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Identifying "bad" Asteroid Spectra: A Cross-Correlative Database Study

Iva Gerasimenko

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IDENTIFYING “BAD” ASTEROID SPECTRA: A CROSS-CORRELATIVE DATABASE STUDY

by

Iva Gerasimenko
Bachelor of Science, Randolph College, 2010

A Thesis
Submitted to the Graduate Faculty

of the

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Master of Science

Grand Forks, North Dakota
May
2015
This thesis, submitted by Iva Gerasimenko in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Wayne Swisher
Dean of the School of Graduate Studies

April 24, 2015
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Title Identifying “bad” asteroid spectra: a cross-correlative database study

Department Space Studies

Degree Master of Science

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Name Iva Gerasimenko

Date 4/2/2015
TABLE OF CONTENTS

LIST OF FIGURES...........................................................................................................ix

LIST OF TABLES................................................................................................................xiii

ABSTRACT ..........................................................................................................................xiv

CHAPTER

I. DESCRIPTION OF DATASETS.........................................................................................1

   Introduction..................................................................................................................1

   SMASS I......................................................................................................................2

   SMASS II ..................................................................................................................3

   S³OS² .........................................................................................................................4

   Sawyer .......................................................................................................................5

   Vilas .........................................................................................................................6

   52 Color Survey ......................................................................................................7

   24 Color Survey ......................................................................................................7

   8 Color Survey ......................................................................................................8

   NEAR IR ................................................................................................................9
II. THEORETICAL BACKGROUND………………………………………………………………………... 12

Identifying Features .................................................................................................................. 12

Spectral Types............................................................................................................................ 12

Mineralogy................................................................................................................................. 13

Normalized Reflectance ............................................................................................................. 14

Mineral Bands............................................................................................................................ 15

Airmass....................................................................................................................................... 15

Atmospheric Dispersion............................................................................................................. 15

Moonlight .................................................................................................................................... 15

Phase Angle............................................................................................................................... 15

Lightcurve.................................................................................................................................. 16

III. POTENTIAL CAUSES OF DISCREPANCIES ..................................................................... 17

Shape.......................................................................................................................................... 17

Surface Heterogeneity................................................................................................................ 18

Temperature................................................................................................................................ 19

Viewing Geometry ..................................................................................................................... 20
Different Standard Stars.................................................................20

Instrumental Problems...................................................................21

Summary................................................................................................21

IV. ANALYSIS OF SPECTRA........................................................................22

3 Juno..................................................................................................22

10 Hygeia............................................................................................23

12 Victoria ...........................................................................................25

56 Melete............................................................................................26

112 Iphigenia .......................................................................................26

115 Thyrra..........................................................................................27

117 Lomia ............................................................................................28

140 Siwa..............................................................................................29

169 Zelia ..............................................................................................30

170 Maria............................................................................................30

173 Ino.................................................................................................31

181 Eucharis.........................................................................................32

184 Dejopeja.........................................................................................32

196 Philomela.......................................................................................33

233 Astreope.......................................................................................34

332 Siri..................................................................................................34

354 Eleonora.......................................................................................35


### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 26 SMASS II taxonomic classes. Horizontal lines show normalized reflectance of 1 (Bus and Binzel 2002)</td>
<td>13</td>
</tr>
<tr>
<td>2. Left: Spectral Flux curves for Vesta and 16 Cygnus B (a solar analog standard star). Right: Reflectance spectrum normalized to unity at ~0.55 µm (Bus and Vilas, 2002)</td>
<td>14</td>
</tr>
<tr>
<td>3. Normalized reflectance of a sphere covered with ordinary chondrite-type material (right) differences in spectral reflectance between the sphere and the end and side view of an ellipsoid (left – units are in magnitudes), both plotted versus wavelength with spectral range of 0.3 to 1.3 (Gradie. 1981)</td>
<td>17</td>
</tr>
<tr>
<td>4. DAWN data for Cornelia crater overlain over terrain (Reddy 2014)</td>
<td>18</td>
</tr>
<tr>
<td>5. Orthopyroxene reflectance spectra taken at 80 K and 448 K (Singer, 1985)</td>
<td>19</td>
</tr>
<tr>
<td>6. Spectra of Juno, SMASS I, SMASS II (light blue), S³OS² (grey), 24 Color Survey (dark blue), 54 Color Survey (red), 8 Color (yellow), SMASSIR (pink). Data obtained from Planetary Data System Small Bodies Node (Ferret) (henceforth the case for all spectra unless specified otherwise)</td>
<td>22</td>
</tr>
<tr>
<td>7. Reflectance spectra of 10 Hygeia, SMASS I, SMASS II, Sawyer, SMASSIR</td>
<td>23</td>
</tr>
<tr>
<td>8. (right) Spectra of 10 Hygeia taken on October 4th and 5th, 2007 and offset for clarity. Numbers in brackets stand for relative rotation phase (Busarev, 2009); (left) Spectra of Hygeia taken at different rotation phases Nov and Dec 26th</td>
<td>24</td>
</tr>
<tr>
<td>10. (left) Spectra of 12 Victoria. SMASS II, S³OS², SMASSIR, 24 Color, 52 Color, 8 Color. (right) Lightcurve of 12 Victoria (Erikson, 1990)</td>
<td>25</td>
</tr>
<tr>
<td>11. (left) Spectra of Asteroid 56 Melete. SMASS II, S³OS², 8 Color. (right) Lightcurve of 56 Melete (Belskaya, 1993)</td>
<td>26</td>
</tr>
</tbody>
</table>
12. Spectra of 112 Iphigenia. SMASS II, S\(^3\)OS\(^2\), NEAR IR .................................................................26

13. Spectra of 115 Thyra. SMASS II, S\(^3\)OS\(^2\) .................................................................................................27

14. (left) Lightcurve of 115 Thyra taken by Michalowski in 2000. (right) Shape model for 115 Thyra taken from DAMIT .................................................................28

15. (left) Spectra of 117 Lomia. SMASS II, S\(^3\)OS\(^2\), 8 Color. (right) Lightcurve for 117 Lomia (Di.Martino, 1995) .................................................................28

16. Spectra of 140 Siwa. SMASS II, S\(^3\)OS\(^2\), 24 Color, Ostrowski, SMASSIR ..................................................29

17. Lightcurves of Siwa taken by Pilcher in 2012. Depending on how one defines the start period of the rotational phase the length of it changes ..............................................29

18. Spectra of 169 Zelia. SMASS I, SMASS II, S\(^3\)OS\(^2\), 24 Color, 8 Color, SMASSIR ...........................................30

19. Spectra of 170 Maria, SMASS II, S\(^3\)OS\(^2\), 24 Color, 8 Color ..................................................................................30

20. Spectra of 173 Ino, SMASS II, S\(^3\)OS\(^2\), Sawyer, 8 Color, NEAR-IR .................................................................31

21. Spectra of 181 Eucharis. SMASS II, S\(^3\)OS\(^2\), Vilas, 24 Color (dark blue), Ostrowski (purple), 8 Color ..................................................................................32

22. Spectra of 184 Dejopeja. SMASS I, SMASS II, S\(^3\)OS\(^2\), 8 Color ..................................................................................32

23. (left) Lightcurve of 184 Dejopeja. (Gil-Hutton, 1994). (right) Shape model for 184 Dejopeja taken from DAMIT ...............................................................................33

24. (left) Spectra of 196 Philomela. SMASS I, SMASS II, 24 Color, 8 Color. (right) Shape model for 196 Philomela taken from DAMIT ...............................................................................33

25. Spectra of 233 Astreope. SMASS II, S\(^3\)OS\(^2\), 52 Color (light red) NEAR IR (dark red), SMASSIR (pink), 8 Color ..................................................................................34

26. (left) Spectra of 332 Siri. SMASS II, S\(^3\)OS\(^2\). (right) Lightcurve of 332 Siri (Cieza, 1999) .................34

27. (left) Spectra of 354 Eleonora. SMASS I, SMASS II, S\(^3\)OS\(^2\), 8 Color. (right) Spectra of 354 Eleonora. 52 Color #1 (grey), 54 Color #2 (blue). SMASS NIR (orange), MIT NEOSR (yellow) ..................................................................................35

28. (left) Spectra of 381 Myrrha. SMASS II, S\(^3\)OS\(^2\), 8 Color. (right) Lightcurve for 381 Myrrha. (Zeigler, 1990) ..................................................................................36
29. Spectra of 388 Chyrabdis. SMASS II, S^3OS^2, 8 Color……………………………………………………………..36
30. Spectra of 402 Chloe. SMASS I, SMASS II, 24 Color, SMASSIR, 8 Color……………………………………..37
31. (left) Spectra of 412 Elisabetha. SMASS II, S^3OS^2. (right) Lightcurve for 412 Elisabetha. (Cooney, 2002)................................................................................................................................................37
32. Spectra of 434 Hungaria, S^3OS^2, SMASS II, Sawyer, NEAR IR (dark red), 24 Color Survey, 52 Color survey (light red), 8 Color ...................................................................................................................38
33. Spectra of 1600 Vyssotsky, a member of the Hungaria family of asteroids. SMASS II, S^3OS^2, SMASSIR...................................................................................................................................................38
34. Spectra of 3873 Roddy, a member of the Hungaria family of asteroids. SMASS II, S^3OS^2..................................................................................................................................................38
35. Spectra of 547 Praxedis, SMASS II, S^3OS^2, NEAR IR................................................................................39
36. Spectra of 579 Sidonia. SMASS II, S^3OS^2, 24 Color, 8 Color........................................................................40
37. Spectra of 598 Octavia, SMASS II, S^3OS^2 ..................................................................................................40
38. Asteroid 599 Luisa. SMASS I, SMASS II, 24 Color, SMASSIR, 8 Color.......................................................41
39. (left) Spectra of 625 Xenia, SMASS II, S^3OS^2, SMASSIR. (right) Lightcurve for 625 Xenia. (Worman, 2003)................................................................................................................................................42
40. Spectra of 808 Merxia. SMASS II, SMASS I, S^3OS^2, SMASSIR (pink), NEAR-IR (red) .................42
41. (left) Lightcurve for 808 Merxia (Ditteon, 2003). Visual Magnitude is plotted versus rotational phase. (right) Shape model of 808 Maerxia taken from DAMIT........43
42. (left) Spectra of 1022 Olympiada, SMASS II, S^3OS^2. (right) Lightcurve of Olympiada obtained by Benishek in 2008........................................................................................................................................43
43. Spectra of 1024 Hale, SMASS II, S^3OS^2..................................................................................................44
44. Spectra of 1094 Siberia, SMASS II, S^3OS^2..............................................................................................44
45. Spectra of 1110 Jaroslawa, SMASS I, SMASS II ......................................................................................45
46. Spectra of 1114 Lorraine, SMASS II, S^3OS^2 ..........................................................................................45
47. (left) Spectra of 1139 Atami. SMASS II, $S^3O_2$, 8 Color. (right) Spectra 1139 Atami. The dark lines are showing limiting reflectance for S type asteroids from Bus and Binzel (2002) [Behrend 2006]........................................................................................................46

