For the two mixtures
with 60 wt% epsomite the 600 °C has the strongest reflectance of the 1.95 μm feature, the reason for this is not known at this time. The slope of the spectra tends to become flatter and then move to an increasing slope, this is similar to results seen in Ostrowski et al. (2010a). The two chlorite mixtures (Fig 4.6c,d) still retain their steep, short wavelength slope throughout the heating process.
Figure 4.6. Reflectance spectra for the four phyllosilicate – evaporite mixtures in the unheated states and after heating in air at the temperatures indicated, the spectra are shifted vertically for clarity. (a) 40 wt% Serpentine – 60 wt% Epsomite, (b) 40 wt% Serpentine – 60 wt% Gypsum, (c) 40 wt% Chlorite – 60 wt% Epsomite, (d) 40 wt% Chlorite – 60 wt% Gypsum. At higher temperatures absorption features disappear and continuum slopes, as defined in Fig. 1, change. The slope change is short wavelength region goes for flat to increasing and the slope change in the long wavelength region goes from decreasing to flat to increasing as temperatures are increased.
4.5 Discussion

We are primarily interested in determining the surface composition of the C and X complex asteroids and will discuss our data with this in mind. This relies on by two points, (1) the spectral similarities between the C asteroids and C chondrites (2) the spectral similarities between C and X complex asteroids. Both the asteroids and meteorites do not spectrally look similar to the phyllosilicates and evaporites (sulfates in the study) that are the major mineral phases in the C chondrites. We will first discuss the differences in albedo of our samples compared to the asteroids and meteorites. We will then discuss the continuum plots for heated 40 wt% phyllosilicate – 60 wt% evaporite mixtures, and we will compare these with similar data for C and X asteroids and C chondrite data. The extent to which heated mixtures resemble the C and X asteroids could explain their surface compositions. We conclude with a discussion of the C chondrites similarities and the remaining challenges in understanding the spectra and surface composition of C and X asteroids.

4.5.1 Albedo differences between heated phyllosilicate-evaporite mixtures and asteroids

The albedo of the C asteroids is normally less than 0.065 (Bowell and Lumme 1979; Zellner 1979; Gradie and Tedesco 1982), but in some cases it has been reported as high as 0.100 (Fornasier et al. 1999). On the other hand the spectral counter part, in the near-infrared region, the X asteroids have a large albedo range of 0.03 to 0.5 (Tedesco et al. 1989, 2002). When comparing these two groups with lab samples it provides a large range for the lab samples to fall into for matching. Albedos were not calculated for the lab samples studied because the spectrum measured did not extend to 0.55 μm for proper
comparison, neglecting the phase angle effects. When analyzing the raw spectrum of the phyllosilicate–evaporite mixtures the reflectance for most of the mixtures, short of 0.9 μm, is in the range of 35 to 55%. This is on the high end of the X complex and as Clark et al. (2004) states ~10% of the asteroids are in this range. This allows for direct continuum slope matching to a few X asteroids, but in order to compare the continuum slopes of the mixtures to the rest of the X and all the C asteroids an opaque darkening agent would be required.

4.5.2 Continuum plots

Continuum slopes have been used many times to aide in the determination of the composition of asteroids. It has for the most part been used as spectral matching technique when comparing asteroids and meteorites. It needs to be noted when possible features should be used for analysis. The best example of this is the 3 μm absorption feature to study the presence of water on asteroid surfaces, although this observation requires careful correction for atmospheric water (Lebofsky 1980; Lebofsky et al. 1990; Jones et al. 1990). Spectral features cannot always be relied upon, especially in the C and X asteroids where features in the visible to near-infrared region are weak or absent. In the near-infrared spectra of C and X asteroids there are no features. The features that are occasionally seen, for example ~1.35 μm feature, are due to atmospheric water and general forgotten. It is even in the DeMeo et al. (2009), taxonomy used in this work, that states the classification of the C and X types are based on their slope. Clark et al. (2010) has looked at the continuum slope of B asteroids, in any classification scheme, and conducted a direct comparison with possible meteorite and terrestrial mineral analogs to determine possible asteroid surface composition.
The main focus here in using continuum slopes is to generate continuum plots to compare fields of asteroids, meteorites and terrestrial analogs. As stated in the methods section a continuum plot is slope of the spectra from 1.0 to 1.75 \( \mu \text{m} \) vs. 1.8 to 2.5 \( \mu \text{m} \). In general continuum slopes disregard any spectral features, except in the case were the features are strong enough to change the spectral slope. Most important, the clustering of slope data and the reproducibility of the slope data when determined by different research groups, as the most meaningful indication that these measurements have merit.

4.5.3 Continuum plots of heated phyllosilicate-evaporite mixtures

The continuum plots for the four phyllosilicate-evaporite mixtures are shown in Fig 4.7. All plots are on the same axis to allow for direct visual comparison of the data. Also included for interpretation of data is a large field for terrestrial phyllosilicates of varying composition and structure as described in Ostrowski (2010a). The temperatures the mixtures are subjected to would completely decompose them into other minerals as described by Klein (2002) for the evaporites and Deer et al. (1962) and Grim (1968) for phyllosilicates. It is unknown if the two minerals when decomposed would form a different mineral compared to what the individual members become or just stay in an amorphous anhydrous phase.
Figure 4.7. Continuum plots for the four phyllosilicate – evaporite mixtures. (a) 40 wt% Serpentine – 60 wt% Epsomite, (b) 40 wt% Serpentine – 60 wt% Gypsum, (c) 40 wt% Chlorite – 60 wt% Epsomite, (d) 40 wt% Chlorite – 60 wt% Gypsum. Fields for the C asteroids, X asteroid, and terrestrial phyllosilicates are indicated for comparison reasons. The 40 wt% Serpentine – 60 wt% Epsomite mixtures heated to and above 1000 °C are the only data that plots in the X asteroid field. In general, the serpentine mixtures data moves up and to the right on the continuum plot towards the asteroid field. In general, the chlorite mixtures data moves vertical towards the asteroid fields with the high temperature data plotting to the right of the X asteroid field.
4.5.3.1 40wt% Serpentine – 60wt% Epsomite

The continuum plot results for the serpentine–epsomite mixture are shown in Fig 4.7a. The not heated sample plots are to the left of the terrestrial phyllosilicate field, but has about the same decreasing continuum slope in the 1.8 to 2.5 \( \mu \text{m} \) region as serpentine itself as reported by Ostrowski et al. (2010a). Heating mixtures between 200 to 500 °C puts the resulting data plots just inside the terrestrial phyllosilicate field in the vicinity of serpentine. As heating temperatures continue to increase up to 800 °C, the data migrates to an increasing short wavelength slope, while at the same time the long wavelength slope is becoming bluer. The increasing blue slope of the long wavelength is counter to what is expected and opposite of the effects on heating as reported by Ostrowski et al. (2010a) and Hiroi and Zolensky (1999). The move in the plot of data parallels the change from C asteroids to X asteroids in the short wavelength region, 1.0 to 1.75 \( \mu \text{m} \), but the strong blue slope from 1.8 to 2.5 \( \mu \text{m} \) keeps the data from matching the asteroids. The intense heating of 1000 °C and up, causes the slope of the long wavelength region to flip to an increasing slope and match the X asteroids. These temperatures have decomposed both mineral phases and any form of water is completely lost. The continuum plot location of the 1000 and 1150 °C samples of 40 wt% serpentine – 60 wt% epsomite mixture plots in a similar location as the high temperature results of serpentine itself as reported by Ostrowski et al. (2010a). This suggests that the decomposition products of a serpentine–epsomite mixture are the same as serpentine itself, which could be olivine at a temperature as low as 600 °C.
4.5.3.2 40wt% Serpentine – 60wt% Gypsum

The continuum plot results for the serpentine–gypsum mixture is shown in Fig 4.7b. The not heated and 100 °C results plot in the same vicinity as serpentine itself as reported by Ostrowski et al. (2010a). Once the samples are heated to at least 250 °C they plot outside the terrestrial phyllosilicate field and closer to the asteroid fields. As the temperature at which samples are heated increases, as expected, the full continuum slope becomes more and more red. In the process the data plots around the asteroids fields, but never in either field. The 400 and 600 °C data points that plot close to the asteroids could help explain some of the water seen on the asteroids surfaces because the structural water is not lost (see later in discussion for more detail). Whereas the 1000 °C sample, which is close to the X asteroid field, is completely decomposed and dehydrated species based on known thermal properties of the starting material.

4.5.3.3 40wt% Chlorite – 60wt% Epsomite

The continuum plot results for the chlorite–epsomite mixture are shown in Fig 4.7c. The addition of epsomite with its strong blue slope to chlorite causes the not heated sample of the mixture to plot below the terrestrial phyllosilicate fields. When heat is applied to the samples, the short wavelength slope starts to flatten out, but it never drops below a value of about 0.28. The short wavelength slope values always keep the data plotting to the right of the asteroid fields. This means that heat treatment is not enough to lower the steep slope of the spectra from 1.0 to 1.75 μm for 40 wt% chlorite – 60 wt% epsomite mixtures to mimic the spectra of C asteroids or even the steeper sloped X asteroids. There is no major change in the long wavelength region until 800 °C where the negative slope is reduced by over half the starting materials value. It is not until the
mixture material is heated to 1000 °C and above that the long wavelength region starts to mimic, but goes a little beyond, the X and C asteroids. The two highest temperature samples that plot just to the right of the X asteroid field would be completely dehydrated and decomposed minerals. The continuum plot location of the 1000 and 1140°C samples of 40 wt% chlorite – 60 wt% epsomite mixture plots in a similar location as the high temperature results of chlorite itself as reported by Ostrowski et al. (2010a). It is possible that the decomposition products of a chlorite – epsomite mixture are the same as chlorite itself, which could be olivine or amorphous anhydrous material.

