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# Mineralogical composition of (25143) Itokawa 1998 $SF_{36}$ from visible and near-infrared reflectance spectroscopy: Evidence for partial melting

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**Abstract**–In March 2001, asteroid (25143) Itokawa, the target of the Japanese Hayabusa spacecraft mission, was in a favorable viewing geometry for ground-based telescopic study. Visible/near-infrared (VNIR) spectra (~0.48 to 0.9 μm) obtained on March 24, 26, and 27 UT, and near-infrared (NIR) spectra (~0.75 to 2.5 μm) obtained on March 10, 11, 12, 23, and 24 UT collectively show absorption features centered near 1.0 and 2.0 μm, which are indicative of olivine and pyroxene. Analyses of these absorption features indicate an abundance ratio of olivine to pyroxene of approximately 75:25 ± 5, respectively, with no significant variation in the relative abundance of these minerals across its surface on a regional scale. The band center positions indicate that the mean pyroxene chemistry is $\sim Wo_{14 \pm 5}Fs_{43 \pm 5}$. There appear to be at least two pyroxene components: primarily a low-Ca orthopyroxene accompanied by a spectrally significant (~15–20%) high Fe-rich pigeonite phase. The mean pyroxene composition is significantly more Fe-rich than the $Fs_{14–26}$ range found in ordinary chondrites. These pyroxene compositions are suggestive of phases crystallized from partial melts. This would indicate that the parent body of (25143) Itokawa reached temperatures sufficient to initiate partial melting (~1050 to 1250 °C), but that it did not attain the degree of melting required for significant melt mobilization and efficient segregation of the basaltic melt component from the unmelted residual olivine portion. Itokawa's spectral band parameters place it near the S(III)/S(IV) boundary, but within the S(III) taxonomic field. In meteoritic nomenclature, Itokawa would be most analogous to an olivine-rich primitive achondrite. Alternatively, if the high Fs value is not related to partial melting, then Itokawa could also represent a rare atypical LL chondrite, or a previously unsampled oxidized Fe-rich chondritic-like assemblage.

## INTRODUCTION

Asteroid (25143) Itokawa 1998 $SF_{36}$ was discovered by the Lincoln Laboratory (LINEAR) program (described by Stokes et al. 2002), on September 26, 1998 (Williams 1998), and was identified as a potential spacecraft target due to the low delta-V requirements for a rendezvous mission. In September 2005, the Japanese spacecraft Hayabusa (MUSES-C) arrived at the near-Earth asteroid (25143) Itokawa for a planned 3.5-month encounter (Fujiwara et al. 2006). This mission is primarily a proof-of-concept engineering mission, designed to demonstrate many technologies and objectives, including ion propulsion engines, autonomous spacecraft navigation and control, surface sample collection, and the first sample return to Earth from a near-Earth asteroid (Fujiwara et al. 2006). The

Table 1. VNIR observing parameters of (25143) Itokawa 1998 $SF_{36}$ (University of Texas McDonald Observatory 2.1 m).

| Observing date (2001) | Start time (UT) | Exposure length (s) | RA (J2000) (h m) | Dec (J2000) (° ′) | Visual mag. | Airmass | Phase angle (°) | Solar distance (AU) | Earth distance (AU) |
|---|---|---|---|---|---|---|---|---|---|
| March 24 | 08:11 | 1200 | 15 25 | +22 42 | 14.1 | 1.136 | 50.5 | 1.024 | 0.044 |
| | 08:36 | 1200 | 15 25 | +22 42 | 14.1 | 1.088 | 50.6 | 1.024 | 0.044 |
| | 10:12 | 1200 | 15 26 | +22 43 | 14.1 | 1.010 | 50.8 | 1.024 | 0.044 |
| | 10:36 | 1200 | 15 27 | +22 44 | 14.1 | 1.013 | 50.9 | 1.024 | 0.044 |
| | 11:09 | 1200 | 15 27 | +22 44 | 14.1 | 1.033 | 51.0 | 1.024 | 0.044 |
| March 26 | 09:46 | 1200 | 16 09 | +22 36 | 14.2 | 1.042 | 59.0 | 1.018 | 0.040 |
| | 10:12 | 1200 | 16 10 | +22 35 | 14.2 | 1.021 | 59.1 | 1.018 | 0.040 |
| | 11:05 | 1200 | 16 11 | +22 35 | 14.2 | 1.012 | 59.2 | 1.018 | 0.040 |
| March 27 | 08:06 | 1200 | 16 32 | +22 14 | 14.2 | 1.333 | 63.2 | 1.015 | 0.039 |
| | 08:31 | 1200 | 16 32 | +22 13 | 14.2 | 1.237 | 63.3 | 1.015 | 0.039 |
| | 09:35 | 644 | 16 33 | +22 12 | 14.2 | 1.084 | 63.5 | 1.015 | 0.039 |