48. Spectra of 1263 Varsavia, SMASS II, $S^3O_2$, 24 Color........................................................................................................47

49. (left) Lightcurve of 1263 Varsavia. (Stephens, 2004). (right) Shape model data for 1263 Varsavia taken from DAMIT........................................................................................................47

50. Spectra of 1284 Latvia, SMASS II, $S^3O_2$, 24 Color, 8 Color...............................................................................................48

51. Spectra of 1807 Slovakia, SMASS I, SMASS II......................................................................................................................48

52. Spectra of 1904 Massevitch, SMASS II, $S^3O_2$, SMASIR.....................................................................................................49

53. Spectra of 2448 Shokolov. SMASS II, $S^3O_2$.........................................................................................................................49

54. Spectra of 3169 Ostro, SMASS II, $S^3O_2$, 8 Color..................................................................................................................50

55. Common pattern observed for 18 asteroids. 8 Color (yellow), 24 Color (dark blue), NEAR-IR (red), SMASS I (green), SMASS II (light blue), $S^3O_2$ (grey)........................................................................55

56. Common Pattern between SMASS I (green) and SMASS II (light blue). 8 Color (yellow), 24 Color (dark blue)..................................................................................................................57
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Summary of Datasets compared. Spectral range is in microns, Ast stands for number of asteroids observed, N is the value of wavelength the spectra were normalized at in microns...</td>
<td>11</td>
</tr>
<tr>
<td>3. Summary of Likely causes for observed discrepancies in the spectra. Asteroids marked green have published evidence that supports the reason stated behind the discrepancy. Asteroids marked blue have evidence that points strongly towards a stated reason for the discrepancy. Asteroids in black have very little evidence to narrow down the cause...</td>
<td>51</td>
</tr>
<tr>
<td>4. Comparison of data from different sets: Number in Common / Number Inconsistent. Subset of 300 asteroids was used rather than all possible asteroids in common for all sets Note that some differences overlap (same asteroid can have 2 or more datasets that do not agree with each other)...</td>
<td>57</td>
</tr>
<tr>
<td>5. Standard stars, phase angle, airmass, diameter and albedo for asteroids in this study. Information is taken from Small Bodies Data Node. M stands for magnitude (absolute for SMASS I, apparent for S3OS2 and SMASS II), Ph stands for phase angle, A for airmass, D for diameter, Al for albedo; c stands for cloudy conditions that introduced small (~5%) erratic variations into the spectra, m stands for moonlight, meaning high (&gt;50%) lunar illumination and h for humidity over 70%...</td>
<td>60</td>
</tr>
</tbody>
</table>
ABSTRACT

The SMASS I, SMASS II and S^3OS^2 asteroid spectral survey data sets as well as those collected by Sawyer (1991) and Vilas (1992) were examined for compositionally significant inconsistencies between spectra taken for the same asteroids. Data was obtained from Small Bodies Node Planetary Data System. Thirty four asteroid spectra were determined to display drastic differences which would affect the mineralogical interpretation of the spectra. Including 354 Eleonora, which prompted the original question, these asteroids were further examined for possible causes of inconsistencies to determine if they were prompted by actual differences in the surface composition or were due to differences in data reduction and calibration.
CHAPTER I

DESCRIPTION OF DATASETS

Introduction: Significant spectral inconsistencies were observed between the SMASS I and II and S3OS2 datasets while examining the asteroid (354) Eleonora (Gaffey et al. 2015). If these spectra were analyzed independently, they would have given different interpretations for mineral composition of the same asteroid. In the case of Eleonora, plausible physical causes for asteroid spectral variation were ruled out, pointing to instrumental, observational or data processing issues as the cause of this discrepancy. This raised the questions as to whether this was a widespread problem and, if so, are the discrepancies due to actual differences on the object (surface heterogeneities), different observational circumstances (e.g., phase angle, pole orientation) or to instrumental, data reduction or observational errors. Where available, Sawyer (Sawyer, 1991), 24 Color (Chapman and Gaffey 1979), 52 Color (Gaffey, Reed, Kelley 1992), 8 Color (Tedesco, Tholen, Zellner, 1985), NEAR-IR (Bus, 2011), SMASSIR (Burbine and Binzel, 2002) and Vilas (Vilas et.al. 1992) datasets were also included in the comparison. It was determined that at least thirty four asteroids showed significant differences when different datasets were compared, which means this is a widespread problem.
SMASS I (Xu et al. 1995)

SMASS stands for the Small Main-Belt Asteroid Spectroscopic Survey. This survey ran from 1991 to 1993 with a goal to obtain visual wavelength (0.4 to 1 microns) spectra for 316 small main belt asteroids (with average diameters of 20 km).

**Instrumentation:** The majority of SMASS I observations were done using a 2.4 m Hiltner telescope with 398 x 598 pixel and 1024 x 1024 pixel CCDs at Michigan Dartmouth MIT (MDM) Observatory at Kitt Peak in Arizona. A Wratten 12 filter - a yellow filter that blocks out the blue part of the spectrum (below 0.5 microns) – was used. Dispersion value was ten angstroms per pixel. Observations were made with the 4.7 arcsec wide slit oriented in a north-south direction which gave spectral resolution of fifty angstroms.

**Calibration:** Multiple bias images were taken to measure electronic noise of the CCD. There was a difficulty in applying flat field images evenly to both red and blue ends of the spectrum as it resulted in lower signal to noise ratio. This problem was more prevalent for faint asteroids. To correct for this issue, asteroid spectra were placed along the same CCD columns. Bright asteroids with known spectral absorption features were also observed to correct for instrumental errors. Spectra were normalized at 550 nm. Telluric features at 760, 900 and 940 nm were removed. The effects of wavelength dependent atmospheric absorptions were corrected by dividing the asteroid spectral flux measurements by the spectral flux measurements of standard stars observed within 0.1 airmasses of the asteroid observations.

**Notes:** Long slit CCD spectroscopy was used to image fainter asteroids than was possible with earlier surveys. It covers a wider range of the visible spectrum in a single exposure which allows
for effects resulting from the asteroid’s rotation lightcurve and atmospheric fluctuations to be neglected.

**SMASS II (Bus 1999; Bus and Binzel 2002 a, b)**

A total of 1341 small asteroids were observed in visible wavelengths. All of the observations for this data set were made between August 1993 and March 1999.

**Instrumentation:** SMASS II observations were performed with 2.4 m Hiltner and 1.3m McGraw-Hill reflecting telescopes in Arizona. This is the same spectrograph as the one which was used for SMASS I. The slit was oriented in the north-south direction on the sky (4.5 arcsec wide and 5 arcmin long). This orientation was chosen in order to minimize the effects of atmospheric dispersion. A spectral resolution of 0.007 micrometers (R ~ 100) was defined by the width of the slit. This resolution is low, but it improves signal to noise ratio for faint asteroids, avoids oversampling of 2-D images, and reduces the effect of wavelength offsets due to drifting of the target across the slit (Bus, 1999).

**Calibration:** IRAF (Image Reduction and Analysis Facility), developed by the National Optical Astronomy Observatories, was used for data analysis. The mean bias level was determined from the unexposed overscan region in each CCD image and subtracted. Images were not flat field corrected. Instead inherent flat characteristics of CCD cameras were used. During conversion of 2D images to 1D, apall feature of IRAF assigned 1 sigma uncertainty based on gain and noise ratio of the detector for each point in the spectrum, which were later used to define error bars for the data. Wavelength calibration was performed through a dispersion model based on Hg-Ar-Xe lamps. Atmospheric extinction was corrected by using the airmass of the observation and
the mean extinction model developed for Kitt Peak. Each asteroid spectrum was divided by the solar analog spectrum and normalized at .55 microns. ‘Bad’ pixels, which resulted from cosmic ray hits or incomplete removal of terrestrial atmospheric bands were removed. Spectra that had significant variations caused by observing through clouds were rejected. The spectral range was set at .435 microns to 0.925 microns for all spectra for consistency and to avoid quantum efficiency reduction of CCD cameras used below and above that range. Limiting range in such a way might cut out some of the data, which reduces the extent to which features can be seen and the validity of taxonomy for SM mass II dataset.

$S^3$OS$^2$ (Lazzaro, et.al., 2004)

$S^3$OS$^2$ stands for Small Solar System Objects Spectroscopic Survey. Eight hundred and twenty asteroids were observed at visible wavelengths. The observations were conducted between November 1996 and September 2001.

**Instrumentation:** A 1.52 m telescope at ESO (Le Silla, Chile) was used to obtain data in spectral range from 490 nm to 920 nm. Boller and Chivens spectrograph with a 2048x2048 pixels CCD was used. A grating of 225 gr/mm with a dispersion of 330 Angstroms/mm in first order was used. Spectra were taken through a 5 arcsec slit oriented in the east-west direction. The slit direction was chosen to reduce loss of light due to movement of the target. This telescope does not have automatic differential tracking. A majority of the asteroids were observed at small zenith distance to compensate for east-west rather than preferred north-south slit orientation.

**Calibration:** Exposures were paused to ensure asteroids were in the slit. Most of the main-belt asteroids were observed at small solar-phase angles, with a median of 13.7 degrees in order to
avoid phase reddening. Spectral data reduction was done using IRAF software with average bias. Wavelength calibration was performed using a He-Ar lamp with spectrum obtained several times each night. Spectra were corrected for airmass using the mean extinction curve of La Silla. Multiple solalogs were observed each run. Asteroid spectra presented in the dataset were not a mean of multiple observations but instead the best one was chosen.

**Notes:** Observing conditions were reported to be between good and excellent for most runs. Seventy percent of the asteroids were observed more than once and 53% of them on two different or consecutive nights.

**Sawyer (Sawyer, 1991)**

About 115 asteroids were observed by Scott Sawyer in the 0.4 to 1.0 microns range as part of a PhD dissertation at the University of Texas, Austin over a period of seven years. Primary focus of this survey was on low albedo asteroids of Tholen classes with weak features in the .5 and 1 micron spectral region.

**Instrumentation:** Data was gathered at McDonald observatory using Struve Warner & Swasey reflector, cassegrain spectrograph and CCD. Sawyer split his observations into three groups – red (0.73-1 microns), visible (0.52-1 microns) [observed with 2.1m telescope and the Electronic Spectrograph 2] and blue (0.4-1 microns) [observed with 2.7 m telescope and Large Cassegrain Spectrograph]. Slit width was 2 mm, resulting in a 15 arcsec view of the sky.

