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The Physical Properties and Composition of Main-Belt Asteroids from Infrared Spectroscopy

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THE PHYSICAL PROPERTIES AND COMPOSITION OF MAIN-BELT ASTEROIDS FROM INFRARED SPECTROSCOPY

by

ZOE A. LANDSMAN
B. S. University of Central Florida, 2011

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics in the Department of Physics in the College of Science at the University of Central Florida Orlando, Florida

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Major Professor: Humberto Campins
ABSTRACT

Asteroids are the remnants of planet formation, and as such, they represent a record of the physical and chemical conditions in the early solar system and its evolution over the past 4.6 billion years. Asteroids are relatively accessible by spacecraft, and thus may be a source of the raw materials necessary for future human exploration and settlement of space. Those on Earth-crossing orbits pose impact hazards for which mitigation strategies must be developed. For these reasons, several missions to asteroids are in progress or planned with the support of the National Aeronautics and Space Administration (NASA) and other national space agencies. The study of asteroid composition and physical surface properties is vital to both our scientific understanding of the solar system’s formation and evolution and to the development of asteroid missions and resource utilization schemes. This dissertation uses infrared spectroscopy to investigate the composition and physical properties of main-belt asteroid surfaces. Our efforts are focused on two populations that are especially relevant to constraining thermal and collisional processes in the asteroid belt: the “M-type” asteroids and primitive asteroid families.

To investigate volatiles in the M-type asteroids, we obtained 2–4 μm spectra of six M-type asteroids using NASA’s Infrared Telescope Facility. We find spectral signatures of hydrated minerals on all six asteroids, with evidence for rotational variability of hydration in one target. Diversity in the shape of the 3-μm feature in our sampled asteroids suggests there are different modes of hydration in the M-type population. Next, we carried out a thermal and compositional study of M-type asteroid (16) Psyche using 5–14 μm spectra from the Spitzer Space Telescope. Psyche is suspected to be a remnant iron core, and it
is the target of an upcoming NASA mission. Using thermophysical modeling, we find that Psyche’s surface is smooth and most likely has a thermal inertia $\Gamma = 5-25 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-1/2}$ and bolometric emissivity $\epsilon = 0.9$, although a scenario with $\epsilon = 0.7$ and thermal inertia up to $95 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-1/2}$ is possible if Psyche is somewhat larger than previously determined. From comparisons with laboratory spectra of silicate and meteorite powders, Psyche’s emissivity spectrum is consistent with the presence of fine-grained ($<75\mu\text{m}$) silicates. These silicates may include a magnesian pyroxene component. We conclude that Psyche is likely covered in a fine silicate regolith, which may also contain iron grains, overlying an iron-rich bedrock.

Finally, we compared the mid-infrared properties of two primitive asteroids families, ancient Themis ($\sim2.5\text{ Gyr}$) and young Veritas ($\sim8\text{ Myr}$). Visible and near-infrared studies show spectral differences between the two families attributed to different degrees of space weathering. To test whether these differences are apparent in the mid-infrared, we analyzed the $5 – 14\mu\text{m}$ Spitzer Space Telescope spectra of 11 Themis-family asteroids and 9 Veritas-family asteroids. We detect a broad $10-\mu\text{m}$ emission feature, attributed to fine-grained and/or porous silicate regolith, in all 11 Themis-family spectra and six of nine Veritas-family asteroids, with $10-\mu\text{m}$ spectral contrast ranging from $1\% \pm 0.1\%$ to $8.5\% \pm 0.9\%$. Comparison with laboratory spectra of primitive meteorites suggests these asteroids are similar to meteorites with relatively low abundances of phyllosilicates. We used thermal modeling to derive diameters, beaming parameters and albedos for our sample. Asteroids in both families have beaming parameters near unity and geometric albedos in the range $0.031 – 0.14$. Spectral contrast of the $10-\mu\text{m}$ silicate emission feature is not correlated with asteroid diameter; however, higher $10-\mu\text{m}$ contrast may be associated with flatter spectral slopes in the near-infrared. There is a slight trend of increasing $10-\mu\text{m}$ contrast with decreasing albedo in the Veritas asteroids, but not the Themis asteroids. Overall, our results indicate the Themis and Veritas family members show variation in regolith texture and/or structure within both families that is not directly related to family age.
I dedicate this dissertation to my father, Joel Philip Landsman, who fostered my love of learning and scholarship.
ACKNOWLEDGMENTS

This monumental undertaking would not be possible without the support and generosity of many individuals. First, I want to acknowledge my advisory committee. To my advisor and committee chair, Dr. Humberto Campins, thank you for your unwavering confidence in me, for welcoming me back to academia, for giving spot-on professional advice, and for all you’ve taught me about science and about this field over the years. To Dr. F. Eloy Hernández, thank you for providing your unique perspective as a chemist and for challenging me to think outside of the Planetary Science box. To Dr. Josh Emery, thank you for taking a chance on working with me when I was a brand-new graduate student, for all the time you’ve spent teaching me the ins and outs of thermophysical modeling, and for demonstrating a careful and thorough approach to doing science that I hope to emulate. To Dr. Dan Britt, thank you for the myriad opportunities you’ve provided for me over the years, for always having an eye on the big picture and reminding me to do the same, and for your entertaining stories. To Dr. Yan Fernández, thank you for the countless times you’ve made yourself available to answer my questions, for always answering those questions with an abundance of patience and kindness, for teaching me nearly everything I know about observing, and for your friendship and sense of humor through many crazy outreach events.

I have benefitted tremendously from the mentoring, encouragement, and advice of the UCF Planetary Science community. This is an exceptional group of people. Among the faculty, I want to especially acknowledge Addie and Josh, who have inspired and encouraged me throughout this endeavor. One of the best parts of this experience has been the camaraderie among my student cohort. I want to especially thank Tracy, Akbar, and Charles for their friendship and support. I’d also like to acknowledge my friends outside of UCF who listened sincerely and patiently to all my asteroid ravings, especially Natalie and Mark.

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\( a \)  \quad \text{Semi-major axis}

\( A_B \)  \quad \text{Bond albedo}

\( \text{AU} \)  \quad \text{Astronomical unit (1 AU = 1.496 \times 10^8 \text{ km})}

\( B_\lambda \)  \quad \text{Planck function}

\( \text{CDF} \)  \quad \text{Cumulative distribution function}

\( \text{CNSA} \)  \quad \text{China National Space Administration}

\( c_p \)  \quad \text{Specific heat capacity}

\( \text{ESA} \)  \quad \text{European Space Agency}

\( e \)  \quad \text{Eccentricity}

\( \text{FRM} \)  \quad \text{Fast-Rotating Model}

\( G \)  \quad \text{Slope parameter}

\( H \)  \quad \text{Absolute magnitude}

\( i \)  \quad \text{Inclination}

\( \text{ILM} \)  \quad \text{Isothermal Latitude Model}

\( \text{IR} \)  \quad \text{Infrared (0.8–1000\,\mu m)}

\( \text{IRS} \)  \quad \text{Infrared Spectrograph (Spitzer Space Telescope instrument)}

\( \text{IRTF} \)  \quad \text{Infrared Telescope Facility}

\( \text{JAXA} \)  \quad \text{Japan Aerospace Exploration Agency}

\( \text{JPL} \)  \quad \text{Jet Propulsion Laboratory}
JWST  James Webb Space Telescope

\textit{Jy}  Jansky (1 Jy = 10^{26} \text{W/m}^2/\text{Hz})

\textit{l_s}  Thermal skin depth

NASA  National Aeronautics and Space Administration

NEA  Near-Earth Asteroid

NEATM  Near-Earth Asteroid Thermal Model

NEO  Near-Earth Object

NIR  Near-infrared (0.8–2.4 \text{µm})

Mid-IR  Mid-infrared (5–40 \text{µm})

PPF  Percent Point Function

PRIMASS  Primitive Asteroids Spectroscopic Survey

PSF  Point Spread Function

\textit{p_v}  Geometric albedo

\textit{r_H}  Heliocentric distance

RMS  Root Mean Square

SDSS  Sloan Digital Sky Survey

SED  Spectral Energy Distribution

SMASS  Small Main-Belt Asteroid Spectroscopic Survey

\textit{S_o}  Solar constant

SPICE  Spitzer IRS Custom Extraction software

SPITE  Spectral Pointing-Induced Throughput Error

STM  Standard Thermal Model

TNG  Telescopio Nazionale Galileo

TPM  Thermophysical Model

UV  Ultraviolet (0.01–0.4 \text{µm})
VIS  Visible (0.4–0.7 µm)
VISNIR  Visible and near-infrared (0.4–2.4 µm)
WISE  Wide-field Infrared Survey Explorer
YORP  Yarkovsky–O’Keefe–Radzievskii–Paddack

α  Phase angle
Δ  Distance to observer
ε  Bolometric emissivity
Γ  Thermal inertia
η  Beaming parameter
θ_e  Emission angle
θ_i  Incidence angle
λ  Wavelength
ρ_{bulk}  Bulk density
φ  Azimuthal angle
CHAPTER 1: INTRODUCTION

Asteroids are the remnants of solar system formation, and as such, are of great scientific interest. The largest asteroids may be nearly intact protoplanets, while the smallest are collisionally disrupted pieces of larger objects that sample a range of compositions, differentiation states, and thermal histories. The asteroids contain a record of the physical and chemical conditions in the early solar system and its evolution. Water-bearing asteroids may have played a role in the delivery of water to Earth (Morbidelli et al., 2000). Through observational studies of asteroids, we place constraints on models of solar system formation and evolution, differentiation, volatile transport, space weathering, and thermal and aqueous alteration processes.

The study of asteroids is also of practical concern. The accessibility of asteroids, especially those on orbits near the Earth, make them potentially valuable resources for extended robotic and crewed space missions. In-situ resource utilization (ISRU) may one day allow the production of fuel, drinking water, habitats, and communication devices in space from the materials on asteroid surfaces (e.g., rock, water, metal). Furthermore, asteroids on Earth-crossing orbits represent potential impact hazards. The presence of such hazards was demonstrated most recently by the Chelyabinsk event, in which a $\sim$19m-diameter asteroid exploded in Earth’s atmosphere near Chelyabinsk, Russia. The bolide released 500 kT TNT of energy, and the resulting shockwave injured over 1500 people and caused significant property damage (Borovička et al., 2016).

Because of their scientific and practical value and relative accessibility, asteroids have been and continue to be the targets of spacecraft missions. The first mission to include an asteroid flyby was NASA’s Galileo, which encountered Asteroid (951) Gaspra in 1991. Two
years later, Galileo also encountered Asteroid (243) Ida, and discovered Ida’s moon, Dactyl. Since then, 10 other asteroids have been encountered by spacecraft sent by NASA, the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the China National Space Administration (CNSA). Several asteroid missions are in progress. These include NASA’s OSIRIS-REx sample-return mission to NEA (101955) Bennu, currently cruising with encounter to begin in 2018, and JAXA’s Hayabusa-2 sample-return mission to NEA (162173) Ryugu, also arriving in 2018. Recently, two asteroid missions were selected from the Discovery mission class finalists. These are Psyche, a mission to metal-rich asteroid (16) Psyche (on which a portion of this dissertation is focused), and Lucy, which will tour six Jupiter Trojan asteroids (see Section 1.1).

Increasing our knowledge of asteroid characteristics improves our understanding of solar system formation and evolution, provides a background for interpreting results from asteroid missions, and informs decisions about resource utilization and hazard mitigation. This dissertation focuses on the study of the composition and other surface properties of several intriguing groups of main-belt asteroids using infrared spectroscopy. The remainder of this introductory chapter is dedicated to developing the framework and motivation for the work presented in this dissertation.

1.1 Asteroid Populations

The asteroids reside in several distinct populations (Figure 1.1). Most exist in the so-called main asteroid belt (or “main belt”) between Mars and Jupiter, with semimajor axes ($a$) between 2.1 and 3.3 AU and inclinations $i < 20^\circ$ (Cibulková et al., 2014). This dissertation focuses primarily on the study of main-belt asteroids; however, the main belt is related to other asteroid populations. Orbital resonances with the gas giants perturb the orbits of main-belt asteroids and produce gaps in the main belt. The near-earth asteroids (NEAs)
are populated primarily by ejected main-belt asteroids (Bottke et al., 2002); thus, the NEAs sample the portions of the main belt that efficiently deliver asteroids to near-Earth space through resonances. Other notable asteroid populations include: the Hungarias, between Mars and the main belt; the Cybeles, between 3.3–3.5 AU; the Hildas, in the 3:2 resonance with Jupiter near 4 AU; and the Jupiter Trojans, which reside in Jupiter’s the L4 and L5 Lagrangian points at 5.2 AU.

Figure 1.1: The first 200,000 numbered asteroids in the space of inclination ($i$) and semi-major axis ($a$). The red points represent main-belt asteroids. Other notable populations are labeled. Mean-motion resonances with Jupiter, which create structure in the asteroid belt, are labeled and denoted with dashed vertical lines. Asteroid orbital elements were obtained from the the The Asteroid Orbital Elements Database (AstOrb; ftp://ftp.lowell.edu/pub/elgb/astorb.html).

1.2 Asteroid-Meteorite Connections

Meteorites are collisionally disrupted pieces of asteroids (or, rarely, the Moon or Mars) on Earth-crossing orbits that have survived to the Earth’s surface. Meteorite collections are biased by physical factors (e.g., the ability of a given material to survive atmospheric entry and terrestrial weathering) and human factors (e.g., some meteorites are more easily identified than others). Nevertheless, meteorites provide ground truth to which asteroid data can be compared and with which asteroid compositional inferences can be made.
In the most broad sense, meteorites are from either primitive or processed parent bodies. Primitive meteorites are generally characterized by the presence of chondrules, millimeter-scale spherical silicate grains. Chondrules condensed early at very high temperatures in the solar nebula, although the exact mechanism of their formation is still debated (Scott, 2002). Further distinction can be made between volatile-rich primitive meteorites, such as the carbonaceous chondrites, and those that are depleted in volatiles, such as the ordinary and enstatite chondrites.

Meteorites from parent bodies that experienced complete or partial melting may be achondritic stones or they may be either stony-irons (a mixture of rock and iron metal) or irons (mostly iron-nickel metal). Because various subclasses of these meteorite types are referred to throughout this dissertation, a summary of the most common meteorite classes is presented in Table 1.1.

Table 1.1: Table of Common Meteorite Classes. Adapted from Figure 8 in chapter “Meteorites” (Encyclopedia of the Solar System) by M. E. Lipschutz and L. Schultz.

<table>
<thead>
<tr>
<th>Chondrites</th>
<th>Ordinary</th>
<th>Enstatite</th>
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<tbody>
<tr>
<td>Carbonaceous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CI,CM,CO,CV,CK</td>
<td>H,L,LL</td>
<td>EH,EL</td>
</tr>
<tr>
<td>Achondrites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irons</td>
<td>Stony-Irons</td>
<td>Stony Achondrites</td>
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<tr>
<td>Hexahedrites</td>
<td>Mesosiderites</td>
<td>Aubrites (Enstatite Achondrites)</td>
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<tr>
<td>Octahedrites</td>
<td>Pallasites</td>
<td>Ureilites</td>
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<tr>
<td>Ataxites</td>
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<td>Brachinite</td>
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<td></td>
<td></td>
<td>Acapulcoites</td>
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<td></td>
<td></td>
<td>Lodranites</td>
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<tr>
<td></td>
<td></td>
<td>Winonaites</td>
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<tr>
<td></td>
<td></td>
<td>HEDs (Howardites, Eucrites, Diogenites)</td>
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<tr>
<td></td>
<td></td>
<td>Martian meteorites</td>
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<tr>
<td></td>
<td></td>
<td>Lunar meteorites</td>
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</tbody>
</table>
Comparison and linkage of asteroids to meteorites is complicated by the fact that asteroids are subject to surface evolutionary processes that change their optical properties. Understanding the nature of these processes, described in the next section, is key to making connections between asteroids and meteorites.

1.3 Asteroid Evolutionary Processes

1.3.1 Melting and Differentiation

The meteorite record shows that early asteroids experienced different degrees of thermal metamorphism. For example, iron meteorites and basaltic meteorites (e.g., the eucrites) must have originated in a parent body that experienced a significant degree of melting and differentiation, while the chondrites are relatively pristine. Parent body heat sources include short-lived radioisotopes (especially \(^{26}\text{Al}\)), accretional gravitational energy, and energy delivered by impacts. Radiogenic heating by \(^{26}\text{Al}\) is probably the most relevant heat source. Meteorite studies show that radiogenic heat from \(^{26}\text{Al}\) decay could internally melt asteroids with diameters \(>\sim 10\) km if they formed in the first \(\sim 1.5\) My after material condensed in the solar nebula (Scheinberg et al., 2015, and references therein).

Complete melting of a large, chondritic parent body should result in differentiation into an iron core, an olivine mantle, and a basaltic crust. The variety of iron meteorites in the meteorite record suggests they originate from \(\sim 50\) unique parent bodies (Goldstein et al., 2009); however, relatively few basaltic meteorites, and even fewer olivine meteorites have been recovered. In the asteroid belt, ground-based spectroscopic and radar studies have pointed to several iron core candidates among the “M” taxonomic class (see Section 1.4 on asteroid taxonomies), but basalt- and olivine-dominant asteroids are rare. Excluding (4) Vesta, the asteroid belt contains only 0.01% basaltic asteroids and 0.37% olivine asteroids, by
The second most massive asteroid, (4) Vesta, has a basaltic surface, and it appears to be an exception.

The prevalence and modes of differentiation in the asteroid belt are not yet thoroughly understood. The Dawn mission to (4) Vesta, long considered to be a nearly intact, differentiated protoplanet, has opened new questions about differentiation. Consolmagno et al. (2015) note that (4) Vesta’s density and mass distribution are inconsistent with a melted chondrite composition, and deep crater basins on its surface lack olivine. They suggest that its source material may have already been processed, or that collisional processes may have changed its physical properties. Indeed, impact simulations indicate that the mantle and crust of differentiated asteroids may be preferentially removed and destroyed in “hit and run” glancing collisions (e.g., Asphaug et al., 2006).

Partial melting of chondritic material may be common in the asteroid belt. Fu and Elkins-Tanton (2014) modeled melting of chondrites and found that melts of CV and CM carbonaceous chondrite compositions are negatively buoyant. This means it is possible for a body to have a differentiated (or partially differentiated) interior while maintaining a CV- or CM-like crust. The same is not true for ordinary or enstatite chondrites, for which melts should ascend to the surface and leave an achondritic crust. The results of Fu and Elkins-Tanton (2014) are consistent with the measurement of paleomagnetism in CV and CM carbonaceous chondrites, which suggests these primitive meteorites originated on a body with a liquid metallic core (Carporzen et al., 2011b).

### 1.3.2 Impact Processes

Asteroids are subject to impacts from other asteroids and comets. Impact events range from micrometeorite bombardment, to crater-forming impacts, to catastrophic collisions. Micrometeorites slowly grind an asteroid surface into very fine, powdery debris. On large asteroids, these fine particles are gravitationally retained as a soil (regolith) on the asteroid’s
surface. Regolith on large asteroids may be comparable to the lunar regolith, which is very fine (median size < 130 µm; Carrier, 1973) and highly porous (~ 40% porosity; Mitchell et al., 1972). The very fine texture of the lunar regolith was immediately noted by the Apollo astronauts; just after his famous first step onto the lunar surface, Apollo 11 astronaut Neil Armstrong reported to Mission Control, “… the surface is fine and powdery. [I can] pick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a small fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles.” The lunar regolith is shown in Figure 1.2.

![Figure 1.2](https://www.hq.nasa.gov/alsj/a11/images11.html)

Figure 1.2: The boot print of Apollo 11 astronaut Buzz Aldrin on a pristine portion of the lunar regolith. The upper layer of the lunar regolith is very fine, and may be similar to the regolith on large asteroids. This image was acquired from NASA’s Apollo 11 Image Library.

Large impacts affect the morphology and internal structure of asteroids. The majority of asteroids with diameters < 500 km are either fractured by impacts (macroporosity > 20%) or loosely-bound rubble piles (macroporosity > 30–50%) that reaccreted after impact disruption (Britt et al., 2002). Asteroid (25143) Itokawa, a suspected rubble pile and the target of JAXA’s Hayabusa mission, is shown in Figure 1.3a. Impacts sculpt the surfaces of asteroids by producing craters and tectonic features, as observed by the Dawn spacecraft.
on (4) Vesta (Figure 1.3b). Impact-related shock can jostle the constituents (e.g., regolith, pebbles, boulders) of an asteroid’s surface and move larger objects to the surface through granular convection (also known as the Brazil Nut Effect), an effect seen on the surface of Itokawa (Figure 1.3a). The presence of admixtures of exogenous material delivered by impacts is supported by the observations of in xenolithic clasts in meteorites (e.g., Zolensky et al., 1996) and is the suspected source of dark material observed by Dawn in and around some craters on (4) Vesta (Reddy et al., 2012, and references therein).

(a) (25143) Itokawa
(b) (4) Vesta

Figure 1.3: At left (a), rubble-pile candidate Asteroid (25143) Itokawa as seen from the Hayabusa spacecraft. Size-sorting of boulders on Itokawa’s surface is likely due to impact-generated granular convection. Image credit: JAXA. At right (b), a Dawn image of the second-largest asteroid (4) Vesta, showing impact craters and impact-related linear grooves on its surface. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

Catastrophic asteroid collisions sometimes result in the production of a family, a group of asteroids that were once part of the same object. Family members cluster in the space of orbital parameters (e.g., semimajor axis, eccentricity, inclination). Families are named after the largest remaining remnant of the family progenitor. Nesvorný et al. (2015) has identified 122 notable asteroid families using a hierarchical clustering method, although there are likely many more families that have not yet been identified. The 98 of these 122 notable asteroid
families that are in the low-inclination portion of main asteroid belt are shown in Figure 1.4. Observational studies of family members provide a unique opportunity to study the hetero- or homogeneity of the parent body. Families can also be used to study the effects of the space environment by comparing observations of young and old families of similar composition (see also Section 1.3.3).

Figure 1.4: Dynamical families (denoted in color) in the main asteroid belt in the spaces of eccentricity (left) and inclination (right) as a function of semi-major axis. The dynamical families and their orbital elements are defined by (Nesvorný et al., 2015) and the orbital data were acquired using NASA’s Planetary Data System (Nesvorný, 2015). Orbital elements for background asteroids were obtained from the the The Asteroid Orbital Elements Database (AstOrb; ftp://ftp.lowell.edu/pub/elgb/astorb.html)

1.3.3 Space Weathering

On airless bodies, exposure to the space environment affects surface properties over time. This so-called space weathering includes the effects of micrometeorite bombardment, incident energetic cosmic and solar rays, the solar wind, and thermal cycling. Space weathering has been studied in the most detail for the Moon. Before the Apollo missions, weathering processes were the suspected source of differences in reflectance between freshly excavated material and older lunar surfaces (Gold, 1955), which was later confirmed from studies of Apollo-era lunar samples (Hapke, 2001). Theoretical models, laboratory simulations,
ground-based observations, and spacecraft missions have shown that space weathering is also important on near-Earth and main-belt asteroids (e.g., Chapman, 1996; Clark et al., 2002; Brunetto et al., 2015; Pieters and Noble, 2016; Kaluna et al., 2016; Markley and Kletetschka, 2016). How it affects the surface depends on the asteroid’s composition and location.

Energy delivered by solar and cosmic rays, solar wind sputtering, and micrometeorite impacts alter the optical properties of minerals on airless surfaces. Insight into how this process affects bright asteroids (e.g., S-types, V-types, and E-types) comes from studies of lunar samples and laboratory studies of ordinary chondrites. For these materials, space weathering reddens spectral slopes, attenuates visible and near-infrared absorption bands, and darkens the surface (Chapman, 1996, and references therein). The suspected mechanism is the formation of nanophase iron rims around silicate grains (see Figure 1.5) and the amorphization of silicates (e.g., Brunetto et al., 2015). The effects of space weathering on S-type asteroids resolved the “S-type Conundrum”, which was the observation that the S-type asteroids have shallower absorption bands and redder slopes than unweathered ordinary chondrites (Chapman, 1996).

The effects of energetic radiation on dark, carbon-rich asteroids (e.g., C-types, P-types, D-types) is less understood, and may result in either reddening or bluing of spectral slopes through the breakdown and formation of organic compounds (Lazzarin et al., 2006; Lantz et al., 2013). Even among asteroids in which lunar-like space weathering is expected, there are differences in the effects of space weathering that are not yet fully understood. On the S-type asteroid (433) Eros, which was visited by the NEAR-Shoemaker probe, space weathering strongly affects albedo much more significantly than spectral slope, which is not the case for S-type asteroids (951) Gaspra and (243) Ida, both of which were visited by the Galileo spacecraft (Pieters and Noble, 2016).
Space weathering produces other changes to the physical and chemical nature of asteroid surfaces. As mentioned in Section 1.3.2, micrometeorite bombardment grinds asteroidal surfaces into fine regolith; however, melt generated from the energy of impact can also weld small particles together to form agglutinates. Portions of the surface and impactor also vaporize upon impact, creating alteration products. The solar wind can alter the composition of airless surfaces by implantation of H$^+$, producing hydroxyl through interactions with silicates (e.g., Schaible and Baragiola, 2014). This is the proposed source of the diurnally varying spectral signature of hydroxylated silicates on the Moon (Sunshine et al., 2009; Pieters et al., 2009; Clark, 2009). Thermal fatigue from diurnal temperature cycling may also be an important source of physical alteration on asteroids and the Moon. Laboratory studies show fragmentation and cracking of meteorite samples exposed to temperature cycling that simulates diurnal variations (Delbó et al., 2014). A visual summary of space weathering processes is presented in Figure 1.6.
1.3.4 Yarkovsky and YORP Effects

Because asteroid surfaces have non-zero thermal inertias, they experience thermal lag when heated by the sun; i.e., the “afternoon” part of the asteroid is hotter than the subsolar point. The result is a net difference in the directions in which sunlight is absorbed and re-radiated as thermal emission. Emitted thermal photons carry momentum $p = h/\lambda$, resulting in a recoil force on the asteroid. For the case of an asteroid with prograde (counterclockwise) rotation, the net force is in the direction of its orbital motion, while the net force opposes the direction of orbital motion for a retrograde rotator (Figure 1.7). This force is referred to as the diurnal Yarkovsky effect. The Yarkovsky effect leads to a slow but measurable drift in semimajor axis for asteroids with diameters less than 10 km (Bottke et al., 2006). Prograde rotators subject to the Yarkovsky effect will see an increase in semimajor axis, while retrograde rotators will drift inward.
Figure 1.7: This figure is reprinted with permission from “Planetary science: Spin control for asteroids” by Binzel (2003), appearing in Nature 425, 131–132.
Retrograde-rotating asteroids in the main belt will experience a decrease in semimajor axis due to the Yarkovsky effect, and those in the inner main belt may end up in the $\nu_6$ secular resonance with Saturn, which efficiently delivers asteroids to near-Earth orbits (Bottke et al., 2002). Indeed, the majority of NEAs are observed to have retrograde orbits (Bottke et al., 2006). The Yarkovsky effect can also be seen in studies of asteroid families. Family members will be left with random spin pole orientations after the family-forming impact. Over time, prograde rotators and retrograde rotators will drift in semimajor axis in opposite directions. Less massive asteroids will drift by a greater amount, which leads to a characteristic “V” shape in a scatter plot of family members’ absolute magnitudes (a proxy for mass) vs. their semimajor axes. Models of Yarkovsky drift are used to constrain the time since the family formed (Vokrouhlický et al., 2006).