4.5.3.4 40wt% Chlorite – 60wt% Gypsum

The continuum plot results for the chlorite–gypsum mixture are shown in Fig 4.7d. Gypsum’s flatter slope than epsomite allows for the not heated sample of 40 wt% chlorite – 60 wt% gypsum mixture to plot on the bottom edge of the terrestrial phyllosilicate field. There is very little flattening in the short wavelength region, a change of less than 0.2 between the not heated sample to the 1000 °C sample. The major change in slope occurs in the long wavelength region where the continuum slope changes from a strong decreasing slope to a weak increasing slope that matches the C and X asteroids. The 1140 °C sample of the chlorite-gypsum mixture is the only data point not on this continuum plot because as reported in Table 4.2. The 600 and 800 °C samples, plotted to the right of the X asteroids, could have some of their chemically bound water left and some of their mineral structure intact because this is the range that chlorite itself decomposes. The continuum plot location of the 600, 800 and 1000 °C samples of 40 wt% chlorite – 60 wt% gypsum mixture plots in similar locations as the high temperature results of chlorite itself as reported by Ostrowski et al. (2010a).
that in mind, it is possible that the decomposition products of a chlorite–gypsum mixture are the same as chlorite itself, which could be olivine or amorphous anhydrous material.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Short λ slope</th>
<th>Long λ slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>40wt% Serpentine-60wt% Epsomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not heated</td>
<td>-0.219±0.054</td>
<td>-0.470±0.014</td>
</tr>
<tr>
<td>200 °C</td>
<td>-0.003±0.021</td>
<td>-0.563±0.005</td>
</tr>
<tr>
<td>300 °C</td>
<td>-0.094±0.032</td>
<td>-0.537±0.014</td>
</tr>
<tr>
<td>400 °C</td>
<td>-0.051±0.017</td>
<td>-0.642±0.008</td>
</tr>
<tr>
<td>500 °C</td>
<td>-0.116±0.015</td>
<td>-0.671±0.025</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.141±0.002</td>
<td>-0.777±0.012</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.155±0.014</td>
<td>-0.653±0.013</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.227±0.004</td>
<td>0.163±0.004</td>
</tr>
<tr>
<td>~1150 °C</td>
<td>0.220±0.016</td>
<td>0.014±0.001</td>
</tr>
<tr>
<td>40wt% Serpentine-60wt% Gypsum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not heated</td>
<td>-0.051±0.008</td>
<td>-0.501±0.005</td>
</tr>
<tr>
<td>100 °C</td>
<td>-0.051±0.005</td>
<td>-0.505±0.008</td>
</tr>
<tr>
<td>250 °C</td>
<td>0.001±0.007</td>
<td>-0.295±0.005</td>
</tr>
<tr>
<td>400 °C</td>
<td>-0.010±0.003</td>
<td>-0.180±0.003</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.269±0.005</td>
<td>-0.073±0.003</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.497±0.004</td>
<td>0.059±0.002</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.313±0.004</td>
<td>0.297±0.001</td>
</tr>
<tr>
<td>1165 °C</td>
<td>0.732±0.012</td>
<td>0.751±0.013</td>
</tr>
<tr>
<td>40wt% Chlorite-60wt% Epsomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not heated</td>
<td>0.810±0.020</td>
<td>-0.988±0.012</td>
</tr>
<tr>
<td>200 °C</td>
<td>0.580±0.028</td>
<td>-1.091±0.003</td>
</tr>
<tr>
<td>300 °C</td>
<td>0.515±0.020</td>
<td>-1.104±0.014</td>
</tr>
<tr>
<td>400 °C</td>
<td>0.648±0.025</td>
<td>-1.068±0.012</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.342±0.015</td>
<td>-0.927±0.019</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.282±0.013</td>
<td>-0.372±0.005</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.404±0.016</td>
<td>0.308±0.002</td>
</tr>
<tr>
<td>~1140 °C</td>
<td>0.516±0.020</td>
<td>0.338±0.054</td>
</tr>
<tr>
<td>40wt% Chlorite-60wt% Gypsum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not heated</td>
<td>0.581±0.004</td>
<td>-0.908±0.010</td>
</tr>
<tr>
<td>200-250 °C</td>
<td>0.619±0.023</td>
<td>-0.550±0.015</td>
</tr>
<tr>
<td>400 °C</td>
<td>0.586±0.019</td>
<td>-0.283±0.007</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.528±0.011</td>
<td>-0.128±0.011</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.469±0.007</td>
<td>0.155±0.005</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.418±0.013</td>
<td>0.304±0.006</td>
</tr>
<tr>
<td>~1140 °C</td>
<td>1.143±0.009</td>
<td>1.510±0.046</td>
</tr>
</tbody>
</table>
4.5.4 Heated phyllosilicate-evaporite mixtures relationship to C and X complex asteroids

Very few heated phyllosilicate-evaporite mixture samples plot in the asteroid fields as seen in Fig 4.7. Only the 1000 and 1150 °C samples of the 40 wt% serpentine – 60 wt% epsomite plot inside the X asteroids field, the 1000 °C data also overlaps into the C asteroid fields as seen in Fig 4.7a. From this matching it would give the idea that the surface of the X asteroids are composed of decomposition products of a mixture of serpentine and epsomite. The problem with this result is that the decomposition products, are completely dehydrated or it could be an amorphous phase. The dehydration matching data works for most of the X asteroids because most have no hydration feature, but not for the few asteroids that contain a 3.0 μm hydration feature (Jones et al. 1990; Rivkin et al. 1995, 2000). As noted above the thermally treated samples have higher albedos than most X asteroids, but the albedo of X asteroids can exceed 30%. The slope matching and high albedo similarities, for a few X asteroids, suggest that the surface of X complex asteroids could be composed of the decomposed product, via heating to 1000 and 1150 °C, of a 40 wt% serpentine – 60 wt% epsomite mixture.

On the other hand, not all of the other results that are close to the asteroids could be directly compared. In the serpentine–gypsum mixtures (Fig 4.7b) there are three temperature results that plot close to the asteroid fields that could mean different composition scenarios. The first is the 1000 °C data point that plots just above and to the right of the X asteroid field. Where the 1000 °C data point plots gives the impression that with the addition of some of the trace material in the carbonaceous chondrites would slightly flatten the sample’s near infrared continuum slope. This would allow for a
stronger matching to the X complex asteroids spectrally. The albedo of the sample is already at the high end of the X asteroid range as reported by Tedesco et al. (2002). With close spectral matching and albedos in the range, it allows for the mineralogy interpretation of X asteroid’s surfaces to be composed of decomposition products of a mixture of 40 wt% serpentine – 60 wt% gypsum because gypsum dehydrated, loss of all structural water, at 130 ºC (Ballirano and Mekkus, 2009) and serpentine decompose at 600 ºC (Deer et al., 1962; Grim, 1968). It is plausible that surface material is in an anhydrous amorphous phase. The second data point of the 40 wt% serpentine – 60 wt% gypsum mixture that is close to the X asteroid field is the sample heated to 600 ºC. This sample has a slightly to shallow long wavelength continuum slope to match the asteroids. The addition of some of the trace materials found in carbonaceous chondrites to the mixture might be enough of a darkening agent to the spectra to flatten out the long wavelength region and bring the continuum slope value closer to zero. At 600 ºC it stands that some of the structural water in serpentine is still present and this could show in the spectrum of the X asteroids as the few that contain a 3 µm hydration feature.

The third 40 wt% serpentine – 60 wt% gypsum that plots close to the C asteroid field is the sample heated to 400 ºC. Again this sample plots just below the field and would require the addition of trace materials as darkening agents to not only flatten the long wavelength region to have the continuum slope to match the asteroids, but also to lower the albedo of the sample. As reported earlier, the albedos for C asteroids are usually less than 0.065 (Bowell and Lumme 1979; Zellner 1979; Gradie and Tedesco 1982), but some asteroids have been observed as high as 0.100 (Fornasier et al. 1999). The importance of the 400 ºC data is that at 400 ºC as reported by Deer et al. (1962) has
only lost absorbed water. The structural water and the hydroxide-cation interaction that remain, as seen in Fig. 4.6b, could show up in the asteroid spectra as the water related features as seen by many authors (Lebofsky 1980; Feierberg et al. 1985; Vilas and Gaffey 1989; Jones et al. 1990; Vilas 1994; Fornasier et al. 1999). This would suggest that the surface of the C complex is composed of heated serpentine, that still has its structural water, mixed with decomposed gypsum and trace amounts of darkening agent, to correct for albedo.

4.5.5 Comparison of heated phyllosilicate-evaporite mixtures to carbonaceous chondrites

Meteorites are the connecting link between terrestrial analogs and the asteroids. There are many types of carbonaceous chondrites that have been linked to the C complex asteroids, but the CI and CM type are the only carbonaceous chondrites that contain evaporites (Rubin, 1997). Both of the evaporites used here, epsomite and gypsum, have only been seen in CIs. The mixture ratios of 40 wt% phyllosilicate and 60 wt% evaporite might seem disproportionate considering that the matrix of CIs and CMs are well known for their phyllosilicates and not their evaporite content. Ostrowski et al. (2010a) stated that for Orgueil when the sulfur in (Fe,Ni)S is taken into account and the magnesium is distributed between serpentine and epsomite that the meteorite contains 27 wt% epsomite and 26 wt% serpentine. This is a little less than the weight percent mixtures used to achieve the flattest spectra to mimic the asteroids. The continuum data for the CM, CI, and CI/CM chondrites are listed in Table 4.3.
**Table 4.3. Continuum slopes of Carbonaceous Chondrites.**

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Short $\lambda$ slope</th>
<th>Long $\lambda$ slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>0.316±0.003</td>
<td>0.199±0.008</td>
</tr>
<tr>
<td>Mighei</td>
<td>0.259±0.001</td>
<td>0.115±0.005</td>
</tr>
<tr>
<td>Cold Bokkeveld</td>
<td>0.268±0.001</td>
<td>0.103±0.005</td>
</tr>
<tr>
<td>Murray</td>
<td>0.507±0.005</td>
<td>0.104±0.008</td>
</tr>
<tr>
<td>Murchison (Hiroi)</td>
<td>0.263±0.004</td>
<td>0.094±0.007</td>
</tr>
<tr>
<td>Murchison (Gaffey)</td>
<td>0.335±0.006</td>
<td>0.071±0.004</td>
</tr>
<tr>
<td>Nogoya</td>
<td>0.124±0.006</td>
<td>-0.049±0.002</td>
</tr>
<tr>
<td>Ivuna #1</td>
<td>-0.036±0.002</td>
<td>-0.157±0.008</td>
</tr>
<tr>
<td>Ivuna #2</td>
<td>0.193±0.010</td>
<td>-0.104±0.005</td>
</tr>
<tr>
<td>Orgueil (Hiroi)</td>
<td>0.052±0.002</td>
<td>-0.069±0.003</td>
</tr>
<tr>
<td>Orgueil (Gaffey)</td>
<td>0.511±0.026</td>
<td>-0.301±0.015</td>
</tr>
<tr>
<td>Alais</td>
<td>0.004±0.0002</td>
<td>0.090±0.005</td>
</tr>
<tr>
<td>Y-86720</td>
<td>0.141±0.007</td>
<td>0.128±0.006</td>
</tr>
<tr>
<td>Y-82162</td>
<td>0.150±0.007</td>
<td>0.129±0.006</td>
</tr>
</tbody>
</table>
The evaporites used in the mixtures have not been seen in the CM chondrites. Temperatures needed to mimic any of the near-infrared spectra of the chondrites would have decomposed the evaporites. As seen in Fig 4.8a most of the CMs on the continuum plot are located near high temperature ovals. The meteorites that plot near the low temperature serpentine–gypsum field plot at the 800 °C end. These temperatures actually produce minerals, if it does not become amorphous, that are similar to the mineralogy of CR, CV and CO chondrites (Rubin, 1997). From a point of view where the mineral phases have become amorphous it is logical to conclude amorphous regions of Cold Bokkeveld, Murray, and Murchison was composed of serpentine and epsomite and ALH 83100 was composed of chlorite and gypsum before meteorite impact induce thermal alteration on the parent body.
Figure 4.8. Continuum plots for carbonaceous chondrites with high temperature, and one lower temperature, fields of the phyllosilicate–evaporite mixtures. The 40 wt% serpentine–60 wt% gypsum high temperature field is formed from the 1000 and 1165 °C data. The 40 wt% serpentine–60 wt% gypsum low temperature field is formed from the 400 to 800 °C data. The 40 wt% serpentine–60 wt% epsomite high temperature field is formed from the 1000 and 1150 °C data. The 40 wt% chlorite–60 wt% epsomite high temperature field is formed from the 1000 and 1140 °C data. The 40 wt% chlorite–60 wt% gypsum high temperature field is formed from the 600 to 1000 °C data. (a) Continuum plot of the CM chondrites compared to heated mixture fields. CMs plot close to 800 °C and higher parts of the heated mixture fields. At these temperatures both of the minerals in the mixtures would be decomposed. (b) Continuum plots of CI and CI/CM chondrites. Most of the CIs, except Alais, plot near the 400 °C end of the 40 wt% serpentine–60 wt% gypsum low temperature field. At this temperature gypsum would be decomposed and serpentine would have lost all of its adsorbed water. The CI/CMs plot close to each other, but to any field.
The CI chondrite’s continuum plot data and their match up to the phyllosilicate–evaporite mixtures are shown in Fig 4.8b. Ivuna and Orgueil plot at the 400 °C end of the low temperature serpentine–gypsum field. This would imply that the spectra of the CIs are dominated by a mixture of 40 wt% serpentine and 60 wt% decomposed gypsum. Both serpentine and gypsum have been observed in the CI chondrites (Tomeoka and Buseck, 1988; Rubin, 1977). The decomposed gypsum acts like opaques in the chondrites in the sense that they mask the residual spectral features in serpentine to flatten the spectra in the long wavelength region. This allows for the mixtures to match the CI chondrites. The matching at 400 °C allows for the structural water to remain and the structure of serpentine also remains which that in time allows the mineral to reabsorb more water to approach the 20 vol% maximum that has been reported in the CIs (Wiik 1969; Jarosewich 1990). In Fig 4.8b Antarctic CI/CM meteorites are plotted and are not near any of the phyllosilicate–evaporite fields. Rubin (1997) summary of minerals in meteorites states that there are no evaporites in the CI/CM meteorites. This shows that since the CIs contain evaporites (DuFresne and Anders, 1961; McSween and Richardson, 1977; Frederiksson and Kerridge, 1988; Zolensky and McSween, 1988) they must be taken into account when conducting spectral matching.