**Calibration:** Quartz lamp exposures were used for flat fielding the data, while argon and neon hollow cathode tube exposures were used for wavelength calibration. Hyades 64 and 16 Cyg B solar analog stars were used for most observations. Night sky emissions were highly variable...
over the exposure time, which made them difficult to remove. Solar analog stars were too hot in the blue end of the spectra, oversaturating it, and strong telluric H$_2$O bands at the red end of the spectra. The problem at the blue end was corrected by increasing the number of solar stars used and then averaging their spectra, while telluric bands could not always be completely removed.

**Note:** High resolution of the obtained data allowed for mineral reflectance measurements (13-25 Angstroms per resolution element) and had a high signal-to-noise ratio. The final reflectance spectrum was obtained by correcting the asteroid/standard star curve by reference to a solar type standard star. The theory that solar analog stars could have introduced significant artifacts into the spectra was checked by Sawyer and was found to be not the case. He also noted that sometimes the same asteroid observed with the same solar analog on different nights will give different results, and suggested that this indicated actual reflectance changes across the surface of the asteroid. However, this usually affects the strength of features rather than an overall shape.

**Vilas** (Vilas et.al. 1992, Vilas and Smith 1985)

Faith Vilas obtained 81 asteroid spectra during the years 1982-1992.

**Instrumentation:** For 1988-1990 period Mount Bigelow in Arizona (Catalina) station with 1.54 m Cassegrain/Coude reflector was used. Spectral range was 0.330 – 0.850 with resolution of 23 angstroms (Vilas, 1993). For 1991-1992 Cerro Tololo Inter-American observatory 1.5m Cassegrain telescope was used. Spectral range of that set was 0.495-0.990 microns with spectral resolution of 16 angstroms through the use of Schott OG 495 filter.
**Calibration:** Five-point running-box average and median filter techniques were used to correct for noise in the spectra. Reflectance of 1 at 0.7 microns was used to scale the spectra. Standard stars were observed multiple times per night and at different airmass values. The effects on spectral slope from different values of solar analog stars to sun ratio were minimal.

**52 Color Survey (Bell et al. 1988; Gaffey, Reed, Kelley 1992)**

52 color survey covered spectral range from 0.8 microns to 2.5 microns and was conducted from 1983 to 1987. 119 asteroids were observed. Spectra was normalized at 0.55 microns in order to scale with the 8-color data.

**Instrumentation:** Three meter reflector telescope located at NASA Infrared Telescope Facility was used. Two circular variable bandpass filters were used to obtain photometry data in 52 bandpasses (32 channels: short CFV 0.8-1.6 microns; 20 channels: long CFV 1.48-2.6 microns).

**Calibration:** Standard stars were observed two or three times for each observation run and then used for extinction coefficient calculations with relation to the 16 Cyg B. Multiple starpacks (models for standard star flux to airmass ratio) were calculated throughout each observing day. Measured asteroid flux was divided by the appropriate starpack, which allowed for the effect of instrument or observational issues to be minimized (both fluxes would be influenced the same way).


**Instrumentation:** McCord Dual Beam Photometer at Mt.Wilson, Mt. Palomar and Kitt Peak
National Observatory was used to obtain data at 24 filters during 1970-1971. Wavelength range was between 0.32 and 1.08 microns.

**Calibration:** Spectra were normalized at 0.57 microns and averaged across multiple observations of the same asteroid. Alpha Lyrae standard star was used. Uncertainty of 2 percent in visual and 4 percent in infrared was caused by the use of this star.

**Note:** Dual beam photometry images asteroid and the nearby patch of the sky repeatedly which allows for effects of observing conditions (such as clouds and atmospheric extinction) to be minimized.

**8 Color Survey: (Tedesco, Tholen, Zellner, 1985)**

**Instrumentation:** Eight-Color Photometer at the 1.54 m Catalina reflector and 2.29 m Steward reflectors were used. Observations were made at University of Arizona. The filters used were at the following wavelengths in microns -0.310 (s), 0.320 (u), 0.430 (b), 0.545 (v), 0.705 (w), 0.860 (x), 0.955 (p), 1.055 (z).

**Calibration:** Data was normalized to 1.0 at the 0.545 micrometer filter. The extinction coefficient at s filter was high - 0.77 magnitudes per airmass unit - but stable. The extinction coefficient at p filter was less but variable.

**Notes:** Faint objects were observed in only five colors rather than all eight. Albedo effects on the spectra were minimized by the normalization procedure.

**NEAR IR (Bus, 2011)**
**Instrumentation:** Observations were taken at the NASA Infrared Telescope Facility at Mauna Kea, Hawaii. SpeX, low to medium resolution (R value of 100 for low and 2500 for high) near-IR spectrograph and imager was used. Wavelength range was 0.8 to 5.5 microns.

**Calibration:** Flat-fielding and arc-lamp images were used for calibration.

**Note:** Multiple observers obtained data in this dataset and Bus edited and compiled it.

SMASSIR (Burbine and Binzel, 2002)

**Instrumentation:** Location for these observations was NASA IRTF at Mauna Kea, Hawaii. Specialized grism and NFSCAM detector were used. Spectral range was from 0.90 to 1.65 microns.

**Note:** Observations were designed to match up with the visual wavelength SMASS II spectral observations.

**Calibration:** Uncertainty resulting from atmospheric interference and/or effect of standard star calibrations was determined to be around five percent.

**Additional Datasets**

Behrend (Behrend et. al, 2006)

**Instrumentation:** TAROT Telescope was used to measure color indexes. Arecibo telescope at wavelength of 12.6 cm was used to obtain the data. Instrumentation included two spectrographs at the Observatoire de Haute-Provence. Multiple telescopes with 20 to 60 cm apertures were used for follow-up observations and data then merged at Geneva Observatory.
Note: A large number of amateur astronomers observers took the photometry and lightcurve data for Atami, which supported the observations done by Behrend. However that also presents a potential problem since the instrumentation and observation methods used varied between the observers.

Ostrowski (Ostrowski, 2011)

Instrumentation: NASA IRTF was used to take observations with a SpeX infrared spectrometer. Wavelength range was 0.8 – 2.5 microns during the years of 2004 to 2008.

Calibration: Instrumental and atmospheric artifacts were removed with IDL software. Spectra were normalized at 0.875 microns and the wavelength was calibrated.

Notes: 17 Asteroids with magnitude down to 17.5 were observed. Automatic tracking was used and slit was oriented normal to the atmospheric diffraction so no signal was lost.

Busarev (Busarev, 2011)

Instrumentation: A 1.25 m telescope of SAI (Sternberg Astronomical Institute) Crimean Observatory was used to take the data. Wavelength range of 0.4 to 0.91 microns was used.

Calibration: Sixteen Cyg B and HD10307 were used as the standard stars. Spectra were taken at 0.40-0.67 and 0.65-0.91 microns and then merged into one. Running average method was used to smooth the spectra.
Table 1: Summary of the major datasets being compared. Spectral range is in microns, Ast stands for number of asteroids observed, λ is the value of wavelength the spectra were normalized at in microns

<table>
<thead>
<tr>
<th>Spectral range(µm)</th>
<th>Ast</th>
<th>λ</th>
<th>years</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observations in Visual Wavelengths</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMASS I</td>
<td>0.40 to 1.0</td>
<td>316</td>
<td>0.55</td>
<td>1991-1993 Slit oriented in North-South</td>
</tr>
<tr>
<td>SMASS II</td>
<td>0.44 to 0.93</td>
<td>1341</td>
<td>0.55</td>
<td>1993-1999 Slit oriented in North-South Asteroid spectra averaged</td>
</tr>
<tr>
<td>S²O³</td>
<td>0.49 to 0.92</td>
<td>820</td>
<td>0.55</td>
<td>1996-2001 Slit oriented East-West, Asteroid spectra not averaged No differential tracking</td>
</tr>
<tr>
<td>Sawyer</td>
<td>0.40 to 1.0</td>
<td>115</td>
<td>0.55</td>
<td>1983-1990 Noisy at blue and red ends</td>
</tr>
<tr>
<td>Vilas</td>
<td>0.33 to 0.85 (y88-90)</td>
<td>81</td>
<td>0.7</td>
<td>1982-1992 Two Different Telescopes were used</td>
</tr>
<tr>
<td></td>
<td>0.49 to 0.99 (y91-92)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Color</td>
<td>0.32 to 1.08</td>
<td>277</td>
<td>0.57</td>
<td>1970-1975 Dual Beam Photometer was used</td>
</tr>
<tr>
<td>8 Color</td>
<td>0.34 to 1.04</td>
<td>589</td>
<td>0.55</td>
<td>1979-1984 Only eight data points for each plot</td>
</tr>
</tbody>
</table>

| **Observations in Near-IR** |      |     |              |                                                                                       |
| 52 Color           | 0.8 to 2.5  | 102  | 0.55         | 1983-1987 Extensive calibration to ensure quality                                       |
| NEAR-IR            | 0.8 to 5.5  | 225  | 1.215        | 2011 Collection of peer-reviewed observations made at IRTF IN 2011                     |
| SMASSIR            | 0.90 to 1.65 | 181  | 0.55         | 1997-2000 Was designed to complement visual observations done by the same team          |
CHAPTER II

THEORETICAL BACKGROUND

**Identifying Features**: Visible and near infrared spectra contain spectral bands that are indicative of the mineral makeup of the surface of an asteroid. Location and shape of the absorption bands are dependent on mineral composition of the asteroid surface. Intensity of diagnostic features is related to the abundance of a particular mineral and the texture (particle size) of the surface regolith. Olivine and pyroxene are common minerals found in asteroids and in meteorites which are naturally delivered samples of asteroids. Pyroxene has two absorption features – one near 1 micron and second near 2 microns. Olivine, on the other hand, only has one diagnostic feature, a broad absorption band centered around 1 microns with two sidelobes around 0.8 and 1.3 microns. Metallic iron, which is also commonly found in meteorites, has a featureless reddish spectrum. [Gaffey 2011; Gaffey et al. 2002; Cloutis et al. 2010 and references therein]

**Spectral Types**: Taxonomic types of asteroids are not indicative of their mineralogy, but instead give us an idea of how different groups of asteroids vary from each other based on presence or absence of features that their spectra show. First two broad divisions introduced by Chapman et.al. in 1975 were C and S. C types had low albedo and featureless spectra, while S had 1 micron absorption features, were redder and had higher albedos. Tholen introduced further variety in classifications when technology improved, allowing for greater differentiation
between spectral curves. Smaller asteroids tend to vary more in their spectral characteristics than larger ones (Xu et al., 1995), prompting need for addition of more classes. C types got subdivided into G, B, F subtypes. S remained the same. M types have a featureless reddish spectrum. E types have a high albedo and featureless spectrum. V types have a strong narrow 1 micron pyroxene feature, similar to the feature in Vesta’s spectrum. R and Q types have both olivine and pyroxene 1 micron feature, while A has a strong olivine 1 micron feature.