A related effect is the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect. The YORP effect describes a net torque on an asteroid due to thermal emission at angles that are not normal to the surface due to irregular surface features. Albedo variations can also produce asymmetry in radiation pressure and lead to a net YORP torque. The YORP effect can increase or decrease an asteroid’s spin rate and can also precess its spin pole, especially on small asteroids, as it scales inversely with the square of the asteroid’s size. On small asteroids ($\leq 30$ km), the YORP effect generally results in an obliquity end state of $0^\circ$ or $180^\circ$ (Durech et al., 2015).

### 1.4 Asteroid Taxonomies

Taxonomies in which asteroids are grouped based on optical characteristics are useful to study the properties and distribution of related populations. Visible and near-infrared spectroscopy of asteroids, discussed in more detail in the next chapter, can be diagnostic of asteroid composition, so colors and spectra are commonly used to classify asteroids. Chap-
man et al. (1975) produced the first asteroid taxonomy using polarimetry, radiometry and spectrophotometry. After comparing the asteroid spectra with the spectra of meteorites, they designated two major classes, “S” and “C”, which resembled stony-metallic and carbonaceous meteorites, respectively. Using cluster analysis, Tholen (1984) designated seven major taxonomic types based on broad-band spectrophotometry, spanning the near-ultraviolet to the near-infrared, for 405 asteroids (the Eight-Color Asteroid Survey; Zellner et al., 1985).

New, more complex taxonomies arose with the advent of CCD detectors and improved visible and near-infrared spectrometers. Using visible spectra for 1447 asteroids from the second phase of the Small Main-belt Asteroid Spectroscopic Survey (SMASSII), Bus and Binzel (2002) created a new taxonomy using the framework of Tholen (1984). Their taxonomy includes 26 total classes, with three major groups (complexes): S, C, and X. S-complex members have a spectral decrease toward the UV and a 1-μm absorption feature. The S-complex endmember classes have characteristics similar to the S-types but with variations in the strength and center of the 1-μm band and the overall spectral shape. The C-complex asteroids generally have flat, featureless visible spectra longward of 0.4 μm, with a drop-off toward the UV short of 0.4 μm. The exception is the presence of the 0.7 μm phyllosilicate absorption feature in some C-complex classes (e.g., Ch, Cgh). The X-complex contains the spectrally degenerate asteroids with no or subtle absorption features and relatively linear, red-sloped spectra.

The Bus and Binzel (2002) taxonomy was modified by DeMeo et al. (2009b), who combined the SMASSII spectra with near-infrared (0.8–2.4 μm) spectra for 371 objects. The DeMeo et al. taxonomy eliminated three of the Bus and Binzel classes and created one, for a total of 24 classes, but the complexes are similar to those in the Bus and Binzel taxonomy. Table 1.2 presents a summary of classes in the Tholen, Bus and Binzel and DeMeo et al. taxonomies.
Meteorite analogs have been proposed for each asteroid taxon. By spectral analogy, the S-types (and the S-endmembers) and the C-types are probably related to ordinary chondrites and carbonaceous chondrites, respectively. The spectrally degenerate X-class represents a range of meteorite analogs, including the enstatite chondrites, the enstatite achondrites, irons, stony-irons, and some carbonaceous chondrites.

Although taxonomic classification is not necessarily diagnostic of mineralogy, asteroid taxonomic classes are related to composition; thus, studying the distribution of classes in the asteroid belt constrains and tests models of solar system evolution. Models of thermal gradients as protoplanets formed in the solar nebula suggest that high-temperature material should dominate the inner asteroid belt, while low-temperature, volatile-rich material should be prevalent in the outer asteroid belt (e.g., Grimm and McSween, 1993). Early observational studies of taxonomic distribution confirmed this view, with the distributions of S-types peaking in the inner belt and C-types in the outer belt (Gradie and Tedesco, 1982; Bell et al., 1989). These studies, however, were biased toward only the largest and brightest asteroids by the limitations of available detectors.

DeMeo and Carry (2013) debiased the Sloan Digital Sky Survey (SDSS) asteroid colors with a total of 58,607 observations and studied the distribution of taxonomic classes from these colors. As expected from previous work, they found that the majority of the mass of the inner-belt is contained in S-type asteroids and the majority of the mass in the outer belt is in C-types; however, accurate sampling of small and dark asteroids shows there is significant
complexity in the distribution of taxons (Figure 1.8). Miscellaneous types are distributed throughout the main belt, with notable mass concentrations related to specific asteroid dynamical families and the largest asteroids, (1) Ceres, (2) Pallas, and (4) Vesta. Dynamical models, such as the Nice model and the Grand Tack, suggest that the gravitational influence of migrating giant planets should cause significant mixing and redistribution of objects in the asteroid belt and transneptunian (or Kuiper) belt. These dynamical models are supported by the distribution of spectral types reported by DeMeo and Carry (2013, 2014).

![Figure 1.8: The mass of each spectral taxonomic asteroid class as a function of semi-major axis.](image)

Figure 1.8: The mass of each spectral taxonomic asteroid class as a function of semi-major axis. The dashed horizontal line represents the limiting mass accessible for the taxonomic distribution studies of the 1980s. This figure is reprinted with permission from “Solar System evolution from compositional mapping of the asteroid belt” by DeMeo and Carry (2014), appearing in Nature 505, 629–634.

### 1.5 Overview of Dissertation

This project began as a near-infrared survey of the primitive asteroid families that efficiently deliver asteroids to near-Earth orbits to better understand the populations from which spacecraft-targeted NEAs (e.g., Bennu and Ryugu, the targets of OSIRIS-REx and Hayabusa2, respectively) originate. Dynamical models suggest that these NEAs most likely came from low-inclination, inner-belt asteroids near the $\nu_6$ secular resonance (Bottke et al., 2017).
so we originally focused on the most prominent primitive families in this region: Polana-Eulalia and Erigone.

My role was to spectroscopically characterize members of the Polana-Eulalia and Erigone families using NASA’s Infrared Telescope Facility (IRTF) in its low-resolution prism mode (0.8 – 2.4µm) and its high-resolution, cross-dispersed (LXD) mode (2 – 4µm). During observation planning, I learned that one Polana family member, (261) Prymno, was likely an interloper. Prymno had been classified as a primitive B-type by Tholen (1984), but in later taxonomies reclassified as a moderate-albedo X-type, e.g., a Tholen M-type. Because (261) Prymno was a large, bright target in the inner asteroid belt, and because unexpected 3-µm hydration features had been observed in other M-types (e.g., Rivkin et al., 2000), we collected 2 – 4µm spectra of (261) Prymno in addition to near-infrared spectra of other Polana and Erigone targets.

Our European collaborators were ultimately very successful in receiving telescope time in support of the survey of inner-belt asteroid families, and have now taken the lead on this project. The survey now continues as PRIMASS, the PRIMtive Asteroids Spectroscopic Survey, and has expanded to include several other families: Clarissa, Sulamitis, Chaldaea, and Klio. Three peer-reviewed journal article on PRIMASS results have been published so far (de León et al., 2016; Pinilla-Alonso et al., 2016; Morate et al., 2016), and I have contributed as a co-author to two of these.

The study of (261) Prymno led to a more comprehensive study of M-type asteroids. The M-types, originally thought to be iron cores, are an intriguing and complex population, with evidence for metal, silicates, and hydrated minerals on their surfaces. Chapter 3 covers a study of hydration in the M-type asteroids using 2 – 4µm spectroscopy. In Chapter 4, I describe a detailed mid-infrared Spitzer Space Telescope study of (16) Psyche, an M-type asteroid and NASA mission target. Finally, to complement PRIMASS and to use the mid-infrared experience I gained working on (16) Psyche, I also carried out a mid-infrared
study of two primitive, outer-belt asteroid families: Veritas and Themis. These families are at opposite age extremes, and provide a unique opportunity to study the effects of space weathering on primitive families. In the next chapter, I describe the methodology used in each of these projects.
CHAPTER 2: METHODOLOGY

The work in this dissertation primarily uses two methods to characterize asteroids: infrared spectroscopy and thermal modeling. Near- and mid-infrared spectroscopy reveals asteroid surface composition through characteristic spectral features and is sensitive to some regolith properties. Thermal models of infrared asteroid spectra can be used to solve for the asteroid’s radius and albedo, and constrain the thermal characteristics of the surface, such as thermal inertia. These methods and the instruments used in our observations are detailed in this chapter.

2.1 Spectroscopy of Asteroids

Spectroscopy provides the best constraints of asteroid composition via remote sensing. Studies of asteroid composition allow us to link asteroids and meteorite classes, probe the chemical, physical, and dynamical evolution of the asteroid belt, and build a framework with which to interpret results from spacecraft missions to asteroids. The work in this dissertation focuses primarily on three wavelength ranges: the near-infrared (0.8–2.4 µm); the 2.0–4.0 µm region; and the mid-infrared (5.0–14.0 µm for the purposes of this work). The motivation and basis for spectroscopy in these wavelength regimes is described below. Although visible (0.4–0.7 µm) spectroscopic observations are not a significant part of the work presented this dissertation, these wavelengths are very important in asteroid studies. They form the basis of most asteroid taxonomic classification schemes and are highly diagnostic of silicate surfaces; thus, I have included a discussion of these wavelengths, as well.
2.1.1 Visible and Near-Infrared Spectroscopy

The majority of asteroid spectral studies use visible (VIS; 0.4–0.7 µm) and near-infrared (NIR; 0.8–2.4 µm) wavelengths. Visible and near-infrared (VISNIR) spectroscopy is possible from ground-based telescopes and can be compositionally diagnostic. Reflectance spectra of the rock-forming mafic minerals pyroxene (most often [Ca,Mg,Fe]$_2$Si$_2$O$_6$) and olivine ([Mg, Fe]$_2$SiO$_4$) contain characteristic absorption features near 1 and 2 µm (Figure 2.1). These features are produced by crystal field absorptions owed to the presence of Fe$^{2+}$ in mineral lattices. Properties of absorption bands (e.g., band center, band area ratios) in asteroid spectra are related to mineral chemistry, so spectroscopy can provide detailed mineralogical characterization of asteroidal surfaces, allowing for inferences into the chemical and physical conditions under which the asteroid formed and evolved.

Some asteroid surfaces, however, produce ambiguous VISNIR spectra. Asteroids with surfaces dominated by low-iron silicates, carbon-rich material, or metallic iron lack diagnostic VISNIR absorptions (Figure 2.1). In these cases, albedo information, spectral slopes, and spectra from other wavelength ranges inform compositional analysis to overcome VISNIR spectral degeneracy.
Figure 2.1: The visible and near-infrared spectrum of Asteroid (6) Hebe, plotted with black circles, displays the absorption features near 1 and 2 μm due to the presence of iron-bearing silicates on its surface. The visible and near-infrared spectrum of (22) Kalliope, plotted with magenta triangles, lacks these absorption features and is less diagnostic. Both spectra were obtained from the Catalog of Asteroid Spectra provided by The MIT-UH-IRTF Joint Campaign for NEO Reconnaissance and the Small Main-Belt Asteroid Spectroscopic Survey (Bus and Binzel, 2003; Bus, 2011).
VISNIR spectroscopy is also complicated by space weathering (Section 1.3.3), which can change spectral properties. Generally, in iron-silicate-bearing asteroids, space weathering removes iron from mineral assemblages, depositing it as reduced nanophase iron coatings on silicate grains. This process results in attenuation of the 1 and 2 $\mu$m spectral absorption features, redder (more positive) spectral slopes, and a decrease in geometric albedo (Clark et al., 2002). Laboratory and observational studies suggest that on primitive, carbon-rich asteroids, space weathering results in either bluer or redder spectral slopes, and may increase albedo (Lantz et al., 2013; Fornasier et al., 2016a). There is much left to learn about space weathering, and appropriate caution is required when comparing the spectra of fresh meteoritic materials with weathered asteroid surfaces.

2.1.2 Spectral searches for water

The presence of hydrated phases and aqueous alteration in carbonaceous chondrites indicates that water should also be present in the asteroid belt (e.g., Mason, 1963). This is consistent with the predictions of solar system evolutionary models and results of observational studies of asteroids. It is still unclear whether the solar nebula’s “snow-line” fell within the asteroid belt, but dynamical models support the idea that water-rich material from the outer solar system has been delivered to and mixed within the asteroid belt (Gomes et al., 2005; O’Brien et al., 2014; Rivkin et al., 2015).

These dynamical models, as well as observational studies, indicate that volatiles are most concentrated in the outer asteroid belt (see Section 1.4 below). Still, there is evidence that impacts deliver small amounts of hydrated material to otherwise dry asteroids. The Dawn spacecraft identified water-rich deposits of dark material on Vesta’s surface, which was likely delivered by impacts (Reddy et al., 2012, and references therein). Carbonaceous chondritic xenoliths have also been identified in ordinary chondrites, the HED meteorites, and lunar samples (Zolensky et al., 1996). As discussed in Chapter 1, laboratory studies show that
water in the form of hydroxyl (OH) in mineral layers may also be created by interactions of solar-wind H\(^+\) with oxygen in silicates (e.g., Schaible and Baragiola, 2014). This mechanism has been proposed to explain the presence of hydroxyl signatures on the Moon, which appear to vary diurnally (Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009).

Water on asteroids can be detected spectroscopically in several wavelength regions, but most detections involve absorption features at either 0.7\(\mu\)m or 3\(\mu\)m. The 0.7-\(\mu\)m absorption feature is attributed to the Fe\(^{2+}\)–Fe\(^{3+}\) charge transfer in phyllosilicates; however, the absence of a 0.7-\(\mu\)m feature in asteroid spectra does not preclude the presence of water. Water can be directly detected by a diagnostic O-H stretch mode absorption feature near 3\(\mu\)m. The shape and band center of the 3-\(\mu\)m feature can distinguish between the presence of water ice and hydroxyl. Structural hydroxyl produces a sharp, “checkmark”-shaped feature with a band center near 2.7\(\mu\)m, while water ice results in a rounded feature with a center near 3.1\(\mu\)m (Figure 2.2).

Figure 2.2: Asteroid spectra showing the sharp 3-\(\mu\)m hydroxyl feature (left) and the rounded 3-\(\mu\)m water ice feature. These spectra were collected using the ground-based Infrared Telescope Facility. No data is available from 2.5–2.8\(\mu\)m due to strong telluric absorptions at these wavelengths. These figures are reprinted with permission from “Outer Main Belt asteroids: Identification and distribution of four 3-\(\mu\)m spectral groups” by Takir and Emery (2012), appearing in Icarus 219, 641–654.

The 3.1-\(\mu\)m water ice absorption feature was first detected in an asteroid in the spectrum of (24) Themis (Campins et al., 2010a; Rivkin and Emery, 2010). Since then, 3-\(\mu\)m
spectral studies have revealed the water-ice feature on other asteroids, and it seems to be more prevalent in the outer asteroid belt (Takir and Emery, 2012; Licandro et al., 2011a). Additionally, there appear to be two other common 3-µm band shapes in addition to the checkmark hydroxyl feature and the round ice feature. The first is the (1) Ceres-like absorption, which has a minimum at 3.05 µm superimposed on a broader feature, and is attributed to the presence of carbonates, ammoniated phyllosilicates, and iron-rich clays (Rivkin et al., 2006b; Takir and Emery, 2012; de Sanctis et al., 2015). The second is the (52) Europa-like absorption, which is centered near 3.15 µm and may be due to the presence of both H₂O and hydroxyl in mineral layers (Takir and Emery, 2012; Rivkin et al., 2015).

### 2.1.3 Mid-infrared spectroscopy

Silicates produce diagnostic spectral features in the mid-infrared (5–40 µm). The most prominent features are the reststrahlen bands, the Christiansen feature, and transparency features. The reststrahlen bands occur at the frequencies of the Si-O stretching and bending fundamental vibrational modes (between 8-25 µm) (Hunt and Logan, 1972b). The Christiansen feature and transparency features occur where the optical constants of the material change rapidly with wavelength. For the Christiansen feature, this occurs near 8 µm (where there index of refraction n = 1), and the transparency features typically occur between reststrahlen bands, where volume scattering, rather than surface scattering, dominates (e.g., Mustard and Hays, 1997).
Figure 2.3: ASTER Spectral Library (Baldridge et al., 2009) spectra of olivine samples showing the effects of grain size (left) and grain packing (right). Reststrahlen bands near 10\,\mu m appear as maxima in the fine and loose samples, but appear as minima, and with much greater spectral contrast, in the coarse and packed samples. The original spectra are bidirectional reflectance spectra and have been converted to emissivity spectra following Kirchoff’s law (e.g., Salisbury et al., 1991).

As shown in Figure 2.3, the characteristics of mid-infrared silicate emission spectra depend on particle sizes and particle packing (Hunt and Logan, 1972b). For solid surfaces and large (>74\,\mu m) silicate particles, surface scattering dominates and reststrahlen features occur as emissivity minima; in spectra of optically thin samples of small (<74\,\mu m) particles (i.e., single grain emission spectra), the reststrahlen bands occur as emissivity maxima. For optically thick samples of small silicate grains, the reststrahlen features again appear as minima. The positions of reststrahlen bands, transparency, and the Christiansen feature are also diagnostic of mineralogy, and their study may be especially useful for asteroids such as
the M-types, which are relatively featureless at shorter wavelengths (e.g., Vernazza et al., 2011).

In comet comae and protoplanetary disks, silicate grains are small and well-separated, so mid-infrared emissivity spectra of the silicates in these targets resemble spectra of single grains (e.g., Stansberry et al., 2004; Lisse et al., 2008). Emery et al. (2006b) found that the emissivity spectra of three Trojan asteroids closely resembled cometary comae, and concluded that silicate grains in the Trojans’ regolith are very fine and/or well-separated. Proposed grain separation mechanisms include fairy-castle regolith structure and the presence of a transparent matrix (e.g., salts) in which the grains are embedded (Emery et al., 2006b; Vernazza et al., 2012b; Yang et al., 2013). Emissivity maxima attributed to fine-grained, underdense silicate regoliths have also been identified in the spectra of primitive main-belt asteroids (Barucci et al., 2002; Dotto et al., 2004; Licandro et al., 2011a, 2012b; McAdam et al., 2015; Landsman et al., 2016), asteroid-comet transition object (944) Hidalgo (Campins et al., 2007), and an M-type asteroid, (21) Lutetia (Barucci et al., 2008; Vernazza et al., 2011). Generally, the main-belt asteroids do not exhibit the very high (∼20%) spectral contrast near 10 µm as seen in the spectra of Trojan asteroids, perhaps due to compositional and/or regolith differences with the Trojans.

For main-belt asteroids, spectral flux is dominated by thermal emission at wavelengths longer than ∼ 3 µm. In order to study spectral emissivity features at these wavelengths, thermal emission must first be modeled and removed. Thermal modeling also allows for the radiometric determination of an asteroid’s physical properties, such as albedo and diameter, and physical thermal models constrain thermal inertia, roughness, and bolometric emissivity. The next section describes the thermal models used in this dissertation.
2.2 Thermal Models

Thermal models are used to compute thermal emission from theoretical temperature distributions across an asteroid’s surface. Assuming the asteroid is a blackbody, spectral flux density is given by,

\[ F_\lambda = \frac{1}{\Delta^2} \int \epsilon_\lambda B_\lambda(T) \cos(\theta_e) dA \]  

(2.1)

where \( \Delta \) is the asteroid’s distance to the observer, \( \epsilon_\lambda \) is the spectral emissivity, \( B_\lambda \) is the Planck function, \( T \) is temperature, \( \theta_e \) is the emission angle, and \( dA \) is the infinitesimal surface area increment. Spectral flux density has dimensions of rate of energy transfer through a surface per unit surface area per unit wavelength or bandwidth, and is commonly expressed in units of \( \text{W/m}^2/\text{nm}, \text{W/m}^2/\text{Hz}, \) and Janskys (Jy; 1 Jy = \( 10^{26} \text{W/m}^2/\text{Hz} \)).

If we assume the asteroid is a sphere with effective radius \( R_{\text{eff}} \), the incremental surface area \( dA \) becomes \( R_{\text{eff}}^2 \sin(\theta_e) d\theta_e d\phi \) where \( \phi \) is the azimuthal angle. Then the spectral flux density as a function of wavelength becomes,

\[ F(\lambda) = \frac{R_{\text{eff}}^2}{\Delta^2} \int_{0}^{2\pi} \int_{0}^{\pi/2} \epsilon_\lambda B_\lambda(T) \cos\theta_e \sin\theta_e d\theta_e d\phi \]  

(2.2)

The goal of thermal modeling is to adjust model inputs so that the modeled spectral energy distribution (SED; i.e, the spectral flux density as a function of wavelength) from the modeled temperature distribution matches a measured spectral energy distribution. Broadly, thermal models are either simple thermal models or thermophysical models. Simple thermal models assume thermal emission from asteroid surfaces is in instantaneous equilibrium with insolation, while thermophysical models explicitly include heat conduction and heat storage in the surface. This dissertation includes results from both types of model, and they are described below.
2.2.1 Simple Thermal Models

The first widely-used asteroid thermal model is the Standard Thermal Model (STM; Morrison and Lebofsky, 1979; Lebofsky et al., 1986; Lebofsky and Spencer, 1989). The STM assumes a spherical, smooth, non-rotating asteroid. Insolation and thermal emission are assumed to be in instantaneous equilibrium (i.e., thermal inertia is zero), so energy balance at the asteroid’s surface is given by

\[ \eta \epsilon \sigma T^4 = \frac{S_o (1 - A_B)}{r_H^2 \cos \theta_i} \cos \theta_i \]  

(2.3)

where \( \epsilon \) is the bolometric emissivity, \( \sigma \) is the Stefan-Boltzmann constant, \( S_o \) is the solar constant (1367 W/m\(^2\)), \( A_B \) is the asteroid’s bond albedo, \( r_H \) is the asteroid’s heliocentric distance, \( \theta_i \) is the solar incidence angle, and \( \eta \) is the beaming parameter.

At the asteroid’s subsolar point, \( \theta_i = 90^\circ \). Then, from Equation 2.3, the subsolar temperature, \( T_{SS} \), is

\[ T_{SS} = \left[ \frac{S_o (1 - A_B)}{r_H^2 \eta \epsilon \sigma} \right]^{1/4} \]  

(2.4)

and the temperature distribution as a function of solar incidence angle can be expressed in terms of the subsolar temperature as \( T(\theta_i) = T_{SS} \cos^{1/4}(\theta_i) \).

The STM uses empirical correction factors to account for some of its non-physical assumptions. The beaming parameter, \( \eta \), modifies the subsolar temperature to account for the effects of roughness, rotation, and thermal inertia (Equation 2.4). Beaming due to roughness increases subsolar temperature, so \( \eta \) must decrease to offset this effect. Non-zero thermal inertia and rotation both decrease the subsolar temperature, so these effects cause \( \eta \) to increase. In the theoretical case of a smooth spherical asteroid with no thermal inertia, \( \eta = 1.0 \). The STM sometimes uses a fixed beaming parameter of \( \eta = 0.756 \), which is the value re-
quired for STM-derived radiometric diameters for (1) Ceres and (2) Pallas to match those from occultation observations (Lebofsky et al., 1986). To account for observations made at non-zero phase angles, the STM applies an empirical phase coefficient of 0.01 mag/degree of phase.

The STM is generally reliable for main-belt asteroids observed at small phase angles \( \alpha \leq 30^\circ \). Application of the STM to NEAs, however, is not straightforward, as NEAs are typically observed at larger phase angles, and typically have higher thermal inertias, than main-belt asteroids. There are several simple thermal models formulated for applicability to NEAs.

The earliest of these “nonstandard” thermal models is the Fast-Rotating Model (FRM), also referred to as the Isothermal Latitude Model (ILM) (Lebofsky and Spencer, 1989; Veeder et al., 1989). In the FRM, temperature is a function of asteroid latitude, rather than incidence angle as in the STM, and the hottest points are along the equator. Nightside emission accounts for 50% of thermal emission in the FRM.

The Near-Earth Asteroid Thermal Model (NEATM; Harris, 1998) is a refinement of the STM, and is currently the most favored simple thermal model. It differs from the STM in two respects: 1) the NEATM allows the beaming parameter \( \eta \) to vary as a free parameter; and 2) the NEATM does not use the phase coefficient, and instead explicitly incorporates the phase angle by integrating over the surface of the asteroid that is sunlit and visible to the observer. The NEATM then avoids some of the extreme assumptions of either the STM or the FRM. Varying the beaming parameter allows color temperature to be fit to the measured spectral energy distribution. This makes the NEATM applicable not just to NEAs, but to any asteroid in which thermal inertia, surface roughness, spin pole orientation, and rotation rate are unknown.

We use the NEATM in each chapter of this dissertation, with both the effective radius and beaming parameter allowed to vary. In our implementation of the NEATM, we calculate the
asteroid’s geometric albedo at each step in parameter space using the Fowler and Chillemi (1992) formula $p_v = (D_o/D_{\text{eff}})^2 10^{-0.4H}$, where $D_o = 1329$ km and $H$ is the asteroid’s absolute magnitude. We then compute bond albedo as the product of the geometric albedo and the phase integral, $q$, $A_B = p_v q$. The phase integral is expressed in terms of the slope parameter, $G$ (Bowell et al., 1989): $q = 0.290 + 0.684G$.

Although simple thermal models such as the NEATM implement a number of idealized simplifications, they are useful for studying the properties of asteroids that are not good candidates for a more detailed thermal model. The thermophysical model, described below, requires the asteroid’s rotational period and spin-pole orientation as model inputs, and these quantities are unknown for many asteroids. Furthermore, the less computationally intensive NEATM (or another simple thermal model) can be used to constrain parameter space for the more complex thermophysical model.

### 2.2.2 Thermophysical models (TPMs)

Thermophysical models (TPMs) use a more realistic approach to thermal modeling. A TPM explicitly includes thermal inertia and surface roughness, so the beaming parameter is not needed. The approach used in this dissertation is described below, and is detailed in Emery et al. (2006b) and Emery et al. (2014). This approach, and most other contemporary TPMs, are based on the work of Spencer et al. (1989) and Spencer (1990).

Generally, the TPM is solved for facets distributed over an asteroid shape model, although the facets may be distributed over a sphere if the asteroid’s shape is unknown. The model computes a temperature for each facet, considering heat flow in the vertical direction and assuming the thermal properties are constant with depth. Energy balance at the asteroid’s surface is given by:
\[ \epsilon \sigma T^4 = \frac{S_\odot (1 - A_B)}{r_{AU}^2} \cos \theta_i + \left. \frac{\Gamma^2}{c_p \rho_{\text{bulk}}} \frac{\partial T}{\partial z} \right|_{z=0} + E_{\text{ref}} + E_{\text{self}} - E_{\text{shadow}} \] (2.5)

where \( \Gamma \) is the thermal inertia, \( c_p \) is the specific heat capacity of the surface material, \( \rho_{\text{bulk}} \) is the bulk density of the surface material, \( \partial T/\partial z \) is the vertical temperature gradient, and \( E_{\text{ref}}, E_{\text{self}}, \) and \( E_{\text{shadow}} \) are terms to account for reflected sunlight, self-heating, and self-shadowing, respectively, associated with surface roughness. At depth \( z \gg l_s \), the TPM assumes \( \partial T/\partial z = 0 \), where \( l_s \) is the thermal skin depth, given by

\[ l_s = \frac{\Gamma}{c_p \rho_{\text{bulk}}} \sqrt{\frac{2}{\omega}}, \] (2.6)

and \( \omega \) is the angular rotation rate.