**4.5.6 Effect opaques could have on mixture spectra and continuum plot data**

Several authors have considered the effects of opaques on mineral spectra. The most common of the opaques studied is carbon black. This is the method used by Clark (1983) and Milliken and Mustard (2007) to see its effect on the spectrum of montmorillonite. They were able to drastically reduce montmorillonite’s albedo and cause it to mimic the spectra of C asteroids. In order to mimic the spectra of the C
asteroids they needed to exceed 5 wt% carbon. The problem is that carbonaceous chondrites do not exceed 4 wt% carbon. Most of the carbon in the meteorites is in an insoluble polymer and the remainder is in the form of volatile colorless compounds. The amount of free carbon is negligible. The bulk of the blackening is due to minor phases like sulfides and sulfide-metal aggregates, or tocholinite (Tomeoka and Buseck, 1985). Hiroi and Zolensky (1999) did not see major overall spectral changes to the phyllosilicates heated to 600 °C with a graphite rod. They do note that graphite rods are not the ideal stimulant for the carbon in the meteorites and thus not in the asteroids. Cloutis et al. (1990b) points out that if all the carbon in the carbonaceous chondrites was in the form of carbon black and was applied to the asteroids, in a weight percent sense, that there would not be enough to eliminate absorption features. The one dominant effect that opaques do have is reducing the albedo of terrestrial analogs to that of the carbonaceous chondrites, C complex asteroids, and most X complex asteroids.

Ostrowski et al. (2010a) conducted continuum slope analysis of the Clark (1983) and Milliken and Mustard (2007) data and noted that the carbon does allow the montmorillonite spectrum to come close to the asteroids, but not match the C asteroids. It shows opaques alone cannot match the spectra of the C and X asteroids. The data does show a trend of weakly flattening the short wavelength, at most a decrease in the continuum slope of 0.15. For the long wavelength it flattens the spectrum by as much as 0.5 with the higher carbon black weight percents. If the maximum amount of free carbon black, 3 wt%, was allowed to be added to the phyllosilicate–evaporite mixtures it would affect the outcomes of each mixture differently. The one common effect to the sample is the reduction of albedo to that of the asteroids. For the 40 wt% serpentine – 60 wt%
epsomite mixture it would not move any of the other data points into the asteroid fields. It would cause most, excluding the 800 and 1165 °C, of the results of the 40 wt% serpentine – 60 wt% gypsum to plot in the asteroid fields. As stated in the previous section, trace amounts of a darkening agent is required to cause the 400 °C sample to match the C asteroid complex. The small amounts of opaques that are in the carbonaceous chondrites are enough to allow for the conclusion that a mixture of 40 wt% dried serpentine and 60 wt% decomposed gypsum is what composes the surface of the C asteroids.

For both mixtures containing chlorite opaques are required to allow for continuum plot matching. In the case of 40 wt% chlorite – 60 wt% epsomite an addition of 3 wt% carbon black would only allow the 800 and 1000 °C samples to match the X asteroids. This could mean that the surfaces of X asteroids are composed of a mixture of decomposed chlorite and epsomite. The early decomposition product of chlorite is olivine and since it is seen in the CMs, the mineralogy would match (Bischoff et al., 2006). In the case of a mixture of 40 wt% chlorite – 60 wt% gypsum the outcome is the same, only the 800 and 1000 °C samples would match the continuum slope data of the X asteroids if 3 wt% carbon black was added. Again giving a similar conclusion that the surface of the X asteroids is composed of a mixture of decomposed chlorite and gypsum. Both outcomes would remove any traces of water from the mineral phase and thus be more like most of the X asteroids which do not show signs of hydration (Clark et al., 2004).
4.6 Conclusion

We report the reflectance spectra of phyllosilicate–evaporite mixtures. First, for the numerical mixing of the two phyllosilicates, serpentine and chlorite, mixed with evaporites, epsomite and gypsum, to determine mixture ratio of 40 wt% phyllosilicate – 60 wt% evaporite. As seen by Fig 4.2, 4.3, 4.4, and 4.5, this mixture ratio has generated the flattest and most C/X asteroid-like spectra. This ratio is close to the 27 wt% epsomite and 26 wt% serpentine, when (Fe, Ni)S is taken into account, in Orgueil calculated by Ostrowski et al. (2010a). To further determine what the surface of the asteroids are composed, laboratory mixtures were heated to various temperatures up to ~1150 °C to further match the spectrum of the C and X asteroids. The heating slowly removes all forms of water and eventually decomposes both minerals in the mixtures.

The C and X asteroid and C chondrite spectra are essentially featureless, while the heated mixtures have weak or no features. To discuss their spectra for comparison, “continuum plots” are used. Continuum plots are plots of the continuum slope between 1.0 and 1.75 μm against the continuum slope between 1.8 to 2.5 μm. The use of continuum slopes is implicit in existing asteroid taxonomies (Bus and Binzel, 2002; DeMeo et al., 2009). Also the use of continuum slopes is implicit in several studies that interpret asteroid spectra by spectrum matching (e.g. Hiroi et al., 1993). Most spectral matching is conducted in one region of the electromagnetic spectrum, where continuum plots break the near-IR into two regions.

The continuum data of all the phyllosilicate–evaporate mixtures have the same trend of the long wavelength region becoming more like the asteroids as temperature is increased. With the exception of two ~1150 °C heated mixtures, the data does not plot above the C and X asteroid fields. In the long wavelength region of the mixtures
containing serpentine there is a trend for the slope to progressively go from a negative to flat to X asteroid like increasing. The slope of the short wavelength region does decrease, flatten out, a small amount as temperatures increase, but never to the point that even matches the moderate sloped X asteroids.

The C and the X asteroids are still proving difficult to match using continuum slopes. Only the 40 wt% serpentine – 60 wt% epsomite mixtures (Fig. 4.7a) heated to 1000 and 1150 °C plot in the X asteroid field and right on the left edge of the C asteroid field. This gives the conclusion that the surface of the X complex is composed of decomposition products of serpentine and epsomite. Epsomite has most likely become an amorphous anhydride because magnesium sulfate is destroyed at 350 °C (Klein, 2002). Serpentine starts to decompose at 600 °C and become olivine (Deer et al., 1962; Grim, 1968), but it is logical to say that by 1000 °C it could be in an amorphous state. It is also possible to say that the surface of the X asteroids is amorphous.

The rest of the mixtures require darkening agents, like carbon or tocholinite, to match the continuum slope data of the asteroids. These darkening agents would be required to match albedo of all the C and most of the X asteroids. A few of the X asteroids have albedos above 30% (Clark et al. (2010) which matches the reflectance of the laboratory heated mixtures. The maximum allowable of carbon black, 3 wt%, added to the chlorite mixtures would only allow for samples heated to 800 °C and above to match the X asteroids. This would imply that the surface of X asteroids is composed of a mixture of decomposed chlorite and epsomite or composed of decomposed chlorite and gypsum with some form a darkening agent. When this is compared to the serpentine–epsomite data at decomposition temperatures the main difference is if darkening agents
are needed or not since the main decomposition product for both serpentine and chlorite is olivine. The 40 wt% serpentine – 60 wt% gypsum mixture heated to 600 and 1000 ºC with trace amounts of carbon black would have the same outcome of matching the X asteroids and the interpretation would be the same as the chlorite mixtures.

The important heating result is the 40 wt% serpentine – 60 wt% gypsum sample heated to 400 ºC. This heated mixture with only trace amounts carbon black, as low as 0.1 wt%, of would match the continuum slopes of the C asteroid field. At this temperature gypsum would be decomposed, but serpentine would only have lost its absorbed water. This match would imply that the surface of the C asteroids is composed of a mixture of serpentine with only its structural water, decomposed gypsum, and trace amounts of darkening agents.

In a mineralogical matching sense to check the conclusion, the heated mixtures were compared to carbonaceous chondrites. The CI chondrites Ivuna and Orgueil plot at the 400 ºC end of a low temperature field of heated 40 wt% serpentine – 60 wt% gypsum matching the mixtures spectral traits. Since both serpentine and gypsum have been observed in the CI chondrites (Tomeoka and Buseck, 1988; Rubin, 1977) and match the C asteroids spectrally, the above conclusion that the surface of the C asteroids are composed of a mixture of dried serpentine, decomposed gypsum, and traces of opaques is possible.

4.7 Acknowledgments

We are grateful to Vincent Chevrier for providing the phyllosilicate samples used in this work, Andy Rivkin and Takahiro Hiroi for comments in an early phase of this work, and NASA for funding. This research utilizes spectra acquired by Mike Gaffey, Takahiro
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CHAPTER 5

Comparison of spherules of heated phyllosilicate-evaporite mixtures to spherules in CI and CR chondrites

Here we examine the differences and similarities of laboratory created phyllosilicate-evaporite mixture spherules and spherules observed in CI and CR chondrites. The mixture spherules are formed during heating of the mixtures to create samples for infrared comparison with the meteorites and asteroids. Dr. Mike Zolensky made the thin sections of the CI and CR meteorites. He also obtained the scanning electron microscope images of the CI meteorite. I created the laboratory mixture spherules and collected images of the mixtures spherules and electron microscope images of the meteorites. I analyzed and preformed a comparison of all the images.

5.1 Abstract

Spherules of unknown composition were generated from heated mixtures of 40 wt% serpentine – 60 wt% epsomite and of 40 wt% chlorite – 60 wt%. Solid spherules in diameters range of 0.01 to 0.06 mm have been observed in CI and CR chondrites (Zolensky et al., 1996). The spherules from the laboratory are hollow with an initial composition of a mixture of phyllosilicates and evaporites and result in an average diameter of a couple of millimeters. Thus the two groups of spherules are not the similar objects. Rounded voids are also present in the matrix phyllosilicate of the CI and CR chondrites. It is possible that the boundary between the voids and the matrix is composed of the same material that was formed as the shell of the phyllosilicate-evaporite mixture spherules.
5.2. Introduction

Carbonaceous chondrites are the most primitive class of meteorites. The CI chondrites are the class that are the most solar-like in composition. Though they do show signs of being aqueous altered from containing minerals like phyllosilicates, sulfates and hydroxides (Zolensky and McSween, 1988). The fine-grained texture of the carbonaceous chondrites does make it difficult to identify these mineral phases. In addition to this, there are large amounts of amorphous phases in the matrix. Rubin (1997) has summarized the different alteration products that are found in the carbonaceous chondrites. In the case of the evaporites, Gounelle and Zolensky (2001) argues that the sulfate veins are a result of remobilization and reprecipitation of the sulfate as a consequence of the meteorites’ interaction with water in the atmosphere after time spent on Earth.