Bus and Binzel (2002) defined 26 taxonomic classes (including previous types A, B, C, D, K, O, Q, R, S, T, V, and X. as well as intermediate types Cb, Cg, Cgh, Ch, Ld, Sa, Sk, Sl, Sq, Sr, Xc, Xe, and Xk) based on SMASS II data. However none of these taxonomic classifications are uniquely related to specific compositions. Asteroids which belong to different taxonomic classes are likely to be composed of different materials, but there is no assurance that asteroids with the same type are composed of similar materials.

Fig 1. 26 SMASS II taxonomic classes. Horizontal lines show normalized reflectance of 1 (Bus and Binzel 2002).

**Mineralogy:** Mineralogy of asteroids differs based on their formation region, size and thermal history. If they simply accreted out of the solar nebula but did not experience strong post-accretionary heating, then their mineral composition would be largely unaltered and their petrology would be sedimentary. Most asteroids experienced some sort of heating during their
lifetime, however this heating event was short-lived. If heating was moderate, then the initial mineral assemblage was metamorphosed, homogenizing the mineralogy and texture. If heating was strong (as is the case for most meteorite parent bodies (e.g. Keil 2000)) then the parent body experienced at least partial melting and differentiation which in turn formed igneous assemblages. If the asteroid experienced sufficient melting and differentiation to develop an iron core, then it would have developed a layered structure of the core, mantle and crust composed of distinct rock types.

**Normalized Reflectance:** Reflected sunlight contains information on the surface mineralogy of the asteroid. Unfortunately the limited spectral coverage provided by a CCD chip severely limits the compositional information that can be derived from the spectrum. Looking at the sun itself will oversaturate the CCD, which means that astronomers need to use solar analog stars which are in the same region of the sky as the asteroid. Asteroid spectral flux curve is then divided by that of a solar analog star in order to determine relative reflectance. Spectra are commonly normalized to a specific wavelength often in the mid-visible near 0.55 µm.

![Fig. 2](image)

**Fig. 2.** Left: Spectral Flux curves for Vesta and 16 Cygnus B (a solar analog standard star). Right: Reflectance spectrum normalized to unity at ~0.55 µm (Bus and Vilas, 2002).
**Mineral Bands:** Location of a mineral band center in asteroid spectrum is not significantly affected by space weathering and particle size (Gaffey, 2011), and is a more reliable indicator of actual mineral composition of the asteroid than the spectral curve shape is.

**Airmass:** Airmass stands for the relative amount of atmosphere the signal has to pass through to get to the object being observed. It is preferable to have airmass values as close to 1 as possible to minimize noise in the resulting data. Having an airmass of 1 means that the target is directly overhead the observer and the light passes through minimal atmosphere. Larger airmass values mean that the target is closer to the horizon.

**Atmospheric Dispersion:** Atmospheric refraction of signal is wavelength dependent, which means that during observation light of a point source (such as an asteroid) is dispersed into a ‘rainbow’ if it is observed at an angle from the vertical. It is crucial to orient the slit of the camera in such a way (most commonly in the north-south direction) that none of this spread out signal gets lost. This effect is less significant when filters are used when observing and disappears completely when the target is directly overhead the observer.

**Moonlight:** On some nights moonlight is more of an issue that others, especially during full moons. Fainter objects will be more difficult to find if they are close to the moon’s position in the sky. The blue part of the spectrum is more strongly affected by the moonlight (Patat, 2004).

**Phase angle:** Mineral absorption bands are affected by the observational geometry, which means their appearance (band, depth, slope) might change based on the location of the observer and which area of the sky the asteroid was relative to them.
**Lightcurve:** Incoming light from the asteroid to Earth dims and brightens over time as asteroid rotates. Lightcurves are often used to get the rotational periods of an asteroid and a rough idea of its shape. Lightcurves are generally sinusoidal in shape, where peaks are closer if the asteroid rotates faster, and are further apart if asteroid rotates slower. A flat lightcurve could mean a nearly polar observing geometry, a spherical shape or an oblate spheroid. Sharp changes in the emitted light are indicative of a complicated morphology or a change in albedo. To get a better constraint for the shape, observations should be taken from multiple points in the asteroids orbit.
CHAPTER III

POTENTIAL CAUSES OF DISREPANCIES

Shape

Fig. 3. Normalized reflectance of a sphere covered with ordinary chondrite-type material (right) differences in spectral reflectance between the sphere and the end and side view of an ellipsoid (left – units are in magnitudes), both plotted versus wavelength with spectral range of 0.3 to 1.3. a/b ratio of an ellipsoid is 3 (Gradie, 1981).

Asteroids are small bodies which often have an irregular shape. For example, in the case of Eros, which is yam shaped, viewing it at different angles would change the shape of the normalized spectral reflectance curve. This effect is more pronounced for asteroids with higher albedos than lower ones. This effect is not pronounced at phase angles between 30º to 60º when observed at wavelengths below 0.7 microns or at low a/b ratios (between 1 and 1.5). The magnitude of introduced change in color variations at higher a/b ratios is around 0.03 microns (Gradie, 1981).
**Surface Heterogeneity:** Large asteroids, such as Vesta, display variations in the mineral surface composition. Recent results from the DAWN mission reveal that Vesta shows variability in composition and albedo across its surface. (De Sanctis, 2012).

Craters from impacts with other asteroids sometimes lead to an observable change in the mineral composition, due to excavation of underlying material or from the contribution of the impactor. This is the case for Vesta, particularly Cornelia crater. The darker material belongs to the impactor and is not native to Vesta (Reddy et.al, 2014).

Fig. 4. DAWN data for Cornelia crater overlain over terrain (Reddy et.al, 2014)

If an asteroid is longitudinally heterogeneous, its spectral shape will vary based on which rotational phase it is observed in, and observations at same rotational phase should yield similar results. If an asteroid is latitudinally heterogeneous and its rotation axis is inclined to its orbital plane, observations taken at different points along its orbit would show this difference.

When a binary asteroid system is observed, such as 1139 Atami, the different members of the system may have different compositions. This effect is largest when the binary bodies are of similar size and smallest when one of the members is only a fraction of the size of the larger
asteroid. An additional complication for observers is presented when the binary asteroids eclipse each other, which is applicable when those asteroids are of similar sizes. Binaries in the main belt are thought to form predominantly through collisions.

**Temperature:** Asteroid surface temperatures are a function of surface albedo and heliocentric distance. The spectra of pyroxene/olivine mineral assemblages are affected by temperature. Asteroids on the inner edge of the main belt would generally have higher temperature than those on the outer edge. Low albedo asteroids would be warmer than those with high albedo. This effect plays a much more significant role for NEOs within Earth’s orbit as they are closer to the sun. Temperature factors are more relevant in thermal IR spectra rather than visible. In general, identifying features for olivine and pyroxene become better resolved and narrower at lower temperatures (cosmic versus room temperature). [Singer and Roush, 1985] Temperature also affects the band positions, so that temperature corrections must be applied to the measured band positions when determining detailed mineralogy.

Fig. 5. Orthopyroxene reflectance spectra taken at 80 K and 448 K (Singer and Roush, 1985).
**Viewing Geometry:** Effect of airmass and phase angle can be calculated, and, if properly corrected for, should not introduce significant changes to the shape of the spectra. Band depth increases with increasing phase angle, which does not indicate actual changes in band intensity in the asteroid but how much material the light passed through. Spectra taken between phase angles 20 to 70 degrees where neither incidence nor emission exceeds 50 degrees should be comparable and relative band depth variations shouldn’t exceed 5 percent. Any larger variations, under these observation constraints, result from grain size or compositional changes. [Shepard and Cloutis, 2011]

**Different Standard Stars:** Standard stars do not match solar spectra perfectly, therefore when observers use different standard stars for their observations, there may be differences in the resulting asteroid spectra. Those differences would mainly affect the slope rather than shape of the absorption features in the resulting spectrum. SMASS only used two standard stars – 16CygB and Hya64. SMASS II also used these stars with addition of HR4486 and HR5384. HD44594 and HD144585 were used by S³OS². 16 Cyg B was also used by 54 Color Survey. Fifty standard stars were used by the Eight Color Survey, including 16 Cyg B and Hya64.

Table 2: Standard Stars (Hardorp (1978), Hoffleit (1982), Hardorp (1982)).

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Alternative Name</th>
<th>Visual Magnitude</th>
<th>Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Cyg B</td>
<td>HD186427</td>
<td>6.2</td>
<td>G5V</td>
</tr>
<tr>
<td>Hya 64</td>
<td>HD28099</td>
<td>8.1</td>
<td>G6V</td>
</tr>
<tr>
<td>HR4486</td>
<td>HD101177</td>
<td>6.4</td>
<td>G0V</td>
</tr>
<tr>
<td>HR5384</td>
<td>HD126053</td>
<td>6.3</td>
<td>G1V</td>
</tr>
<tr>
<td>HR2290</td>
<td>HD44594</td>
<td>6.6</td>
<td>G1.5V</td>
</tr>
<tr>
<td>HR5996</td>
<td>HD144585</td>
<td>6.3</td>
<td>G4 IV-V</td>
</tr>
</tbody>
</table>
**Instrumental Problems:** Eliminating all over causes for difference in the asteroid spectra would necessitate examining instrumentation used to see if it introduced a persistent problem into all of the spectra taken. If no systematic error is observed, random errors are also possible, in which case only a few spectra will be affected. Since SMASS I and II were taken with the same instrument, any systematic error that might have been present would apply to all measurements. SMASS and S³OS² were performed using different instruments, however aside from resolution differences, different instrumentation should not introduce a large enough variation in the same asteroid to change the shape of the spectral curve and band positions. As a generalization, the instrumental effects (e.g., wavelength dependent sensitivity and throughput) are the same for the asteroid observations and the standard star observations and should cancel out when the asteroid flux curve is divided by the standard star flux curve.