The surface roughness implementation in this dissertation is similar to that of Spencer (1990) and is described in detail in Emery et al. (1998). Briefly, roughness elements are modeled as spherical-section craters distributed with constant crater density across the surface. Roughness is parameterized by \( f \), the fractional coverage of craters, and \( \gamma \), the half-angle of the crater opening. Each crater is divided into a number of equal-area elements. The model calculates the geometry of each element to determine its illumination, visibility, degree of shadowing, and the effects of multiple scattering and self-heating on the temperature of that element.

The TPM computes a temperature for each roughness element (or for each facet, if roughness is neglected). This implementation of the TPM uses the Crank-Nicolson finite difference method to numerically solve the heat diffusion equation for temperature. The surface boundary condition is solved iteratively over \( \sim 360 \) time steps and a number of depth steps penetrating \( \sim 8 \) thermal skin depths.
2.3 Instruments

The observational components of this dissertation utilize data from both ground- and space-based telescopes, described in this section.

2.3.1 NASA’s Infrared Telescope Facility

Chapter 3 presents both archival and proprietary data collected using The Infrared Telescope Facility (IRTF) is a 3.0-m infrared telescope located on Mauna Kea in Hawaii. NASA funds the operation of the IRTF, and 50% of its time is allocated for solar system studies. The IRTF has imaging and spectroscopic instruments for optimized for wavelengths through the infrared. Chapter 3 in this dissertation presents data collected with SpeX (Rayner et al., 2003), the IRTF’s 0.7–5 µm spectrograph. SpeX received an upgrade (“New SpeX”) in mid-2014, but the work described in Chapter 3 was collected using the the so-called “Old Spex”. Old SpeX used a Raytheon Aladdin 3 1024 × 1024 InSb detector and operated in either a low-resolution (resolving power $\lambda/\Delta \lambda \sim 200$) prism mode across 0.8–2.5 µm or one of several high-resolution (resolving power $\lambda/\Delta \lambda \sim 2000$–2500) cross-dispersed mode. Chapter 3 made use of both prism mode the Long Cross-Dispersed (LXD) 1.95–4.2 µm mode, which covers the 3-µm region diagnostic of hydration in asteroids.

2.3.2 Telescopio Nazionale Galileo

Chapter 3 also presents data collected by my collaborators, Vania Lorenzi and Noemí Pinilla-Alonso, using the Telescopio Nazionale Galileo (TNG). The TNG is an optical and infrared 3.58-m telescope located at the Roque de los Muchachos Observatory in La Palma, Canary Islands, Spain and funded by the Italian National Institute of Astrophysics. Some of the data in Chapter 3 were collected using the TNG’s Near Infrared Camera Spectrometer (NICS Baffa et al., 2001), which has low-resolution (resolving power $\lambda/\Delta \lambda \sim 50–500$) and high resolution
(R~2500) spectroscopic modes and imaging modes in the near-infrared (0.9–2.5 µm). NICS uses a 1024 × 1024 HgCdTe Hawaii detector.

### 2.3.3 NASA’s Spitzer Space Telescope

Chapters 4 and 5 utilize archival data collected using NASA’s Spitzer Space Telescope. The Spitzer Space Telescope (sometimes shortened to “Spitzer”) is a 0.85-m infrared (3.6–160 µm) space telescope in an Earth-trailing heliocentric orbit. Spitzer has three science instruments: an infrared imager operating at 3.6 µm, 4.5 µm, 5.8 µm and 8.0 µm; an infrared spectrograph operating across 5–38 µm, and far infrared imager operating at 24 µm, 70 µm, and 160 µm. Spitzer was launched in 2003 and entered service at the end of that year. Its cryogen supply lasted until May 2009, at which point Spitzer entered the Spitzer Warm Mission. Without cryogenic cooling, the telescope’s thermal background emission is too great for observations at mid- and far-infrared wavelengths. In the Warm Mission, only the two shortest wavelengths of the infrared imaging camera are in use.

The observations presented in Chapters 4 and 5 were obtained during Spitzer’s cryogenic phase. Both chapters use data obtained the the Infrared Spectrograph (IRS; Houck et al., 2004a). The IRS operates with four spectroscopic modules: Short-Wavelength, High Resolution (SH; λ = 9.9–19.6 µm, resolving power λ/Δλ~600); Long-Wavelength, High Resolution (LH; λ = 18.7–37.2 µm, resolving power λ/Δλ~600); Short-Wavelength, Low-Resolution (SL; λ = 5.2–14.5 µm, resolving power λ/Δλ~64–128); and Long-Wavelength, Low-Resolution (LL; λ = 13.3–38.0 µm, resolving power λ/Δλ~64–128). This dissertation focuses on spectra collected with the SL module, which consists of two orders: SL2 (5.2–7.6 µm) and SL1 (7.4–14.2 µm). SL makes use of a 128 × 128 Si:As detector. The IRS also has “Red” and “Blue” peak-up cameras with bandpasses centered at 22 µm and 16 µm, respectively. The peak-up cameras are used to precisely align targets on the slit.
CHAPTER 3: HYDRATION IN THE M-TYPE ASTEROIDS

The work presented in this chapter was previously published as “A new investigation of hydration in the M-type asteroids” by Landsman et al. in Icarus 252, pp. 186–198, May 2015. See Elsevier License Number 4071551250279 in Appendix A.

3.1 Introduction

The Tholen M-type asteroids are the moderate-albedo subgroup of the spectrally degenerate X taxonomic class, which also includes the high-albedo E-type and low-albedo P-type asteroids (Tholen, 1984). The X-class asteroids have flat-to-red visible and near-infrared spectral slopes and no absorption features at the resolution of the Eight Color Asteroid Survey, on which Tholen’s taxonomy is based. Because the visible and near-infrared spectra of M-type asteroids lack strong diagnostic absorption features, their mineralogy is difficult to infer. It was originally suggested that at least some subset of the M-type asteroids are the liberated iron cores of differentiated bodies and the parent bodies of the nickel-iron meteorites (Bell et al., 1989).

More subtle spectral structure has been detected with new instrumentation. Studies in the 2.0–4.0-µm region, which is diagnostic of hydrated and hydroxylated (H$_2$O-±OH-bearing) minerals (Rivkin et al., 2002), have revealed that hydration is common among the M-type asteroids (Jones et al., 1990; Rivkin et al., 1995, 2000). Rivkin et al. (2000) reported that 10 out of a surveyed 27 M-type asteroids have a 3-µm feature diagnostic of hydration. Over the last decade, several studies have shown that diagnostic silicate absorption features are present in the visible and near-infrared (∼0.4–2.0 µm) spectra of most M-type asteroids (e.g., Hardersen et al., 2005; Fornasier et al., 2010; Ockert-Bell et al., 2010; Hardersen et al.,
2011). In the largest of these studies, Hardersen et al. (2011) reported that 27 out of 45 M-type asteroids show absorption features attributed to pyroxenes, olivine, phyllosilicate and/or hydroxides.

Radar reflectivity provides a measure of the bulk density of the surfaces of asteroids. Radar investigations of M-type asteroids show that they are likely to have elevated metal content compared to other taxonomic types. In a study of 19 M-types, Shepard et al. (2010) found a mean radar albedo of \( \sigma_{OC} = 0.28 \pm 0.13 \), which is slightly higher than the mean for other classes. For comparison, Magri et al. (2007) report the mean radar albedos of the S-types (\( N = 27 \)) and the C-types (\( N = 25 \)) to be \( \sigma_{OC} = 0.140 \pm 0.044 \) and \( \sigma_{OC} = 0.127 \pm 0.050 \), respectively. The highest radar albedos among the M-types are consistent with a composition dominated by porous iron-nickel regolith, while the remaining M-types have radar albedos suggesting surfaces akin to stony-iron meteorites or high-iron carbonaceous chondrites (Shepard et al., 2010).

The mineralogy of M-type asteroids remains largely unconstrained, and the origin of their hydrated minerals is unknown. Most interpretations of spectroscopic and radar results require that the M-types be highly thermally evolved, and any primordial water of hydration should have been driven out. This has led to the suggestion that the hydrated minerals were delivered by impacts of ice- or water-rich material (Busarev, 2002; Shepard et al., 2013). Evidence for this hypothesis comes from the discovery of dark material on (4) Vesta, interpreted as carbonaceous chondrite-like material delivered to the surface via impacts (Reddy et al., 2012, and references therein). In contrast, several scenarios in which the hydrated materials are endogenic have also been suggested (e.g., Vilas, 1994; Rivkin et al., 2000; Hardersen et al., 2011). It is also important to keep in mind that the X-complex asteroids are spectrally degenerate in the visible and near-infrared. Uncertainties in albedo and the effects of viewing geometry on spectral shape (e.g., Carvano and Davalos, 2014) mean the M-type asteroids could be a compositionally diverse, unrelated collection of objects that produce
similar visible and near-infrared spectra. Improving our understanding of the mineralogy on M-type asteroids will place constraints on their composition and thermal and collisional evolution.

In this chapter, we focus on the detection and analysis of absorption features in the 0.8–4-μm spectra of M-type asteroids. We used NASA’s IRTF to carry out a 2–4-μm spectroscopic study of six M-type asteroids, as this region is especially diagnostic of hydrated minerals. The shape and center of the 3-μm hydration feature is indicative of the nature and extent of aqueous alteration on asteroids, and can be used to probe thermal history (Takir and Emery, 2012). We also carried out spectroscopy of three of these asteroids in the 0.8–2.4-μm range using the Telescopio Nazionale Galileo. This wavelength range contains several absorption features due to mafic minerals, which are proving to be common on M-type asteroids, and is also useful for constraining the spectral continuum throughout the 2–4-μm region.

3.2 Observations and Data Reduction

3.2.1 IRTF Spectra

We observed six M-type asteroids over three nights using the SpeX instrument (Rayner et al., 2003) at NASA’s 3.0-m Infrared Telescope Facility (IRTF), located on Mauna Kea in Hawaii. SpeX is a low- and medium-resolution spectrograph, described in more detail in Chapter 2. We operated SpeX in the Long Cross-dispersed (LXD) Mode, which allows for simultaneous coverage of the K and L bands (1.9 μm–2.4 μm and 2.8 μm–4.2 μm, respectively). We chose a 0.8" × 15" slit, which results in a spectral resolving power of λ/Δλ ≈ 1000. For each target, the position angle of the slit was oriented along the parallactic angle to minimize light loss due to differential atmospheric refraction. We captured spectra in AB pairs of equal integration time by nodding the telescope 10" along the length of the slit, i.e., nodding between positions A and B. For each asteroid target, we obtained a spectrum of a local
standard star of approximately G2V spectral type at a similar airmass to the asteroid, and
we obtained spectra of at least one solar analog star at several different airmasses throughout
each night (see Table 3.3). After observing each calibration star, we ran the SpeX calibration
macro, which automatically takes several flat field images and wavelength-calibration argon
lamp arc images.

Table 3.1: Properties of observed asteroids.

<table>
<thead>
<tr>
<th>Name</th>
<th>a (AU)</th>
<th>D (km)</th>
<th>P (h)</th>
<th>p_r</th>
<th>H</th>
<th>G</th>
<th>Th.</th>
<th>B&amp;B</th>
<th>DM.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(69) Hesperia</td>
<td>2.98</td>
<td>138.1 ± 4.7</td>
<td>5.655</td>
<td>0.14</td>
<td>7.05</td>
<td>0.19</td>
<td>M</td>
<td>X</td>
<td>Xk</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>2.29</td>
<td>40.1 ± 1.0</td>
<td>11.497</td>
<td>0.15</td>
<td>9.69</td>
<td>–</td>
<td>M</td>
<td>Xe</td>
<td>–</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>2.80</td>
<td>135.1 ± 2.1</td>
<td>5.385</td>
<td>0.12</td>
<td>7.30</td>
<td>0.29</td>
<td>M</td>
<td>Xe</td>
<td>Xe</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>2.33</td>
<td>50.9 ± 1.3</td>
<td>8.002</td>
<td>0.11</td>
<td>9.44</td>
<td>0.19</td>
<td>B</td>
<td>X</td>
<td>–</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>2.38</td>
<td>59.1 ± 2.3</td>
<td>4.653</td>
<td>0.16</td>
<td>8.71</td>
<td>0.19</td>
<td>X</td>
<td>X</td>
<td>Xk</td>
</tr>
<tr>
<td>(418) Alemanna</td>
<td>2.59</td>
<td>54.1 ± 4.6</td>
<td>4.671</td>
<td>0.19</td>
<td>9.77</td>
<td>–</td>
<td>M</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

a: Tedesco et al. (2004)
b: (69) Hesperia: Hannš et al. (2013b); (216) Kleopatra: this work; other asteroids: Warner et al. (2009)
c: (69) Hesperia: MPC 17257; (216) Kleopatra, (261) Prymno, (337) Devosa: MPC 17258
Td: Tholen (1984)
B&B: Bus and Binzel (2002)
DeMeo et al. (2009b)
This object does not have a spectrum typical of other B-class asteroids, and was grouped into the
X-complex by Bus and Binzel (2002)

The list of our target asteroids and their physical properties are given in Table 3.1, and
observing circumstances for our targets are given in Table 3.2. Observations took place on
UT July 15, 2013, UT September 24, 2013 and UT September 25, 2013. For the July 15
observing run, seeing was ∼ 0.7′′ and cirrus cloud cover was present during the first quarter
of the night. On September 24, cirrus clouds were also present early in the night, and seeing
was ∼ 1′′. Although transient, thin cirrus clouds were present throughout the September 25
night, most of the night was clear, and seeing was ∼ 0.9′′.
Table 3.2: Observing circumstances – IRTF observations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date (UT)</th>
<th>Start time (UT)</th>
<th>V mag.</th>
<th>Phase angle (deg)</th>
<th>Total int. time (min)</th>
<th>Avg. airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(69) Hesperia</td>
<td>2013-07-15</td>
<td>12:52</td>
<td>12.7</td>
<td>18.2</td>
<td>25.0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>2013-09-24</td>
<td>12:16</td>
<td>11.3</td>
<td>1.5</td>
<td>24.0</td>
<td>1.4</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>2013-07-15</td>
<td>11:07</td>
<td>12.2</td>
<td>8.8</td>
<td>12.0</td>
<td>1.2</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>2013-09-24</td>
<td>14:15</td>
<td>10.6</td>
<td>23.9</td>
<td>16.0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>14:35</td>
<td>10.5</td>
<td>23.6</td>
<td>18.7</td>
<td>1.0</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>2013-07-15</td>
<td>06:28</td>
<td>13.2</td>
<td>20.0</td>
<td>30.0</td>
<td>1.3</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>2013-09-24</td>
<td>05:21</td>
<td>12.8</td>
<td>16.8</td>
<td>26.0</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>05:34</td>
<td>12.8</td>
<td>17.1</td>
<td>22.0</td>
<td>1.4</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>2013-09-24</td>
<td>10:13</td>
<td>12.6</td>
<td>5.1</td>
<td>17.7</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>09:23</td>
<td>12.6</td>
<td>5.3</td>
<td>18.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3.3: Calibrator stars – IRTF observations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Observation date</th>
<th>Standard star (spectral type)</th>
<th>Solar analog</th>
</tr>
</thead>
<tbody>
<tr>
<td>(69) Hesperia</td>
<td>2013-07-15</td>
<td>SAO 53622 (G2V)</td>
<td>SAO 90896 (51 Peg)</td>
</tr>
<tr>
<td></td>
<td>2013-09-24</td>
<td>SAO 76514 (G2V)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>2013-07-15</td>
<td>SAO 47343 (G1V)</td>
<td>SAO 90896 (51 Peg)</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>2013-09-24</td>
<td>SAO 76514 (G2V)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>SAO 93314 (G5D)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>2013-07-15</td>
<td>SAO 47343 (G1V)</td>
<td>SAO 90896 (51 Peg)</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>2013-09-24</td>
<td>SAO 164338 (G2V)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>SAO 164338 (G2V)</td>
<td>SAO 90896 (51 Peg)</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>2013-09-24</td>
<td>SAO 128385 (G2V)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
<tr>
<td></td>
<td>2013-09-25</td>
<td>SAO 128385 (G2V)</td>
<td>SAO 90896 (51 Peg), SAO 94049 (Hy 106)</td>
</tr>
</tbody>
</table>

3.2.1.1 Spectral Extraction

To reduce the spectra, we used Spextool, an IDL package for the extraction and reduction of SpeX data (Cushing et al., 2004). For each target asteroid, there is a dataset consisting of the asteroid spectrum files, spectrum files for at least one local standard star, solar analog spectrum files, and a series of flat field and argon arc frames. The Spextool reduction pro-
ceeds as follows. All the flat field images in a dataset are combined and the resulting master flat is normalized. For LXD-mode spectra, Spextool produces a wavelength calibration frame by combining the argon arc image with a sky frame, which is generated from an AB pair according to the equation $sky = (A + B) - |(A - B)|$ (Cushing et al., 2004).

Once the master flat field frame and wavelength calibration frames are produced, calibration of the asteroid and standard star spectra begins. First, each pixel in the spectrum is corrected for nonlinearity in observed counts. Next, each AB pair is subtracted to remove additive sky and telescope background signal, and the resulting difference image is flat-fielded. All flat-fielded spectra for each target in each data set are combined into a single frame. Spextool computes the average spatial profile for each order in the spectrum and estimates the extraction parameters, which include the radius of the point spread function, aperture radius, background limits, and degree of the polynomial fit to the background. The user can adjust these parameters. Finally, Spextool extracts both the target and wavelength calibration frame spectra. A wavelength solution is found, and the target spectra are wavelength-calibrated.

### 3.2.1.2 Other Corrections

We used a set of IDL-based routines (Volquardsen et al., 2007) and an ATRAN atmospheric model (Lord, 1992) to remove telluric contamination in our target spectra. ATRAN produces a model atmospheric spectrum based on the amount of precipitable water in the atmosphere, the target’s airmass and the altitude and spectral resolution of the telescope. Models are generated for a range of precipitable water values, and the one that best removes telluric features is used. For each object, we compared the amount of precipitable water in the best-fit atmospheric model to the precipitable water for that night, which we calculated using 225-GHz optical depth measurements from the Caltech Submillimeter Observatory.\(^\text{1}\)

\[^{1}\text{http://cso.caltech.edu/tau/}\]
to ensure an acceptable match of these independent measurements. After telluric correction, we divided each asteroid spectrum by the solar analog spectrum and each local standard star spectrum. The resulting spectra are averaged together to produce one spectrum for each set of asteroid, solar analog and local standard star data.

At wavelengths longer than \( \sim 3.3 \mu m \), all of our asteroid spectra show apparent excess reflectivity due to the contribution of thermal flux from the asteroid’s surface (figure 3.1). Although thermal emission does not contribute significantly to the 3.0-\( \mu m \) band, it does affect our estimate of the spectral continuum, so we model and remove it.

![Figure 3.1: The measured spectrum of each asteroid (black points) with the best-fit thermal flux model (red).](image)

For each asteroid, we modeled the thermal spectral irradiance using the Near-Earth Asteroid Thermal Model (NEATM; Harris, 1998), the mathematical basis of which is presented in Chapter 2. Our NEATM inputs include heliocentric distance, geocentric distance, absolute magnitude, diameter, geometric albedo, and the slope parameter, \( G \) (Table 3.1). We
used the Minor Planet Center’s Ephemeris Service\textsuperscript{2} and the JPL Small-Body Database\textsuperscript{3} to find values for these inputs. For asteroids for which $G$ is unknown, we used the default value of 0.15 (Bowell et al., 1989).

To determine the relative thermal excess, we divide the modeled thermal spectral irradiance by a reflectance model. Our reflectance model is simply the solar spectral irradiance\textsuperscript{4}, scaled to the asteroid’s spectral irradiance in the Johnson V-band. Because we did not take photometric measurements in the V-band, we estimate the V-band irradiance using the apparent V-magnitude, $m_v$. We calculate $m_v$ using the relationship between $m_v$, geometric albedo, phase angle, slope parameter, heliocentric distance, geocentric distance, radius and solar magnitude (see Equation 1 in Jewitt and Luu, 1995a). The rotational variation in each asteroid’s apparent magnitude is not accounted for in this model.

Because many M-type asteroids have significantly red spectral slopes in the near-infrared, we modified the modeled thermal excess by multiplying the model by a straight line extrapolated from the spectral slope in the K band. We used a Monte Carlo routine to find which value of $\eta$ produces the best fit model. The Monte Carlo routine generates $10^5$ random numbers selected from the standard normal distribution (a normal distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$). The routine then generates $10^5$ synthetic fluxes by adding the nominal flux to the 1-$\sigma$ errorbars multiplied by each of these $10^5$ random numbers (Figure 3.2a). For each synthetic flux, our routine fits the NEATM using $\chi^2$ minimization. We then have best-fit $\eta$ values for each synthetic spectrum. We use the mean of the distribution of $\eta$ values to as the final value of $\eta$ to generate the NEATM, and we report the standard deviation of the $\eta$ distribution as the 1-$\sigma$ uncertainty on $\eta$ (Figure 3.2b). Once we have the

\textsuperscript{2}http://www.minorplanetcenter.net/iau/MPEph/MPEph.html
\textsuperscript{3}http://ssd.jpl.nasa.gov/sbdb.cgi
\textsuperscript{4}Zero Airmass Solar Spectral Irradiance Table. Standard E490-00, American Society for Testing and Materials.
final NEATM, we compute the relative thermal excess and subtract it from our observed flux. The best-fit NEATMs for each asteroid are shown in Figure 3.1.

![Figure 3.1: NEATM values for each asteroid.](image)

(a) Synthetic spectra for (136) Austria  
(b) Histogram of $\eta$ values

Figure 3.2: At left (a), the measured spectrum of (136) Austria (red circles) is shown with each of the $10^5$ synthetic spectra generated in the Monte Carlo routine (black points). At right (b), the distribution of best-fit beaming parameter ($\eta$) values for the synthetic spectra is shown as a histogram.

To help characterize the spectral continuum across the 3-µm region, we combined each LXD spectrum with data at shorter wavelengths by normalizing each spectrum in the overlap region, $\sim 2.2$ µm. For asteroid (418) Alemannia, we combined the LXD data with our NICS near-infrared spectrum. For asteroids (69) Hesperia and (261) Prymno, spectra from $\sim 0.4$ – 2.4 µm were downloaded from the The MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance Database. For asteroids (136) Austria, (216) Kleopatra and (337) Devosa, we used visible ($\sim 0.4$ – 0.9 µm) spectral data from the Small Main-belt Asteroid Spectroscopic Survey, Phase II (Bus and Binzel, 2003) and near-infrared ($\sim 0.8$ – 2.4 µm) spectra from Bus (2011). In the case of (216) Kleopatra and (261) Prymno, we combine our LXD data with the database spectra rather than our NICS data because of lower signal-to-noise in the NICS data; however, both datasets generally agree in spectral shape and slope (figure 3.3). The somewhat redder slope in our NICS spectrum of (261) Prymno compared to the

---

5http://smass.mit.edu/minus.html
IRTF spectrum may be caused by systematic effects, differences in viewing geometry, or possible rotational variability. Prymno’s phase angle differed by nearly 20° between the two observations.

Figure 3.3: Our near-infrared spectra (grey datapoints) for asteroids (216) Kleopatra, left, and (261) Prymno, right, compared with IRTF data (black lines) from Bus (2011) (Kleopatra) and the MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance Database (Prymno).

3.2.2 TNG Spectra

Collaborators Noemí Pinilla-Alonso and Vania Lorenzi obtained and reduced low-resolution near-infrared spectra of asteroids (216) Kleopatra, (261) Prymno and (418) Alemannia. These spectra were obtained with the 3.58-m Telescopio Nazionale Galileo (TNG), situated at the “Roque de los Muchachos” observatory in La Palma, Spain. They used the high-throughput low resolution mode of the Near Infrared Camera Spectrometer (NICS), described in Chapter 2. All spectroscopic modes use the large field camera (LF), which has a plate scale of 0.25′′/pixel. These observations were obtained with a 2.0″-wide slit, corresponding to a spectral resolving power $\lambda / \Delta \lambda \sim 25$ quasi-constant along the spectra, and the Amici prism disperser. The Amici disperser consists of two low-dispersion (BaF2) and one high-dispersion (IRG2) prisms arranged in a configuration that disperses the light
without deviating from the central wavelength (Oliva, 2000; Baffa et al., 2001). The slit was oriented in the parallactic angle, and the tracking was at the asteroid’s proper motion. Pinilla-Alonso and Lorenzi took several images through the Js filter to locate the object in the field of view and place the slit over the object.

Table 3.4: Observing circumstances – TNG observations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date (UT)</th>
<th>Start time (UT)</th>
<th>V mag.</th>
<th>Phase angle (deg)</th>
<th>Total int. time (min)</th>
<th>Avg. airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(216) Kleopatra</td>
<td>2013-10-29</td>
<td>01:34</td>
<td>9.8</td>
<td>10.6</td>
<td>0.4</td>
<td>1.05</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>2013-01-24</td>
<td>07:01</td>
<td>14.1</td>
<td>24.9</td>
<td>12.0</td>
<td>1.53</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>2013-10-29</td>
<td>00:52</td>
<td>13.3</td>
<td>17.5</td>
<td>8.0</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table 3.5: Calibrator stars – TNG observations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Observation date</th>
<th>Solar analog (spectral type)</th>
<th>Solar analog airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(216) Kleopatra</td>
<td>2013-10-29</td>
<td>SA 115-271 (F8D)</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA 98–978 (F8D)</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA 93–101 (G5D)</td>
<td>1.16</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>2013-01-24</td>
<td>SA 98–978 (F8D)</td>
<td>1.14</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>2013-10-29</td>
<td>SA 115-271 (F8D)</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA 98–978 (F8D)</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA 93–101 (G5D)</td>
<td>1.16</td>
</tr>
</tbody>
</table>

The series of spectra consisted of consecutive exposures of 90 seconds following an ABBA scheme, where A is the position of the object in the slit during the first acquisition and B is a position shifted by 10" along the slit. The ABBA scheme was repeated several times in order to increase the signal to noise ratio (S/N). The total on-object exposure time is listed in Table 3.4. The observational method and reduction procedure followed Licandro et al. (2001, 2002), including: flat-field corrections; removal of the sky and background signature; and extraction of a 1D-spectrum. The consecutive AB extracted pairs were wavelength-calibrated using a look-up table based on the theoretical dispersion predicted by ray-tracing and adjusted to best fit the observed spectra of calibration sources and telluric absorptions.
In order to correct for telluric absorptions and to obtain the relative reflectance, each AB pair of each asteroid was divided by the spectra of the solar analogue stars (Table 3.5). Subpixel offsetting was applied when dividing the spectra to correct for errors in the wavelength calibrations due to instrumental flexure. Pinilla-Alonso and Lorenzi compared the reflectance spectra of the same asteroid obtained with different solar analogues to ensure low uncertainty in the slope. After discarding those with clear bad quality, the rest were averaged to increase the final S/N. Typically, the uncertainty in the slope of the final spectrum is ≤ 1%/1000 Å (de León et al., 2010; Lorenzi et al., 2014).

3.3 Data Analysis

3.3.1 IRTF Data

Hydrated and hydroxylated minerals produce several absorption features in the 3-μm region. In mineral lattices, interlayer hydroxyl produces a stretch absorption feature at 2.7 μm, while adsorbed water molecules produce a symmetric stretch feature at 3.1 μm and an antisymmetric stretch feature near 2.9 μm (Lebofsky, 1980; Rivkin et al., 2002). A water ice feature centered at 3.1 μm has been detected on two main-belt asteroids (Campins et al., 2010a; Rivkin and Emery, 2010; Licandro et al., 2011a). The shape of the 3-μm feature is related to composition and the thermal history of the asteroid. In a study of the 3-μm region on outer-main belt asteroids, Takir and Emery (2012) identify four spectral groups, which likely represent differences in thermal alteration.