Understanding pre-alteration composition/mineralogy of the CI chondrites is important to better understand the early solar system. In the course of studying the CI chondrites Orgueil and Alais, Zolensky et al. (1996) discovered many rounded, yellowish-brown objects. On average these objects are between 10 to 60 µm in diameter but can be as large ass 100 µm. These rounded objects also look similar to the “organized elements” observed in carbonaceous chondrites by Nagy (1975). Investigation of the rounded objects consists of fine-grained, flaky phyllosilicates of serpentine and saponite, or they are poorly crystalline ferromagnesian material with the similar composition as the phyllosilicates (Zolensky et al., 1996). These are the materials that dominate the known minerals in CI chondrites (Bass, 1971; Tomeoka and Buseck, 1988). It has been suggested that the rounded phyllosilicates aggregates were originally
glassy spherules that went through various stages of aqueous alteration (Zolensky et al., 1996).

In the process of determining the surface composition of C and X asteroids using terrestrial analogs of minerals found in carbonaceous chondrites, spherules of unknown composition were created. We have therefore performed a visual inspection of them and compared them to the rounded phyllosilicates in the CI chondrites for comparison.

5.3. Method

In order to study asteroid surface composition, laboratory mixtures of 40 wt% serpentine – 60 wt% epsomite and 40 wt% chlorite – 60 wt% epsomite were generated. Mineral samples were crushed and then sieved to a grain size less than 63 µm using a #230 U.S. Standard Testing Sieve attached to a Humboldt MFG. Co shaker. Two-gram samples of the mixtures were created. Independent samples of the phyllosilicate-evaporite mixtures were then heated from 100 to ~1150 ± 1%°C in 200°C intervals. The heating durations for the 200 to 800°C treatments were 24 hours, and for the highest temperature samples the heating duration was six hours. All samples were heated in an air atmosphere and allowed to cool to room temperature in a desiccator.

Digital photos using a Hewlett-Packard Photosmart M425 digital camera were taken. All sides of the formed spherules were photographed. Randomly selected spherules were broken to photograph their interiors. Images are compared to of thin sections of CI and CR chondrites using an electron microscope. The CI meteorites are Ivuna, two thin section, and Orgueil, four thin section. The CR meteorites Al Rais and Acfer 187, one thin section each. Two thin sections of Orgueil were examined using a
scanning electron microscope (SEM) to study spherules and rounded voids in the meteorite.

5.4 Observations and comparisons

5.4.1 Phyllosilicate-evaporite mixtures
Figure 5.1 Stages of heating of the 40wt% serpentine – 60wt% epsomite mixture. Spherules are produced in all samples. (a) Smooth surface large bubble of the topside of 300°C sample. (b) Rough surface of the bottom side of the 300°C sample. (c) 500°C sample, first to produce individual spherules. (d) Arrow points to broken spherule showing spherules are hollow. (e) 800°C sample, loose material starts to darken and individual spherules becoming conglomerates. (f) Broken pieces showing material is hollow. (g) 1000°C sample, spherules forming conglomerates on main body. (h) Broken piece from main body to show material is hollow.
Figure 5.1 is of examples of spherules created from heated mixtures of 40 wt% serpentine – 60 wt% epsomite. In the process of being heated, the mixture samples released their water forming a slurry mixture that when dried in the heated process expanded and solidified. As seen with the sample heated to 300 °C the side not against the heating tube was allowed to expand and solidified with a smooth surface (Fig 5.1a). While the other side (Fig 5.1b) solidified as an uneven surface where the raised surface is smooth and the recessed surface is rough. The temperature of 300 °C is close to the decomposition temperature of epsomite (Klein, 2002), so most the mineral is gone. By 500 °C the dehydration from slurry mixture to dried sample happens faster preventing the material from forming one large body (Fig 5.1c,d). As seen in Fig 5.1c individual spherules start to form. Figure 1d shows that the individual spherules, just like the large objects, are hallow. This is believed to be caused by the rapidly escaping water vapor. Figure 5.1e,f continues the slurry, bubbling action that is all the samples, but by this point the temperature is high enough to destroy any residual minerals (Deer et al., 1962; Grim, 1968; Klein, 2002). At this temperature, as the free fine-grained material is darkening, albedo is being reduced. Figure 5.1g,h shows that the water evaporation is happening so rapidly from the slurry that as the spherules are being created they conglomerate.
Figure 5.2 Stages of heating of the 40wt% chlorite – 60wt% epsomite mixture. Spherules start formation at 300°C. (a) 300°C sample, rough body with little and small spherules/bubbling occurring. (b) 600°C sample, spherules become larger as surface becomes more coarse. Minerals are decomposing resulting in a darkening of material. (c) 800°C sample, small conglomerate pieces are of topside were large hollow spherules are formed. Large conglomerate piece is of the bottom side were only small spherules are formed. (d) 1140°C sample, high heat causes complete decomposition of minerals and darkening of material. Mostly only small spherules are formed.
Figure 5.2 is of examples of spherules created from heated mixtures of 40 wt% chlorite – 60 wt% epsomite. By 300 °C, a slurry mixture has been formed in the drying process, and a single conglomerate body of small objects is formed (Fig 5.2a). Water vapor is allowed to leave the slurry slowly or unhindered because very little bubbling occurs. By 600 °C, the mixture minerals are decomposed (Deer et al., 1962; Grim, 1968; Klein, 2002) and can be seen by darkening in the sample material (Fig 5.2b). Figure 5.2b also shows the formation of small spherules that cover the conglomerate. The two small conglomerate pieces in Fig 5.2c are of the topside of the sample and show that the lack of resistance allows the spherules to grow larger. Also, the large piece is the bottom side, were spherule growth is hindered and results in a large quanity of small hollow spherules. The only change from the 800 °C that occurs at 1140 °C is the darkening of the sample, the greatest reduction in albedo of all the 40 wt% chlorite – 60 wt% epsomite samples.

5.4.2 CI and CR chondrites

Figure 5.3 is electron microscope images of thin sections of the CI chondrite Alais. The rounded objects in the thin section of Alais are hollow. The rounded objects are small with the largest having a diameter of about 0.1 mm. The matrix that surrounds them is composed of serpentine and amorphous material (Brearley, 2006). The veins, which are empty in the thin section, have mostly been made by gypsum (Richardson, 1978).
Figure 5.3 Electron microscope image of the CI chondrite Alais. (a) Thin section 6695-8 contains many small rounded voids, diameter less than 0.03 mm, are located near empty veins. (b) Thin section 6695-9 contains few large rounded voids of diameters less than 0.1 mm.
Figure 5.4 is electron microscope images of thin sections of the CI chondrite Ivuna. The rounded hollow objects in Ivuna are more described by irregular spherules. They are on average smaller than the rounded objects in Alais, with an average diameter of 0.02 mm. The lighter color in the rounded objects in Fig 5.4a is a leaching of the phyllosilicate and carbon from the matrix into the voids. The matrix of Ivuna is also composed of serpentine and amorphous material (Brearley, 2006). Even though carbon leaching is occurring in Ivuna and not Alais, there is more carbon in Alais (Wiik, 1967). The leaching could have occurred from more aqueous alteration or greater fluid mobilization from the evaporites.
Figure 5.4 Electron microscope images of the CI chondrite Ivuna. Both are from the thin section Ivuna-1. (a) Free irregular rounded voids of diameters 0.2 mm and less. Discoloration is caused by leaching of surrounding material during thin section creation. (b) Few rounded voids in lower half. Darkness of sample makes it difficult to identify objects.
Figure 5.5 is electron microscope images of thin sections of the CI chondrite Orgueil. Of the imaged carbonaceous chondrites, Orgueil has a small clustering of the largest rounded voids, with diameters less than 0.2 mm (Fig 5.5a). It also has the most rounded voids and occasionally has large fields of the voids (Fig 5.5b). Not all the rounded objects are voids. The yellow shaded round objects in Fig 5.5c,d are spherules of serpentine as reported by Zolensky et al. (1996). These are small spherules with a diameter of about 0.02 mm. Serpentine is the most common phyllosilicate in Orgueil, (Brearley, 2006) and the most common evaporite is epsomite (Richardson, 1978).
Figure 5.5 Electron microscope images of the CI chondrite Orgueil. (a) Thin section Orgueil-2. Tight field of large rounded voids with diameters averaging 0.2 mm. (b) Thin section A1. Large field of rounded voids with diameters averaging 0.02 mm. (c) Thin section Orgueil-4. Yellowish rounded objects in matrix are spherules of phyllosilicates. Most spherules fall on diagonal line from lower left to upper right. (d) Thin section MZ2. Large well defined phyllosilicate spherule, diameter about 0.03 mm.
Figure 5.6 is a part of a thin section of the CR chondrite Acfer 187. The large voids seen in Fig 5.6 are typical of Acfer 187 in this thin section but not in the meteorite in general. Matrix material is interlaced in the voids. The matrix of Acfer is mostly serpentine (Brearley, 2006), but some of the darker matrix material has increased amounts of magnetite and sulfides (Endress et al., 1994). The bright yellow spheres are spherules of fine-grained serpentine. They have an average diameter of about 0.04 mm.
Figure 5.6 Electron microscope image of CR chondrite Acfer 187. Orange spherules of diameters 0.04 mm are composed of phyllosilicates.
Figure 5.7 is of a thin section of CR chondrite Al Rais. There are many large irregular voids in Al Rais. The yellow colored spherules are mostly glassy (non-crystalline) material. While a few are composed of fine-grained serpentine a few also included saponite, and a few are composed of the glassy material and the phyllosilicates (Zolensky et al., 1996). Most of yellowish spherules are found near the rim of chondrules, while only a sparse few are distributed in the matrix.
Figure 5.7 Electron microscope image of CR chondrite Al Rais; from the thin section USNM 1794-1. (a) Yellow spherules of glassy (non-crystalline) material near outside edge of meteorite, made from phyllosilicates. (b) Larger spherule on edge of void and rare small spherule in matrix of meteorite.
5.4.3 Comparison of meteorites to heated phyllosilicate-evaporite mixtures

There are two major differences between the spherules in the phyllosilicate-evaporite mixtures and the ones in the CI and CR chondrites. The first major difference is the spherules in the meteorites are solid phyllosilicate material, while the ones in the mixtures are hollow voids. Even though the starting material is similar to the composition of the spherules, a different formation process took place. It has suggested that the spherules in the phyllosilicates have an origin as rounded glassy material that formed before the accretion of the object into the parent body. It then went through stages of aqueous alteration to form the phyllosilicates (Zolensky et al., 1996). On the other hand, the spherules in the mixture sample are created when water vapor is leaving a slurry mixture and when heat is applied to the phyllosilicate-evaporite mixture. The water vapor forms gas pockets that allow the slurry to solidify into spherules as it is escaping. Voids are nothing like solid spherules of a known composition.