Hayabusa spacecraft is currently scheduled to return the sample capsule via a parachute-assisted landing in Woomera, Australia, and end its mission in June 2010.

A large body of spectral data was gathered in March 2001 via ground-based telescopes in order to ensure that good constraints of the composition of Itokawa were obtained before the subsequent spacecraft encounter in September 2005. Detailed rotationally resolved ground-based observations were collected to address questions about the mineralogy of the asteroid and whether any possible differences in mineralogy across its surface could be detected. In addition, the observations were also made to provide context for the spectral data that Hayabusa acquired by utilizing a data set of wider wavelength coverage (0.45 to 2.5 μm) and higher resolution spectra (~100), which will be used to help calibrate data obtained from the spacecraft sensors. Some specific goals of the ground-based study are: 1) to determine the general composition of the asteroid; 2) to identify any meteorite analogues to Itokawa; 3) to look for indications of heterogeneity or homogeneity in the mineralogical composition over the surface of the asteroid; and 4) to determine if significant changes in viewing geometry (e.g., phase angle) alter the response of the spectral data.

Asteroid (25143) Itokawa is classified as a member of the Apollo dynamical class of asteroids based on its orbital parameters (Williams 1998). This asteroid is a sub-kilometer object with dimensions of 535 × 294 × 209 m (Fujiwara et al. 2006), and a rotation period of 12.132 h (Kaasalainen et al. 2003). This object is also a potentially hazardous asteroid (PHA), and thorough knowledge of its characteristics could provide some insight into the physical characteristics of other PHAs. Due to the upcoming encounter of the PHA (99942) Apophis 2004 MN4 with the Earth in April 2029, and this asteroid's remote probability of impact in 2036 (e.g., Chesley 2006), information obtained from Itokawa could be especially significant in designing and implementing an overall strategy to defend the Earth from impact by a PHA. In addition, detailed knowledge of Itokawa's physical properties could also provide information on how such relatively small near-Earth objects with relatively low delta-Vs could be utilized as potential resources for future space exploration.

## OBSERVATIONS AND DATA REDUCTION

Spectral reflectance observations of asteroid (25143) Itokawa were obtained at two separate telescopes with instrumentation producing overlapping wavelength ranges in order to maximize coverage in the spectral region where mineralogically diagnostic features are prominent. Observing parameters surrounding the individual VNIR spectra and grouped NIR spectra are listed in Tables 1 and 2. In an effort to address the spatial coverage of the asteroid's surface throughout the observations, calculated sub-Earth latitudes and rotational phases during each night are included in Table 3 for the NIR observations. The rotational phases presented are defined such that 0.00 phase corresponds to the starting time of the first two-minute SpeX observation obtained on March 11. The individual sets of data are discussed here.

### Visible/Near-Infrared (VNIR) Observations

VNIR observations were obtained of (25143) Itokawa on the nights of March 24, 26, and 27 UT using the facility CCD cassegrain spectrograph (ES2) at the 2.1 m Otto Struve telescope, University of Texas McDonald Observatory with a 150 l/mm grating and a 0.3 arcsecond slit. A Schott GG475 filter was used to prevent second order effects from contaminating the NIR portion of the spectra. The spectra have a resolution of ~10.4 Å (where resolution is defined as 2× the dispersion/element). Spectra of the solar analogue star SAO 65083 were obtained at varying airmasses on all three nights of observations in order to correct for changes in extinction with airmass throughout each night of observations. Data reduction followed the methods described in Vilas and Smith (1985) and Vilas and McFadden (1992).