We begin our analysis of the 3-μm region by estimating the spectral continuum across 2–4 μm. We assume the continuum to be straight line, which we fit by least-squares regression to several points in the K band and to a region longward of the 3-μm feature that is free of other absorptions, typically around 3.4 μm. We also considered choosing a best-fit function of 1/λ for the continuum, as in the methods of Rivkin et al. (1995) and Rivkin et al. (2000).
1/\lambda function mimics spectral continuum behavior in the 2–3.5-\mu m region in iron meteorites (e.g., Miyamato, 1987); however, we wanted to avoid assuming a metal composition for the M-type asteroids, so we chose a straight-line continuum as in Takir and Emery (2012).

Once a continuum is established, we then determine the depth of the band, \( D_{3\mu m} \), as a fraction of the continuum reflectance at 3 \( \mu \)m, \( R_c \), using the average reflectance of five points centered at 3 \( \mu \)m, \( R_{3\mu m} \) (see Equation 3.1).

\[
D_{3\mu m} = \frac{R_c - R_{3\mu m}}{R_c}
\]  

(3.1)

Formal error propagation gives an uncertainty on the band depth of

\[
\sigma_{D_{3\mu m}} = \frac{R_{3\mu m}}{R_c} \sqrt{\left( \frac{\sigma_c}{R_c} \right)^2 + \left( \frac{\sigma_{3\mu m}}{R_{3\mu m}} \right)^2}
\]  

(3.2)

where \( \sigma_c \) is the uncertainty of the continuum reflectance at 3 \( \mu \)m and \( \sigma_{3\mu m} \) is the uncertainty of the 5 averaged reflectance points centered on 3 \( \mu \)m. We consider the asteroid’s spectrum to show a 3-\( \mu \)m feature if there is at least a 2-sigma detection, i.e., \( D_{3\mu m} > 2\sigma_{D_{3\mu m}} \).

Figure 3.4: Spectrum of (69) Hesperia showing the estimated continuum across the 3-\( \mu \)m region. The five red data points centered at 3 \( \mu \)m are used to calculate the band depth.
To characterize the shape of the 3-µm feature, we calculate the ratio of the reflectance at 2.90 µm to the reflectance at 3.05 µm, \( R(2.90)/R(3.05) \). To avoid this measure being skewed by an outlier point at either wavelength, we use the average reflectance of 3 points at 2.90 µm and 3.05 µm to represent \( R(2.90) \) and \( R(3.05) \), respectively. This ratio is one criterion used by Takir and Emery (2012) to distinguish between a “sharp” 3-µm feature, attributed to interlayer OH, and a “rounded” 3-µm feature attributed to water ice. Takir and Emery (2012) also determine whether a line or higher-order polynomial best fits the 3-µm region; however, we find that our data are sufficiently uncertain that applying this criterion results in ambiguity. We note that for many of the asteroids in this study, the 3-µm feature appears to be linear with a band center in the spectral region unavailable to us because of atmospheric opacity, so in these cases we assume the band center occurs at < 2.85 µm (see Section 3.4). For spectra where both sides of the band are well-defined, we identify the band center as the wavelength at which a 2nd-order polynomial fit to the 3-µm region has the lowest value. We report the band width as the distance between the local maxima (at the “wings” of the band) of a higher-order polynomial fit across the 3-µm region. Finally, we visually inspect the spectra for qualitative interpretation.

3.3.1.1 Rotationally-Resolved Spectra

On 2013 September 25, we obtained ten sets of spectra for asteroid (216) Kleopatra over ~ 20% of the asteroid’s rotation period (Figure 3.7a). Because the object is highly nonspherical and irregular (Ostro et al., 2000), the thermal properties of the illuminated surface may change over short time scales; thus, we found an independent NEATM solution for each of these spectra. We characterized the 3-µm region for each spectrum as described above in Section 3.3.1. We calculated a continuum line for each spectrum independently; however, in order to make a robust comparison of the 3-µm band depth between sets, we used an average continuum line to calculate the band depth.
We also present a light curve that corresponds to the timing of our spectral coverage (Figure 3.8a). This light curve was generated by collaborator Josef Hanuš. To generate this artificial light curve, collaborator Hanuš used a convex shape model of (216) Kleopatra produced by the light curve inversion technique of Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001). The shape model was derived according to the approach described by Hanuš et al. (2011) using 55 dense-in-time light curves from 10 apparitions between 1977 and 2006, and 421 individual sparse-in-time measurements. The dense-in-time data came from the Asteroid Photometric Catalogue (APC\textsuperscript{6}, Piironen et al., 2001) and Warner (2006). The derived sidereal rotation period ($P = 5.385283 \pm 0.000005$ h) and pole orientation ($\lambda = 72 \pm 5^\circ$, $\beta = 21 \pm 5^\circ$) are in agreement with the majority of previous determinations (e.g., De Angelis, 1995; Kaasalainen and Viikinkoski, 2012). This model is stored in the publicly available Database of Asteroid Models from Inversion Techniques (DAMIT\textsuperscript{7}, Ďurech et al., 2010).

To generate a light curve for a given geometry and time based on the known shape model, rotational state and scattering parameters, collaborator Hanuš used a ray-tracing algorithm described, for example, in Kaasalainen and Torppa (2001). As the accuracy of the rotation period is high, the expected rotational shift of the light curve generated for an epoch in year 2013, when the spectroscopic observations were acquired, caused by the period uncertainty should not be more than $\sim 10^\circ$, thus significantly below our requirements.

Taking zero phase to occur on JD 2456561.005, we applied a light-time correction of 0.009 days to the times each set of spectra were collected to link our observations to the light curve. The light curve is shown in figure 3.7b, with the timing of each spectral set denoted.

\textsuperscript{6}http://asteroid.astro.helsinki.fi/
\textsuperscript{7}http://astro.troja.mff.cuni.cz/projects/asteroids3D
3.3.2 TNG Data

The shorter wavelengths (0.8 µm - 2.4 µm) are highly diagnostic of silicate mineralogy. The detection of 0.9-µm and 1.9-µm features attributed to low-Ca, low-Fe orthopyroxenes on many M-type asteroids has been important to compositional interpretations of this class of objects. We focus the analysis of our short-wavelength spectra on these bands.

We begin analysis of these data by fitting a linear continuum across the “wings” of each apparent band. This continuum line is then divided out of the spectrum, and several polynomials of order 2 and higher are fit to the continuum-divided band. The band center is taken as the average wavelength corresponding to the lowest reflectance value in each polynomial. Band depths are calculated in the same manner as we describe in section 3.3.1 for the 3-µm region, using an average of 5 points centered on the band center.

3.4 Results

3.4.1 IRTF Spectra

Our results for each asteroid are summarized in Table 3.6 and our spectra are presented in figures 3.5 and 3.6. We identify a 3-µm feature in each asteroid in our study, with apparent diversity in the shape, center and depth of the band among the asteroids.

Table 3.6: Results

<table>
<thead>
<tr>
<th>Name</th>
<th>Continuum slope (µm⁻¹)</th>
<th>3.0-µm band depth (%)</th>
<th>3.0-µm band center (µm)</th>
<th>3.0-µm band width a (µm)</th>
<th>R(2.90)/R(3.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(69) Hesperia</td>
<td>0.093 ± 0.002</td>
<td>6.2 ± 0.9</td>
<td>&lt; 2.85</td>
<td>-</td>
<td>0.964 ± 0.009</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>0.019 ± 0.002</td>
<td>4.2 ± 1.7</td>
<td>3.08</td>
<td>2.92 – 3.27</td>
<td>1.06 ± 0.02</td>
</tr>
<tr>
<td>(216) Kleopatra b</td>
<td>0.12 ± 0.001</td>
<td>5.7 ± 0.8</td>
<td>&lt; 2.85</td>
<td>-</td>
<td>0.979 ± 0.007</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>0.164 ± 0.006</td>
<td>8.5 ± 2.6</td>
<td>&lt; 2.85?</td>
<td>-</td>
<td>1.03 ± 0.03</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>0.098 ± 0.003</td>
<td>5.1 ± 1.8</td>
<td>3.11?</td>
<td>2.94 – 3.26</td>
<td>1.05 ± 0.02</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>0.111 ± 0.004</td>
<td>7.3 ± 1.0</td>
<td>2.99?</td>
<td>-</td>
<td>1.03 ± 0.01</td>
</tr>
</tbody>
</table>

aNot given for objects where the short edge of the band is ill-defined
bResults from average spectrum
Figure 3.5: Our highest-quality 2 - 4-µm spectrum for each asteroid (black), combined with spectral data at shorter wavelengths (medium grey). The 2–4-µm spectra have had the thermal component removed. Shaded background regions (light grey) indicate wavelengths where atmospheric transparency is low. For asteroids (216) Kleopatra and (261) Prymno, our NICS spectra from 0.8 - 2.4 µm are shown, but these spectra were not used to calculate the continuum (see section 3.2.1.2, figure 3.3).

The spectra of asteroids (69) Hesperia and (216) Kleopatra are consistent with with the broad “checkmark”-shaped (or “sharp”) 3-µm feature described by Rivkin et al. (2002)
and Takir and Emery (2012) and attributed to interlayer hydroxyl in silicate assemblages. Asteroid (136) Austria apparently has a rounded 3-µm feature centered near 3.1 µm. The shape of the 3-µm band for (261) Prymno, (337) Devosa and (418) Alemannia is less apparent. Within the uncertainties, R(2.90)/R(3.05) for (261) Prymno is not diagnostic of feature shape. For (337) Devosa, R(2.90)/R(3.05) is consistent with a rounded feature, but the scatter in the data complicate quantitative assessment. (418) Alemannia’s spectrum appears qualitatively similar to the “checkmark”-shaped 3-µm feature, but R(2.90)/R(3.05) is not consistent with this; however, increased noise in the data around 2.85 µm may inflate the value R(2.90)/R(3.05). We discuss these results in section 3.5.

Figure 3.6: The 3-µm region in each of our spectra. The spectrum has been divided by the estimated continuum to show the shape of the feature. Spectra for (69) Hesperia and (216) Kleopatra are consistent with the “checkmark” feature, while (136) Austria has a rounded feature.

We observed asteroids (69) Hesperia, (216) Kleopatra, (337) Devosa and (418) Alemannia on multiple nights (see Table 3.2). The spectra in Figure 3.5 and the results in Table 3.6
come from the night with the best signal-to-noise for each asteroid. For asteroids observed more than once, all results agree within $2\sigma$.

### 3.4.1.1 Rotationally Resolved Spectra of asteroid (216) Kleopatra

![Rotationally resolved spectra for asteroid (216) Kleopatra](image)

Figure 3.7: Rotationally resolved spectra for asteroid (216) Kleopatra. The red line across each spectrum represents our estimate of the continuum.

We report a statistically significant variation in the depth of the 3-μm band within the 10 spectra we obtained throughout $\sim$20% of Kleopatra’s rotational period. The thermally-corrected spectra and their band depths are shown in Figure 3.7, and the timing of our
observations with respect to the asteroid’s light curve are shown in Figure 3.8 (a). We also find that the continuum slope, calculated as described in Section 3.3.1, varies within the formal error bars; however, there are likely additional uncertainties in the spectral slope due to variations in seeing, guiding and differential atmospheric refraction throughout the observations (Rayner et al., 2009). The value of the beaming parameter, $\eta$, that results in the best NEATM fit does not change significantly. Discussion of the implications of these results is left for Section 3.5.

![Figure 3.8](image)

(a) Artificial light curve for asteroid (216) Kleopatra.  
(b) Temporal trends in band depth, continuum and beaming parameter.

Figure 3.8: Left: Light curve for asteroid (216) Kleopatra over one rotational period, with red squares representing when each spectrum was collected. Right: The 3-µm band is significantly deeper in spectra collected at UT 14:49, 15:17 and 15:23. The continuum slope reddens at UT 14:43, although this measurement is less certain than the band depth. The beaming parameter, $\eta$, does not change significantly throughout our observations.

### 3.4.2 TNG Spectra

Previous studies in the near-infrared have shown absorption features in two of our TNG targets, (216) Kleopatra (Hardersen et al., 2005; Fornasier et al., 2010; Ockert-Bell et al.,...
and (418) Alemannia (Hardersen et al., 2011). Results from our TNG spectra neither confirm nor contradict the presence of these features.

There are no absorption features detectable above the noise in our TNG spectrum of (216) Kleopatra. The level of scatter in our data is comparable to the depth of the previously reported features. We do detect shallow absorptions near 0.9 µm in our 0.8 - 2.4 µm spectra for (261) Prymno and (418) Alemannia (figure 3.9). The band center for (261) Prymno is λ = 0.89µm and the band depth is 2.5% ± 0.9%, and the band center and depth in (418) Alemannia are λ = 0.93µm and 3.0% ± 1.6%, respectively. Our detection of a 0.9-µm feature in (418) Alemannia’s spectrum is in agreement with a feature reported by Hardersen et al. (2011), which they attribute to orthopyroxene; however, we also see absorption features in this wavelength region in our solar analog star spectra (Figure 3.10). Because the 0.9-µm features in (261) Prymno and (418) Alemannia may be telluric or stellar in origin, we cannot confidently attribute them to the silicate features seen in other M-type asteroids.
Figure 3.10: The 0.9-µm region in asteroids (261) Prymno (top) and (418) Alemannia (bottom), shown with the spectra of the solar analogs we used to reduce each asteroid.

3.5 Discussion

3.5.1 Comparison With Other Published Results

The visible near-infrared spectra of many M-types have revealed the presence of diagnostic absorption features. Most common are weak features at 0.9 µm and 1.9 µm (henceforth, Band I and Band II), attributed to low-Fe, low-Ca orthopyroxenes (Hardersen et al., 2005). Radar studies and comparisons with meteorite spectra also provide compositional insight. In this section, we present the published information about the asteroids in our study. This information is summarized in Table 3.7.
3.5.1.1 (69) Hesperia

Hardersen et al. (2005), Fornasier et al. (2010) and Neeley et al. (2014) report the presence of a weak (2 - 3%) Band I in the spectrum of (69) Hesperia. Hardersen et al. (2005) also report a qualitative Band II. Fornasier et al. (2010) find a feature at 0.43 μm, which they attribute to hydrated minerals.

Radar results from Shepard et al. (2011) suggest that the surface of (69) Hesperia is dominated by metal. In a search of the RELAB database, Fornasier et al. (2010) find a metal meteorite to be the best match for (69) Hesperia, but they note that the meteorite spectrum does not satisfactorily match the visible and near-infrared spectrum of the asteroid. Neeley et al. (2014) use several methods of parametric comparison between M-type asteroid spectra and meteorite spectra. They also synthesize these results with radar data and best-fit matches from the RELAB database, and conclude that iron meteorites are the best analog to (69) Hesperia.

3.5.1.2 (136) Austria

Hardersen et al. (2005) find that the near-infrared spectrum of (136) Austria is featureless within the scatter in their data; however, a weak Band I is reported by Ockert-Bell et al. (2010). A search of the RELAB database by Ockert-Bell et al. (2010) shows an enstatite chondrite to be the best meteorite match to (136) Austria, but parametric comparisons show that iron meteorites and stony-irons cannot be ruled out as analogs (Ockert-Bell et al., 2010; Neeley et al., 2014). Rivkin et al. (2000) report the presence of a 3-μm feature in (136) Austria in their spectrophotometric study of M-type asteroids, which we confirm in this work. We note that the band depth reported by Rivkin et al. (2000) is 12% ± 6%, deeper than our detection (4.2% ± 1.7%). This discrepancy may indicate longitudinal variability.
of the 3-µm feature, or it may be due to systematic differences in the instruments or data reduction methods used.

3.5.1.3 (216) Kleopatra

Hardersen et al. (2005), Fornasier et al. (2010), and Ockert-Bell et al. (2010) confirm the presence of a Band I feature in (216) Kleopatra, and Ockert-Bell et al. (2010) also report a Band II feature. Fornasier et al. (2010) report a 0.43-µm feature attributed to hydrated minerals. Fornasier et al. (2010), Ockert-Bell et al. (2010) and Neeley et al. (2014) report that iron meteorites are the best meteoritic analog. Rivkin et al. (2000) do not report a 3-µm feature for (216) Kleopatra in their spectrophotometric study of M-type asteroids; however, our detection of this feature shows that it is shallow (≈6%) and would not have been detected within the uncertainties in the Rivkin et al. (2000) study.

Figure 3.11: The radar shape model of (216) Kleopatra. The horizontal scale bar represents 100 km, and latitude and longitude contours are spaced by 10°. This figure is reprinted with permission from Ostro et al. (2000), appearing in Science 288, #5467, 836–839.

(216) Kleopatra has a very high radar albedo, indicating significantly elevated surface metal content compared to typical main-belt asteroids (Ostro et al., 2000; Shepard et al.,
The object’s radar shape is a highly elongated and resembles a “dumbbell” or “dog-bone” (Ostro et al., 2000, Figure 3.11). Results from imaging with adaptive optics have confirmed this shape and revealed that Kleopatra is a triple system (Descamps et al., 2011). The primary object’s bulk density, derived from the orbits of its moonlets, is \( \rho = 3.6 \pm 0.4 \) \( \text{g/cm}^3 \), compatible with a highly metallic composition with a typical rubble pile macroporosity (Descamps et al., 2011). Mueller et al. (2005) found that (216) Kleopatra has one of the highest thermal inertias among the main belt asteroids. Such an elevated thermal inertia is also consistent with a metallic composition.

3.5.1.4 (261) Prymno

(261) Prymno was classified by Tholen (1984) as a B-type asteroid, although later observations show that it has a red visible and near-infrared spectral slope. It has been reclassified as a moderate-albedo X-complex asteroid (Bus and Binzel, 2002; DeMeo et al., 2009b). Shepard et al. (2015) report a moderate radar albedo of 0.24 \( \pm \) 0.06, consistent with elevated metal content, but inconsistent with a metal-dominated composition. Studies of the Band I and II regions in Prymno’s spectrum have not been previously published, and as discussed, our results for these bands are inconclusive.

3.5.1.5 (337) Devosa

Neeley et al. (2014) find that Band I is present in the spectrum of (337) Devosa, and report that iron meteorites or stony-irons are the best meteoritic matches. Fornasier et al. (2011) also report the presence of Band I in (337) Devosa, as well as a weak 0.43-\( \mu \text{m} \) band. They find that an iron meteorite is the best match to (337)’s near-infrared spectrum. Vernazza et al. (2009) find that the spectrum of an irradiated sample of the Vaca Muerta mesosiderite is compatible with the spectral properties of (337) Devosa. Rivkin et al. (2000) did not report a 3-\( \mu \text{m} \) feature in (337) Devosa, but as is the case with (216) Kleopatra, the uncertainties in
the 3-µm region in their study would preclude the detection of a feature with depth \( \sim 5\% \), as we report in this work.

### 3.5.1.6 (418) Alemannia

Hardersen et al. (2011) report the presence of Band I in (418) Alemannia’s spectrum. This asteroid was also observed by Fornasier et al. (2010) but they do not report any spectral features.

Table 3.7: Summary of published results.

<table>
<thead>
<tr>
<th>Name</th>
<th>0.43-µm feature</th>
<th>0.9-µm ± 1.9-µm feature</th>
<th>3-µm feature</th>
<th>Radar albedo consistent with metal</th>
<th>Meteoritic analogs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(69) Hesperia</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>IM</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>IM, SIM, EC</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>IM</td>
</tr>
<tr>
<td>(261) Prymno</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>IM, SIM</td>
</tr>
<tr>
<td>(418) Alemannia</td>
<td>No</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
</tbody>
</table>

References: Fornasier et al. (2010, 2011)

References: Hardersen et al. (2005); Fornasier et al. (2010, 2011); Ockert-Bell et al. (2010); Hardersen et al. (2011); Neeley et al. (2014)

IM = iron meteorite, SIM = stony-iron meteorite, EC = enstatite chondrite.

References: Vernazza et al. (2009); Fornasier et al. (2010); Ockert-Bell et al. (2010); Neeley et al. (2014)

References: Ostro et al. (2000); Shepard et al. (2010, 2011, 2012)

### 3.5.2 Interpretation of results

There is apparent diversity in the shape of the 3-µm feature among the asteroids in this study. (69) Hesperia and (216) Kleopatra have the linear, “checkmark” feature associated with hydroxylated minerals. (136) Austria has a rounded feature centered near 3.1 µm. A similar feature has been attributed in asteroids to either water-ice (Campins et al., 2010a; Rivkin and Emery, 2010; Licandro et al., 2011a; Takir and Emery, 2012) or goethite, an iron hydroxide mineral (FeO(OH); Beck et al., 2011; Rivkin et al., 2011). The presence of a
rounded feature due to water ice on (136) Austria, which has a semimajor axis of $a = 2.29$, is unexpected. Models of thermal evolution in the asteroid belt predict water ice to be a relevant constituent at a heliocentric distance $> 2.7$ AU (Grimm and McSween, 1993); however, on dusty asteroids, models show that buried ice can exist over billions of years in the inner belt (Schorghofer, 2008). Austria’s rounded feature may be caused by water ice, either replenished from a subsurface reservoir or relatively recently formed, or another substance.

The shapes of the 3-µm features in the spectrum of asteroids (261) Prymno, (337) Devosa and (418) Alemannia are not clearly either “checkmark” or rounded. The lower signal-to-noise ratio in the diagnostic region, compared with the other asteroids in our study, hinders our ability to characterize the feature’s shape. We also consider the possibility that the shape of the 3-µm feature on these asteroids has not been described in the literature. Much of the previous work on asteroids in this spectral region has been focused on primitive asteroid types in the outer main belt. (21) Lutetia, also an M-type asteroid, has a shallow, broad 3-µm feature dissimilar to those typically found in the spectra of C-complex asteroids (Rivkin et al., 2011). Surface processes and mineralogies on some M-type asteroids likely differ from those on primitive asteroids. In the case of (21) Lutetia, the hydrated minerals common to the C-complex do not seem to be present (Rivkin et al., 2011).

The observed rotational variability of the 3-µm band on (216) Kleopatra is intriguing. Although we cannot constrain the exact orientation of Kleopatra’s shape during our observations, the extreme non-sphericity and irregularity of the object could reasonably produce changes in illumination and visibility of facets throughout the $\sim 20\%$ of its rotational period over which we took spectra. As previously discussed, the bulk density, radar albedo, and thermal inertia of (216) Kleopatra are difficult to reconcile with a primitive composition. If Kleopatra is made up mostly of the iron core of a fully differentiated object, the hydrated minerals on its surface are likely exogenic. On the other hand, if Kleopatra is highly col-
lisionally evolved, it may be more like a rubble pile made up of metal core and primitive crust material. The presence of paleomagnetism in the CV carbonaceous chondrite Allende suggests that its parent body was partially differentiated, with a convecting metallic core and an unmelted outer layer (Carporzen et al., 2011a). The collisional disruption of such a body might produce something like Kleopatra.

3.5.2.1 Origin of hydrated minerals on M-types

An important question in understanding the composition and evolution of M-type asteroids is whether the hydrated minerals are endogenic or exogenic. Most interpretations of the near-infrared spectra of M-types require that the asteroids have experienced significant heating that should have driven out any primordial water. Even the M-types that are not likely to be purely metallic have been likened to thermally evolved meteorites, such as stony irons and iron meteorites with silicate inclusions (Vernazza et al., 2009; Neeley et al., 2014). Delivery of primitive material to thermally evolved asteroids by impacts is one proposed mechanism to explain the presence of hydrated mineral features on M-types (Busarev, 2002; Shepard et al., 2013).

This hypothesis is supported by the results of the Dawn mission’s encounter with asteroid (4) Vesta. Dawn found water-rich deposits of dark material on Vesta’s surface, interpreted as carbonaceous chondrite-like impactors (Reddy et al., 2012, and references therein). We also note that carbonaceous clasts have been identified in ordinary chondrites, the HED meteorites, lunar samples and carbonaceous chondrites (Zolensky et al., 1996). The majority of these carbonaceous clasts are CM2 material, which is abundant in hydrated minerals (Zolensky et al., 1996). Finally, dynamical models of the solar system (e.g., Gomes et al., 2005; O’Brien et al., 2014) predict delivery of primitive material to the inner solar system.

Another possibility is that hydrated minerals on M-type asteroids are produced by interactions of solar wind protons with oxygen-bearing minerals, as is the proposed mechanism
for production of hydrated minerals on the Moon (e.g., Clark, 2009; Sunshine et al., 2009; Pieters et al., 2009). The depth of the 3-µm band on the moon varies diurnally and seems to be dependent on instantaneous solar insolation (Sunshine et al., 2009). NASA’s OSIRIS-REx mission to (101955) Bennu, arriving in August 2018, will provide an ideal opportunity to study the relationship between the 3-µm band and solar insolation in an asteroid.

We must also consider that the hydrated minerals are endogenic, and perhaps the M-types have a primitive composition not represented in meteorite collections. Near-infrared spectra of M-types are generally compatible with aqueously altered primitive meteorites, such as CMs and CIs, but the M-types have significantly higher albedos. We note a good spectral match between (69) Hesperia and the CM carbonaceous chondrite Murchison\(^8\) (figure 3.12); however, the reflectivity of Murchison at 0.55 µm is quite low (~ 0.03), in contrast with (69) Hesperia’s geometric albedo of \(p_v = 0.1402\). Still, several proposed scenarios would allow primitive asteroids to have moderate albedos.

![Figure 3.12: Spectrum of (69) Hesperia overplotted with the spectrum of CM chondrite Murchison (RELAB Sample ID MB-TXH-064-HC). This sample has been heated to 600°C for one week, which is sufficient to drive out adsorbed terrestrial water (Beck et al., 2010).](http://www.planetary.brown.edu/relabdocs/relab.htm)

\(^8\)Murchison spectrum obtained from the RELAB Spectral Database, http://www.planetary.brown.edu/relabdocs/relab.htm
Vilas (1994) proposes that M-types could be analogous to highly aqueously altered carbonaceous chondrites. In a moderately reducing environment, iron is leached from phyllosilicates and sequestered as magnetite and elemental iron. The combination of dark, primitive material and highly reflective metal grains can produce the albedo ranges seen in the M-type asteroids (Vilas, 1994); recently, however, Fornasier et al. (2014) investigated a sample of 600 primitive main-belt asteroids and do not find a relationship between albedo and the 0.7-\(\mu\)m hydration feature. Rivkin et al. (2000) suggest the M-types could be CI-like material with veins of high-albedo salts exposed at the surface, as seen in some CI chondrites. Another possibility is that the M-types have had some dark carbonaceous material incorporated into high-albedo carbonates during aqueous alteration episodes (Rivkin et al., 2000).

Finally, we note that the visible-wavelength spectral degeneracy of the X-complex asteroids has likely resulted in compositionally unrelated asteroids being grouped together; i.e., the M class may consist of metallic objects, high-temperature silicate objects, and primitive objects. The near-infrared spectral diversity seen among the M-types supports this idea.

Although our study is not yet diagnostic of the origin of hydrated minerals on M-type asteroids, we can use our results to make some predictions. The M-type asteroids in our study have 3-\(\mu\)m depths <10%. Ground-based, disk-integrated observations of (4) Vesta constrain its 3-\(\mu\)m band depth to 1% (Hasegawa et al., 2003; Rivkin et al., 2006a). The primitive asteroids observed by Takir and Emery (2012) have 3-\(\mu\)m band depths >10%, with some objects in the sample showing band depths >20%. Thus, the relatively weak 3-\(\mu\)m absorption features we observe are consistent with an exogenic origin.