**Summary:** Overall the shape and temperature caused variations are too small to explain differences observed in the spectra. Surface Heterogeneity will change the spectra most drastically as it will be indicative of actual mineral composition differences in the asteroid. Instrumental problems are not a strong concern for SMASS I/II observations since they were taken with the same setup. The resulting differences could also be due to combination of several causes.
CHAPTER IV

ANALYSIS OF SPECTRA

Thirty seven asteroids were found to have significant discrepancies in spectra when different datasets were examined. ‘Significant’ means that interpretations of spectral class or mineralogy would differ when spectra for the same object are analyzed individually. Most of the comparisons were between SMASS I/II and S3OS2. Where available Vilas, Sawyer, 24 and 52 Color, and NEAR-IR spectra were also used as well as additional datasets and lightcurves.

3 Juno

Fig. 6. Spectra of Juno, SMASS I, SMASS II (light blue), S3OS2 (grey), 24 Color Survey (dark blue), 54 Color Survey (red), 8 Color (yellow), SMASSIR (pink). Data obtained from Planetary Data System Small Bodies Node (Ferret) (henceforth the case for all spectra unless specified otherwise).

Asteroid (3) Juno is one of the largest (diameter – 234 km. (diameter and albedo as taken from Small Bodies Data Node, here and henceforth)), and is therefore one of the most well-studied asteroids. Juno is often selected as a target of observation in order to calibrate the
telescope to this known object. It is therefore surprising to find a mismatch in its spectra among three different datasets.

$S^3O^2$ data shows a feature longward of .7 microns is due to Earth’s atmosphere affecting the collected spectrum. SMASH I matches $S^3O^2$ data but not SMASH II over the interval of .7 to .9 microns. 24 color survey and 8 color survey data matches SMASH I data but doesn’t match SMASH II data. 54 color survey matches the shape of SMASH I spectral curve. SMASSIR continues from where SMASH II left off, showing a red slope that other near infrared spectra show but doesn’t match SMASH I. 8 Color data matches SMASH I and $S^3O^2$ but not SMASH II.

All of the datasets assign S class to Juno’s spectra. SMASH II spectra appears to be the most discordant, with peak at 0.7 rather than 0.8 microns for SMASH I and $S^3O^2$. It is an average of two spectra, taken years apart, while all other spectra were taken months apart. Observational problems are the likely reason for deviation observed in SMASH II.

10 Hygeia

Fig. 7 Reflectance spectra of 10 Hygeia, SMASH I, SMASH II, 8 Color, Sawyer, SMASHIR.
Fig. 8. (right) Spectra of 10 Hygeia taken on October 4\textsuperscript{th} and 5\textsuperscript{th}, 2007 and offset for clarity. Numbers in brackets stand for relative rotation phase (Busarev, 2009); (left) Spectra of Hygeia taken at different rotation phases Nov and Dec 26\textsuperscript{th}.

Fig. 9. Spectra of 10 Hygeia taken on August 23\textsuperscript{rd}, 1979 and December 26\textsuperscript{th}, 1980 for 8 Color Survey.

Asteroid 10 Hygeia is one of the largest at 433 km in diameter. SMASS I spectra differs significantly from SMASS II in the terms of slope past 0.7 microns, and has a red slope past 0.65 microns like Busarev’s spectra does at 0.000 phase. Sawyer and SMASS II spectra have a flat slope which matches Busarev spectra at a relative rotation phase of 0.340. SMASSIR matches SMASS II but not I. It has a slight blue slope up to 1.25 microns and a red slope past that. Sawyer and SMASS I are very noisy past 0.8 microns. Hygeia was observed five times within several months by Busarev in 2009, and he obtained 4 different spectra that would fall under C, B, F and S taxonomies. He believes that the most likely cause is heterogeneity of the mineral composition of the surface due to large impacts from impactors with different chemical compositions. The magnitude of heterogeneity is debatable, as it seems unusually high for a small rotational phase change between 0.377 and 0.566. The presence of heterogeneity is likely.
8 Color data has a similar red slope to SMASH I data. Observations taken on different dates (23rd of August, 1979 and 27th of December, 1980) differ past 0.85 microns, with later observation showing a redder slope.

12 Victoria

![Graph showing spectra of 12 Victoria](image)

Fig. 10. (left) Spectra of 12 Victoria. SMASH II, S^3OS^2, SMASHIR, 24 Color, 52 Color, 8 Color. (right) Lightcurve of 12 Victoria (Erikson, 1990).

12 Victoria is a moderately large – 113 km in diameter – asteroid with albedo of 0.18.

Victoria is a highly irregular nonconvex object as follows from Arecibo studies by Mitchell (1995). Victoria’s longest equatorial dimension to shortest equatorial dimension ratio is 1.25 ± 0.01 (Dotto et. al, 1995). This ratio is too small to cause significant changes in the spectra. The shape of spectra past 0.7 microns is strikingly different between SMASH II and S^3OS^2. This difference results in assignment of different spectral classes for the spectra – S in SMASH case and D in S^3OS^2 case. Features seen in S^3OS^2 spectra at 0.82 and 0.9 microns are most likely due to incomplete atmospheric correction. SMASHIR, 24 Color, 8 Color and 53 Color data matches SMASH II but not S^3OS^2, which points to likely observation problems with S^3OS^2. Lightcurve for Victoria has a relatively large amplitude variation (Erikson, 1990).
56 Melete

![Spectra of Asteroid 56 Melete. SMASS II, S3OS2, 8 Color. (right) Lightcurve of 56 Melete (Belskaya, 1993)](image)

Asteroid 56 Melete is a moderately large (113 km) asteroid with albedo of 0.07. SMASS II spectral curve is assigned the P classification by Tholen and Xk by Bus, while S3OS2 curve is assigned the S classification by Lazarro. S3OS2 spectra is featureless with a red slope and does not resemble an S type asteroid, while SMASS II and 8 Color spectra have a red slope up to 0.7 and then a slight blue slope past 0.8 microns. Since two datasets match, but not S3OS2 that means there could be an observational problem with it. The Lightcurve of 56 Melete is mostly flat, implying a relatively spherical object (Belskaya, 1993).

112 Iphigenia

![Spectra of 112 Iphigenia. SMASS II, S3OS2, NEAR IR.](image)

Fig. 12. Spectra of 112 Iphigenia. SMASS II, S3OS2, NEAR IR.
Asteroid 112 Iphigenia is 72 km in diameter with albedo of 0.04. $S^3OS^2$ deviates from SMASS spectra starting at .7 microns. SMASS II data was taken at lower apparent magnitude of Iphigenia than $S^3OS^2$ data (15 vs 13.3 respectively). NEAR-IR data spectra has a red slope up to 1.4 microns and is flat past that.

**115 Thyra**

Fig. 13. Spectra of 115 Thyra. SMASS II, $S^3OS^2$.

Asteroid 115 Thyra has a diameter of 80 km and albedo of 0.27. SMASS II has a reflectance peak centered at 0.72 microns. $S^3OS^2$ spectral band center is at 0.78, which suggests variable olivine abundance across the surface and a higher olivine content on the SMASS II observed face. Which is possible but not likely, and in turn could signify a problem with either of the two spectra. 24, 8 and 52 Color spectra show the same shape, however the reflectance value for 8 Color peaks around 1 and not 1.2 like it does in the SMASS II case. $S^3OS^2$ spectral curve is assigned spectral class K and not S. Lightcurve for Thyra shows two distinct peaks, which suggests a non-spherical shape for the asteroid. Database of Asteroid Models from Inversion Techniques (DAMIT) does indeed show a complex shape for Thyra (Ďurech J., et al. 2010).
Fig. 14. (left) Lightcurve of 115 Thyra taken by Michalowski in 2000. (right) Shape model for 115 Thyra taken from DAMIT.

117 Lomia

Fig. 15. (left) Spectra of 117 Lomia. SMASS II, S^3OS^2, 8 Color. (right) Lightcurve for 117 Lomia (Di.Martino, 1995)

Asteroid 117 Lomia is 148 km in diameter with albedo of 0.05. S^3OS^2 and SMASS II spectral curves are both X classes, but deviate from each other at 0.7 microns. Observations were made at a similar phase angle, apparent magnitude and airmass values. 8 Color data has a featureless slope between 0.7 and 0.9 microns that matches SMASS II but not S^3OS^2. Lomia’s lightcurve is symmetric with well-defined peaks (Di Martino, 1995), which means this is a non-spherical object. Since two datasets match and one doesn’t, the observational problem with S^3OS^2 could be a likely cause.
140 Siwa

Fig. 16. Spectra of 140 Siwa. SMASS II, S₃OS², 24 Color, Ostrowski, SMASSIR.

Fig. 17. Lightcurves of Siwa taken by Pilcher in 2012. Depending on how one defines the start period of the rotational phase the length of it changes.

Asteroid Siwa has a diameter of 109 kilometers. Its albedo is 0.07. S₃OS² has a flat slope while SMASS II has a red slope. 24 color data is noisy and has a reddish slope. SMASS II data was obtained when moonlight was a problem and conditions were cloudy. Siwa is a highly irregular object, due to the fact that multiple observations by different astronomers yielded different measurements of rotation period for this asteroid and due to complex shape of its lightcurve [Pilcher, 2012]. Ostrowski spectra in the near infra-red is featureless with a reddish slope. Siwa will be an interesting object for further study.
169 Zelia

Fig. 18. Spectra of 169 Zelia. SMASS I, SMASS II, S^3OS^2, 24 Color, 8 Color, SMASSIR.

Zelia (169) has a diameter of 33 kilometers. The shape of S^3OS^2 reflectance curve doesn’t agree with the spectral curve of SMASS. Lazzaro says: The spectra were corrected for airmass by using the mean extinction curve of La Silla (Tüg, 1977). Combined with the high airmass (2.08), this could account for the discrepancy. 8 Color data matches SMASS I, II and 24 Color data up to 0.8 microns and then shows a featureless slope rather than a blue one. 24 Color data matches that for SMASS I and II, which suggests that data obtained through those datasets is a more accurate representation of mineral composition of its surface than is the case for S^3OS^2. SMASS assigns S classification to Zelia, while S^3OS^2 assigns O. SMASSIR data shows a defined red slope, which casts doubt at the blue slope that S^3OS^2 data shows.

170 Maria

Fig. 19. Spectra of 170 Maria, SMASS II, S^3OS^2, 24 Color, 8 Color.
Maria (diameter 44 km) is a namesake of Maria family of asteroids. This large (3k members) family is known to have a reddish albedo and have undergone extensive collision dynamics due to its old age (about 3 Gyr) (Kim 2014). Which means that surface heterogeneity due to impactors with different composition might have played a role in Maria’s case. 24 color data is noisy, deviating from SMASS II, I and S³OS² data between 0.7 and 1 microns. SMASS II has a band minimum at 0.88, while S³OS² and 24 color survey do not. 8 Color data falls between S³OS² and SMASS II data past 0.8 microns. Furthermore S³OS² data seems to be approaching a band minimum that lies beyond 0.9 microns. Both SMASS II and S³OS² observations were taken at the same phase angle (19.7) and had similar apparent magnitude values.