The other major difference is the size of the spherules. The spherules in the heated phyllosilicate-evaporite mixtures are a couple of millimeters in diameter, while the spherules in the meteorites all have diameters much smaller than one millimeter. As stated above, the spherules of known composition are at most 0.1 mm in diameter, but most are in the range of 0.01 to 0.06 mm (Zolensky et al., 1996). Even the rounded voids observed in the meteorite thin sections have smaller diameters. One possible cause of this difference in size is that the meteorite spherules, and rounded voids are formed in a “pressured” environment, which is material completely surrounding it that would restrict growth. This same effect is seen in Fig 5.2c with the large piece. The bottom of the
heating tube restricts the growth of the bubbles and only small spherules are formed, but these spherules are still bigger than the spherules and rounded voids in the meteorites.

The rounded voids in the meteorites can be formed another way that is much different than the hollow spherules of the laboratory mixtures. The rounded voids in the meteorites could have formed by fluid mobilization of the material that once was present; either during aqueous alteration on the parent body or from the time the meteorite has spent on Earth. The rounded voids could also have resulted form the soft/weak material that filled the voids being removed in the process of making the thin section. This is not intentional, but happens because they are weak. To investigate similarities between the rounded voids and the spherules of the laboratory mixtures, SEM of a thin section was studied (Fig 5.8). Figure 5.8a is of the large rounded void field. Figure 5.8b is a higher magnitude image of this field; the void on the left side of the image is part of one of the large rounded voids. The matrix of Orgueil around the large rounded voids is mostly serpentine, but there is a small irregular shaped amorphous material in the upper left Fig 5.8b. The bulk of the small rounded objects in Fig 5.8b are magnetite. Magnetite is a possible product of thermal treatment to phyllosilicates (Gavin and Chevrier, 2009). The voids were possibly once filled with evaporites like the veins (Richardson, 1978), but there is no way to know in the case of this thin section. The SEM has shown that the voids in Orgueil are surrounded by similar material to the phyllosilicate-evaporite mixture spherules. This means that if the rounded voids in Orgueil were once composed of epsomite, then the boundary between the voids and the matrix could be similar material as the shell of the spherules created in the laboratory.
Figure 5.8 Scanning electron microscope image of large rounded void field in Fig 5.5a of Orgueil. (a) Large rounded void field surrounded by matrix of serpentine. (b) Higher magnitude image of void field. Rectangular and small rounded objects are magnetite. Irregular shaped object in top left is amorphous material.
5.5 Conclusion

In the process of sample generation for comparison via near infrared spectroscopy, mixtures of 40 wt% serpentine – 60 wt% epsomite and of 40 wt% chlorite – 60 wt% were generated, resulting in spherules of unknown composition. Spherules have been observed in CI and CR chondrites (Zolensky et al., 1996). The spherules in the meteorites are solid spherules composed of serpentine, while the spherules from the laboratory are hollow with an initial composition of a mixture of phyllosilicates and evaporites. The other difference between the spherule groups is size. The spherules for the meteorites have diameters in the range of 0.01 to 0.06 mm, whereas the phyllosilicate-evaporite mixtures are larger with diameters of a couple of millimeters. Thus, the two groups of spherules are not the similar objects.

Rounded voids are also present in the matrix of CI and CR chondrites. The matrix, in Orgueil, that surrounds these rounded voids is mostly composed of serpentine, one of the primary phyllosilicates in CI chondrites (Brearley, 2006). It is possible that the voids once contained evaporites, and this would allow for the hypothesis that the boundary between the voids and the matrix is composed of the same material that was formed as the shell of the phyllosilicate-evaporite mixture spherules. The rounded voids are much smaller than the phyllosilicate-evaporite mixture spherules with most having diameters less than 0.1 mm. The size difference could just be a result of the differing formation environments.
5.6 Acknowledgment

I am grateful to Mike Zolensky for access to meteorite thin sections and use of instrumentation at Johnson Space Center, as well as the helpful conversation and input on possible meanings the spherules.
CHAPTER 6
Conclusions and Future Work

6.1 Conclusions
This research has examined the relationships between terrestrial analogs, carbonaceous chondrites and C and X complex asteroids. In a sense it can be compared to reverse engineering an asteroid to determine the current surface composition of the C and X asteroids. The near infrared spectrum is useful for determining mineralogy of an object, but in the case of the C and X asteroids and the carbonaceous chondrites this region is featureless. Continuum slopes can be used to study these asteroids and meteorites. Continuum slopes are already being used to determine the taxonomy of the asteroids. To compare continuum slopes the observation range of 0.8 to 2.5 \( \mu \text{m} \) is divided into the short wavelength region, 1.0 to 1.75 \( \mu \text{m} \), and the long wavelength region, 1.8 to 2.5 \( \mu \text{m} \), and graphed the regions against each other on what is referred to as “continuum plots.”

Phyllosilicates are the most common mineral in the matrix of the carbonaceous chondrites, which are believed to originate for the C asteroids. In this work, I performed heating experiments on a suite of terrestrial phyllosilicates to investigate the effects on the near infrared continuum slope. Before heating, phyllosilicate’s spectrum looks nothing like that of the asteroids and meteors. The phyllosilicates plot large field below the asteroids and meteorites because of a decreasing long wavelength slope caused by water and cation-hydroxide bonds. The C asteroids and C meteorites form discrete and well-defined clusters of on the continuum plot. The C chondrites form two fields, one composed of CI, CV, CK and CR classes overlaps the C asteroid field and the CM
chondrites plot to the right of the C asteroid. The meteorites identified as CI/CM chondrites plot on the interface between the C chondrite and the CM chondrite fields.

A heat treatment on five terrestrial phyllosilicates causes a removal of features and flattening of the near infrared spectrum. This effect makes the spectra of the phyllosilicates look similar to the C asteroids. Heating to temperatures below 700°C will only cause the continuum data to move around within the terrestrial phyllosilicate field. The three important phyllosilicates are serpentine, montmorillonite and chlorite because they have been observed in the carbonaceous chondrites. Heating to temperatures above 700°C moves montmorillonite the region occupied by the C asteroids, while heating serpentine and chlorite to >700°C moves their data into the CM chondrite field. The data is consistent with the surfaces of the C asteroids being composed of dehydrated phyllosilicates, serpentine or montmorillonite. The dehydration of the phyllosilicates also causes the albedos to decrease to values almost as low as observed for the C asteroids, and the presence of opaques would lower the albedo further.

The addition of evaporites to the terrestrial analogs is the next stage in understanding the composition of the C and now also X asteroids because of there spectral similarity to the C asteroids. First, numerical mixing of the phyllosilicates, serpentine and chlorite, mixed with evaporites, epsomite and gypsum, determined mixture ratio of 40 wt% phyllosilicate – 60 wt% evaporite to have the most C/X asteroid like spectrum. Heating experiments on laboratory mixtures were conducted again to further match the spectrum to that of the C and X asteroids. In the heating process eventually both minerals of the mixtures are decomposed. The heated mixtures have weak or no features. The continuum data of all the phyllosilicate–evaporate mixtures
have the same trend of the long wavelength region becoming more like the asteroids as temperature is increased. The long wavelength region of the mixtures containing serpentine there is a trend for the slope to progressively go from a negative to flat to X asteroid like increasing. The slope of the short wavelength region does decrease, flatten out, a small amount as temperatures increase, but never to the point that even matches the moderate sloped X asteroids.

The C and the X asteroids are still proving difficult to match using continuum slopes. Only the 40 wt% serpentine – 60 wt% epsomite mixtures (Fig. 4.7a) heated to 1000 and 1150 °C plot in the X asteroid field and right on the left edge of the C asteroid field. This gives the conclusion that the surface of the X complex is composed of decomposition products of serpentine and epsomite. It is also possible to say that the surface of the X asteroids is amorphous. The rest of the mixtures require darkening agents, like carbon or tocholinite, to match the continuum slope data of the asteroids. These darkening agents would be required to match albedo of all the C and most of the X asteroids. The maximum allowable of carbon black, 3 wt%, added to the chlorite mixtures would only allow for samples heated to 800 °C and above to match the X asteroids implying that the surface of X asteroids are composed of a mixture of decomposed chlorite and epsomite or decomposed chlorite and gypsum with some form a darkening agent. Only trace amounts of carbon black would be required for the results of the 40 wt% serpentine – 60 wt% gypsum sample heated to 400 °C to match the continuum slopes of the C asteroid field. This match would imply that the surface of the C asteroids is composed of a mixture of serpentine with only its structural water, decomposed gypsum, and trace amounts of darkening agents.
Most authors agree that the surfaces of the C asteroids are probably composed of a majority phyllosilicates whose spectra are weakened by the presence of opaques and space weathering. The presence of opaques is not alone sufficient to weaken features to the observed degree and cause the observed continuum slope trends. Neither does the grain size variations a likely explanation for the asteroid-to-asteroid spectral differences, although grain size does affect laboratory spectra. The slope difference are possible a result of asteroid surfaces consisting in large part of the decomposition products of heated phyllosilicates and evaporites.

The near IR spectra for seventeen asteroids that belong to the C and X complexes have been observed. Literature data for these asteroids in the visible and spectral features suggestive of the water and water related components on the asteroids (the UV slope, the 0.7 μm absorption and the 3 μm absorption) has been obtained. Spectral features for water have been detected in all 17 asteroids, but only three asteroids, 24 Themis, 34 Circe, and 51 Nemausa have all three features. Using the Bus-DeMeo taxonomy classes have been assigned to 17 asteroids in the C and X complexes.

Of the variance in the C and X asteroid spectra, 88% of it can be explained by continuum slope. Examination of the spectra of the present asteroids and literature supplemented data there is large amount of overlap internally in the complexes, except for the B and Cgh type. The Cgh type is because of stronger water related features. The B type does not overlap because of a slight negative continuum slope as defined the Bus-DeMeo taxonomy. There is a small amount of overlapping between the complexes, where most of the overlapping is by the Cgh field that across the lower half X complex field.
Associations between asteroid classes and meteorite classes have been made to suggest parent sources for the carbonaceous chondrites. The CI chondrites are linked with the Cgh asteroids, individual CV and CR chondrites are linked with Xc asteroids, and a CK chondrite is linked with the Ch or Cgh asteroids. The unusual CI/CM meteorites are linked with C asteroids, while the CM chondrites are linked with the Xk asteroids.

6.2 Future Work

Spectral matching of terrestrial analogs to C and X asteroids is improving. A major problem that still exists is samples having the proper albedo. Future work would investigate the effects of opaques on the spectrum of the phyllosilicate-evaporite mixtures. The opaques would have to consist of proper weight percent with the CI and CM chondrites. Carbon black would be the first material studied. Material would be added before or after heating the mixtures to examine its effect on both albedo and the near infrared spectrum. This should help understand the albedo differences. Another project is to conduct X-ray diffraction on the phyllosilicate-evaporite mixtures. This would allow for a more definitive conclusion on what the surface composition of the C and X asteroids is.
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APPENDIX A

Spectral Features in C and C-like Asteroids and the Possible Presence of Phyllosilicates

SPECTRAL FEATURES IN C AND C-LIKE ASTEROIDS AND THE POSSIBLE PRESENCE OF PHYLOSILICATES. D. R. Ostrowski1, D. W. G. Sears1,2, and K. M. Giezen1, C. H. S. Lacy1,3, Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, AR 72701, USA (dostraw@uark.edu), 1Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA, 2Department of Physics and Astronomy Sciences, University of Arkansas, Fayetteville, AR 72701, USA.

Introduction: Main belt asteroids (MBA) and near Earth asteroids (NEA) are classified into 26 discrete classes. The NEAs are a small fraction of the total asteroid population. For the NEAs alone there are about 4500 known, with an even smaller fraction of these that have spectra that can be classified. The large unknown population of asteroids has a need to be classified, in the mineralogical sense. For classification the mineralogically important spectral range is 0.8 - 2.5 μm. This can give the scientific community an idea of how asteroids are formed.