If exogenous hydration in igneous asteroids is common in the asteroid belt, we predict weak 3-\(\mu\)m features will be prevalent in the E-type and S-type asteroids. Thus, more 2 - 4 \(\mu\)m spectroscopy of M-types as well as E-types and S-types is needed. Work in other wavelength ranges, especially the mid-infrared, will provide more insight into the thermal properties and composition of the M-types. Theoretical and experimental studies of the
efficacy of hydration in asteroids by volatile-rich impactors and by solar wind interactions are ongoing (e.g., Schaible and Baragiola, 2014; Avdellidou et al., 2017). Results from such studies will refine our understanding of the origin of hydration in the M-types. Although they were originally considered to be featureless, we now know there is diversity among subtle absorption features in the M-types in all wavelength regions studied.

3.6 Summary

In summary,

1. We report the presence of a 3-μm feature, diagnostic of hydrated minerals, in six M-type asteroids. Our 3-μm results for (136) Austria agree with previous work (Rivkin et al., 2000), but we find 3-μm features in (216) Kleopatra and (418) Alemannia, which were originally interpreted to be “dry” (Rivkin et al., 2000).

2. We detect rotational variability of the depth of the 3-μm feature in (216) Kleopatra.

3. Our 0.8 - 2.4 μm spectra for (261) Prymno and (418) Alemannia show absorption features at 0.9 μm, but we cannot conclude that these features are caused by silicates.

4. More high-resolution 2 - 4 μm spectroscopy of M-types and thermally evolved asteroids such as E-types and S-types is necessary to determine how prevalent hydrated minerals are among these types. Thermal modeling of M-type asteroids will provide insight into their physical properties, which will help clarify composition, thermal history and the origin of their hydrated minerals.
CHAPTER 4: THERMAL AND SPECTRAL STUDY OF ASTEROID (16) PSYCHE WITH THE SPITZER SPACE TELESCOPE

The work presented in this chapter has been submitted for publication in the journal *Icarus* on March 10, 2017, and is in review.

### 4.1 Introduction

As introduced in the previous chapter, the M-type asteroids are an intriguing population. Their high metal content suggests that some M-types may be remnants of differentiated protoplanets, while the presence of both hydrated silicates and reduced, high-temperature material implies a complex thermal and dynamical history. Because this population is so unique, the M-type asteroid (16) Psyche (henceforth, Psyche) has been selected as the target of a NASA Discovery-class mission set to launch in 2023 (Elkins-Tanton et al., 2016).

Studies of Psyche across many wavelength ranges indicate it likely has very high metal content. Shepard et al. (2017) find that Psyche’s radar reflectivity ranges from 0.3 to 0.5 across its surface, which corresponds to a regolith bulk density of 3.4–4.8 g/cm$^3$ using the model developed by Shepard et al. (2010). For comparison, the average S-type asteroid radar albedo of $0.14 \pm 0.05$ corresponds to a regolith bulk density of $2.0 \pm 0.2$ g/cm$^3$ (Magri et al., 2007; Shepard et al., 2010). Assuming large asteroids have a regolith porosity $\geq 40\%$ (i.e, similar to lunar regolith; Sánchez and Scheeres, 2014; Hapke and Sato, 2016), Psyche’s regolith must contain high-density phases such as iron metal.

Radar albedo correlates only to the bulk density of the upper $\sim 1$ meter of regolith. Psyche’s mass and volume are necessary to calculate its overall bulk density. Psyche’s mass
was first reported as $8.7 \pm 2.6 \times 10^{-12} \, \text{M}_\odot$, determined from gravitational perturbations of Psyche on asteroid (94) Aurora’s orbit (Viateau, 2000). This and mass determinations from studies of Psyche’s perturbations on the orbits of other small bodies and Mars result in an average reported mass of $13.7 \pm 3.8 \times 10^{-12} \, \text{M}_\odot$ ($\sim 10^{19}$ kg; e.g., Baer and Chesley, 2008; Konopliv et al., 2011; Zielenbach, 2011; Carry, 2012).

Using a radar-constrained shape model for Psyche and its average mass, Shepard et al. (2017) report a bulk density of $\rho = 4.5 \pm 1.4 \, \text{g/cm}^3$. With this mass and a shape model constrained by disk-resolved adaptive optics imaging and stellar occultation profiles, Hanuš et al. (2017) report a bulk density for Psyche of $\rho = 3.7 \pm 0.6$. These density estimates would suggest that Psyche’s macroporosity is high ($\sim 40\%$) if its composition is dominated by iron-nickel metal; however, without knowing its bulk composition, Psyche’s macroporosity is not well constrained. Psyche’s adopted mass is near the Carry (2012) threshold mass of $\geq 10^{20}$ kg for which asteroids are likely to have no macroporosity, but this threshold is based on the compressibility of silicate grains. If Psyche is metallic, and thus, less compressible, it may have large internal voids despite its high mass.

Matter et al. (2013) used thermophysical modeling of ground-based mid-infrared interferometric data to study Psyche’s thermal properties. They report a thermal inertia of $114–133 \pm 40 \, \text{J m}^{-2} \, \text{K}^{-1} \, \text{s}^{-1/2}$ and a smooth (or very low roughness) surface. Because thermal inerti-\tis of large, dusty main-belt asteroids are typically near $30 \, \text{J m}^{-2} \, \text{K}^{-1} \, \text{s}^{-1/2}$, Matter et al. (2013) interpret Psyche’s high thermal inertia to be consistent with elevated metal content.

There is also evidence for at least some silicate material on Psyche’s surface. Near-infrared spectroscopy of Psyche has revealed evidence for orthopyroxene, and pyroxene abundance may be anti-correlated with radar albedo across Psyche’s surface (Hardersen et al., 2011; Sanchez et al., 2017). Interestingly, a weak 3-μm absorption feature attributed to hydroxylated silicates is also present on Psyche’s surface, and it may vary rotationally (Takir et al., 2017).
To further constrain Psyche’s surface properties, including its composition, we have carried out a mid-infrared (5-14\,\mu m) study using data collected with the Spitzer Space Telescope’s Infrared Spectrograph. We consider two datasets obtained during different epochs and rotational phases. Our investigation includes thermal modeling and analysis of Psyche’s emissivity spectrum.

4.2 Observations and Data Reduction

4.2.1 Spitzer Infrared Spectrograph Observations

This study uses observations made with the Spitzer Space Telescope’s Infrared Spectrograph (IRS) instrument (Houck et al., 2004a), described in Chapter 2. Observing circumstances are presented in Table 4.1. The IRS observed Psyche using its Short-Wavelength, Low-Resolution module (SL; resolving power $\lambda/\Delta\lambda\sim60–130$, $\lambda$=5.2–14.2\,\mu m). The SL module consists of two orders: SL2 (5.2–7.6\,\mu m) and SL1 (7.4–14.2\,\mu m). The SL2 and SL1 observations were proposed and carried out by Cruikshank and van Cleve (2004c) and Lim et al. (2005), respectively, and we obtained these datasets from the Spitzer Heritage Archive\(^1\).

Table 4.1: Observing Circumstances – Spitzer IRS

<table>
<thead>
<tr>
<th>IRS mode</th>
<th>Int. time (s)</th>
<th>Int. cycles</th>
<th>Date</th>
<th>Start time (UT)</th>
<th>$r_H^{a,b}$ (AU)</th>
<th>$\Delta^{a,c}$ (AU)</th>
<th>$\alpha^{a,d}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL2</td>
<td>6</td>
<td>1</td>
<td>2004-05-14</td>
<td>00:57:25</td>
<td>2.82323</td>
<td>2.5682</td>
<td>20.86</td>
</tr>
<tr>
<td>SL1</td>
<td>6</td>
<td>2</td>
<td>2006-03-17</td>
<td>15:27:12</td>
<td>2.79517</td>
<td>2.4547</td>
<td>20.73</td>
</tr>
</tbody>
</table>

\(^{a}\)Obtained from JPL’s Horizons ephemeris system (http://ssd.jpl.nasa.gov/?horizons)

\(^{b}\)Heliocentric distance

\(^{c}\)Distance from Spitzer

\(^{d}\)Phase angle

For IRS observations with the SL module, the Spitzer Space Telescope nods 20\,\arcsec between two positions along the slit, producing spectra in “AB” pairs. Typically, IRS science targets

\(^{1}\)http://sha.ipac.caltech.edu/applications/Spitzer/SHA/
can be precisely located using a peak-up imaging mode; however, Psyche was too bright for peak-up imaging, and was observed in Mapping Mode. In Mapping Mode, the telescope points at three positions along the direction perpendicular to the slit, separated by 1.8–2.0" (about half the slit width). The resulting flux map is used to correct for flux loss due to pointing error (see Section 4.2.2 for more details).

4.2.2 Data Reduction and Uncertainties

We begin with Spitzer’s Basic Calibration Data (BCD) products retrieved from the Spitzer Heritage Archive. The BCD spectra have already received standard corrections, such as flat-fielding, dark current subtraction, and wavelength calibration. Our first step is to remove background flux, which is dominated by emission from the zodiacal cloud at our chosen wavelengths. To remove this background emission, we take the difference of the “AB” spectral pairs produced by nodding the telescope along the direction of the slit. We then extract and flux-calibrate each background-subtracted spectrum using the SPitzer IRS Custom Extractor\textsuperscript{2} (SPICE) v. 2.5.1, a JAVA-based tool developed by the Spitzer Science Center for the extraction of IRS data. Our data reduction process closely follows that of Comet S-W 1 as described in Recipe 16 of the Spitzer Data Cookbook\textsuperscript{3}.

Although main-belt asteroid spectra in mid-infrared wavelengths are dominated by thermal emission, some fraction of the light received by Spitzer is reflected sunlight. We model reflected sunlight as the solar spectral irradiance\textsuperscript{4}, scaled to the asteroid’s spectral irradiance in the Johnson V-band. We estimate the V-band irradiance using the apparent V-magnitude, \(m_v\). We calculate \(m_v\) using the asteroid’s geometric quantities, its radius and geometric albedo, and the “H,G” formalism of Bowell et al. (1989) as described in Jewitt

\textsuperscript{2}http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/tools/spice/
\textsuperscript{3}http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/cookbook/
\textsuperscript{4}Zero Airmass Solar Spectral Irradiance Table. Standard E490-00, American Society for Testing and Materials.
and Luu (1995b). For this calculation, we assume the effective diameter of 226 ± 23 km and a geometric albedo of 0.15 (e.g., Shepard et al., 2017). In SL1, the reflected solar flux component is at most < 1% of the total flux (see Figure 4.1b), so we neglect it in our thermal modeling. However, in SL2, the reflected flux makes up ~19% of the total flux at the shortest wavelengths (Figure 4.1b); thus, we subtract the estimated reflected flux from SL2 (Figure 4.1a).

![Figure 4.1: Top (a): The SL2 spectrum shown as measured (solid line) with the modeled reflected solar flux component subtracted (dashed line). Bottom (b): The ratio of reflected solar flux to total measured flux for SL2 (dotted line) and SL1 (dashed-dotted line).](image)

Because Psyche was observed in Mapping Mode, the asteroid’s point spread function (PSF) is generally offset from the center of the slit at each map step. This introduces wavelength-dependent flux loss for a given offset distance, an effect termed Spectral Pointing-Induced Throughput Error (SPITE; Sloan et al., 2003). To correct for SPITE, we compute the average flux at each map position and fit a Gaussian function to these points. Then we compute the offset of a map step from the peak of the Gaussian, i.e., the distance of the slit from the center of the asteroid’s PSF at that map position (Figure 4.2). The wavelength-
dependent flux loss is then computed and corrected using the offset distance following the
procedure described in Nerenberg and Sloan (2003) and Keremedjiev and Sloan (2006). First,
we compute a theoretical PSF (Equation 10.1.10 in Schroeder, 1987),

$$\text{PSF} = \frac{1}{(1 - \epsilon_{\text{obs}}^2)^2} \left[ \frac{2J_1(v)}{v} - \frac{\epsilon_{\text{obs}}^2}{\epsilon_{\text{obs}}v} \frac{2J_1(\epsilon_{\text{obs}}v)}{\epsilon_{\text{obs}}v} \right]^2$$ (4.1)

where $J_1$ is the first-order Bessel function of the first kind, $\epsilon_{\text{obs}}$ is the obscuration ratio
(the ratio of the diameter of the secondary mirror to the diameter of the primary mirror),
and $v$ is a dimensionless quantity given by

$$v = \frac{\pi D \theta}{\lambda}.$$ (4.2)

Here, $D$ is the diameter of the primary mirror in meters, $\theta$ is the angular offset from the
center of the PSF in radians, and $\lambda$ is the wavelength of light in meters. For the Spitzer
Space Telescope, $D = 0.85$ m and $\epsilon_{\text{obs}} = 0.33$.

For a given offset from the center of the slit, we then calculate the throughput by convolv-
ing the PSF for that offset with a rectangular slit (a square wave with a pulse width equal to
the angular slit width). Finally, we compute correction factors for each wavelength by taking
the ratio of the calculated throughput for a given offset with the calculated throughput for
zero offset. We make the SPITE correction by dividing the measured spectral flux density
at each wavelength by the correction factor for that wavelength.
Figure 4.2: The wavelength-averaged flux density (filled circles) at each map step, shown for the SL2 spectrum. We fit the flux at each of the three map positions with a Gaussian (dashed line) and compute the offset ($\Delta x$) from the center of the asteroid’s PSF to the slit.

Uncertainties in absolute flux calibration are not included in the formal point-to-point errorbars computed by SPICE. The additional uncertainty in absolute flux for Spitzer’s IRS is $\leq 10\%$ (Decin et al., 2004) in flux. To account for this uncertainty in our thermal model-derived quantities, we fit each run of each thermal model three times: once to the nominal spectrum, once to the nominal spectrum with 10% in flux added point-wise, and once to the nominal spectrum with 10% in flux subtracted point-wise. This method was used in Emery et al. (2014).

From $\sim13.5$-$15\mu m$, Spitzer SL1 spectra show an excess of emission due to an artifact known as the 14-$\mu m$ teardrop. As recommended by the IRS Instrument Handbook\textsuperscript{5}, we do not fit thermal models or interpret spectra at wavelengths longer than $13.2\mu m$.

\textsuperscript{5}http://irsa.ipac.caltech.edu/data/SPITZER/docs/irs/irsinstrumenthandbook/
4.3 Data Analysis

Our analysis involves both thermal modeling and the study of spectral features. As discussed in Chapter 2, thermal models allow us to derive relevant physical properties, including diameter, albedo, and thermal inertia. We gain further insight into Psyche’s surface properties and composition by investigating its emissivity spectrum. The emissivity spectrum is computed by dividing the measured spectral energy distribution (SED) by the modeled SED. The residual emissivity spectrum is a function of both composition and the scattering properties of the material on Psyche’s surface.

4.3.1 Thermal Modeling

Table 4.2: Inputs for thermal modeling

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute magnitude (H)</td>
<td>5.85 ± 0.04</td>
<td>A,B,C</td>
</tr>
<tr>
<td>Slope parameter (G)</td>
<td>0.12±0.04</td>
<td>A,B,C</td>
</tr>
<tr>
<td>Rotation period (hours)</td>
<td>4.195948 ± 0.000001</td>
<td>D,E,F,G</td>
</tr>
<tr>
<td>Spin pole ecliptic longitude (λ, °)</td>
<td>34 ± 5</td>
<td>D,E,F,G, H</td>
</tr>
<tr>
<td>Spin pole ecliptic latitude (β, °)</td>
<td>-7 ± 5</td>
<td>D,E,F,G, H</td>
</tr>
</tbody>
</table>

A Muinonen et al. (2010a)  B Oszkiewicz et al. (2011b)
C https://wiki.helsinki.fi/display/PSR/Asteroid+absolute+magnitude+and+slope
H Shepard et al. (2017)

4.3.1.1 NEATM

We begin thermal modeling with the Near-Earth Asteroid Thermal Model (NEATM; see Chapter 2). In the NEATM, the asteroid’s subsolar temperature depends on the bolometric emissivity ($\epsilon$) as $T \propto \epsilon^{-1/4}$. Generally, $\epsilon$ is assumed to be 0.9-0.95 for silicate surfaces. In the case of a potentially metallic asteroid like Psyche, this assumption may be incorrect. Metallic iron has a lower emissivity than silicates\(^6\). For example, Gundlach and Blum (2013)

\(^6\)See Table 2-1 in Brewster (1992)
assume an emissivity value of 0.66 for their thermal calculations involving M-type asteroids.

We fit the NEATM for 4 values of emissivity: 0.95, 0.9, 0.7, and 0.5.

We fit the NEATM by stepping through a grid of values for the beaming parameter, $\eta$. For each value of beaming parameter, we use a $\chi^2$-minimization routine based on Brent’s optimization method (Brent, 1973) to find the diameter value that produces the best-fit model flux. Brent’s method uses inverse quadratic interpolation to find the value $x$ that minimizes the function $f(x)$ when given three values $x_a$, $x_b$, and $x_c$ such that $f(x_a)$, $f(x_b)$, and $f(x_c)$ that bound the minimum.

### 4.3.1.2 Spherical TPM

Because Psyche’s spin rate, pole orientation, and general shape are known, it is a good candidate for thermal modeling with the thermophysical model (TPM; Chapter 2). We begin by assuming Psyche’s shape is spherical, and calculate the temperature distribution for facets distributed across the surface of the visible hemisphere.

For the spherical TPM, we step through a grid of thermal inertia values, and for each thermal inertia, we use Brent’s method to find the effective diameter that produces an SED that best fits the data. We assume a regolith bulk density of 4.5 g/cm$^3$ based on Psyche’s radar reflectivity and constraints on its density from radar, adaptive optics imaging, and occultation data (Shepard et al., 2017; Hanuš et al., 2017). The emissivity and specific heat capacity of Psyche’s surface depend on its composition. Published specific heat capacities for meteorites range from $\sim$400-900 J/kg K for stony meteorites, $\sim$450-550 J/kg K for stony-irons, and $\sim$350-600 J/kg K for iron meteorites (Szurgot, 2011; Consolmagno and Britt, 2013; Consolmagno et al., 2013, and references therein).

We consider three compositional scenarios: [1] surface dominated by silicates ($c_p = 700$ J/kg K, $\epsilon = 0.9$); [2] surface is a mixture of silicates and iron metal ($c_p = 500$ J/kg K, $\epsilon = 0.7$); [3] surface dominated by iron metal ($c_p = 400$ J/kg K, $\epsilon = 0.5$). We also consider three
roughness scenarios: [1] smooth (RMS surface slope = 0°); [2] moderately rough ($\gamma = 53^\circ, f = 0.77$; RMS surface slope = 20°); [3] very rough ($\gamma = 90^\circ, f = 1.0$; RMS surface slope = 66°).

4.3.1.3 TPM with Shape Models

More reliable results can be obtained by using a thermophysical model in which the heat diffusion equation is solved for facets distributed on a shape model rather than a sphere. There are two published shape models for Psyche. The first one is produced by the lightcurve inversion method (Kaasalainen et al., 2002) applied to optical disk-integrated data. This model was later scaled in size by stellar occultation measurements (Ďurech et al., 2011) and disk-resolved images from the near infrared camera mounted on the Keck II telescope (Hanuš et al., 2013a). We downloaded this model from the public Database of Asteroid Models from Inversion Techniques (DAMIT\(^7\); Ďurech et al., 2010). Moreover, Shepard et al. (2017) recently derived a shape model based on optical lightcurves and delay-Doppler images. This shape model was provided us by Dr. Shepard.

Using the lightcurve-based shape model of Kaasalainen et al. (2002) we have determined the rotational phase of Psyche as viewed from Spitzer during both observations. The uncertainty in the rotation phase is about ten degrees, which is small enough for our purposes and conclusions. The synthetic lightcurves and both shape model projections at the two epochs of observations by Spitzer are shown in Figures 4.3 and 4.4. The synthetic lightcurves were generated by collaborator Josef Hanuš.

---

At top (a), Psyche’s synthetic lightcurve for one rotational period beginning at the start of SL2 observations. At bottom (b and c), lightcurve-inversion and radar shape models, respectively, shown at a rotational phase of 225°, corresponding to the observation geometry at the beginning of SL2 observations.
At top (a), Psyche’s synthetic lightcurve for one rotational period beginning at the start of SL1 observations. At bottom (b and c), lightcurve-inversion and radar shape models, respectively, shown at a rotational phase of 225°, corresponding to the observation geometry at the beginning of SL1 observations.

As with the spherical models, we consider emissivity values of $\epsilon=0.9$, 0.7, and 0.5 and three cases of surface roughness: [1] smooth (RMS surface slope = 0°); [2] moderately rough (RMS surface slope = 20°); [3] very rough (RMS surface slope = 66°). We do not vary the effective radius as in the spherical TPM, and instead assume a fixed size as constrained by
the radar, occultation, and adaptive optics data, and assume a fixed geometric albedo of $p_v = 0.15$.

With this high fidelity version of the thermophysical model, we consider only the SL1 data, as the SL2 data are not as reliable or constraining. The wavelength range covered by SL2 is less diagnostic of thermal properties than the broader and longer wavelength range covered by SL1 (Figure 4.5). The presence of fine-grained silicates, which are more transparent at wavelengths shorter than $\sim 8 \mu$m in this wavelength range, also complicates fitting to SL2. In the presence of a steep thermal gradient, the warmer subsurface is detected at wavelengths where silicates are transparent. This appears as an excess in thermal flux at those wavelengths, and makes the spectrum deviate from a blackbody curve. There is additional uncertainty in SL2 from our subtraction of modeled reflected light.
Figure 4.5: Six SEDs produced from our thermophysical model, over the 5–40 μm range. We use the viewing geometry of Psyche’s SL2 observations. The wavelength ranges covered by SL2 and SL1 are denoted. At longer wavelengths, the differences in the SEDs become more apparent.

The differences between the radar shape model and the lightcurve-only shape model, as well as the reported ±10% uncertainties in the dimensions of the shape models, contribute some additional uncertainty to the thermal inertia determination. To constrain this uncertainty, we consider both the nominal shape models and also “flex” the dimensions of each shape model by ±10% (so that the surface of area of each facet increases or decreases by 19% of the nominal area). As shown in Figure 4.6, how much the shape model uncertainty affects the thermophysical model’s goodness of fit and best-fit thermal inertia depends upon the value of bolometric emissivity used.
Figure 4.6: The effects of shape model uncertainties on the goodness-of-fit for each thermophysical model as a function of thermal inertia. Each panel shows $\chi^2$ as a function of thermal inertia for six shape model cases: the radar shape model and the lightcurve-only shape model at its nominal sizes and at the extrema of their 10% size uncertainties. Each row represents a different value of bolometric emissivity ($\epsilon$). Solid horizontal lines represent the 1-, 2- and 3-$\sigma$ $\chi^2$ cutoff values. These curves are calculated for the SL1 data and use the smooth surface thermophysical model.
For all thermal models, the derived range of values for each free parameter is determined by computing cutoff values of the $\chi^2$ goodness-of-fit parameter for 1-, 2-, and 3-$\sigma$ confidence levels. Each combination of model free parameter values that produces a fit with a $\chi^2$ less than or equal to a cutoff value will be considered acceptable within the confidence level for that cutoff value. The cumulative distribution function (CDF) for $\chi^2$, that is, the probability that $\chi^2$ for a model fit to a dataset with $k$ degrees of freedom will be valued $\leq x$ is given by

$$F_{\chi^2}(x, k) = \frac{\gamma \left( \frac{k}{2}, \frac{x}{2} \right)}{\Gamma_{\text{func}} \left( \frac{k}{2} \right)}$$  \quad (4.3)$$

where $\gamma$ is the incomplete gamma function and $\Gamma_{\text{func}}$ is the gamma function. To compute a cutoff value of $\chi^2$ for the 1-$\sigma$ confidence level for a given number of degrees of freedom $k$, we want the $\chi^2$ value $x_{1\sigma}$ such that $F_{\chi^2}(x_{1\sigma}, k) = 0.683$; i.e., there is a 68.3% probability that $\chi^2$ will be $\leq x_{1\sigma}$. For the 2-$\sigma$ and 3-$\sigma$ confidence levels, we want cutoff values $x_{2\sigma}$ and $x_{3\sigma}$ such that $F_{\chi^2}(x_{2\sigma}, k) = 0.954$ and $F_{\chi^2}(x_{3\sigma}, k) = 0.997$.

The cutoff values are computed from the percent point function (PPF) for $\chi^2$, which is the inverse of the CDF. The PPF for $\chi^2$ is computed numerically, and we use a Python routine in SciPy’s scipy.stats.chi2 package\(^8\) to calculate the cutoff values from the PPF. Because these cutoff values are based on a theoretical ideal $\chi^2$ distribution, we add to them the minimum computed $\chi^2$ value from our model fits. The number of degrees of freedom are the number of data points in the spectrum we are fitting minus the number of free model parameters.

To ensure that spectral points are independent of each other and to decrease computation time when fitting models, the spectra are binned by at least a factor of five.

\(^8\)https://docs.scipy.org/doc/scipy-0.18.1/reference/generated/scipy.stats.chi2.html
4.3.2 Emissivity Spectrum

We computed Psyche’s emissivity spectrum by dividing the SL2 and SL1 spectra by one of the well-fitting thermal models described in Section 4.4.1. The choice of model does not affect the diagnostic spectral features as long as the model fits well. The residuals show relative emissivity, which can be diagnostic of silicate mineralogy and regolith properties (see Chapter 2). To preliminarily constrain Psyche’s mineralogy, we compared its emissivity spectrum with laboratory spectra of powdered individual minerals and meteorites. We focused on the SL1 spectrum, as SL1 covers the 9-11 \( \mu m \) region containing diagnostic stretching reststrahlen bands. We obtained the laboratory spectra from the ASTER database (Baldridge et al., 2009), the ASU Spectral Library (Christensen et al., 2000), and the RELAB database\(^9\). The ASTER data originally appeared in Salisbury et al. (1991). Additionally, Dr. Pierre Vernazza provided us with the spectra of KBr-dispersed meteorite powders that were published in Vernazza et al. (2011). KBr is transparent in the mid-infrared, so the dispersed meteorite powders spectroscopically mimic underdense regolith. Table 4.3 describes all samples used in this analysis.

The RELAB and ASTER bidirectional spectra are approximated as emissivity spectra following Kirchoff’s law (e.g., Salisbury et al., 1991). Kirchoff’s law only applies quantitatively for directional-hemispherical reflectance spectra, but may be used to make qualitative comparisons between bidirectional spectra and asteroid emissivity spectra. We also note that thermal gradients in the asteroid’s surface effect emissivity spectra in ways that are not necessarily replicated to high fidelity in laboratory measurements (e.g., Logan et al., 1973; Donaldson Hanna et al., 2012).