**173 Ino**

![173 Ino](image)

Fig. 20. Spectra of 173 Ino, SMASS II, S³OS², Sawyer, 8 Color, NEAR-IR.

Asteroid 173 Ino has a diameter of 154 km and albedo of 0.07. Sawyer data matches S³OS² but not SMASS. Lightcurve for Ino is relatively flat, which implies a spherical object (Michalowski, 2005). S³OS² observations were taken at phase angle of 6 versus 10 for SMASS II. SMASS II data is an average of two observations, since during the first one lunar illumination of the sky was high. 8 Color data matches Sawyer and S³OS² data but not SMASS II data.
**181 Eucharis**

![Graph of 181 Eucharis spectra](image)

Fig 21. Spectra of 181 Eucharis. SMASS II, S³OS², Vilas, 24 Color (dark blue), Ostrowski (purple), 8 Color.

181 Eucharis is 106 km in diameter with albedo of 0.11. Data for Eucharis exhibits several different slopes and as a result different classifications. S³OS² is X, while SMASS II is K. Vilas has a slope similar to 24 Color data but different from both SMASS II and S³OS². Ostrowski spectra has a flat slope up to 1 microns and a red slope 1.2 microns onwards.

**184 Dejopeja**

![Graph of 184 Dejopeja spectra](image)

Fig. 22. Spectra of 184 Dejopeja. SMASS I, SMASS II, S³OS², 8 Color.

Asteroid 184 Dejopeja has a diameter of 66 km and albedo of 0.19. SMASS II spectral slope flattens out past 0.7 microns, while S³OS² slope is red past 0.7 microns. 8 Color data falls between them, which makes determining which one is more correct inconclusive. Dejopeja
might be a metallic asteroid (Crane, 2012). Lightcurve for Dejopeja implies an irregular nonspherical object due to sharp changes in brightness vs time and which is evident in the shape model (Gil-Hutton, 1994).

![Lightcurve of 184 Dejopeja](image1)

**Fig. 23.** (left) Lightcurve of 184 Dejopeja. (Gil-Hutton, 1994). (right) Shape model for 184 Dejopeja taken from DAMIT.

### 196 Philomela

![Spectra of 196 Philomela](image2)

**Fig. 24.** (left) Spectra of 196 Philomela. SMASS I, SMASS II, 24 Color, 8 Color. (right) Shape model for 196 Philomela taken from DAMIT.

Asteroid 196 Philomela is 136 km in diameter with albedo value of 0.23. 24 Color data and 8 Color data matches the shape of SMASS I data but SMASS II differs from 0.7 to 0.9 microns. Observational problems with SMASS II are likely since it is the only dataset out of 4 that doesn’t match with the rest. Shape model for Philomela shows an elongated object, with a a/b ratio of around 1.5 (Licandro, Galladro and Tancredi 1994).
233 Astreope

Fig. 25. Spectra of 233 Astreope. SMASS II, S^3OS^2, 52 Color (light red), NEAR IR (dark red), SMASSIR (pink), 8 Color.

Asteroid 233 Astreope is 102 km in diameter with 0.09 albedo. SMASS I and II spectra falls into a K class, while S^3OS^2 into T. 52 Color Survey and 8 Color data agrees with S^3OS^2 data between 0.87 and 0.93 microns. Only SMASS II spectra has a flat slope after 0.7 microns, NEAR IR and 52 color Survey match the slope of S^3OS^2 spectra, and 52 Color survey matches S^3OS^2 but not SMASS II. NEAR-IR data is featureless. Since three spectra agree with each other and SMASS II doesn’t, an issue might lie with SMASS II observation.

332 Siri

Fig. 26. (left) Spectra of 332 Siri. SMASS II, S^3OS^2. (right) Lightcurve of 332 Siri (Cieza, 1999)
Asteroid 332 Siri is 40 km in size with albedo of 0.17. SMASS spectral slope flattens out past 0.7 microns, while S^3OS^2 slope is red past 0.7 microns. Lightcurve of Siri has a high amplitude in differential magnitude variation, which implies it’s an irregular object (Cieza, 1999).

**354 Eleonora**

![Spectra of 354 Eleonora. SMASS I, SMASS II, S^3OS^2, 8 Color. (right)Spectra of 354 Eleonora. 52 Color #1 (grey), 54 Color #2 (blue). SMASS NIR (orange), MIT NEOSR (yellow).](image)

Fig. 27. (left) Spectra of 354 Eleonora. SMASS I, SMASS II, S^3OS^2, 8 Color. (right) Spectra of 354 Eleonora. 52 Color #1 (grey), 54 Color #2 (blue). SMASS NIR (orange), MIT NEOSR (yellow).

Asteroid 354 Eleonora is 155 km in diameter with albedo of 0.20. S^3OS^2 has a flat slope after 0.7 microns, SMASS I has a less red slope with an odd feature between 0.9 and 1 microns which is likely an atmospheric artifact. SMASS II has a shallow feature from 0.75 to 0.9 microns. 8 Color data matches SMASS I data. 24 Color data shows a blue slope past 0.75 microns, reaching a minimum at 1 microns. In near infrared region 52 Color, SMASS NIR, NEAR-IR and MIT NEOSR data plots on top of each other. This asteroid was studied in detail by M.Gaffey who ruled out the possibility that differences in the spectra arise from actual physical differences in Eleonora and instead are caused by observational/instrumentation issues.

**381 Myrrha**

35
Myrrha is a large (120 km) asteroid with an albedo of 0.061. SMASS II shows a flat featureless spectra, similar to the slope for 8 Color data, while S$^3$OS$^2$ spectra has a red slope longward of .7 microns. Lazzaro classifies Myrrha as an X class, while Bus as C. Lightcurve for 381 Myrrha shows significant variations in magnitude with rotational phase, which means it’s a non-spherical object.

### 388 Chyrabdis

Asteroid 388 Chyrabdis is 114 km in size with albedo of 0.05. SMASS II data is flat and featureless, while S$^3$OS$^2$ deviates at 0.85 microns. SMASS II spectra is assigned class C while S$^3$OS$^2$ class X. Both observations were made at the same phase angle and apparent magnitude values. 8 Color data matches SMASS II data but not S$^3$OS$^2$. 
**402 Chloe**

Fig. 30. Spectra of 402 Chloe. SMASS I, SMASS II, 24 Color, SMASSIR, 8 Color.

Chloe is an 85 km asteroid with albedo of 0.148. 24 Color data matches SMASS I and II data up to 0.8 microns and then deviates (however is too noisy to say anything conclusive). SMASS I has a red slope and seems to approach reflectance peak at 0.95 microns while that peak is at 0.75 for SMASS II data. Past 0.8 microns SMASS II has a slight blue slope. 8 Color data matches SMASS I closely but not SMASS II.

**412 Elisabetha**

Fig. 31. (left) Spectra of 412 Elisabetha. SMASS II, S³OS². (right) Lightcurve for 412 Elisabetha. (Cooney, 2002)

Asteroid 412 Elisabetha is 90 km in diameter with albedo of 0.05. SMASS spectral slope is flat, while S³OS² slope is red past 0.7 microns. The Lightcurve for Elisabetha has one broad and one narrow peak which means that the object is roughly spherical with some irregularities.
434 Hungaria

Fig. 32. Spectra of 434 Hungaria, $S^3O^2$, SMASS II, Sawyer, NEAR IR (dark red), 24 Color Survey, 52 Color survey (light red), 8 Color.

Fig. 33. Spectra of 1600 Vyssotsky, a member of the Hungaria family of asteroids. SMASS II, $S^3O^2$, SMASSIR.

Fig. 34. Spectra of 3873 Roddy, a member of the Hungaria family of asteroids. SMASS II, $S^3O^2$. 
434 Hungaria is a well-studied asteroid, as it is a namesake of Hungaria family of asteroids. Two of the asteroids that had aberrant spectra – Roddy and Vyssotsky – are also part of that family. Roddy is a small (<10 km) binary system (Warner, 2013). Since these asteroids are in the same family, we would expect their surface composition to be the same or very similar. This general assumption does not seem to hold for Hungaria family, which implies that original body could have undergone extensive metamorphism. In which case different fragments of the same object would have different compositions.

SMASS II shows a reflectance peak at 0.7 for all three asteroids. S^3OS^2 data is flat in 434 Hungaria case, but has a red slope for Vyssotsky (very noisy) and a reflectance peak at 0.79 for Roddy. 8 Color data for Hungaria matches Sawyer and S^3OS^2 data but not SMASS II. SMASSIR data for Vyssotsky matches SMASS II and shows a slight red slope with a gap from 1.38 to 1.5. Both Vyssotsky and Hungaria asteroids have very high albedos – 0.51 and 0.47-0.567 respectively, while albedo is not available for Roddy (Gil-Hutton et. al., 2007).

**547 Praxedis**

![Fig. 35. Spectra of 547 Praxedis, SMASS II, S^3OS^2, NEAR IR.](image)

Asteroid 547 Praxedis is 58 km in diameter with albedo of 0.08. S^3OS^2 differs from .7 microns to 0.9 microns. S^3OS^2 spectrum is classified as T, while SMASS as X. NEAR-IR data has a
red slope that flattens past 1.4 microns. NEAR-IR data shows a similar slope to $S^3OS^2$ data but not SMASS II.

**579 Sidonia**

![Graph of 579 Sidonia](image)

Fig. 36. Spectra of 579 Sidonia. SMASS II, $S^3OS^2$, 24 Color, 8 Color.

Asteroid 579 Sidonia is 86 km in diameter with albedo of 0.18. 24 Color data matches SMASS II data. $S^3OS^2$ data differs from .7 microns and classified as K/D, while SMASS as S/K.

SMASS data was obtained when moonlight was an issue, however overall it does not appear to be noisier than $S^3OS^2$ data. In the blue part of the spectrum before 0.5 microns the data does seem to be noisy, but cannot be compared to $S^3OS^2$ since it cuts off at 0.5. 8 Color data matches $S^3OS^2$ up to 0.8 microns and has a blue slope past that.

**598 Octavia**

![Graph of 598 Octavia](image)

Fig. 37. Spectra of 598 Octavia, SMASS II, $S^3OS^2$. 
Asteroid 598 Octavia is 72 km in diameter with albedo of 0.05. SMASS spectral slope is smaller, while $S^3OS^2$ slope is much steeper past 0.75 microns. SMASS data was obtained when lunar illumination was higher than 50 percent. Both datasets were obtained at very similar visual magnitude (13.3/13.8) and phase angle values (4.5, 4.3). SMASS spectra was assigned C/X classification by Bus, while $S^3OS^2$ is assigned D/Cb.