The C and C-like asteroids make up about 50% of the MBAs. The composition of these asteroids is unknown. It has been shown by spacecraft flybys and telescopic observations that C asteroids are possibly rubble piles. In recent experimental observation it has been suggested that these bodies generally considered to be featureless, do contain features in their relatively flat spectra [1].

Experimental: To date we have obtained seven observing runs between 2004 and 2006 on NASA’s IRTF that has yielded spectra of 35 asteroids. The spectral range observed is from 0.8 μm to 2.5 μm. The spectra were coupled with the visible wavelengths (0.4-0.9 μm) from the MIT SMASH [2-9]. The data is compared against a phyllosilicate database to check for the possible connection.

A phyllosilicate database has been built. It is separated by the three layer types; 1:1, 2:1, and 2:1:1. Spectra for this database has been acquired from the USGS spectral library [10].

Results: Of the asteroids observed, five are C and six are C-like. Figure 1 depicts the visual and infrared spectra of the C asteroids obtained and Fig 2 does this for C-like asteroids. The noise in the spectra at 1.4 and 2.0 μm is where the possible absorption features for phyllosilicates are present.

C Chondrites: The carbonaceous chondrites most closely resembling the C asteroids in their reflectivity spectra are the CI and CM chondrites, which are those most close to solar composition. Researchers agree that they consist essentially of phyllosilicates, but there is considerable uncertainty as to their exact nature; chlorite, serpentine, mica, montmorillonite, and many others have been mentioned [11]. Figure 3 displays the spectra of CI and CM chondrites [12].

Spectra of Phyllosilicates: The phyllosilicates are divided into three layer types: the 1:1, 2:1, and 2:1:1, which are composed of tetrahedral and octahedral
sheets stacked on top of each other. As seen in Fig 4 there are absorption features at 1.915, 1.985, and 2.315 μm that identify the structural type of 2:1, 2:1:1, and 1:1 respectively.

There are two sources for the differences in the spectra. First is the already stated three different layer types that each have identifying absorption features. The other difference in the spectra is the shift in the absorption features of the layer type identifiers. This is due to the primary metal element in each of the clays.

Comparing absorption bands is a method of connecting the mineralogy of the asteroids to that of the phyllosilicates. When the above stated phyllosilicate identifier bands were applied to the asteroid spectra the lack of absorption bands was apparent. The phyllosilicates contain strong bands where the asteroids have very weak bands that are covered by noise in the spectra. This could be the result of one or multiple alteration processes.

The alteration processes that are possibly affecting C asteroids are dehydration, space weathering, and impacts. Their importance is the ability to remove both hydrated and structural water. All these methods and the loss of water will cause a flattening of the spectra. This could account for the difference in the phyllosilicate and asteroid spectra.

![Figure 4: Visible and infrared spectrum of phyllosilicate clays. A range of metal elements were selected to depict both structural and elemental differences. a. The spectrum of the structure types 1:1. b. The spectrum of the structure type 2:1. c. The spectrum of the structure type 2:1:1.](image)

**Discussion:** Visually the spectra for the C and C-like asteroids look similar to that of the CI and CM chondrites. The CI and CM continuum ratio (Fig 5) fall directly in line with that of the asteroids. This would mean that the C and C-like asteroids could be parent bodies for the CI and CM meteorites.

Studying the differences in continuum slope for the 1.8-2.5 μm versus the 1.0-1.75 μm a definite trend is seen (Fig 5). All the asteroids line up together and are parallel to the phyllosilicates. The difference is in the 1.8-2.5 μm continuum, which for the asteroids increase with wavelength. For the phyllosilicates the continuum between 1.8 and 2.5 μm drops drastically (Fig 4). One possibility for the difference between the asteroids and the phyllosilicates could be structural water. It has a very strong absorption feature that can depress the spectra around it. This would mean that the C and C-like asteroids are depleted in or contain no forms of water in their mineralogy.

![Figure 5: Continuum slope comparison between the C and C-like asteroids, CI and CM meteorites, and phyllosilicates.](image)

**Conclusion:** While there appears to be a link between CI and CM chondrites and the C asteroids, the nature of this linkage is unclear. Even more problematic is the difference between terrestrial phyllosilicates and the asteroids and meteorites. A difference in the amount and distribution of water between the terrestrial phyllosilicates and the C chondrites and C asteroids might explain the difference, and further experimentation will address this.

**References:**
Spectral Features in C and C-like Asteroids and the Possible Presence of Phyllosilicates

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C and C-like Asteroids

- C and C-like are the most abundant of main belt asteroids
- Contain small absorption features
- Some are known to contain some form of water
- Reflectance spectroscopy suggest link between C and C-like asteroids with Cl and CM chondrites

Theory

- Mineralogical makeup of C and C-like asteroids are unknown
- Cl and CM chondrites are mostly composed of phyllosilicates
- Investigate link between carbonaceous meteorites and asteroids
- Phyllosilicates are possible terrestrial analogs of C and C-like asteroids

Procedure

- Phyllosilicate from USGS spectral mineral database
- Categorize infrared absorption features
- Obtained 11 C and C-like asteroid infrared spectra
- Obtained 7 Cl and CM chondrite spectra
- Visual comparison of asteroids, meteorites and phyllosilicates spectra

Phyllosilicates Spectra

- Continuum between 1.8 - 2.5 μm drastically drops
- Cation-OH bonds dip between 2.15-2.40μm
NIR Reflectance: Montmorillonite

Phyllosilicates Similar to Asteroids

253 Mathilda

Conclusion
- Visually C and C-like asteroid spectra look similar to that of CI and CM chondrites, possible parent source
- Phyllosilicates spectra are similar to asteroids and meteorites, except in long wavelength
- Difference in reflectance spectra caused by various water features
- Water in asteroids and meteorites are not chemically bound
APPENDIX B

A Study of Phyllosilicates as Possible Components of the Surface of C Asteroids

Abstract and poster to the Asteroids, Comets, and Meteorites Conference 2008.
A STUDY OF PHYLLOSILICATES AS POSSIBLE COMPONENTS OF THE SURFACES OF C ASTEROIDS. D. R. Ostrowski, D. W. G. Sears, and K. M. Gietsch, C. H. S. Lacey, 

Introduction: The detailed mineralogy of the C and C-like asteroids, which constitute ~50% of MBAs, is poorly known. A 3 µm feature suggests hydrated silicates [1], while 0.7 µm feature has been attributed to Fe bearing phyllosilicates [2,3,4]. The meteorites most closely resembling the C asteroids in their reflectivity spectra are the CI and CM chondrites. The 0.7 and 3 µm spectral features have been used to link the meteorites to the asteroids [4]. The spectra are otherwise usually considered featureless [5], although recent efforts suggest otherwise [6]. C chondrites consist essentially of phyllosilicates, but there is considerable uncertainty as to their exact nature; chlorite, serpentine, mica, montmorillonite, and many others are possible [7]. In order to explore the mineralogical nature of the surface of C asteroids we obtained new spectra for 11 C asteroids and we have looked at the spectra of 22 terrestrial phyllosilicates. We have also performed heating experiments on the phyllosilicates to simulate impact heating.

Experimental: Between 2004 and 2006 we made seven runs on the NASA IRTF telescope and obtained 11 spectra for C and C-like asteroids in the range 0.8 to 2.5 µm. Data in the range 0.4-0.9 µm were taken from the SMASS database [8-15]. Data for two CI and five CM chondrites and for terrestrial phyllosilicates came from the PDS [16] and the USGS [17], respectively.

Since the spectra are essentially featureless, we focus on continuum slope, plotting the slope between 1.8 and 2.5 µm against that at 1.0 and 1.75 µm.

Results: Fig. 1 shows the data. The upper grey ellipse shows the range occupied by our 11 asteroids, while the lower ellipse shows the field of data for phyllosilicates. Actual data are given in ref. [18]. Superimposed on these are our data for heated terrestrial phyllosilicates, montmorillonite and natonite, and the Hiroi et al data for Murchison [19].

Discussion: Although not presented in the manner of Fig. 1, it has been known for some time that the spectra of C asteroids do not precisely match the spectra of C chondrites, and we now extend that conclusion to terrestrial phyllosilicates. What is significant is that although the terrestrial phyllosilicates spread fairly uniformly along the ellipse in Fig. 1, when heated in the laboratory to ~500°C they migrate to the asteroid ellipse and then after heating at 900°C they converge to a region in the middle of the ellipse. Temperatures in excess of 800°C can reduce or remove the near infrared hydroxide features which we presume is associated with a collapse of the phyllosilicate structure and the formation of other phases. Similar heating experiments have been performed on Murchison [19,20], which show very similar trend. Heating to 500°C moves the data to the tip of the asteroid ellipse, and subsequent heating moves it down to the central region.

Fig. 1: Continuum slope comparison between asteroids (upper ellipse), terrestrial phyllosilicates (lower ellipse), heated phyllosilicates and Murchison.

Conclusion: The present data suggest that the surfaces of asteroids consist of a variety of primary phyllosilicates heated to ~500°C by repeated impact heating. The range of primary compositions includes Murchison-like mineralogies. Changes in the spectra by impact heating in the range of 500-1300°C are also a possibility for explaining the range of C asteriod spectra.

A Study of Phyllosilicates as Possible Components of the Surface of C Asteroids


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Introduction
- C and C-like Asteroids
  - Are the most abundant type in the main asteroid belt
  - Contain small halos in infrared spectrum, previously thought to be hydration [1]
- Some are known to contain some form of water on 3 µm feature [2]
- Phyllosilicate and 0.7 µm attributed to iron-bearing phyllosilicates [5]
- Reflection spectroscopy suggests link between C and C-like asteroids with CI and CM chondrites
- Carbonaceous Chondrites
- CI and CM chondrites are most close to solar composition
- Water-bearing meteorites
  - CM contains up to 19% and CI contains up to 20%
- Clast essentially of phyllosilicates, but there is uncertainty in their exact nature [4]
  - Examples of common phyllosilicates: chlorite, serpentine, olivine, and montmorillonite

Background
- Mineralogical makeup of the C and C-like asteroids are unknowns and needs to be determined
- Investigate the link between carbonaceous meteorites and asteroids can be done by using phyllosilicates
- Phyllosilicate""""s infrared spectra can be altered by thermal treatment to simulate impact heating

Experimental
- Phyllosilicate spectra obtained from the USGS spectral mineral database [5]
- Obtained 2 C-like C-like asteroid spectra (0.8-1.5 µm) with NASA's SBT. Data is collated with visible wavelength (0.4-0.9 µm) from the MIT SAMS [6]
- Obtain CI and CM chondrite spectra from PDS [7]
- Visual comparison of asteroids, meteorites and phyllosilicates spectra
- Thermally treat phyllosilicates from 300 to 1100 °C and between 6 to 24 hours
  - Compare continuum slope between 1.8 and 2.5 µm against that of 1.6 and 1.79 µm

Thermal Treatment
- Increasing heat flattens the near infrared spectrum
- High temperatures drive out both adsorbed and chemically bound water

Continuum Comparison
- Fig. 4. Comparison of C-like spectra, carbonaceous chondrites and phyllosilicates
- Continuous ratio of CI and CM chondrites are located in many line as C and C-like asteroids
- Phyllosilicate fine line is shifted down because of negative continuum 1.8 to 2.5 µm. Shift is believed to be caused by different forms of water
- Thermal treatment (900 °C) brings phyllosilicates and Murchison into the elliptical region of asteroids and further heating (1000 °C) brings the data to small region in the center of the elliptical field

Infrared Spectra
- Fig. 2. Visible and infrared spectra of C asteroids. (left) Visible and infrared spectra of C-like asteroids
- Fig. 3. Visible and infrared spectra of CI and CM chondrites
- Fig. 5. Comparison of spectra between hydrated meteorites [6] and phyllosilicates and asteroids, meteorites, phyllosilicates

Conclusions
- Visually C and C-like asteroid spectra look similar to that of CI and CM chondrites, possible parent source
- Thermal treatment of phyllosilicates in mass of 500 °C causes infrared spectra to become more like C and C-like asteroids
- Detailed continuous slope comparison shows slow for non-iron bearing phyllosilicates and carbonaceous chondrites to be compared to C asteroids
- Asteroid surfaces could be made of impact heated phyllosilicates

References
APPENDIX C

An Investigation of Phyllosilicates, C Chondrites, and C Asteroids using Continuum Slopes on Near Infrared Spectra

AN INVESTIGATION OF PHYLLOSILICATES, C CHONDRITES, AND C ASTEROIDS USING CONTINUUM SLOPES OF NEAR INFRARED SPECTRA. D. R. Ostrowski¹, D. W. G. Sears¹, K. M. Gietzen¹, and C. H. S. Laey¹, ¹Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, AR 72701, USA (dostrow@uark.edu), ²Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA, ³Department of Physics, University of Arkansas, Fayetteville, AR 72701, USA.