\(^9\)http://www.planetary.brown.edu/relab/
Table 4.3: Laboratory samples used as comparisons to Psyche

<table>
<thead>
<tr>
<th>Figure</th>
<th>Material</th>
<th>Database</th>
<th>Sample ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.14</td>
<td>Antigorite</td>
<td>ASTER</td>
<td>antigorite.1</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Clinochlore</td>
<td>ASTER</td>
<td>clinochlore.1</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Lizardite</td>
<td>ASTER</td>
<td>lizard.1</td>
<td>&lt; 60 µm particles</td>
</tr>
<tr>
<td></td>
<td>Montmorillonite</td>
<td>ASU</td>
<td>583</td>
<td>Powdered</td>
</tr>
<tr>
<td>4.16a</td>
<td>Olv (Fo1)</td>
<td>ASTER</td>
<td>olivine.13</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Olv (Fo91)</td>
<td>ASTER</td>
<td>olivine.12</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
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<td>Olv (Fo1)</td>
<td>ASTER</td>
<td>olivine.13</td>
<td>75–250 µm particles</td>
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<tr>
<td></td>
<td>Olv (Fo91)</td>
<td>ASTER</td>
<td>olivine.12</td>
<td>75–250 µm particles</td>
</tr>
<tr>
<td>4.16b</td>
<td>Pyx (En87Fs13)</td>
<td>ASTER</td>
<td>enstatite.1</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Pyx (En87Fs13)</td>
<td>ASTER</td>
<td>enstatite.1</td>
<td>75–250 µm particles</td>
</tr>
<tr>
<td></td>
<td>Pyx (En25Fs75)</td>
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<td>BIR1DL006A</td>
<td>&lt; 45 µm particles</td>
</tr>
<tr>
<td></td>
<td>Pyx (En50Fs50)</td>
<td>RELAB</td>
<td>BIR1DL004A</td>
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</tr>
<tr>
<td></td>
<td>Pyx (En75Fs25)</td>
<td>RELAB</td>
<td>BIR1DL004A</td>
<td>&lt; 45 µm particles</td>
</tr>
<tr>
<td>4.15a</td>
<td>Allende (CV3)</td>
<td>ASTER</td>
<td>Allende1</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Ivuna (CI1)</td>
<td>ASTER</td>
<td>Ivuna</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Murray (CM2)</td>
<td>ASTER</td>
<td>Murray</td>
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<td>Orgueil (CI1)</td>
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<td>Orgueil.2</td>
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<td>4.15b</td>
<td>Allende (CV3)a</td>
<td>–</td>
<td>–</td>
<td>Powder dispersed in KBr</td>
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<tr>
<td></td>
<td>Ivuna (CI1)a</td>
<td>–</td>
<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td></td>
<td>Murray (CM2)a</td>
<td>–</td>
<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td></td>
<td>Orgueil (CI1)a</td>
<td>–</td>
<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td></td>
<td>Tagish Lake (C2)a</td>
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<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td>4.17a</td>
<td>ALHA 77299 (H3)</td>
<td>ASTER</td>
<td>ALHA 77299</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>ALHA 77214 (L3)</td>
<td>ASTER</td>
<td>ALHA 77214</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>TIL 82402 (LL6)</td>
<td>ASTER</td>
<td>TIL 82402</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Greenwell Springs (LL4)a</td>
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<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td>4.17b</td>
<td>ALH 84007 (Aubrite)</td>
<td>ASTER</td>
<td>ALH 84007</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>Happy Canyon (EL6)</td>
<td>ASTER</td>
<td>Happy Canyon</td>
<td>&lt; 75 µm particles</td>
</tr>
<tr>
<td></td>
<td>ALHA 81021 (EL6)a</td>
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<td>–</td>
<td>Powder dispersed in KBr</td>
</tr>
<tr>
<td></td>
<td>LEW 88180 (EH5)a</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td></td>
<td>NWA 2212 (EL6)a</td>
<td>–</td>
<td>–</td>
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aOriginally appears in Vernazza et al. (2011)

Table 4.4: Mineral formulas

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<thead>
<tr>
<th>Mineral Name</th>
<th>Chemical Formula</th>
<th>Mineral Group</th>
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</thead>
<tbody>
<tr>
<td>Forsterite (Fo)</td>
<td>Mg₂SiO₄</td>
<td>Nesoilicate - Olivine (olv)</td>
</tr>
<tr>
<td>Fayalite (Fa)</td>
<td>Fe₂SiO₄</td>
<td>Nesoilicate - Olivine (olv)</td>
</tr>
<tr>
<td>Enstatite (En)</td>
<td>MgSiO₃</td>
<td>Inosilicate - Pyroxene (pyx)</td>
</tr>
<tr>
<td>Wollastonite (Wo)</td>
<td>FeSiO₃</td>
<td>Inosilicate - Pyroxene (pyx)</td>
</tr>
<tr>
<td>Clinoclore</td>
<td>(Mg₅Al)(AlSi₃)O₁₀(OH)₈</td>
<td>Phyllosilicate - Chlorite</td>
</tr>
<tr>
<td>Antigorite</td>
<td>Mg₃(Si₂O₅)(OH)₄</td>
<td>Phyllosilicate - Serpentine</td>
</tr>
<tr>
<td>Lizardite</td>
<td>Mg₃(Si₂O₅)(OH)₄</td>
<td>Phyllosilicate - Serpentine</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>(Na, Ca)₀.₃₃(Al, Mg)₂(Si₄O₁₀)(OH)₂·nH₂O</td>
<td>Phyllosilicate - Smectite</td>
</tr>
</tbody>
</table>
4.4 Results

4.4.1 Thermal Modeling

4.4.1.1 NEATM

The NEATM results are presented in Table 4.5 and the modeled flux is shown with measured SEDs in Figure 4.7. In general, the NEATM does not fit the SL2 data well at its longer wavelengths (Figure 4.7a). For both SL2 and SL1, the NEATM fits equally well for each value of bolometric emissivity ($\epsilon = 0.95, 0.9, 0.7, \text{and } 0.5$). The derived effective diameters for the SL2 dataset are, on average, smaller than those derived for SL1. This is unsurprising, as the SL2 observations were made near a lightcurve minimum (viewing a smaller total surface area), while the SL1 observations were made near a lightcurve maximum (see Figures 4.3 and 4.4).

Figure 4.7: Example NEATM fits to the SL2 (left; a) and SL1 (right; b) spectra.
Table 4.5: NEATM results

<table>
<thead>
<tr>
<th>Observation</th>
<th>$\epsilon$</th>
<th>$D_{eff}$ (km)</th>
<th>$p_v$</th>
<th>$\eta$</th>
<th>$T_{SS}$ (K)</th>
<th>$\chi^2_{min}$</th>
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<tr>
<td>SL2 (2004-05-14)</td>
<td>0.95</td>
<td>158 ± 12</td>
<td>0.32 ± 0.06</td>
<td>1.0 ± 0.1</td>
<td>228 ± 4</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>163 ± 13</td>
<td>0.31 ± 0.06</td>
<td>1.1 ± 0.1</td>
<td>228 ± 4</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>185 ± 15</td>
<td>0.24 ± 0.05</td>
<td>1.5 ± 0.1</td>
<td>228 ± 4</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>218 ± 17</td>
<td>0.17 ± 0.03</td>
<td>2.1 ± 0.1</td>
<td>228 ± 3</td>
<td>31.8</td>
</tr>
<tr>
<td>SL1 (2006-03-17)</td>
<td>0.95</td>
<td>232 ± 26</td>
<td>0.15 ± 0.03</td>
<td>1.1 ± 0.1</td>
<td>229 ± 5</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>239 ± 24</td>
<td>0.14 ± 0.03</td>
<td>1.2 ± 0.1</td>
<td>229 ± 5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>271 ± 25</td>
<td>0.11 ± 0.02</td>
<td>1.5 ± 0.1</td>
<td>229 ± 5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>320 ± 33</td>
<td>0.08 ± 0.02</td>
<td>2.2 ± 0.2</td>
<td>229 ± 4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

$^a$ 3-σ range of values are given. Absolute flux calibration uncertainty is included.

$^b$ Computed from the upper and lower ends of diameter range. Uncertainty in absolute magnitude is also included.

4.4.1.2 Spherical TPM

The results from spherical thermophysical modeling are presented in Table 4.6. The $\chi^2$ goodness-of-fit parameter is shown as a function of thermal inertia for all cases of emissivity and surface roughness in Figures 4.8 and 4.9. For the SL2 dataset, the spherical TPM produces better fits than the NEATM, and produced good fits for all values of surface roughness and bolometric emissivity considered. For SL1, the spherical TPM fits the data well for each surface roughness regime with the bolometric emissivity $\epsilon=0.9$ and 0.7, but in the $\epsilon=0.5$ model runs, only the rough models produce an acceptable fit. Examples of modeled flux are shown with measured SEDs in Figure 4.10. In general, we find that surface roughness, bolometric emissivity, and thermal inertia are poorly constrained with the spherical TPM. There is degeneracy in which different combinations of roughness, thermal inertia, bolometric emissivity, and effective diameter can result in similar modeled temperature distributions. This degeneracy is addressed further in section 4.5.1.

4.4.1.3 TPM with Shape Models

Finally, the most well-constrained results, obtained using Psyche’s shape models, are shown in Table 4.7, and the goodness-of-fit for each TPM run using the radar shape model run is shown as a function of thermal inertia in Figure 4.11. We consider only the SL1 dataset for this high-fidelity modeling, as it is more diagnostic of thermal properties and reliable than
SL2, as previously discussed. We find that the best fits are produced by smooth models with \( \epsilon = 0.9 \) and low thermal inertias (5–25 J m\(^{-2}\) K\(^{-1}\) s\(^{-1/2}\)). The smooth models fit significantly better than either the moderately rough or very rough models for all cases of emissivity. The smooth, \( \epsilon = 0.7 \) models result in a marginal fit with \( \Gamma = 80–95 \) J m\(^{-2}\) K\(^{-1}\) s\(^{-1/2}\). The \( \epsilon = 0.5 \) models do not fit to \( 3\sigma \). The temperature distribution and modeled SED computed with a TPM using Psyche’s radar shape model are shown in Figure 4.12.
Figure 4.8: At left (a), the $\chi^2$ parameter as a function of thermal inertia for each case of epsilon and surface roughness considered for the SL2 data, assuming a spherical asteroid. In (b) and (c), the region near $\chi^2_{\text{min}}$ is shown at closer scale. The dashed horizontal line in (b) and (c) is the 1-σ cutoff value for $\chi^2$.

Table 4.6: Spherical thermophysical modeling results$^a$

<table>
<thead>
<tr>
<th>Observation</th>
<th>$\epsilon$</th>
<th>$\Gamma$ (J m$^{-2}$ K$^{-1/2}$)</th>
<th>$D_{\text{eff}}$ (km)</th>
<th>$p_v$,$^b$</th>
<th>$T_{\text{SS}}$ (K)</th>
<th>$\chi^2_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL2 (2004-05-14)</td>
<td>0.90</td>
<td>5–87</td>
<td>164–222</td>
<td>0.16–0.30</td>
<td>224–241</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>40–183</td>
<td>166–234</td>
<td>0.15–0.29</td>
<td>224–239</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>$&gt;100$</td>
<td>$&gt;174$</td>
<td>$&lt;0.27$</td>
<td>$&lt;238$</td>
<td>1.9</td>
</tr>
<tr>
<td>SL1 (2006-03-17)</td>
<td>0.90</td>
<td>2–74</td>
<td>241–380</td>
<td>0.06–0.14</td>
<td>232–270</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>66–200</td>
<td>295–412</td>
<td>0.05–0.09</td>
<td>240–274</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>$&gt;225$</td>
<td>$&gt;342$</td>
<td>$&lt;0.07$</td>
<td>$&lt;269$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$^a$ 3-σ range of values are given. All three roughness cases and absolute flux calibration uncertainty are included in the uncertainties.

$^b$ Computed from the upper and lower ends of diameter range. Uncertainty in absolute magnitude is also included.
Figure 4.9: At left (a), the $\chi^2$ parameter as a function of thermal inertia for each case of $\epsilon$ and surface roughness considered for the SL1 data, assuming a spherical asteroid. In (b) and (c), the region near $\chi^2_{\text{min}}$ is shown at closer scale. The dashed horizontal lines in (b) and (c) are the 1-, 2-, and 3-$\sigma$ cutoff values for $\chi^2$.

Figure 4.10: Example spherical thermophysical model fits to the SL2 (left; a) and SL1 (right; b) spectra.
Figure 4.11: The $\chi^2$ parameter as a function of thermal inertia for each case of epsilon and surface roughness considered for the SL1 data, using the nominal radar-based shape model of Shepard et al. (2017). In the inset plot, the region near $\chi^2_{\text{min}}$ is shown at a closer scale. The dashed horizontal lines in (b) and (c) are the 1-, 2-, and 3-σ cutoff values for $\chi^2$. The smooth models (circular markers) fit significantly better than the rough models (square and diamond markers).

Table 4.7: Thermophysical modeling results using shape models\textsuperscript{a}

<table>
<thead>
<tr>
<th>Observation</th>
<th>$\epsilon$</th>
<th>Roughness (RMS slope)</th>
<th>$\Gamma$ (J m$^{-2}$ K$^{-1}$ s$^{-1/2}$)</th>
<th>$\chi^2_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL1 (2006-03-17)</td>
<td>0.90</td>
<td>$&lt; 20^\circ$</td>
<td>5–25</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>$&lt; 20^\circ$</td>
<td>80–95</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

\textsuperscript{a} 3-σ range of values are given. All three roughness cases, both shape models, and $\pm 10\%$ uncertainty in the effective diameters of the shape models are included in the uncertainties.
Figure 4.12: At left, Psyche’s radar shape model showing the temperature distribution modeled with a thermophysical model with $\Gamma=20 \text{ J m}^{-2} \text{ K}^{-1/2} \text{ s}^{-1/2}$, $\epsilon=0.9$, and no surface roughness. At right, the disk-integrated flux from this thermal model (red line) is overplotted on the measured SED (black points with errorbars).

4.4.2 Emissivity Spectrum

Psyche’s emissivity spectra for the SL2 and SL1 datasets are shown in Figure 4.13. We focus on interpreting the SL1 spectrum, as it covers a more diagnostic wavelength range than SL2. We note a broad maximum centered near 10 $\mu$m with a minimum just longward of 12 $\mu$m. Smaller peaks are present near 8.6 $\mu$m, 9.1 $\mu$m, 9.6 $\mu$m, 10.0 $\mu$m, 10.8 $\mu$m, and 11.6 $\mu$m. The contrast of the overall broad plateau from 8-12.0 $\mu$m is well above the noise and is consistent with the presence of fine-grained silicates on Psyche’s surface.
Figure 4.13: The emissivity spectra of (16) Psyche for SL2 (a) and SL1 (b) datasets. The SL2 data are binned to 60% of the original resolution to improve the signal-to-noise ratio of the spectrum.
Figure 4.14: The SL1 emissivity spectrum of (16) Psyche shown with the spectra of individual phyllosilicate spectra. Vertical lines highlight maxima in Psyche’s reststrahlen band region. Mineral spectra are described in Table 4.3. The laboratory spectra are scaled to show several spectra on one plot.
Figure 4.15: The SL1 emissivity spectrum of (16) Psyche shown with the spectra of carbonaceous chondrites. Vertical lines highlight maxima in Psyche’s reststrahlen band region. The carbonaceous chondrite spectra at right are dispersed in KBr and were provided to us by Dr. Pierre Vernazza. These originally appeared in Vernazza et al. (2011). The laboratory spectra are scaled to show several spectra on one plot.
Figure 4.16: The SL1 emissivity spectrum of (16) Psyche shown with the spectra of individual mafic mineral spectra. Vertical lines highlight maxima in Psyche’s reststrahlen band region. Olivines are shown at left and pyroxenes are shown at right. The laboratory spectra are scaled to show several spectra on one plot.
First we compared Psyche’s SL1 emissivity spectrum to that of several phyllosilicates and found that Psyche’s spectrum is qualitatively dissimilar to the selection we chose (Figure 4.14). We then compared Psyche against carbonaceous chondrites, which are generally rich in phyllosilicates (Figure 4.15). We considered both KBr-dispersed and non-dispersed samples. As with the phyllosilicates, the spectral match to the carbonaceous chondrites is qualitatively poor, although we note the coincidence of the peaks of the spectra of the dis-
persed samples of Ivuna, Murray, Orgueil, and Tagish Lake roughly correspond to Psyche's ∼9.6 µm reststrahlen peak.

Next we considered the mafic rock-forming minerals olivine and pyroxene (Figure 4.16), using samples with both fine (<75 µm) and coarse (75-250 µm) particle size regimes. For both olivine and pyroxene, the fine samples match the overall contrast of Psyche's broad 8-12 µm spectral emission plateau better than the coarse samples. There is a coincidence of the ∼9.6 µm and ∼10.05 µm peaks in Psyche's spectrum with peaks in the fayalitic olivine (Fo1) spectra, but Psyche's ∼9.1 µm peak and the 10.5-11.5 µm region do not match. The forsteritic olivine (Fo91) spectra are generally a poor match.

Magnesian pyroxenes match some of the features of Psyche's spectrum. The peaks near 9.1, 9.6, and 10.05 µm are nearly coincident with peaks in the En87 sample. Psyche's broad 11.0 µm feature is not well-matched by the pyroxenes, except perhaps by the fine-grained En87 spectrum, which has somewhat lower spectral contrast than Psyche's spectrum. The lower three spectra in Figure 4.16b show the effect of increasing proportions of enstatite to ferrosilite. As enstatite is increased, the first prominent peak in the reststrahlen band region shifts shortward, from 10.1 to 9.8 µm. In the En87 spectra, this peak occurs near 9.7 µm. Psyche's most prominent peak occurs at 9.6 µm. If pyroxene is contributing to Psyche's emissivity spectrum, it may be very magnesian, or it may be mixed with other minerals.

Finally, we considered the spectra of ordinary chondrites, enstatite chondrites, and an enstatite achondrite (which are also known as aubrites; Figure 4.17). Both the dispersed and the non-dispersed ordinary chondrites are poor matches to Psyche's emissivity spectrum (Figure 4.17a). There are similarities between Psyche's spectrum and the spectra of non-dispersed samples of an aubrite (ALH 84007) and an enstatite chondrite (Happy Canyon), as seen in Figure 4.17b. Psyche's spectral contrast is similar to both spectra, and the positions of its 9.1, 9.6 and 10.05 µm peaks are nearly coincident with peaks in the spectrum of Happy Canyon and, to some extent, the aubrite, but there are compositionally important differences.
Psyche’s 11-µm region is broader and flatter than that in the spectra of Happy Canyon and the aubrite, and is more similar to the dispersed enstatite chondrite spectra shown at the bottom of Figure 4.17b.

Although this preliminary spectral analysis is not conclusive, Psyche’s emissivity spectrum is consistent with the presence of fine-grained (<75 µm) silicates. The Happy Canyon match is qualitatively encouraging, and indicates that a magnesian pyroxene phase may be present. Psyche’s spectral contrast and reststrahlen features are more consistent with non-dispersed pyroxene than the dispersed samples. This suggests that the silicate regolith is fine-grained, but not be underdense. Near-infrared spectral studies have shown evidence for pyroxene on Psyche’s surface, but interpretations of these spectra show the pyroxene to be more ferroan than our initial emissivity analysis suggests (Hardersen et al., 2011; Sanchez et al., 2017). A more thorough analysis of Psyche’s emissivity spectrum, which would include more diverse minerals, more grain regimes, and linear mixing of minerals, may prove diagnostic of Psyche’s surface composition.

4.5 Discussion

4.5.1 Exploring bolometric emissivity space

Both the NEATM and the spherical thermophysical model produced good fits to the SL1 spectrum for all values of bolometric emissivity (ε) considered. With all other parameters held constant, a lower value of ε produces a relatively hotter subsolar point. Increasing thermal inertia (or beaming parameter, η, in the case of the NEATM) compensates for the increase in temperature associated with a lower value of ε. Allowing the diameter to vary compensates for the overall flux level in the modeled SED. Indeed, as we decrease ε in our model runs, both thermal inertia (or η for the NEATM) and effective diameter must be greater than in the ε=0.9 case to produce SEDs that fit our data.
There is a limit to this degeneracy. For the lowest value of $\epsilon$ considered ($\epsilon = 0.5$), there is a point at which increasing thermal inertia no longer changes the shape of the model SED because the model asteroid is essentially isothermal. This is apparent in our results for the spherical TPM fit to SL1, where the $\chi^2$ goodness-of-fit parameter asymptotes as a function of thermal inertia when $\epsilon = 0.5$ because the SED is no longer changing significantly (Figure 4.9).

We constrain $\epsilon$ for the spherical models by comparing derived effective diameters for each $\epsilon$ case to results from studies of Psyche’s size. A radar shape model for Psyche produced by Shepard et al. (2017), and constrained by lightcurve inversion, occultation data, and adaptive optics imaging (Kaasalainen et al., 2002; Ðurech et al., 2011; Hanuš et al., 2013a; Drummond et al., 2016), has dimensions of $279 \text{ km} \times 232 \text{ km} \times 189 \text{ km}$, with a spherical volume-equivalent diameter of $226 \text{ km}$ ($\pm 10\%$). In the case of the NEATM, our results for the SL2 dataset show that for $\epsilon = 0.95$ and 0.9, the derived effective diameters ($158 \pm 12 \text{ km}$ and $163^{+13}_{-14} \text{ km}$) are smaller than even the smallest radar-derived dimension ($189 \text{ km}$). The derived diameters for the $\epsilon = 0.7$ and 0.5 cases are consistent with the lower end of radar-constrained dimensions (and consistent with the fact that the SL2 observations were made while Spitzer was viewing a smaller surface area of Psyche). For SL1, effective diameters derived in the $\epsilon = 0.95$ and 0.9 cases are most consistent with shape model constraints. The $\epsilon = 0.7$ case requires an effective diameter on the larger end of the radar constraints, and the $\epsilon = 0.5$ requires the effective diameter be greater than the greatest radar dimension plus its 10% uncertainty. Additionally, the geometric albedos derived for SL2 with $\epsilon = 0.5$ and for SL1 with $\epsilon = 0.95$ and $\epsilon = 0.9$ ($0.17 \pm 0.03$, $0.15 \pm 0.03$, and $0.14 \pm 0.03$, respectively) are the most consistent with Psyche’s previously reported geometric albedo of $0.15 \pm 0.03$ (e.g., Shepard et al., 2017). We find similar results for the spherical thermophysical models.
Figure 4.18: The reduced $\chi^2$ statistic as a function of effective radius for the NEATM. The left frame (a) shows results for the SL2 spectrum, while the right frame (b) shows results for the SL1 spectrum. The red, green, purple, and blue curves represent emissivity values of 0.95, 0.90, 0.70, and 0.50, respectively. The colored, shaded region around each $\chi^2$ vs. radius curve represents the spread due to uncertainties in the overall flux calibration. The grey shaded region in the background represents the $\pm 20\%$ ($2\sigma$) range of effective radius values derived from radar studies by Shepard et al. (2017). The inset plots show the $\chi^2$ vs. radius curves (colored, dashed lines) near the minima. The solid black line in each inset plot is the $1\sigma$-cutoff value for $\chi^2$.

The highest fidelity results are those in which we include Psyche’s shape model in the TPM. For SL2, the TPM results using Psyche’s shape model are poorly constrained. For SL1, the $\epsilon = 0.9$ ($\Gamma = 5$–25 J m$^{-2}$ K$^{-1}$ s$^{-1/2}$) models fit best when we consider only the nominal shape models (Figure 4.6). When we consider the $\pm 10\%$ uncertainty in its dimensions, the $\epsilon = 0.7$ TPM also fits, with a relatively high thermal inertia of 80–95 J m$^{-2}$ K$^{-1}$ s$^{-1/2}$. The $\epsilon = 0.5$ models do not fit well even when we consider the reported uncertainties on the shape models. We argue that the $\epsilon = 0.9$ case is the most likely. The $\epsilon = 0.9$ case is also consistent with the emissivity spectra presented above, which suggest a fine-grained silicate regolith is present on Psyche’s surface. A surface covered in powdered silicate should have $\epsilon \geq 0.9$ and a low thermal inertia. The higher thermal inertia/lower emissivity case is possible if Psyche is on the larger end of its reported size range.
Matter et al. (2013) studied Psyche’s thermophysical properties using ground-based interferometric data. They report that Psyche is smooth, as we also conclude, but they find that Psyche has a higher thermal inertia of $114 – 133 \pm 40 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$. Heliocentric distance affects the temperature distribution on an asteroid’s surface, and is related to thermal inertia as $\Gamma \propto r_H^{-3/4}$ (e.g., Delbó et al., 2015). Matter et al. (2013) observed Psyche at a heliocentric distance of $r_H = 2.70 \text{ AU}$, and our SL1 observations took place when Psyche had $r_H = 2.80 \text{ AU}$. Psyche’s thermal inertia should be measured as 1.03 times greater at 2.70 AU than at 2.80 AU, which is not sufficient to explain the differences in these results. Psyche’s orientation appears to correspond to that of our SL1 observations during at least one observing epoch included in the Matter et al. (2013) study, so it is not apparent if rotational variability is the source of the thermal inertia discrepancy, either. We note that these are two different datasets, obtained with different observational techniques, and modeled with different thermal models. Ideally, modeling this dataset with the Matter et al. (2013) model, and modeling the Matter et al. (2013) dataset with the model described here, would provide a test of the source(s) of the differences in thermal inertia.

4.5.2 Is Psyche a metal world?

Psyche’s emissivity spectrum indicates fine-grained silicates are present on its surface. If, as our TPM results suggest, Psyche’s surface has a bolometric emissivity $\epsilon = 0.9$ and a thermal inertia of $5-25 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$, then Psyche is likely covered in a fine-grained, silicate regolith. If Psyche’s actual size is toward the larger end of the reported uncertainties, then Psyche’s bolometric emissivity could be closer to $\epsilon=0.7$ and its thermal inertia may be as high as $95 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$. In this case, the silicates may be thinly distributed, or mixed with slightly coarser silicate or iron grains. Our TPM results also show that Psyche’s surface is smooth (consistent with the results of Matter et al., 2013). We note that for the SL2 dataset, we were able to marginally fit a TPM with a very rough surface and a high thermal
inertia \((600 - 750 \, \text{J m}^{-2} \, \text{K}^{-1} \, \text{s}^{-1/2})\). We find this scenario unlikely, as it is not supported by our SL1 results, which are more robust and constraining.

At its geometry during our observations, Psyche’s subsolar temperature of \(T_{SS} \sim 230\) K is near the brittle-ductile transition temperature of \(T_{BD} = 200\) K below which iron meteorites exhibit brittle behavior upon impact. \((\text{Matsui and Schultz}, 1984)\). If Psyche has primarily metallic bedrock, ductile behavior may explain the smooth surface. Impact experiments \((\text{Matsui and Schultz}, 1984)\) on iron meteorites suggest that impactors into ductile iron surfaces may produce metal spall, but the metal does not readily fracture. Psyche, if metallic, may be relatively free of boulders. Metal spall could be part of Psyche’s regolith, contributing to its high radar albedo.

Models suggest that hit-and-run collisions can strip crust and mantle material from a differentiated protoplanet and leave its core exposed \((\text{e.g., Asphaug et al., 2006})\). The silicates observed on Psyche’s surface may be remnant crust material, or they may be exogenous. As discussed in greater detail by \text{Sanchez et al.} (2017), if Psyche were produced by a hit-and-run collision, the residual silicates would be those from the core-mantle boundary. Because olivine is more dense than pyroxene, and should crystallize first in a “magma ocean”, olivine is a more likely core-mantle boundary silicate. Our preliminary emissivity analysis is more consistent with the presence of pyroxene than olivine, and near-infrared spectroscopy also suggest pyroxene is present on Psyche’s surface \((\text{Hardersen et al., 2011; Sanchez et al., 2017})\). \text{Elkins-Tanton et al.} (2013) propose several scenarios in which pyroxene rather than olivine might be present at the core-mantle boundary. They also note that some IVA iron meteorites contain pyroxene, not olivine, and may originate from Psyche.