**599 Luisa**

Fig. 38. Asteroid 599 Luisa. SMASS I, SMASS II, 24 Color, SMaSSIR, 8 Color.

Asteroid 599 Luisa is 65 km in diameter with albedo of 0.137. All three datasets match well up to 0.75. 24-color data has only one datapoint past 0.75 so it can’t be used for comparison.

SMASS II data reaches a peak at 0.75 microns and then has a slight blue slope, while SMASS I data has a red slope and a gap at 0.95 microns. SMaSSIR continues where SMASS II left off and has a flat slope up to 1.1 microns and red after. 8 Color data matches SMASS I but not SMASS II.
625 Xenia

Fig. 39. (left) Spectra of 625 Xenia, SMASS II, $S^3OS^2$, SMASSIR. (right) Lightcurve for 625 Xenia. (Worman, 2003).

Asteroid 625 Xenia is 28 km in diameter with albedo of 0.22. SMASS spectra has a blue slope after 0.75 microns while $S^3OS^2$ has a flat slope. SMASS has a Sa classification while $S^3OS^2$ an A/Ld classification. SMASSIR matches SMASS II, it has a flat slope up to 1.1 and then a red slope with a feature at 1.8. SMASS observations were made during high (>50%) lunar illumination and is as noisy as SMASS II.

808 Merxia

Fig. 40. Spectra of 808 Merxia. SMASS II, SMASS I, $S^3OS^2$, SMASSIR (pink), NEAR-IR (red).
Asteroid 808 Merxia is 33 km in diameter with albedo of 0.22. Between .75 microns and 1 microns all three spectra differ. $S^3OS^2$ drops off sharply. SMASSIR continues from where SMASS II left off and agrees with the shape of SMASS I and NEAR-IR, showing a red slope past 0.9 microns. $S^3OS^2$ looks the most discordant. Merxia was originally a part of a much larger body ($\geq 100$ km) [Vokrouhlicky and Broz, 2006]. Lightcurve for Merxia is shows two distinct maxima, which means it’s not a spherical object, which the shape model also shows (Ditteon, 2003).

Fig. 41. (left) Lightcurve for 808 Merxia (Ditteon, 2003). Visual Magnitude is plotted versus rotational phase. (right) Shape model of 808 Maerxia taken from DAMIT.

1022 Olympiada

Fig. 42. (left) Spectra of 1022 Olympiada, SMASS II, $S^3OS^2$. (right) Lightcurve of Olympiada obtained by Benishek in 2008.
Asteroid 1022 Olympiada is 26 km in diameter with albedo of 0.16. SMASS spectral slope is blue after 0.8 microns, while the slope of S$^3$OS$^2$ remains the same from 0.5 to 0.9. Lightcurve for Olympiada shows significant magnitude variations, which means it is a highly irregular object (Benishek, 2008). Albedo variations could also be the cause, however a 26 km object might be too small to retain evidence of impacts with objects of different composition.

**1024 Hale**

![Spectra of 1024 Hale, SMASS II, S$^3$OS$^2$.](image1)

Fig. 43. Spectra of 1024 Hale, SMASS II, S$^3$OS$^2$.

Asteroid 1024 Hale is 41 km in diameter with albedo of 0.06. S$^3$OS$^2$ spectra has a red slope while SMASS II data is mostly flat with reflectance value of 1 and noisy past 0.8 microns.

**1094 Siberia**

![Spectra of 1094 Siberia, SMASS II, S$^3$OS$^2$.](image2)

Fig. 44. Spectra of 1094 Siberia, SMASS II, S$^3$OS$^2$. 
Asteroid 1904 Siberia is 19 km in diameter with an albedo of 0.01. SMASS spectra has a flat slope after 0.7 microns while $S^3OS^2$ has a red slope and reaches a reflectance peak at 0.9 microns.

**1110 Jaroslawa**

![Graph of 1110 Jaroslawa](image)

Fig. 45. Spectra of 1110 Jaroslawa, SMASS I, SMASS II.

SMASS I and II spectra for 1110 Jaroslawa have a similar overall shape, however the strength of the feature past 0.72 microns changes. This is likely indicative of real compositional changes in the asteroid, since SMASS I and II were obtained with the same instrumental setup.

**1114 Loraine**

![Graph of 1114 Loraine](image)

Fig. 46. Spectra of 1114 Loraine, SMASS II, $S^3OS^2$. 
Lorraine is 64 km in diameter with albedo of 0.05. SMASS II spectra remains flat at reflectance value of 1 while S3OS2 spectra has a red slope from 0.5 to 0.9 microns.

**1139 Atami**

Fig. 47. (left) Spectra of 1139 Atami. SMASS II, S3OS2, 8 Color. (right) Spectra 1139 Atami. The dark lines are showing limiting reflectance for S type asteroids from Bus and Binzel (2002) [Behrend 2006].

SMASS II spectra suggests an S type asteroid, while S3OS2 a C type asteroid. 8 Color data matches SMASS II but not S3OS2. Atami is a binary asteroid, with two asteroids of similar size (7x4.4x4.4 km) orbiting each other. [Behrend, 2006] These asteroids are both S types so it is unclear where the C type spectra originated from. One of the possibilities is that Lazzaro observed a solar analog star rather than the asteroid. Reflectance spectrum taken by Behrend looks similar to SMASS spectrum. Figure 7 is showing a spectra of Atami taken by Behrend, which matches the shape of spectral curve of SMASS I and II spectra between regions of 450 and 750 nanometers.
1263 Varsavia

Fig. 48. Spectra of 1263 Varsavia, SMASS II, S³OS², 24 Color.

SMASS II has a blue slope starting at 0.75 microns, while S³OS² has a red slope starting at 0.75 microns. 24 Color data is very noisy to be of use. Lightcurve for Varsavia is noisy but implies a non-spherical object, which the shape model from DAMIT shows, with a large flat face on the end-on view and an elongated shape (Stephens, 2004).

Fig. 49. (left) Lightcurve of 1263 Varsavia. (Stephens, 2004). (right) Shape model data for 1263 Varsavia taken from DAMIT.
1284 Latvia

Fig. 50. Spectra of 1284 Latvia, SMASS II, S3OS2, 24 Color, 8 Color.

Asteroid Latvia has a diameter of 37 km and albedo of 0.11. S3OS2 data matches 24 color data, while SMASS II differs from .8 microns. 8 Color data shows a blue slope past 0.85 microns while S3OS2 does not.

1807 Slovakia

Fig. 51. Spectra of 1807 Slovakia, SMASS I, SMASS II.

The shape of both spectra is the same, however strength and reflectance peak location differs (0.76 for SMASS I and 0.72 for SMASS II). Size and albedo for this object were not listed.
1904 Massevitch

Asteroid 1904 Massevitch has a diameter of 18 km and albedo of 0.16. SMASS II spectra is classified as R, while S$^3$OS$^2$ as Q. The reflectance peak is roughly at the same wavelength value, but different reflectance value (1.2 vs 1). S$^3$OS$^2$ data is noisier and shows significant differences in slope, which resemble the difference seen for Atami. Unlike the observation conditions for Atami however, for Massevitch S$^3$OS$^2$ observations airmass was low (1.03), and visual magnitude was the same as SMASS II.

2448 Shokolov

SMASS II data shows a change of slope past 0.7 microns while S$^3$OS$^2$ data is featureless and noisy. SMASS II data was obtained in less than ideal conditions when moonlight was
obscurring some of the signal which could be the reason for the difference in the spectra. Both observations were taken at the apparent visual magnitude of 14.

**3169 Ostro**

Fig. 54. Spectra of 3169 Ostro, SMASS II, S\textsuperscript{3}OS\textsuperscript{2}, 8 Color.

Spectra for SMASS goes up to reflectance value of 1.1 while S\textsuperscript{3}OS\textsuperscript{2} spectra stays at value of 1.0. Phase angle and visual magnitude for both observations was essentially the same. SMASS assigns spectral class of Xe to Ostro, while S\textsuperscript{3}OS\textsuperscript{2} assigns Cb. Size and albedo have not been determined for this asteroid. 8 Color data matches SMASS II but not S\textsuperscript{3}OS\textsuperscript{2}.
Chapter V
DISCUSSION

It is now clear that Eleonora was not the only asteroid whose spectra showed significant
discrepancies between different datasets. Lazzaro noted that thirty-nine asteroids in his dataset
were in disagreement with the classification assigned by Tholen and Bus, especially 1139 Atami,
yet did not explore why those differences existed. We summarize the likely causes for the
observed discrepancies below and state why these causes were chosen, in order of confidence
level from highest to lowest.

Table 3. Summary of Likely causes for observed discrepancies in the spectra. Asteroids marked
green have published evidence that supports the reason stated behind the discrepancy.
Asteroids marked blue have evidence that points strongly towards a stated reason for the
discrepancy. Asteroids in black have very little evidence to narrow down the cause.

<table>
<thead>
<tr>
<th>Asteroid Name</th>
<th>Likely Cause</th>
<th>Asteroid Name</th>
<th>Likely Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Juno</td>
<td>SMASS II Observational issue</td>
<td>412 Elisabetha</td>
<td>Observational Issue/ S.Heterogeneity</td>
</tr>
<tr>
<td>10 Hygeia</td>
<td>Surface Heterogeneity</td>
<td>434 Hungaria</td>
<td>S. Heterogeneity</td>
</tr>
<tr>
<td>12 Victoria</td>
<td>Irregular shape</td>
<td>547 Praxedis</td>
<td>SMASS II observational issue</td>
</tr>
<tr>
<td>56 Melete</td>
<td>S^3OS^2 observational issue</td>
<td>579 Sidonia</td>
<td>Observational Issue/ S.Heterogeneity</td>
</tr>
<tr>
<td>115 Thyra</td>
<td>Irregular shape/ S.Heterogeneity</td>
<td>599 Luisa</td>
<td>SMASS II observational issue</td>
</tr>
<tr>
<td>117 Lomia</td>
<td>S^3OS^2 observational issue</td>
<td>598 Octavia</td>
<td>Observational Issue/ S.Heterogeneity</td>
</tr>
<tr>
<td>140 Siwa</td>
<td>Irregular shape/ Albedo variation</td>
<td>625 Xenia</td>
<td>Observational Issue/ S.Heterogeneity</td>
</tr>
<tr>
<td>169 Zelia</td>
<td>S^3OS^2 observational issue</td>
<td>808 Merxia</td>
<td>Observational Issue/ Irregular shape</td>
</tr>
<tr>
<td>170 Maria</td>
<td>SMASS II observational</td>
<td>1022 Olympiada</td>
<td>Observational Issue/</td>
</tr>
</tbody>
</table>
Cases which have evidence in literature

**Surface Heterogeneity**: When observations of the same asteroid at different rotational phases yield different spectral curves it is reasonable to assume that surface heterogeneity might play a role. Only 10 Hygeia has published observations taken at different rotational phases. 173 Ino, 181 Eucharis and 434 Hungaria showed a similar variation in spectra across databases, making them candidates for further observation and the likely cause for discrepancies stemming from surface composition differences. Surface heterogeneity is not common among asteroids, but without further evidence it is hard to rule it out as a possible option.