Introduction: The complex of C asteroids constitutes about ~25% of the asteroid population [1], however because spectral features are weak or absent, little is known about their detailed mineralogy. Many asteroids contain a feature at 3 μm caused by water absorption [2], and this correlates with a weak 0.7 μm feature thought to be due to Fe³⁺ in phyllosilicates [3, 4]. Similar features are observed in CM chondrites. A feature at 0.9 μm has been used to draw conclusions about the similarity of the C asteroid Mathilde and C chondrites [5]. Like C asteroids, the C chondrites show relatively featureless spectra, especially when compared with spectra for phyllosilicates (Fig. 1). However, most authors assume that the C chondrites are related to the C asteroids and therefore that the surfaces C asteroids are composed of Fe-rich phyllosilicates. However, there are two caveats that should be borne in mind. One is that the silicates in C chondrites are highly complex mixtures of phases, which are in general poorly characterized. In fact, for many years the matrix of some C chondrites was referred to as PCP ("poorly characterized phase") [6]. The second caveat, is that due to the mechanical weakness of C chondrites they are rare on earth and there are almost certainly major selection effects in the delivery of meteorites to earth and to our museums [7]. The material reaching Earth may not be representative.

We are proposing an alternative approach, which is to characterize a wide variety of phyllosilicates and predict the appearance of their spectra were they to be present on asteroid surfaces [8, 9]. A well-known characteristic of asteroid surfaces is that they have been heavily impacted, heated, and mixed in regolith [10]. Such processes have been well-studied using meteorites and lunar samples and the net effect is heating [11]. Thus we have subjected a suite of phyllosilicates of diverse composition and structure to heat treatments and obtained their near-IR spectra. We compare the results with data for eleven C asteroids, we have obtained using IRTF [12], and for C chondrites using spectra obtained from the on-line databases. Here we report recent developments in our work.

Experimental: Since the heat treatments weaken and remove absorption features, to produce the relatively flat spectra we see on asteroids, we focus on the slopes of their continua as defined in Fig. 1. We chose the spectra regions 1.0-1.75 and 1.8-2.5 μm because there often seemed to be a discontinuity at ~1.8 μm but within these intervals the spectra are reproducible and well-characterized. A negative slope at long wavelengths reflects a variety of complex water-host interations, while the meaning of a positive slope is unclear. We obtained five phyllosilicates from Ward's Scientific (Table 1). Samples were heated in air and argon at temperatures 100-1100°C in 100°C intervals and the IR spectra obtained.

Table 1. Phyllosilicates used in the present study with relevant data.

<table>
<thead>
<tr>
<th>Sample, Catalog No., Location</th>
<th>Nominal Composition</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite, 46E0995, Edgar, Florida</td>
<td>Al₃(Si₂O₅)(OH)₁₂</td>
<td>1:1</td>
</tr>
<tr>
<td>Serpentine, 46E7263, Eden Mills, Vermont</td>
<td>Mg₃Si₂O₅(OH)₁₂</td>
<td>1:1</td>
</tr>
<tr>
<td>Nontronite, 49E5108 Cheney, Washington</td>
<td>Na₂₃₋₅Fe⁶⁺Si₂₃₋₅Al₂O₁₀(OH)₂·4(H₂O)</td>
<td>2:1</td>
</tr>
<tr>
<td>Montmorillonite, 46E0438 Panther Creek, Colorado</td>
<td>(Na,Ca)₉₋₁₀(Al,Mg)₂Si₂O₅(OH)₂·(H₂O)₁₀</td>
<td>2:1</td>
</tr>
<tr>
<td>Chlorite, 46E1923, Madison Co., North Carolina</td>
<td>Mg₆Fe⁶⁺₂(Al,Si)₂O₁₀(OH)₂₃</td>
<td>2:1:1</td>
</tr>
</tbody>
</table>

Fig. 1. Representative spectra for an asteroid, a meteorite and a terrestrial phyllosilicate explaining how continua slopes were determined. The spectra are normalized to 0.875 μm and are displaced vertically for clarity. Such slopes seem to be an excellent way to characterize the spectra as discrete features are first weakened and removed.
Results: Figure 2 summarizes the results of our phyllosilicate measurements. The phyllosilicates occupy a large field with negative slopes over the longer wavelength interval with no simple correlation with composition or structure. Upon heating, their data migrate across the phyllosilicate field in reasonable agreement with prior work of Hiroi and coworkers whose heating experiments terminated at 600°C [13, 14]. Above 700°C the data leave the phyllosilicate field and form a number of fairly well-constrained fields with positive long wavelength slopes. It is well known that phyllosilicates lose their chemically bound water when heated to >600°C.

Fig. 2: Continua in the short wavelength interval plotted against against continua in the long wavelength region. (a, above) Phyllosilicates, C asteroids, and CM chondrites plot in the fields indicated. Other classes of C chondrite, plot in the C asteroid field. (b, below) The fields marked AK, AM, AS, AC, AN, refer to data for samples of kaolinite, montmorillonite, serpentine, chlorite, and nontronite, respectively, heated above 700°C.

Discussion: Taken at face value, our experiments are consistent with the conclusion that C asteroids are mineralogically most similar to kaolinite and montmorillonite that has been heated by impact processes to temperatures in excess of 700°C. This conclusion is broadly consistent with the proposed mineralogy of many of the C chondrite classes that plot in the C asteroid field. Similarly, our experiments are consistent with the idea that CM chondrites are composed of serpentine and chlorite heated above 700°C, and again this is consistent with the understood mineralogy of the CM class. While a large variety of phyllosilicates have been reported in CM and other C chondrites (see ref 15 for a review), there has been no suggestion that nontronite is present in C asteroids or CM chondrites and this is consistent with the present data.

While we have limited our analysis to the near IR, studies made outside this interval (reviewed in the Introduction above) and which largely related to the presence of water, and phyllosilicates on the C asteroids, are essentially in agreement with our findings. We mention in passing that the heating experiments of Hiroi are consistent with the surfaces of C asteroids being heated equivalents of the CM and CI chondrites [13].

A perplexing issue for C asteroid and C chondrite spectroscopic studies is why the CM chondrites, which contain up to 20 volume % water, and are supposed to be composed of phyllosilicates, have such featureless spectra (Fig. 1). Half the water in these meteorites is not associated with phyllosilicates, but is trapped in the icy solids (such as MgSO₄·7H₂O, epsomite), which are probably evaporites, as water of crystallization [15]. A mixture of phyllosilicates and cryohalite would explain the loss of certain spectral features, but not the loss of the negative long wavelength continuum slopes. Either the silicates in C chondrites are "painted" with an opaque (possible organic) substance, or the minerals are largely amorphous. This would be consistent with the CM chondrites consisting of amorphous impact dehydrated phyllosilicates to which water had subsequently been added. In this case, the surfaces of asteroids are not phyllosilicates, but are largely amorphous.

Investigation of Phyllosilicates, C Chondrites, and C Asteroids Using Continuum Slopes of Near Infrared Spectra

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Introduction

- While C asteroids sometimes display a 3.0 μm water feature [1], and a 0.7 μm Fe²⁺ feature [2], matching their C-chondrites is difficult due to the weak features in their reflectance spectra.
- C chondrites consist essentially of phyllosilicates, but there is uncertainty in their exact nature [3]. CMa and CMb contain up to 10 and 20%, water [4].
- Images of asteroid surfaces show that impact, thermal processing, and regolith gardening are important in determining their nature.
- Laboratory heating experiments on CMs provide a reasonable match in continuum shape for the spectra of five C asteroids [5]. Heating studies of five phyllosilicates heated only to 500°C suggest the phyllosilicate on C asteroid surfaces was seaponite, which is rare in CM chondrites [6].
- Here we report heating experiments on five terrestrial phyllosilicates up to 1100°C and compare results with spectra of carbonaceous chondrites and seaponite C asteroids. We rely mainly on continuum slopes as a basis for comparison.

Experimental

- Phyllosilicates heated at 100°C intervals between 300 to 1100°C.
- Heating durations for 300 to 900°C samples were 24 hours, and six hours for 1000 and 1100°C.
- Reflectance spectra of the heated phyllosilicates were used using a Nicolet 7100 FTIR over the range 0.5 to 2.5 μm.
- Asteroids observed using IRTF over the range 0.5 to 2.5 μm.
- Meteorite spectra from online databases and publications [5,7,8].
- We quantify the curves by comparing the continuum slope between 1.0 to 1.75 μm with the continuum slope between 1.8 to 2.5 μm.

Conclusion

- Continuum plots are useful. Venus phyllosilicates occupy a large field with negative slopes in 1.8-2.5 μm regions, heating above 700°C moves the data into narrowly constrained fields that, nontronite asides, overlap with the C asteroids and C chondrites.
- C asteroids are mineralogically most similar to heated ilmenite and magnetite.
- C chondrites classes, except for the CMs, appear to have similar mineralogy.

References

APPENDIX D

Asteroidal Origins for Carbonaceous Chondrites

Abstract and poster to the 72\textsuperscript{nd} Annual Meeting of the Meteoritical Society, 2009.
ASTEROIDAL ORIGINS FOR CARBONACEOUS CHONDRITES. D. R. Ostrowski¹, D. W. G. Sears¹,², C. H. S. Lucy¹,³ and K. M. Gietzen¹. ¹Arkansas Center for Space and Planetary Sciences. E-mail: dostrow@uark.edu. ²Department of Chemistry and Biochemistry. ³Department of Physics, University of Arkansas.

Introduction: While it is generally assumed that C chondrites are related to C complex asteroids, relatively few details are available. The UV slope and weak water-related features at 0.7 μm, and 3.0 μm are available for comparison and close matches have been reported between asteroid 31 Euphrosyne with meteorite Belgica 7904 and between asteroid 704 Interamnia and Yamato 82162 [1]. CM chondrites have been linked to the G asteroids [2]. Here we have developed a method of comparison by using the slopes of the continua in their IR spectra.

Methods: Our asteroid database consists of IR spectra for 18 C and X complex asteroids we have collected with the NASA IRTF telescope on Mauna Kea, HI. Data for meteorites were taken from the NASA PDS database. Plots were prepared of the continuum slope between 1.8-2.5 μm against the continuum slope of 1.0-1.75 μm.