Finally, we consider the presence of hydroxyl on Psyche’s surface detected by \text{Takir et al.} (2017). Because Psyche has been heavily thermally and collisionally altered, the signatures of hydroxyl reported by \text{Takir et al.} (2017) are unlikely to be endogenic in origin. Psyche’s 3-\(\mu\)m feature has a band depth of \(\sim 3\%\) across its surface, comparable to the shallowest band
depths observed in the M-types in our study described in Chapter 3. There are two proposed exogenic origins for Psyche’s hydration: delivery by impacts of hydrated meteorites, as in the dark material observed in Vesta (Reddy et al., 2012; Shepard et al., 2013) or implantation of hydrogen from the solar wind (Schaible and Baragiola, 2014), as suggested for the Moon (Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009). That the hydroxyl seems to cover the entire surface may support the solar wind as a factor, but we cannot rule out that volatile-rich meteorites have contributed to Psyche’s hydroxyl. NASA’s *Psyche* mission may shed new light on the origin of Psyche’s hydration.

### 4.6 Summary

(16) Psyche is an intriguing asteroid with evidence for both metal and silicates, and is the target of a NASA’s *Psyche* mission, set to launch in 2023 and arrive in 2030. Using Spitzer Space Telescope observations made with the Infrared Spectrograph, we performed a thermal and spectral analysis of Psyche. Our thermal analysis shows Psyche’s surface is consistent with a bolometric emissivity $\epsilon = 0.9$ and a thermal inertia of $5-25 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$; however, if Psyche is slightly larger than expected, its emissivity may be $\epsilon = 0.7$ and its thermal inertia may be as high as $95 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$. Psyche’s surface is likely smooth, which is consistent with but not diagnostic of a ductile, metal-rich bedrock. Psyche’s emissivity spectrum is consistent with the presence of fine-grained silicates on Psyche’s surface, and is qualitatively similar to the spectra of powdered pyroxene and enstatite chondrites. We expect the *Psyche* mission to encounter not a pristine iron core, but rather a complex, evolved object that will provide new insight into planet formation and hit-and-run collisions.
CHAPTER 5: THE VERITAS AND THEMIS ASTEROID FAMILIES IN THE MID-INFRARED

The work presented in this chapter was previously published as “The Veritas and Themis asteroid families: 5–14μm spectra with the Spitzer Space Telescope” by Landsman et al. in *Icarus* 269, pp. 62–74, May 2016. See Elsevier License Number 4071551163414 in Appendix A.

5.1 Introduction

Asteroid families are the remnants of catastrophic collisions. Family members initially cluster in the parameter space of their proper orbital elements, and smaller members experience a change in semimajor axis over time as a result of the Yarkovsky effect (Chapter 1). Spectroscopy of asteroid families can be diagnostic of the parent body’s composition and degree of aqueous alteration, and spectral hetero- or homogeneity within a family can reveal the state of differentiation of the parent body (Cellino et al., 2002). Families with taxonomically primitive (B- and C-complex) members are of particular interest because these asteroid classes have experienced relatively little alteration since they formed. They are likely to contain organic materials, hydrated minerals, and even water-ice (e.g., Campins et al., 2010a; Rivkin and Emery, 2010; Licandro et al., 2011b). The study of primitive asteroids provides constraints on models of solar system formation and evolution and is relevant to the origin of Earth’s water and organic molecules.

Themis and Veritas are two compositionally primitive families residing in the outer main belt, with low inclinations and low eccentricities (Figure 5.1). The Veritas asteroid family is dynamically young, 8.3 ± 0.5 Myr (Nesvorný et al., 2003). In a study of visible (0.4 –
0.9 µm) spectroscopy from large surveys, Mothé-Diniz et al. (2005) reported homogeneity among the Veritas asteroids, with all Veritas members in the study falling within the C taxonomic complex. Previously, Di Martino et al. (1997) had reported evidence for both C and D types among the Veritas asteroids.

Figure 5.1: The Themis and Veritas asteroid families in the parameter spaces of the sine of inclination vs. semimajor axis (left) and the sine of inclination vs. eccentricity (right).

At ∼ 2.5 Gyr, the Themis family falls at the opposite age extreme (Marzari et al., 1995; Nesvorný et al., 2003). Themis family members studied with visible spectroscopy are typically B-types and C-types, with a smaller number of X-types, consistent with a parent body mineralogy similar to CM meteorites (Florczak et al., 1999; Mothé-Diniz et al., 2005). A visible and near-infrared spectroscopic study of the Themis family and a young (< 10 Myr) sub-family, Beagle, shows a range of spectral slopes within the Themis family, while the Beagle asteroids tend to be bluer, brighter, and with less variation in their spectral slopes (Fornasier et al., 2016b). These trends are attributed to heterogeneity in the Themis parent body, space weathering effects, or both. Kaluna et al. (2016) also studied visible spectra and albedos of Themis and Beagle asteroids, and they, too, report that the Beagle asteroids are
bluer and brighter than the other Themis members, suggesting space weathering results in
the reddening and darkening of the C-complex asteroids in this family. 2–4 µm spectroscopy
of (24) Themis, the largest member of the Themis family, has revealed the presence of water
ice and organics on its surface (Campins et al., 2010a; Rivkin and Emery, 2010). A marginal
detection of a spectral feature consistent with water ice was detected in spectra (90) Antiope,
another large Themis member (Hargrove et al., 2015).

Other studies of primitive asteroid families in VISNIR wavelengths have shown relations-
ships between spectral properties and family age. Nesvorný et al. (2005) reported a trend of
SDSS colors with family age for primitive asteroids, with the young Veritas asteroids at one
end of the trend line and the ancient Themis family at the other end. Ziffer et al. (2011) com-
pared NIR spectra of the Themis and Veritas family members. They found that the Themis
family members have red (positive) NIR slopes, while the Veritas family members have blue
(negative) NIR slopes. Observed differences between the Themis and Veritas family may be
due to the large difference in the ages of the two families, compositional differences, differ-
ences in thermal evolution, or a combination of these (Nesvorný et al., 2005; Ziffer et al.,
2011).

We aim to investigate whether similar spectral trends exist in the mid-infrared (here, 5
-14 µm) by comparing spectra for the Themis and Veritas families acquired with the Spitzer
Space Telescope. This wavelength range is ideally suited to study both the composition
and the physical properties of primitive asteroids. In this chapter, we present the results
of a thermal and compositional analysis of 5 -14 µm Spitzer Space Telescope spectra of 20
Themis and Veritas asteroids. Our sample (Table 5.1) consists of 9 Veritas asteroids and
11 Themis asteroids, including 8 Themis asteroids previously studied by Licandro et al.
(2012a). We use simple thermal modeling to derive diameters, albedos, and the degree to
which beaming is significant (i.e, the beaming parameter, η). We then remove the modeled
thermal contribution in each asteroid’s spectrum to reveal emissivity spectra, which we analyze to constrain regolith properties and aqueous alteration history.

Table 5.1: Analytic proper orbital elements and taxonomic classification

<table>
<thead>
<tr>
<th>Object</th>
<th>Family</th>
<th>$a_p$ (AU)</th>
<th>$e_p$</th>
<th>$i_p$ (deg)</th>
<th>Taxonomic class</th>
</tr>
</thead>
<tbody>
<tr>
<td>(24) Themis</td>
<td>Themis</td>
<td>3.13393</td>
<td>0.1525</td>
<td>1.0829</td>
<td>$C_b$, $C_c$, $B_a$, $C_e$</td>
</tr>
<tr>
<td>(90) Antiope</td>
<td>Themis</td>
<td>3.14543</td>
<td>0.1552</td>
<td>0.0231</td>
<td>$C_b$, $C_c$, $C_f$, $C_e$</td>
</tr>
<tr>
<td>(222) Lucia</td>
<td>Themis</td>
<td>3.13457</td>
<td>0.15520</td>
<td>1.0486</td>
<td>$B_b$</td>
</tr>
<tr>
<td>(223) Rosa</td>
<td>Themis</td>
<td>3.08982</td>
<td>0.13470</td>
<td>1.5128</td>
<td>$X_b$, $X_c$</td>
</tr>
<tr>
<td>(316) Goberta</td>
<td>Themis</td>
<td>3.17127</td>
<td>0.1370</td>
<td>1.3465</td>
<td>$C_c$</td>
</tr>
<tr>
<td>(379) Huenna</td>
<td>Themis</td>
<td>3.13564</td>
<td>0.1569</td>
<td>0.0307</td>
<td>$B_b$, $C_d$</td>
</tr>
<tr>
<td>(383) Janina</td>
<td>Themis</td>
<td>3.13374</td>
<td>0.15330</td>
<td>1.4096</td>
<td>$B_c$, $B_d$</td>
</tr>
<tr>
<td>(468) Lina</td>
<td>Themis</td>
<td>3.14105</td>
<td>0.15970</td>
<td>1.2205</td>
<td>$X_k$</td>
</tr>
<tr>
<td>(492) Gismonda</td>
<td>Themis</td>
<td>3.11169</td>
<td>0.15220</td>
<td>1.2663</td>
<td>-</td>
</tr>
<tr>
<td>(515) Athalia</td>
<td>Themis</td>
<td>3.12074</td>
<td>0.15620</td>
<td>1.0428</td>
<td>$C_d$</td>
</tr>
<tr>
<td>(526) Jena</td>
<td>Themis</td>
<td>3.12237</td>
<td>0.15580</td>
<td>1.4211</td>
<td>$B_b$, $C_e$</td>
</tr>
<tr>
<td>(1086) Nata</td>
<td>Veritas</td>
<td>3.16534</td>
<td>0.06260</td>
<td>9.2998</td>
<td>$C_h$, $C_d$</td>
</tr>
<tr>
<td>(2428) Kamenyar</td>
<td>Veritas</td>
<td>3.16967</td>
<td>0.06340</td>
<td>9.3056</td>
<td>$C_d$</td>
</tr>
<tr>
<td>(2934) Aristophanes</td>
<td>Veritas</td>
<td>3.16615</td>
<td>0.06230</td>
<td>9.1895</td>
<td>$C_d$</td>
</tr>
<tr>
<td>(3090) Tjossem</td>
<td>Veritas</td>
<td>3.16909</td>
<td>0.06300</td>
<td>9.2301</td>
<td>$C_g$</td>
</tr>
<tr>
<td>(5592) Oshima</td>
<td>Veritas</td>
<td>3.16806</td>
<td>0.05990</td>
<td>9.3869</td>
<td>$C_e$</td>
</tr>
<tr>
<td>(5594) Jimmiller</td>
<td>Veritas</td>
<td>3.16823</td>
<td>0.06040</td>
<td>9.3114</td>
<td>-</td>
</tr>
<tr>
<td>(7231) Porco</td>
<td>Veritas</td>
<td>3.16583</td>
<td>0.06280</td>
<td>9.2301</td>
<td>-</td>
</tr>
<tr>
<td>(8726) Massamotonasu</td>
<td>Veritas</td>
<td>3.17264</td>
<td>0.06030</td>
<td>9.5147</td>
<td>-</td>
</tr>
<tr>
<td>(13537) 1991 SG</td>
<td>Veritas</td>
<td>3.17133</td>
<td>0.06400</td>
<td>9.2301</td>
<td>$C_f$</td>
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</tbody>
</table>

*aNesvorny (2015)
bTholen (1984)
cLazzaro et al. (2004), using the Bus and Binzel (2002) criteria
dBus and Binzel (2002)
eDeMeo et al. (2009a)
fHasselmann et al. (2012), using the Bus and Binzel (2002) criteria

5.2 Observations and Data Reduction

As in Chapter 4, the spectra presented here were obtained with the Infrared Spectrograph (IRS; Houck et al., 2004b) on NASA’s Spitzer Space Telescope (Werner et al., 2004) using the short-wavelength, low-resolution module (SL), which consists of two orders, SL1 and SL2. All the Veritas asteroids and eight of the Themis asteroids were observed by Campins et al. (2008), and (24) Themis, (90) Antiope, and (379) Huenna were observed by Cruikshank
and van Cleve (2004a,b). The spectra were obtained from the Spitzer Heritage Archive\textsuperscript{1}. Details of the observing circumstances for the Veritas-family asteroids and (24) Themis, (90) Antiope and (379) Huenna are presented in Table 5.2. Observing circumstances and data reduction for the remaining eight Themis-family asteroids previously studied by Licandro et al. (2012a) are described in that paper. The data reduction process, detailed below, for the asteroids listed in Table 5.2 is similar to that described in Licandro et al. (2012a) and to that described in Chapter 4 for (16) Psyche.

\textsuperscript{1}http://sha.ipac.caltech.edu/applications/Spitzer/SHA
Table 5.2: Observing circumstances

<table>
<thead>
<tr>
<th>Object</th>
<th>Start date (UT)</th>
<th>Int. time (s), SL2</th>
<th>Int. time (s), SL1</th>
<th>$r_H^a$ (AU)</th>
<th>$\Delta^b$ (AU)</th>
<th>$\alpha^c$ (deg)</th>
<th>Spitzer proposal ID$^d$</th>
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<tbody>
<tr>
<td>(24) Themis</td>
<td>2005-06-08 01:28</td>
<td>6.29</td>
<td>6.29</td>
<td>3.542</td>
<td>3.37</td>
<td>16.64</td>
<td>91</td>
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<tr>
<td>(90) Antiope</td>
<td>2005-07-12 23:31</td>
<td>29.36</td>
<td>6.29</td>
<td>3.165</td>
<td>3.05</td>
<td>18.76</td>
<td>88</td>
</tr>
<tr>
<td>(379) Huenna</td>
<td>2004-10-24 11:41</td>
<td>60.95</td>
<td>6.29</td>
<td>3.167</td>
<td>3.01</td>
<td>18.78</td>
<td>91</td>
</tr>
<tr>
<td>(1086) Nata</td>
<td>2009-01-24 19:44</td>
<td>37.75</td>
<td>18.87</td>
<td>3.031</td>
<td>2.97</td>
<td>19.34</td>
<td>50672</td>
</tr>
<tr>
<td>(2428) Kamenyar</td>
<td>2009-04-02 15:57</td>
<td>243.79</td>
<td>44.04</td>
<td>3.405</td>
<td>3.09</td>
<td>16.91</td>
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</tr>
<tr>
<td>(2934) Aristophanes</td>
<td>2009-03-09 19:07</td>
<td>182.84</td>
<td>58.72</td>
<td>3.144</td>
<td>3.10</td>
<td>18.50</td>
<td>50672</td>
</tr>
<tr>
<td>(3090) Tjossem</td>
<td>2009-01-17 12:39</td>
<td>304.74</td>
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<td>2.972</td>
<td>2.38</td>
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<td>50672</td>
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<tr>
<td>(5592) Oshima</td>
<td>2009-01-08 02:56</td>
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<td>88.08</td>
<td>3.367</td>
<td>3.09</td>
<td>17.40</td>
<td>50672</td>
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<td>(5594) Jimmiller</td>
<td>2008-11-30 11:07</td>
<td>426.64</td>
<td>73.4</td>
<td>3.189</td>
<td>2.56</td>
<td>16.11</td>
<td>50672</td>
</tr>
<tr>
<td>(7231) Porco</td>
<td>2008-10-17 14:54</td>
<td>304.74</td>
<td>44.04</td>
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<tr>
<td>(8726) Masamotonasu</td>
<td>2008-12-18 00:15</td>
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<td>3.005</td>
<td>2.95</td>
<td>19.65</td>
<td>50672</td>
</tr>
<tr>
<td>(13537) 1991 SG</td>
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<td>31.46</td>
<td>2.912</td>
<td>2.51</td>
<td>20.05</td>
<td>50672</td>
</tr>
</tbody>
</table>

$^a$Heliocentric distance

$^b$Distance from Spitzer

$^c$Phase angle

$^d$88 – Cruikshank and van Cleve (2004a)

91 – Cruikshank and van Cleve (2004b)

50672 – Campins et al. (2008)
As in Chapter 4, we begin with Spitzer’s Basic Calibrated Data (BCD), which have already been processed with standard corrections (e.g., flat-fielding, dark current correction, non-linear detector response correction). All the spectra were captured in two nod positions along the slit direction, separated by \( \sim 1/3 \) of the slit length, \( 20'' \). We removed the sky background by taking the difference of pairs of spectral images from each nod position. Background-subtracted spectra were masked for bad pixels and then extracted using version 2.5.1 of the JAVA-based Spitzer IRS Custom Extraction (SPICE\(^2\)) software. SPICE generates a spatial flux profile from the input background-subtracted spectral image, identifies the peak in the spatial profile, and extracts the spectrum along the peak ridge.

Like (16) Psyche in Chapter 4, the spectra of (24) Themis, (90) Antiope, and (379) Huenna were obtained in the IRS’s “Spectral Mapping Mode”. For these three asteroids, we computed and applied the correction for spectral pointing-induced throughput error as described in Chapter 4.

For each asteroid, we averaged together all extracted spectra in each order (SL1 and SL2). Uncertainties in absolute flux calibration for SL data are \( \leq 10\% \) (Decin et al., 2004; Houck et al., 2004b) and were reflected in both the spread of the individual extracted spectra and flux mismatches in the averaged SL1 and SL2 spectra. Because the signal-to-noise ratio is higher in SL1 than SL2, we scaled the SL2 spectrum to SL1 at \( \sim 7.5 \)\( \mu \)m. All scale factors were in the range 1.1 – 0.9. We added the 10\% absolute flux uncertainty in quadrature to the formal errorbars for all analyses in which absolute flux is relevant, such as thermal modeling. The final spectra were then binned to increase signal-to-noise.

\(^2\)http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/tools/spice/
5.3 Data Analysis

5.3.1 Thermal Model

As discussed in previous chapters, asteroid spectra in the 5–14 µm region are dominated by thermal emission. To model this emission, we employed the Near-Earth Asteroid Thermal Model (NEATM; Harris, 1998), discussed in detail in Chapter 2, Section 2.2.1. Model inputs, presented in Tables 5.2 and 5.3, include heliocentric distance (r), distance from the Spitzer Space Telescope (∆), phase angle (α), absolute magnitude (H) and slope parameter (G). We determined both the beaming parameter and diameter using a Monte Carlo method. This method is similar to that described in Chapter 3, Section 3.2.1.2, with two changes: (1) here, we allowed both diameter and beaming parameter to vary (only the beaming parameter varied in Chapter 3); (2) we used N = 10^4 synthetic spectra, rather than the 10^5 used in Chapter 3.

Once we derived a diameter and beaming parameter for each asteroid, we calculated its geometric albedo, p_v, using the relationship $D = 1329 \times (10^{-0.2H} / \sqrt{p_v})$. Uncertainty in the albedo is dominated by the uncertainty in the H magnitude, typically $\sim$10%, resulting in a 20% uncertainty in albedo after propagation.

5.3.2 Emissivity Spectra

We computed emissivity spectra by dividing the measured spectral flux density by the modeled thermal contribution, as described for (16) Psyche in Chapter 4. To analyze the presence and, if applicable, center and strength of the broad 10-µm emissivity feature due to fine-grained silicates, we employed the following steps for each asteroid’s spectrum. First, we normalize the emissivity spectrum to 0.9 at 12 µm, which is a typical value of emissivity for silicates. Next we estimated the spectral continuum by fitting a line from the region
shortward of the band, \( \sim 8.0 \mu m \), to the region longward of the band, \( \sim 12.25 \mu m \) (e.g., Figure 5.2). The continuum slopes for all asteroids were \( \leq \pm 5\% \).

![Figure 5.2: The emissivity spectrum of (24) Themis (solid black line) with its estimated continuum (solid red line). The blue points represent the parts of the spectrum used to estimate the continuum line.](image)

We then determined the spectral contrast at 10\( \mu m \) relative to the continuum using a Monte Carlo technique. Here, we created \( 10^5 \) synthetic spectra from the scatter in the 8–12\( \mu m \) region using the method described in Chapter 3, Section 3.2.1.2. For each synthetic spectrum, we fit a fourth-order smoothing spline polynomial to the 10-\( \mu m \) band. We calculate the ratio of each polynomial to the continuum at 10\( \mu m \) as a measure of the band’s spectral contrast. The band center is taken to be the wavelength at which the polynomial has its maximum value.
After completing this process for each synthetic spectrum, we compute the mean and standard deviation of the $10^5$ derived values of 10-µm contrast and band center. These means and standard deviations represent our final derived values and their uncertainties. If the mean synthetic spectral contrast at 10 µm is greater than the 3σ uncertainty on that quantity, we consider this a positive detection of a 10-µm emissivity feature.

We also used a Monte Carlo technique to study the position of the ~12-µm emissivity minimum, which McAdam et al. (2015) found to be related to degree of aqueous alteration in primitive meteorites. We fit a third-order smoothing spline polynomial to each of $10^5$ synthetic emissivity spectra in the 10.5–13.0 µm wavelength range, and computed the wavelength at which the polynomial minimum near 12 µm occurs. As before, we use the frequency distribution of these values to compute the final 12-µm minimum and its uncertainty. The spectra of asteroids with no detectable 10-µm emission feature have little spectral contrast in the 10.5 – 13 µm region, so the position of the emissivity minimum is not well constrained in these cases. Thus, we exclude asteroids with no statistically significant emission feature at 10 µm from this analysis.

5.4 Results

5.4.1 Thermal Model

The NEATM-derived parameters for (24) Themis, (90) Antiope and (379) Huenna and the Veritas asteroids in this sample are presented in Table 5.3 and the best-fit NEATMs are shown in Figure 5.3. The eight Themis-family asteroids analyzed by Licandro et al. (2012a) are also included in Table 5.3, and their spectra with the best-fit NEATMs found by Licandro et al. (2012a) are shown in Figure 5.4.
Figure 5.3: The measured spectral energy distributions (black circles with red errorbars) for the three Themis and the nine Veritas asteroids analyzed in this chapter, shown with the best-fit NEATM (solid blue line).
Figure 5.4: The measured spectral energy distributions (black circles with red errorbars) for the eight Themis asteroids analyzed by Licandro et al. (2012a). These datasets and thermal models were provided by Dr. Licandro and also appear in Figure 1 of Licandro et al. (2012a).
For the Veritas family asteroids, we find an average beaming parameter and geometric albedo of \( \bar{\eta} = 1.0 \pm 0.1 \) (with a range of 0.86–1.24) and \( \bar{p}_v = 0.09 \pm 0.03 \) (with a range of 0.06–0.14), respectively. Including the NEATM results for the eight Themis asteroids modeled by Licandro et al. (2012a), we find an average beaming parameter and albedo of \( \bar{\eta} = 1.0 \pm 0.1 \) (with a range of 0.81–1.15) and \( \bar{p}_v = 0.07 \pm 0.02 \) (with a range of 0.03–0.11), respectively, for the Themis family sample. Our NEATM results for (24) Themis and (90) Antiope are consistent with those found by Hargrove et al. (2015) for the same dataset. Discrepancies between our NEATM-derived parameters and those reported by the WISE/NEOWISE team (Table 5.3; Masiero et al., 2011) are likely due to non-spheroidal asteroid shapes among the smaller bodies in this sample. Brown (1985) showed that spherical thermal models can produce systematic problems in diameter determinations for ellipsoidal asteroids.

### 5.4.2 Emissivity Spectra

The continuum-divided 8 – 12.5 \( \mu \)m emissivity spectra for both the Themis and Veritas asteroids are shown in Figures 5.6 and 5.5, and the spectral contrast at 10\( \mu \)m and emission band centers are given in Table 5.4. According to the criteria described in Section 5.3.2, all 11 of the Themis asteroids and 6 of the 9 Veritas asteroids in this sample have a statistically significant 10-\( \mu \)m emission band. Average 10-\( \mu \)m emission for both families is similar (1.7\% \pm 0.8\% for Veritas, 3.6\% \pm 2.0\% for Themis), with ranges of 0\% (no significant emission)–3.7\% and 1.0\%–8.5\% for the Veritas and Themis families, respectively.