**10 Hygeia**: Surface heterogeneity is the likely cause, since SMASS I and II differed in slope significantly and used the same instrumental setup. SMASSIR data shows a flat bluish slope, not
a blue slope that SMaSS I has. Observations by Busarev of Hygeia produced significantly
different spectra with flat or blue slopes. 8 Color data taken at different dates also showed
variation in reflectance values past 0.7 microns.

**Albedo variation/Irregular Shape:** Lightcurves were available for fourteen asteroids. Only a few
of them suggested a spherical object, while majority pointed to an irregular object being the
case. A/b ratio (longest equatorial to shortest equatorial dimension) was low for almost all of
the asteroids as far as existing data showed, which means that it is unlikely that shape
irregularities significantly affected the resulting spectra. 196 Philomela has a 1.5 a/b ratio
accirdng to Licandro. 808 Merxia model from DAMIT showed a highly elongated object, which
means it also could have a moderate a/b ratio. It will be important to distinguish if the
variations observed in the lightcurves are due to shape or albedo variations.

12 Victoria: Victoria is possibly a highly irregular object, as follows from its lightcurve and
Arecibo observations by Erikson.

115 Thyra: Lightcurve shows significant brightness variation. Model shows a complex object
with a large flat face.

140 Siwa: Lightcurve shows significant brightness variation and different observers have been
getting different rotational phase durations for this object.

184 Dejopeja: Lightcurve shows significant brightness variation. Model shows a complex object
with a large flat face.

332 Siri: Lightcurve shows significant brightness variation.
**Observational Error:** Where one spectra differed significantly from the rest, especially if other spectra matched each other, it cast doubt on the accuracy of the discrepant measurement.

**354 Eleonora:** After extensive review and testing of possibilities Dr. Gaffey determined the issue to arise from observational errors rather than the actual differences in the asteroid.

**1139 Atami:** Observations by Behrend gave evidence for Atami being a binary system where both bodies are spectral type S. This means that while Atami is not a solitary body, the differences between the binaries are not large enough to account for F spectrum. With SMASS, 8 Color and Behrend observations showing a clear S curve and $S^3OS^2$ a flat spectrum, $S^3OS^2$ result is suspect.

**A common pattern:** For majority of the spectra the cause for discrepancy was not readily apparent and difference was between SMASS II and $S^3OS^2$ past 0.7 microns. $S^3OS^2$ spectra had a red slope in almost all cases while $S^3OS^2$ a blue or a flat one. This brings about a question if this could be a systematic error within $S^3OS^2$ or if there could be an issue with SMASS II.
Fig. 52. Common pattern observed for 18 asteroids. 8 Color (yellow), 24 Color (dark blue), NEAR-IR (red), SMASS I (green), SMASS II (light blue), $S^3$OS$^2$ (grey).

Eleven times out of fifteen $S^3$OS$^2$ data used the HD144585 standard star. Similarly eleven times out of fifteen SMASS II data used HD28099 standard star. It will be good to check both of these stars versus the same asteroid to see if they could have affected the spectra. 24 Color data covers the spectral range in these graphs but has too few datapoints to say with
confidence in most cases whether it matches SMASS II or $S^3OS^2$. Together with 8 Color data it becomes easier to narrow down which dataset is more likely to be accurate.

**1284 Latvia:** 8 Color data matches SMASS II but not $S^3OS^2$. It is likely that an observational issue with $S^3OS^2$ is the cause.

**170 Maria:** 8 Color data falls between SMASS II and $S^3OS^2$, 24 Color data shows a red slope past 0.7 microns, while the rest of the datasets show a blue or featureless slope.

**579 Sidonia:** 8 Color data matches $S^3OS^2$ but not SMASS II, while 24 data matches SMASS II but not $S^3OS^2$.

**3 Juno:** SMASS II deviates from all the rest which is likely due to an observational issue.

**547 Praxedis, 112 Iphigenia:** NEAR-IR data has a similar slope to $S^3OS^2$ data while SMASS II is featureless. Likely problem with SMASS II.

**381 Myrrha, 117 Lomia:** 8 Color data matches SMASS II but not $S^3OS^2$.

**12 Victoria:** $S^3OS^2$ deviates from all the rest of the datasets.

SMASS I and II Inconsistent spectra also show a pattern where SMASS II has a blue or featureless slope while SMASS I has a redder slope. 8 Color and 24 Color data in the cases shown matches SMASS I but not SMASS II.
Fig. 53: Common Pattern between SMASS I (green) and SMASS II (light blue). 8 Color (yellow), 24 Color (dark blue).

**General Comments**

Table 4: Comparison of data from different sets: Number in Common / Number Inconsistent. Subset of 300 asteroids was used rather than all possible asteroids in common for all sets. Note that some differences overlap (same asteroid can have 2 or more datasets that do not agree with each other).

<table>
<thead>
<tr>
<th></th>
<th>SMASS I</th>
<th>SMASS II</th>
<th>(S^3\text{OS}^2)</th>
<th>Sawyer</th>
<th>Vilas</th>
<th>24 C.</th>
<th>52 C.</th>
<th>NIR</th>
<th>8 C.</th>
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<td>29/6</td>
<td>6/0</td>
<td>3/0</td>
<td>13/0</td>
<td>11/0</td>
<td>2/0</td>
<td>15/1</td>
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<tr>
<td>SMASS II</td>
<td><strong>96/15</strong></td>
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<td>227/34</td>
<td>27/2</td>
<td>8/0</td>
<td>57/3</td>
<td>31/3</td>
<td>19/2</td>
<td><strong>95/12</strong></td>
</tr>
<tr>
<td>(S^3\text{OS}^2)</td>
<td>29/6</td>
<td><strong>227/34</strong></td>
<td>----</td>
<td>29/2</td>
<td>8/0</td>
<td>61/9</td>
<td>35/3</td>
<td>20/6</td>
<td><strong>103/11</strong></td>
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<tr>
<td>Sawyer</td>
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<td>27/2</td>
<td>29/2</td>
<td>----</td>
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<td>11/0</td>
<td>10/0</td>
<td>2/0</td>
<td>25/1</td>
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<tr>
<td>Vilas</td>
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<td>8/0</td>
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<td>4/0</td>
<td>0</td>
<td>6/0</td>
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<tr>
<td>24 C.</td>
<td>13/0</td>
<td>57/3</td>
<td>61/9</td>
<td>11/0</td>
<td>5/0</td>
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<td>6/0</td>
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<td>52 C.</td>
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<td>31/3</td>
<td>35/3</td>
<td>10/0</td>
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<td>6/0</td>
<td>4/0</td>
<td>----</td>
<td>9/0</td>
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<tr>
<td>8 C.</td>
<td>15/1</td>
<td><strong>95/12</strong></td>
<td>103/11</td>
<td>25/2</td>
<td>6/0</td>
<td>46/6</td>
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<td>9/0</td>
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<td>12/0</td>
<td>17/7</td>
<td>1/0</td>
<td>0</td>
<td>9/0</td>
<td>7/0</td>
<td>2/0</td>
<td>9/0</td>
</tr>
</tbody>
</table>
Upon closer examination inconsistencies among the 300 asteroids in common between $S^3OS^2$, SMASS II and SMASS I it becomes apparent that some datasets disagree more than others. In particular SMASS II has over thirty asteroids that do not match $S^3OS^2$ data, fifteen that do not match SMASS I data and twelve that do not match 8 Color data. $S^3OS^2$ also shows significant discrepancies with virtually all of the major datasets in this study.

Such a large number of discrepancies casts doubt on the reliability of the $S^3OS^2$ data set. Their telescope did not have automatic differential tracking, the slit wasn’t oriented in the optimal position to capture the entire spectrum (east-west vs preferred north-south) and they chose to not average spectra that they obtained before publishing them. It is important to note that classification system based on spectra that do not go beyond 1 micron is not robust. This is due to the fact that identifying features for olivine and pyroxene extend beyond 1 micron. Only Sawyer and SMASS I datasets went to 1 microns, SMASS II and $S^3OS^2$ stopped at 0.93 and 0.92 respectively.

Twenty seven of the spectra in SMASS II case were taken under less than ideal conditions, when humidity, cloud cover or lunar illumination were high. These conditions would have caused the data to be noisier, especially at bluer wavelengths. It is not clear why majority of SMASS II deviations show a bluer slope than other datasets past 0.7 microns. Calibration issue could be the cause.
Conclusion and Future Work: The initial justification for this project was to determine whether the discrepancy in the 354 Eleonora spectra was the unique case where the visual spectra from all three databases disagreed. It was determined that at least thirty-four asteroids also showed significant differences when different datasets were examined, which means this is a widespread problem. Majority of those discrepancies were between SMASS II and $S^3OS^2$ datasets (thirty-four) rather than between SMASS I and II (fifteen). For some we were able to establish the cause from the available literature, for others further observations will be required in the future. Proposed course of action is to obtain spectra at different rotational phases for asteroids in this study to determine if they possess compositional heterogeneity or albedo variations. The cause of the deviation past 0.7 microns between SMASS II and $S^3OS^2$ should be determined.

As visual wavelength observations do not cover the entire range where olivine and pyroxene show features, it is preferable to follow it with an observation in NEAR-IR in order to ensure accurate spectral classification. Lightcurves which showed significant brightness variations should be followed up with observations in the infrared to determine the cause.

It is now clear that when studying asteroids it is important to cross reference your data with different datasets in order to see where it stands and how robust it is. Accurate determination of mineralogy of asteroids will be crucial for future mining missions, for benefit of the asteroid science and in an event of the impending impact.
Appendix

Table 5. Standard stars, phase angle, airmass, diameter and albedo for asteroids in this study. Information is taken from Small Bodies Data Node. M stands for magnitude (absolute for SMASS I, apparent for S3OS2 and SMASS II), Ph stands for phase angle, A for airmass, D for diameter, Al for albedo; c stands for cloudy conditions that introduced small (~5%) erratic variations into the spectra, m stands for moonlight, meaning high (>50%) lunar illumination and h for humidity over 70%.

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