Results: On such “continuum plots” the chondrites plot in the same general region as the C and X complex asteroids.

The two CI chondrites in this study (Ivuna andOrgueil) showed poor agreement between data from different laboratories, presumably reflecting their heterogeneity, however the data do not readily connect them with either the C or X asteroids.

The CM chondrites plot with the X complex asteroids, especially the Xc class. Migei and Nogoya are slight outliers but could be connected to the Xc or X asteroid classes.

Most of the remaining C chondrite classes plot in the C asteroid fields. The CR, CV, and CK chondrites are linked to the Cg, Cgh, or Ch asteroids. A group of Antarctic CI/CM chondrites are spectrally similar to the B and X classes.

Discussion: Continuum plots are a successful method for quantitatively comparing spectra for meteorites and asteroids.

The number of individual classes of asteroid and C chondrites is large relative to the number of IR spectra available, so some of the data fields are poorly populated. However, based on existing data a number of new meteorite-asteroid links are proposed that are reasonable in terms of the known mineralogy of meteorites and proposed mineralogy of asteroids [3]

Asteroidal Origins for Carbonaceous Chondrites

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3Department of Physics, Fayetteville, AR 72701

Introduction

- It is generally assumed that C chondrites are related to the C asteroid family, even though relatively few details are available.
- A link between C class asteroids and specifically CM chondrites is made because both groups have low albidos and for the most part featureless spectra [1].
- C asteroids sometimes display a UV slope, weak water related features at 3.0 μm [2] and a 0.7 μm Fe³⁺ feature [3] similar to one in C chondrites.
- Close matches have been reported between asteroid 31 Euphrosyne and meteorite Beigica 7904 and between asteroid 704 Interamnia and meteorite Yamato 82162 [4].
- CM chondrite parent bodies have been suggested to be asteroids 13 Egeria and 19 Fortuna [5].
- In general, compositional fingerprinting of C chondrites and C asteroids is difficult due to the weak features in their reflectance spectra, though the meteorites have stronger features than the asteroids.
- Images of asteroid surfaces show that impact, thermal processing, and regolith gardening are important in determining their nature.
- Here we have developed a method of comparison by using the slopes of the continua in the their near infrared spectra.

Experimental

- Asteroids have been observed by using NASA's IRTF on Mauna Kea, HI in the range 0.8 to 2.5 μm and also have been obtained from an online database [7].
- Meteorite spectra are from online databases and publications [4,7,8].
- We quantify the curves by plotting the continuum slope between 1.0 and 1.75 μm and the continuum slope between 1.8 and 2.5 μm

Discussion

- Continuum plots are a useful method for quantitatively comparing spectra for meteorites and asteroids.
- The number of classes of asteroids and C chondrites is large relative to the number of IR spectra available, thus some of the data fields are poorly populated.
- A number of new meteorite-asteroid links are proposed (Table 1).
- Links are reasonable in terms of known phyllosilicates in C chondrites and comparison of asteroids to heated phyllosilicates [9,10].

References:

Appendix E

Heating Experiments on Phyllosilicate-Evaporite Mixtures: Implications for the Surface Composition of C Asteroids

HEATING EXPERIMENTS ON PHYLLOSILICATES-EVaporITE MIXTURES: IMPLICATIONS FOR THE SURFACE COMPOSITION OF C ASTEROIDS. D. R. Ostrowski, D. W. G. Sears, C. H. S. Lacy, and K. M. Gietzen, 1, 2Arkansas Center for Space and Planetary Sciences, (dostrow@uark.edu), 3Department of Chemistry and Biochemistry, 4Department of Physics, University of Arkansas, Fayetteville, AR 72701, USA.

Introduction: The complex of C and X asteroids constitutes about 40% of both the debiased near-Earth and main belt asteroid populations [1], but due to the spectral features being weak or absent, little is known about their detailed mineralogy. Many of the C complex asteroids contain a feature at 3 μm caused by water absorption [2], and this feature has been correlated with a broad, weak 0.7 μm feature stated to be due to Fe⁺ in phyllosilicates [3, 4]. Similar features are observed in CM chondrites. The C asteroids and the C chondrites both show relatively featureless spectra, especially when compared with spectra for phyllosilicates and evaporites (Fig. 1). However, it is still assumed that the C chondrites are related to the C asteroids and therefore the surfaces C asteroids are composed mostly of Fe-rich phyllosilicates, with other minerals such as opaque minerals and evaporites. However, there are three caveats that should be kept in mind. One is that the silicates in C chondrites are highly complex mixtures of phases, which generally are poorly characterized. The second caveat, is that due to the mechanical weakness of C chondrites they are rare on earth and there are almost certainly major selection effects in the delivery of meteorites to earth [5]. The material reaching Earth may not be representative of the C and X asteroid complexes. The third caveat is that some of the evaporites might be terrestrial origin [6], but given the amount of evaporites in these observed falls, we suspect that any terrestrial component is minor.

We are proposing an alternative approach, which is to characterize a small set of phyllosilicates mixed with evaporites that are both known to be in C chondrites. A simple mass-balance calculation demonstrates that evaporites may constitute as much as 45.06% by mass in Alais and 26.93% in Orgueil. A well-known characteristic of asteroid surfaces is that they have been heavily impacted, heated, and mixed in regolith [7]. Such processes have been well-studied using meteorites and lunar samples and the net effect is heating [8]. Thus we have subjected the suite of phyllosilicate-evaporite mixtures to heat treatments and obtained their near-IR spectra. We compare the results with data for C and X complex asteroids and for C chondrites.

Experimental: The phyllosilicates serpentine and chlorite are the most common phyllosilicates in C chondrites. These phyllosilicates have been mixed with the evaporates epsomite and gypsum, which are common evaporates in C chondrites. Numerical mixing of the reflectance spectra of the silicates and the evaporites was conducted to produce the flattest (most asteroidal) spectra. These mixtures were heated between 100 and ~1100°C for 24 hours, 8 hours for the two highest temperatures, and the IR spectra obtained.

Since the heat treatments weaken and remove absorption features, to produce the relatively flat spectra we see on asteroids, we focus on the slopes of their continua as seen in Fig. 1. We chose the spectral regions 1.0-1.75 and 1.8-2.5 μm because there often seemed to be a discontinuity at ~1.8 μm in the phyllosilicates, but within these intervals the spectra are reproducible and well-characterized [9, 10].

Fig. 1. Representative spectra explaining how continua slopes were determined. The spectra are normalized to 0.875 μm and are displaced vertically for clarity. Slopes appear to be an excellent way to characterize and compare the spectra of C and X complex asteroids because their spectra are for the most part featureless.

Results: Figure 2 summarizes the results of work. The phyllosilicates occupy a large field with negative slopes over the longer wavelength interval. The mixture of phyllosilicates and evaporites plots in or near the terrestrial phyllosilicates field. Ovals for the C and X asteroid complexes and for CM chondrites are above the phyllosilicates because of an overall flat to slight increasing slope. Upon heating, the data points migrate through the phyllosilicate field. Above 600°C for the mixes with gypsum and above 1000°C for the mixes with epsomite the data leave the phyllosilicate field and move closer to or into the CM chondrite field.
Discussion: The sample of 40wt% serpentine-60wt% epsomite heated to 1150°C is the only mixture to plot in an asteroid field, the X complex. The experiments are consistent with the idea that CM chondrites are composed of any one of these mixtures heated to or above 1000°C, above 800°C in Fig 2d. Most C chondrites, the major exception being the CMs, plot in the C asteroid field [10]. Yet, none of the mixtures heated to any temperature plot in the C asteroid field. This is because they maintain, at higher treatment temperatures, a slightly steeper continuum slope in the 1.8 to 2.5 μm region. The only sample that plots close to the C asteroid field is the 400°C 40wt% serpentine-60wt% epsomite, where it plots just below the field. This is most likely due to the minerals retaining water of crystallization. The increasing positively-sloped continuum past 1.8 μm could be flattened out by the minerals being “painted” with an opaque (possible organic) substance.

An issue for C asteroid and C chondrite spectroscopic studies is why the CM and CI chondrites can contain up to 10 and 20 volume % water respectively, are supposed to be composed of phyllosilicates and some evaporites. Both of these mineral species can contain large amounts of water. It is possible for both of them to jointly hold most of the meteorite water [11]. The high temperatures required to cause the mixtures spectra and continuum data to be similar to the asteroids and meteorites would remove all forms of water and turn the minerals into decomposition products or an amorphous state. The question is what is happening with the water? It is most likely subsurface to allow these minerals to form and is lost to space weathering effects when impact and gardening brings it to the surface. In the case of the CM chondrites consisting of impact dehydrated minerals the water could be added later. The heating experiments of Hiroi are also consistent with the surfaces of C asteroids being heated equivalents of the CM and CI chondrites [12].

Heating Experiments on Phyllosilicates-Evaporite Mixtures: Implications for the Surface Composition of C and X Asteroids

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Carbonaceous Chondrites
- CI and CM chondrite mineralogy displays evidence of aqueous alteration
  - CH, CV and CO chondrites showing some stages of aqueous alteration
  - Known mineral phases are mostly phyllosilicates and evaporites
  - Evaporites can hold up to half of the meteorite water
    - Episalite can hold 6.7-8.6 wt% water for Orgueil
  - 0.7 μm feature in CMs gives Fe-phyllosilicate like to C asteroids

C and X Complex Asteroids
- C and X asteroids constitute about 40% of both the debiased near-Earth and main belt asteroid populations (Gietzen et al. 2010 submitted)
- Little is known about their detailed mineralogy
- Most X asteroids have similar albedos to C asteroids
- X asteroids are slightly steeper sloped than C asteroids
- Many C and some X asteroids have shown the 3.0 μm O-H feature
- OH and ClH have a weak and broad 0.7 μm band spectral feature attributed to hydrated iron oxides associated with phyllosilicates (Viss and Geffery, 1999)
- XH have a faint feature between 0.8-1.0 μm

Procedure
- Phyllosilicate (serpentine and chlorite) are mixed with evaporites (episalite and gypsum)
- Numerical mixing of the reflectance spectra of the silicates and the evaporites was conducted to produce the fastest (least asteroidal) spectra
- Mixtures heated between 100 and ~1100°C for 24 hours, 8 hours for the two highest temperatures
- IR spectra obtained
- Measure the continuum slopes between 1.0-1.75 μm and 1.8-2.5 μm
- Plot long wavelength continuum slope vs. short wavelength continuum slope

Numerical Mixing

Reflectance of Mineral Mixtures

Continuum Plot: Asteroid and Heated Mixtures
- 40 wt% Serpentine - 60 wt% Epsomite
  - X complex
  - Terrestrial phyllosilicate field

Continuum Plot: Asteroid and Heated Mixtures
- 40 wt% Serpentine - 60 wt% Gypsum
  - C complex
  - Terrestrial phyllosilicate field

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Conclusion

- 40wt% Serpentine - 60wt% Epsomite heated to 1000 and 1150°C are the only mixtures to plot in X asteroid field
- 400°C 40wt% Serpentine - 60wt% Gypsum plots just below the C asteroid field
  - Is closest sample to matching just the C asteroids
- Increasing positively-sloped continuum from 1.0 to 1.75 μm could be flattened out by the minerals being painted with an opaque substance

Water Conclusion

- Water is located in both phyllosilicates and evaporites in CI chondrites and probably some asteroids, in about equal amounts.
- Impact heating on the surface will have removed water from these phases to produce decomposition products much of which is amorphous
- Water-rich phases may still be abundant below the asteroid surface
- C chondrites must be subsurface ejecta from major impacts