Results on the emissivity minimum in the 10.5 – 13 \( \mu \)m region for each asteroid are reported in Table 5.4, and that spectral region is shown in Figure 5.7. For all asteroids, the location of the emissivity minimum in this region falls closer to the longer wavelength end of the 11.4 – 12.3 \( \mu \)m range identified by McAdam et al. (2015) in primitive meteorite spectra. This suggests that the Themis and Veritas spectra are similar to the less aqueously altered meteorites studied by McAdam et al. (2015).
Table 5.3: Derived asteroid properties

<table>
<thead>
<tr>
<th>Object</th>
<th>Derived from this work</th>
<th>Cited values from literature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D$ (km)</td>
<td>$\eta$</td>
</tr>
<tr>
<td>(24) Themis</td>
<td>202.9 ± 10.2</td>
<td>1.02 ± 0.01</td>
</tr>
<tr>
<td>(90) Antiope</td>
<td>114.2 ± 7.1</td>
<td>0.81 ± 0.01</td>
</tr>
<tr>
<td>(222) Lucia$^\dagger$</td>
<td>59.8 ± 0.8</td>
<td>1.03 ± 0.02</td>
</tr>
<tr>
<td>(223) Rosa$^\dagger$</td>
<td>61.2 ± 0.3</td>
<td>0.85 ± 0.01</td>
</tr>
<tr>
<td>(316) Goberta$^\dagger$</td>
<td>46.8 ± 1.2</td>
<td>1.15 ± 0.04</td>
</tr>
<tr>
<td>(379) Huenna</td>
<td>98.9 ± 4.6</td>
<td>0.99 ± 0.01</td>
</tr>
<tr>
<td>(383) Janina$^\dagger$</td>
<td>48.5 ± 0.3</td>
<td>1.12 ± 0.01</td>
</tr>
<tr>
<td>(468) Lina$^\dagger$</td>
<td>59.7 ± 0.5</td>
<td>0.95 ± 0.01</td>
</tr>
<tr>
<td>(492) Gismonda$^\dagger$</td>
<td>50.3 ± 1.1</td>
<td>1.12 ± 0.03</td>
</tr>
<tr>
<td>(515) Athalia$^\dagger$</td>
<td>43.0 ± 0.2</td>
<td>1.07 ± 0.01</td>
</tr>
<tr>
<td>(526) Jena$^\dagger$</td>
<td>52.3 ± 0.5</td>
<td>1.10 ±002</td>
</tr>
<tr>
<td>(1086) Nata</td>
<td>73.3 ± 1.3</td>
<td>1.03 ± 0.02</td>
</tr>
<tr>
<td>(2428) Kamenyar</td>
<td>29.6 ± 0.5</td>
<td>0.90 ± 0.04</td>
</tr>
<tr>
<td>(2934) Aristophanes</td>
<td>27.0 ± 0.6</td>
<td>0.88 ± 0.03</td>
</tr>
<tr>
<td>(3090) Tjossen</td>
<td>10.0 ± 0.7</td>
<td>1.2 ± 0.2</td>
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<tr>
<td>(5592) Oshima</td>
<td>24.6 ± 0.2</td>
<td>0.91 ± 0.06</td>
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<tr>
<td>(5594) Jimmiller</td>
<td>16.1 ± 0.1</td>
<td>0.91 ± 0.06</td>
</tr>
<tr>
<td>(7231) Porco</td>
<td>14.4 ± 0.4</td>
<td>1.1 ± 0.1</td>
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<tr>
<td>(8726) Masamotonasul</td>
<td>15.1 ± 1.1</td>
<td>1.2 ± 0.1</td>
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<tr>
<td>(13537) 1991 SG</td>
<td>15.9 ± 0.6</td>
<td>0.86 ± 0.03</td>
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</table>

$^a$ Asteroid Absolute Magnitude and Slope Database (for all asteroids except 13537; Muinonen et al., 2010b; Oszkiewicz et al., 2011a)

$^b$ Asteroid Absolute Magnitudes V12.0 (for 13537 only; Tholen, 2009)

$^c$ Asteroid Lightcurve Derived Data V14.0, summary file (Harris et al., 2014)

Masiero et al. (2011)

*Average value of two WISE measurements

$^\dagger$NEATM analysis by Licandro et al. (2012a)
Table 5.4: Results from 10-µm band analysis

<table>
<thead>
<tr>
<th>Object</th>
<th>Family</th>
<th>10-µm spectral contrast (%)</th>
<th>10-µm band center (µm)</th>
<th>Emissivity minimum location (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(24) Themis</td>
<td>Themis</td>
<td>3.8 ± 0.2</td>
<td>10.14 ± 0.08</td>
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<td>Themis</td>
<td>0.8 ± 0.1</td>
<td>10.1 ± 0.2</td>
<td>12.45 ± 0.03</td>
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<td>Themis</td>
<td>2.4 ± 0.2</td>
<td>10.3 ± 0.2</td>
<td>12.21 ± 0.02</td>
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<td>(223) Rosa</td>
<td>Themis</td>
<td>1.0 ± 0.1</td>
<td>10.3 ± 0.1</td>
<td>12.09 ± 0.03</td>
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<tr>
<td>(316) Goberta</td>
<td>Themis</td>
<td>6.1 ± 0.8</td>
<td>10.0 ± 0.1</td>
<td>12.10 ± 0.05</td>
</tr>
<tr>
<td>(379) Huenna</td>
<td>Themis</td>
<td>1.8 ± 0.2</td>
<td>10.3 ± 0.1</td>
<td>12.59 ± 0.04</td>
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<td>(383) Janina</td>
<td>Themis</td>
<td>2.6 ± 0.2</td>
<td>10.0 ± 0.1</td>
<td>12.24 ± 0.04</td>
</tr>
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<td>(468) Lina</td>
<td>Themis</td>
<td>2.8 ± 0.1</td>
<td>10.1 ± 0.1</td>
<td>12.33 ± 0.03</td>
</tr>
<tr>
<td>(492) Gismonda</td>
<td>Themis</td>
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<tr>
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<td>3.3 ± 0.1</td>
<td>10.3 ± 0.1</td>
<td>12.56 ± 0.03</td>
</tr>
<tr>
<td>(526) Jena</td>
<td>Themis</td>
<td>3.2 ± 0.2</td>
<td>10.0 ± 0.1</td>
<td>12.38 ± 0.02</td>
</tr>
<tr>
<td>(1086) Nata</td>
<td>Veritas</td>
<td>1.8 ± 0.1</td>
<td>10.4 ± 0.1</td>
<td>12.50 ± 0.02</td>
</tr>
<tr>
<td>(2428) Kamenyar</td>
<td>Veritas</td>
<td>1.8 ± 0.2</td>
<td>10.2 ± 0.1</td>
<td>12.51 ± 0.04</td>
</tr>
<tr>
<td>(2934) Aristophanes</td>
<td>Veritas</td>
<td>2.0 ± 0.4</td>
<td>9.9 ± 0.3</td>
<td>12.36 ± 0.04</td>
</tr>
<tr>
<td>(3090) Tjossem</td>
<td>Veritas</td>
<td>No band detected</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(5592) Oshima</td>
<td>Veritas</td>
<td>1.8 ± 0.2</td>
<td>10.0 ± 0.7</td>
<td>12.47 ± 0.04</td>
</tr>
<tr>
<td>(5594) Jimmiller</td>
<td>Veritas</td>
<td>No band detected</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(7231) Porco</td>
<td>Veritas</td>
<td>1.4 ± 0.4</td>
<td>10.5 ± 0.2</td>
<td>12.20 ± 0.04</td>
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<td>(8726) Masamotonasu</td>
<td>Veritas</td>
<td>3.7 ± 0.7</td>
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<td>12.39 ± 0.04</td>
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<tr>
<td>(13537) 1991 SG</td>
<td>Veritas</td>
<td>No band detected</td>
<td>–</td>
<td>–</td>
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</table>
Figure 5.5: The continuum-divided emissivity spectra for each Veritas-family asteroid (red line). The continuum is represented by the blue line. The polynomial fits to the 8–12.5-µm region are shown in grey.
Figure 5.6: The continuum-divided emissivity spectra for each Themis-family asteroid (red line). The continuum is represented by the blue line. The polynomial fits to the 8–12.5-μm region are shown in grey.
Figure 5.7: The emissivity spectra in the 10.5–13.0-µm region (grey) with a third-order smoothing spline polynomial fit (black). The Themis asteroids are plotted in the left panel and the Veritas asteroids are plotted in the right panel. Each asteroid’s number designation is printed to the bottom-left of its spectrum. The spectra are plotted from top to bottom in order of decreasing wavelength position of the emissivity minimum.
5.5 Discussion

5.5.1 Regolith Properties and Processes

The mid-infrared emissivity spectra of our sample do not show any obvious trends distinguishing the two families; however, there is interesting variation within the two families. We find that 10-µm contrast is generally \( \sim 1-3\% \), but there are notable outliers from both families: (8726) Masamotonasu (3.7% \( \pm \) 0.7%) from the Veritas family and (316) Goberta and (492) Gismonda from the Themis family (6.1% \( \pm \) 0.8% and 8.5% \( \pm \) 0.9%, respectively).

In mid-infrared spectra of cometary comae and Trojan asteroids, contrast of the 10-µm emission band is 10–20% (Emery et al., 2006a), higher than that for our sample of Themis and Veritas asteroids. As discussed in Chapter 2, laboratory studies show that grain size and regolith porosity affect the extent and shape of the 10-µm band. Smaller grains and more optically thin samples result in greater spectral contrast (e.g., Hunt and Logan, 1972a; Vernazza et al., 2012a). As suggested by Licandro et al. (2012a) in the initial analysis of the Themis asteroids’ mid-infrared spectra, the 10-µm spectral contrast in our sample may be lower than that seen in comets and Trojan asteroids due to larger silicate grains, a denser regolith structure, and/or a smaller fraction of silicate dust on the surfaces of the Themis and Veritas asteroids. The higher 10-µm contrast observed in the three outliers in this sample may be the result of differences in grain size and/or regolith structure compared with the rest of the sample. We consider some processes and factors that are likely to affect asteroidal regoliths.

Electrostatic dust levitation can affect regolith structure. Colwell et al. (2005) modeled dust transport by electrostatic levitation on Near-Earth Asteroid (433) Eros and found that observed dust ponds may be produced by this mechanism. In particular, they found that dust tends to accumulate in craters and shadowed regions. Thus, if dust levitation is an
important process on the Themis and Veritas asteroids, differences in geomorphology among these asteroids may affect areal distributions of fine dust grains.

Sublimation of ices also affects regolith structure by producing a dust mantle of particles too massive to be entrained in sublimating gases. A clear spectral signature of water ice has been observed on the largest member of the Themis family, (24) Themis (Campins et al., 2010a; Rivkin and Emery, 2010). In the spectrum of (90) Antiope, another large Themis member, a 3-µm absorption feature consistent with water ice has been reported by Hargrove et al. (2015). Additionally, the Themis family contains several small asteroids with cometary activity (Hsieh and Jewitt, 2006; Licandro et al., 2011c). Different distributions of sublimating near-surface volatiles among the Themis and Veritas asteroids may result in variations in dust properties within the families, which can produce the mid-infrared variability we observe. The beaming parameters we find for this sample are typically around unity, which suggests the Themis and Veritas asteroids have low thermal inertias and little infrared beam- ing. Constraining spin pole orientations and shapes will allow for thermophysical modeling and the determination of thermal inertias, which will further clarify regolith structure and variability.

Recent impacts also affect asteroid regoliths. A young (< 10 Myr) collisional sub-family, Beagle, has been identified within the Themis family, and its members are both spectrally bluer in the visible and NIR and brighter than the other Themis asteroids (Nesvorný et al., 2008; Fornasier et al., 2016b; Kaluna et al., 2016). Of our sample, only (90) Antiope is identified as a member of the Beagle family by Nesvorny (2015). We note that (90) Antiope is quite large (D = 105.5 ± 5.9 km; this work) compared to the Beagle family parent, (656) Beagle (D = 47.58 ± 0.33 km, Fornasier et al., 2016b). Furthermore, it is a double asteroid with a similarly large companion (Descamps et al., 2007), and thus is not representative of the majority of the sampled Beagle asteroids. Finally, we note that Fornasier et al. (2016b) consider (90) Antiope to be a member of the Themis family, and analyze it as such.
5.5.2 Visible and NIR Results and Derived Quantities

We consider the possibility of a relationship between the mid-infrared spectra of the asteroids with strongest emissivity features, (8726) Masamotonasu from Veritas and (316) Goberta and (492) Gismonda from Themis, and results from other wavelength ranges. In their NIR study of Themis and Veritas asteroids, Ziffer et al. (2011) reported that, among their sample, Masamotonasu has the flattest slope of all the Veritas asteroids. Goberta has the second flattest slope of the Themis asteroids in their sample, and was the only Themis asteroid that couldn’t be well fit with a CM/CM2 meteorite spectrum. There is no published NIR data for Gismonda. If some effect, compositional, collisional, or otherwise, is both flattening NIR slopes and increasing 10-$\mu$m contrast, we would expect future NIR spectra of Gismonda to be similarly flat.

Results from WISE data show low average albedos for both families: 0.066 ± 0.021 (N = 3052) for Themis and 0.066 ± 0.020 (N = 686) for Veritas (Masiero et al., 2013). Our results from Spitzer spectra indicate that there are four moderate albedo ($p_v > 0.1$) asteroids: Themis asteroid (222) Lucia (Licandro et al., 2012a) and Veritas asteroids (3090) Tjossem, (5594) Jimmiller$^3$, and (7231) Porco (Table 5.3). Tjossem and Jimmiller are two of the three asteroids with no statistically significant 10-$\mu$m band, and the detection of the 10-$\mu$m band for Porco is marginal, while Lucia has a well-defined 10-$\mu$m band. Visible and NIR spectroscopy of Lucia and Tjossem show that these asteroids are broadly typical of their respective families (Mothé-Diniz et al., 2005; Ziffer et al., 2011), and are thus unlikely to be interlopers, despite their elevated albedos. Nevertheless, we note that of the 8 members of the Veritas family in our sample that have been taxonomically classified, (3090) Tjossem is the only asteroid belonging to the Cg class (Mothé-Diniz et al., 2005). Future visible and

\footnote{We note that (5594) Jimmiller is one the asteroids for which our diameter and albedo determination is inconsistent with that from the WISE dataset.}
near-infrared spectroscopy of (5594) Jimmiller and (7231) Porco will help clarify if these two moderate-albedo objects are likely to be family members or interlopers.

Asteroid mass should play a role in the contrast of the 10-µm band, as more massive asteroids can retain smaller silicate grains and should have dustier surfaces; however, we find no clear significant correlation between the contrast of the 10-µm band and asteroid diameter in our sample (Figure 5.8a). Albedo and the 10-µm feature also seem to be uncorrelated (Figure 5.8c). There are hints of relationships between 10-µm contrast and the beaming parameter and rotation period for the Themis family. In the Themis sample, beaming parameter is weakly positively linearly correlated with 10-µm contrast (Pearson’s correlation coefficient $r = 0.61$, $p = 0.045$; Figure 5.8b), while rotation period is weakly negatively linearly correlated with 10-µm contrast ($r = -0.61$, $p = 0.046$; Figure 5.8d).

We consider the relationship between beaming parameter and 10-µm contrast. In the NEATM, the beaming parameter modifies subsolar temperature as $\eta \sim T_{SS}^{-4}$; thus, a lower subsolar temperature is better fit by a higher beaming parameter. This is consistent with a higher thermal inertial and thus a denser regolith. The trend we observe, however, is that asteroids with a higher beaming parameter also have higher spectral contrast at 10-µm, which we interpret to be consistent with smaller regolith grains and/or an underdense regolith. We consider several explanations for this seemingly counterintuitive trend. First, there may be a systematic effect in our data analysis. Licandro et al. (2012a) showed that the choice of beaming parameter in the NEATM does not affect the 10-µm spectral contrast in the resultant emissivity spectrum. We further consider the meaning of the 10-µm feature. As mentioned previously, separation of silicate grains increases the contrast at 10-µm, an effect that can be achieved by the suspension of grains in matrix that is transparent in the mid-infrared, so an underdense regolith is not necessary to produce the observed spectral contrast (Emery et al., 2006a). The contrast of the 10-µm feature may also be affected by chemical and/or physical processes that are not yet well understood.
Figure 5.8: The Themis asteroids are plotted as blue squares and the Veritas asteroids are plotted as cyan triangles. Spectral contrast at 10\(\mu\)m as a function of (a) diameter, (b) beaming parameter, (c) albedo, and (d) rotation period. In panels a–c, we include only the asteroids with a significant detection of the 10-\(\mu\)m feature. In panel d, we include only the asteroids with both a significant detection of the 10-\(\mu\)m feature and a published rotation period (Table 5.3).
We also note that the beaming parameter is an empirical quantity and is not a straightforward proxy for thermal inertia. As discussed in Chapter 2, effects due to the asteroid’s shape, spin-pole orientation, and rotation, for example, are also wrapped into the beaming parameter. We see a statistically significant negative correlation of rotation period with 10-µm contrast (Figure 5.8b). Subsolar temperature decreases as rotation rate increases; thus, the beaming parameter must be elevated to account for the decrease in subsolar temperature associated with a faster spin rate. The trend of 10-µm contrast with beaming parameter may then be related to the asteroid’s rotation period rather than its thermal inertia, as the beaming parameter is related to rotation period in such a way that the trends of both quantities with 10-µm contrast are consistent. Faster rotation lowers the effective gravity at an asteroid’s surface, which may aid in the formation of fairy castle structures. The presence of such structures may explain the high 10-µm contrast seen on the Trojan asteroids (Emery et al., 2006a).

Finally, we note that, because our sample is small, this and other possible trends discussed in this work are tentative. More mid-infrared data on primitive asteroids, especially the Themis and Veritas asteroids, will provide clarification.

5.5.3 Comparison with Laboratory Studies of Meteorites

The Themis and Veritas families are intriguing targets of study because they have been exposed to the space environment for very different periods of time. In the mid-infrared, we do not observe differences between the families that can be directly attributed to space weathering. The average 10-µm band contrast and center for each family are statistically indistinguishable, given the variance within each family. Laboratory work does suggest that space weathering affects the mid-infrared spectra of primitive material. Lantz et al. (2015) irradiated the Murchison CM meteorite with He\(^+\) and Ar\(^+\) ions to simulate space weathering and studied the spectrum of Murchison before and after irradiation. In the mid-infrared,
they found irradiation produced shifts in the positions of olivine, enstatite, and phyllosilicate peaks, as well as dampening and broading of peaks. The search for similar changes in spectra of primitive asteroid families of different ages is complicated by several factors. First, the observed shifts in spectral peaks are subtle, < 0.1 \mu m, making them difficult to detect at the signal-to-noise ratio and resolution of the asteroid spectra presented here. Second, the position, amplitude, and shape of features in mid-infrared asteroid family spectra are confounded by grain size effects, thermal processes, and differences in original composition between and within families.

Mid-infrared laboratory studies of aqueous alteration also provide context for this work on Themis and Veritas asteroids. In Section 5.4.2, we used the trend between the position of the 10–13\mu m minimum and degree aqueous alteration in carbonaceous meteorites, identified by McAdam et al. (2015), as a tentative proxy for degree of aqueous alteration in the Themis and Veritas asteroids. Beck et al. (2014) investigated the degree of aqueous alteration in primitive meteorites using the intensities of the 3-\mu m hydration feature and the 11.2-\mu m olivine feature to quantify the relative amounts of phyllosilicates to olivine. When 3-\mu m intensity is plotted against 11.2-\mu m intensity for their sample, they find a linear evolution from CV to CM chondrites. Performing this analysis for the Themis and Veritas asteroids is currently precluded by a paucity of 2–4\mu m spectra for the asteroids in our sample and a low signal-to-noise ratio in the 11.2-\mu m region in many of our Spitzer spectra. Published 3-\mu m spectra for (24) Themis show the presence of a rounded feature with band depth of \sim 10\%, attributed to water ice rather than hydrated silicates (Campins et al., 2010a; Rivkin and Emery, 2010). A spectrum published by Hargrove et al. (2015) shows the possibility of a shallower 3-\mu m feature on (90) Antiope that could be attributed to small quantities of either water ice or hydrated minerals. The highly aqueously altered meteorites in the Beck et al. (2014) study show checkmark-shaped 3-\mu m features with band depths > 10\%. This is consistent with the position of the 10–13\mu m minimum in our sample, which suggests the
Themis and Veritas families are like less aqueously altered meteorites. An analysis of the 10–13 \( \mu \text{m} \) minimum in the Beck et al. (2014) meteorite spectra would nicely complement the work of McAdam et al. (2015) and this study.

### 5.6 Summary

In this mid-infrared spectral study of the Themis and Veritas asteroid families, we do not find differences between the families that can be attributed to space weathering, although there is variation of spectral properties within each family. We report that all 11 of the Themis-family asteroids and six of nine Veritas-family asteroids in this sample have a statistically significant 10-\( \mu \text{m} \) silicate emission band in their 5–14 \( \mu \text{m} \) Spitzer spectra. Ranges of spectral contrast at 10-\( \mu \text{m} \), which is sensitive to regolith grain size and porosity, are consistent between the two families and are typically \( \sim \)1–3%. This suggests the Themis and Veritas asteroids have denser regolith structures and/or larger grains than the Trojan asteroids. Three asteroids within our sample have higher 10-\( \mu \text{m} \) spectral contrast than the rest of the sample: (8726) Masamotonasu, (316) Goberta and (492) Gismonda. Once contraints on the shape and spin-pole orientation of more Themis and Veritas asteroids are established, thermophysical modeling will provide more insight into their regolith structures.

Comparison with a laboratory study (McAdam et al., 2015) of the 12-\( \mu \text{m} \) spectral region in primitive meteorites suggests the asteroids in our sample are more similar to less aqueously altered meteorites. Results from thermal modeling show that these asteroids have low to moderate albedos. An average beaming parameter \( \bar{\eta} \) near unity for both families indicates infrared beaming is not significant in these asteroids and suggests low thermal inertias. We identify a tentative correlation between the beaming parameter and 10-spectral contrast and between rotation period and 10-spectral contrast in the Themis asteroids. These trends may be related, as rotation period is parameterized in the beaming parameter. Faster rotation
changes the effective gravity of an asteroid’s surface, which may drive the formation of fairy castle structures, thus enhancing 10-μm spectral contrast. Finally, there may be a trend of flatter NIR spectral slopes with moderate albedos. Once shape models and spin pole orientations are established for more Veritas and Themis asteroids, these trends can be further investigated with thermophysical modeling.
CHAPTER 6: SUMMARY AND DISCUSSION

In the work presented in this dissertation, we used infrared spectroscopy to constrain the composition and physical properties of two asteroid populations: the M-type asteroids and primitive families. In this chapter, I discuss the impact of our results and goals for future work to expand upon these results.

6.1 The M-Type Asteroids

Although members of the M-type taxon were at one time considered to be analogous to iron meteorites, it is clear from detailed studies that the M-types are compositionally diverse. Radar and visible and near-infrared spectroscopy have revealed evidence for mafic silicates and hydrated minerals on M-type asteroids, challenging the notion that these objects are likely to be entirely metallic.

Our 2–4 µm study of six M-type asteroids follows up on the spectrophotometric work of Rivkin et al. (2000), who found evidence for a 3-µm hydration feature on over 35% of their sample of 27 M-types. Our study, obtained with newer and more sensitive instrumentation than those in the Rivkin et al. (2000) study, has resulted in two important findings. First, with our relatively high signal-to-noise data in the L-band, we detected a 3-µm hydration feature on two asteroids thought to be “dry”, (216) Kleopatra and (418) Alemannia. Second, with the high spectral resolution afforded by the SpeX instrument’s LXD mode, we found that the shape of the 3-µm feature varies among the M-types in our sample. Takir and Emery (2012) reported that the shape of the 3-µm is related to hydrated mineralogy and thermal evolution of asteroids. Although our sample is small, our results indicate that modes of hydration among the M-type asteroids are diverse.
The best evidence for the presence of metal on M-type asteroids comes from radar studies. M-types with high radar albedos are interpreted to be metallic (or metal-rich), as radar albedo is sensitive to both the density and dielectric properties of the top meter of an asteroid’s surface. Interestingly, radar albedo does not seem to correlate with hydration in the M-types. Three of the six hydrated asteroids in our study have been studied at radar wavelengths, and two of these, (69) Hesperia and (216) Kleopatra, have radar albedos consistent with the presence of metal. Several other high-radar albedo M-types, including (16) Psyche, have 3-μm hydration features.

M-type asteroid (16) Psyche, the target of a planned NASA mission, is an example of the apparent contradictions that are pervasive in studies of M-type asteroids. Compared to asteroids in the C- and S-classes, (16) Psyche has a high radar albedo and relatively high bulk density, and so it is inferred to be a metal core stripped of its crust and mantle by a “hit-and-run” glancing collision. Despite that, our thermal modeling and spectral analysis of its mid-infrared spectrum detailed in Chapter 4 show that its surface contains a dusty, fine-grained silicate layer that likely contains pyroxene. Pyroxene has also been detected in Psyche’s NIR spectrum (e.g., Hardersen et al., 2011; Sanchez et al., 2017). Our thermal measurements only probe the top ∼0.1–1 mm of Psyche’s surface, so our results do not preclude the existence of a metallic layer below the silicates. Iron grains may also be mixed with the fine silicates on Psyche’s surface.

Signatures of hydroxyl and/or water have been detected on Psyche, a result that seems incompatible with the thermal history necessary to create metal and/or reduced pyroxene (Takir et al., 2017). These hydrated silicates may be exogenic, perhaps from impacts of hydrated meteorites. This mechanism may be common in the asteroid belt, and may be responsible for the presence of hydrated signatures on other M-type asteroids. As discussed, carbonaceous xenoliths have been identified in high-temperature meteorites, and dark, hydrogen-rich material on basaltic asteroid Vesta has been attributed to impacts of
carbonaceous chondrites (e.g., Zolensky et al., 1996; Shepard et al., 2013; Reddy et al., 2012). NASA’s Psyche mission, planned for launch in 2023 and arrival at Psyche in 2030, will improve our understanding of Psyche’s composition and origin. Still, caution should be exercised to avoid applying results of the Psyche mission to other M-type asteroids, as this taxon seems to be highly diverse.

Future work should include detailed spectral modeling of the mid-infrared spectra of Psyche. None of the single-mineral or meteorite spectra to which we compared Psyche’s emissivity spectrum were an identical match. Mixing models may provide additional insight into Psyche’s mineralogy. Additionally, the Spitzer Heritage Archive contains Spitzer Space Telescope spectra for 26 additional M-type asteroids. Thermal and spectral analyses of this dataset will improve our understanding of the range of compositions and surface properties in the M taxon.

More laboratory studies and theoretical models will constrain the likelihood and efficiency of exogenous hydration on the M-types. For example, Avdellidou et al. (2017) are using hydrocode simulations constrained by dynamical models and laboratory impact studies to determine whether impacts of hydrated material from the Themis and Hygiea families can result in the 3-µm band observed on Psyche. Laboratory studies (e.g., Schaible and Baragiola, 2014) are placing constraints on the efficiency of solar-wind hydrogen implantation in the main asteroid belt.

Additional studies of M-type asteroids in the 2–4 µm region will provide further insight onto the degree and type of hydration found on these asteroids. We have collected 2–4 µm spectra for six additional M-type asteroids using the IRTF, and analysis and publication of this dataset is in progress. Moving forward, infrared space telescopes will offer unique insight into this wavelength region. JAXA’s AKARI spacecraft observed 66 asteroids (including many M-type asteroids) from 2.5–5 µm (Usui et al., 2017). When released, this dataset will provide a valuable supplement to ground-based observations in this wavelength regime, which
are limited by the opacity of the Earth’s atmosphere from 2.5–2.8 µm. The James Webb Space Telescope (JWST), set to launch in 2018, will have spectroscopic capabilities from 0.6–5.0 µm with its NIRSpec spectrometer. This instrument will provide greater sensitivity to faint targets than ground-based instruments operating in the 3-µm region, and, like AKARI, will be unimpeded by telluric opacity across 2.5–2.8 µm (e.g., Rivkin et al., 2016).

### 6.2 Primitive Asteroid Families

Our mid-infrared study of the primitive asteroid families Veritas and Themis demonstrates that family differences at VISNIR wavelengths are not necessarily apparent in the mid-infrared. As discussed, space weathering on primitive (volatile- and carbon-rich) surfaces can convert iron in silicate structures to npFe0 and alter organic chemistry. This may result in either redder or bluer spectral slopes in VISNIR wavelengths and either darker or brighter surfaces, while the effects of space weathering in the mid-IR are subtle. Our results suggest that variation in regolith properties within the families, to which the mid-IR is sensitive, is greater than differences between the mid-IR spectra of these families due to space weathering. As shape models and pole orientations become available for more members of these families, thermophysical modeling can be performed, and we can explore whether differences in thermal properties (e.g., thermal inertia) are apparently between families, or if they vary greatly within each family.

We found that the position of the emissivity minimum near 12 µm in the spectra of the Themis and Veritas asteroids is similar to that in less-aqueously altered carbonaceous chondrites, following the methods of McAdam et al. (2015). This is consistent with the detection of water-ice on (24) Themis (Campins et al., 2010a; Rivkin and Emery, 2010), which suggests that these outer-belt asteroids have not received significant heating.
The JWST may help advance our understanding of the Themis and Veritas families and of primitive asteroid families in general. The high sensitivity of JWST’s mid-IR spectrometer, MIRI, will be able to measure mid-infrared spectra for faint asteroid targets. Mid-IR observations of primitive asteroids in inner-, middle-, and outer-belt families, at a range of asteroid sizes, will provide context for our results on the Themis and Veritas families. As discussed above, the JWST’s capabilities in the 3-µm region will be able to probe hydration on asteroids in more detail than ground-based studies. Takir and Emery (2012) found a trend of 3-µm feature shape with semimajor axis in primitive asteroids. JWST will be able to acquire 3-µm spectra of more outer-belt primitive asteroids, which are typically fainter and more difficult to observe (since they are both dark and are further from Earth). In particular, 3-µm spectroscopy of Themis and Veritas family members will allow us to confirm the lack of aqueous alteration inferred from our mid-IR study.

The year 2018 will see the arrival of both NASA’s OSIRIS-REx mission at (101955) Bennu and JAXA’s Hayabusa2 mission at (162173) Ryugu. Bennu and Ryugu are both primitive (low-albedo, C-complex) near-Earth asteroids which likely originated in the inner asteroid belt (e.g., Campins et al., 2010b, 2013). Ahead of these missions, our collaborators continue work on PRIMASS, the PRIMitive Asteroids Spectroscopic Survey. PRIMASS originally focused on the visible and near-infrared characterization of inner-belt primitive families to shed light on the origins of the targets of OSIRIS-REx and Hayabusa2; however, the survey is now expanding to the middle- and outer-belt. As these results are finalized, they will provide more context for interpreting our mid-infrared results on the Themis and Veritas asteroid families. Finally, ESA’s Gaia mission will contribute to asteroid visible spectroscopy. Gaia is expected to obtain visible (0.35–0.9 µm) spectra of approximately 300,000 asteroids, and its coverage in the near-UV is especially important, as these wavelengths inaccessible from the ground. Primitive asteroids in particular may have absorption features in the near-UV...
(e.g., de León et al., 2012), and Gaia data can be used to explore how these features vary within and between primitive families.
APPENDIX

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