Table 2. NIR observing parameters of (25143) Itokawa 1998 SF$_{36}$ (NASA Infrared Telescope Facility).

| Observing date (2001) | Start time (UT) | End time (UT) | RA (J2000) (h m) | Dec (J2000) (° ′) | Visual mag. | Airmass range | Phase angle (°) | Solar distance (AU) | Earth distance (AU) | No. of obs. |
|---|---|---|---|---|---|---|---|---|---|---|
| March 10 | 11:40 | 12:05 | 12 55 | +17 03 | 14.96 | 1.001–1.004 | 23.96 | 1.073 | 0.088 | 12 |
| | 12:30 | 12:45 | 12 55 | +17 03 | 14.96 | 1.007–1.015 | 23.97 | 1.073 | 0.088 | 6 |
| | 13:08 | 13:33 | 12 55 | +17 04 | 14.96 | 1.042–1.068 | 23.99 | 1.073 | 0.088 | 12 |
| | 14:06 | 14:46 | 12 55 | +17 05 | 14.95 | 1.144–1.271 | 24.01 | 1.073 | 0.088 | 16 |
| March 11 | 10:44 | 11:05 | 13 00 | +17 25 | 14.88 | 1.038–1.060 | 24.71 | 1.070 | 0.084 | 10 |
| | 11:49 | 12:14 | 13 00 | +17 26 | 14.88 | 1.001–1.004 | 24.75 | 1.069 | 0.084 | 12 |
| | 12:50 | 13:30 | 13 01 | +17 27 | 14.87 | 1.018–1.065 | 24.78 | 1.069 | 0.084 | 18 |
| | 14:13 | 14:38 | 13 01 | +17 28 | 14.87 | 1.159–1.230 | 24.81 | 1.069 | 0.084 | 12 |
| March 12 | 10:42 | 11:22 | 13 06 | +17 50 | 14.80 | 1.020–1.066 | 25.61 | 1.066 | 0.081 | 20 |
| | 12:00 | 12:40 | 13 06 | +17 51 | 14.79 | 1.001–1.012 | 25.67 | 1.066 | 0.080 | 20 |
| March 23 | 11:00 | 11:25 | 15 08 | +22 39 | 14.11 | 1.120–1.206 | 47.37 | 1.027 | 0.046 | 12 |
| | 11:42 | 12:07 | 15 08 | +22 40 | 14.10 | 1.060–1.097 | 47.51 | 1.027 | 0.046 | 12 |
| | 12:30 | 12:55 | 15 09 | +22 40 | 14.10 | 1.009–1.029 | 47.60 | 1.027 | 0.046 | 12 |
| | 13:22 | 13:47 | 15 10 | +22 41 | 14.10 | 1.001–1.003 | 47.67 | 1.027 | 0.045 | 12 |
| | 14:01 | 14:16 | 15 10 | +22 41 | 14.10 | 1.011–1.021 | 47.78 | 1.027 | 0.045 | 6 |
| March 24 | 11:35 | 11:50 | 15 28 | +22 50 | 14.10 | 1.125–1.148 | 51.10 | 1.024 | 0.044 | 6 |
| | 12:28 | 12:53 | 15 29 | +22 51 | 14.10 | 1.020–1.049 | 51.25 | 1.024 | 0.044 | 12 |
| | 14:08 | 14:33 | 15 30 | +22 51 | 14.10 | 1.006–1.019 | 51.47 | 1.024 | 0.043 | 12 |
| | 15:00 | 15:25 | 15 31 | +22 51 | 14.10 | 1.052–1.098 | 51.63 | 1.023 | 0.043 | 12 |

During these observations, excursions in humidity varied up through ~50% due to a weather system moving through the area, and the effects of telluric water, which we were unable to remove, are apparent near 0.73, 0.82, and 0.93 μm in spectra from all three nights. The best indicator of spectral quality is the peak-to-peak scatter within a spectrum. The individual spectra from all three nights are shown in Figs. 1, 2, and 3. All three nights show the lower wavelength edge (though not the band center of the 1.0 μm mafic silicate absorption band, indicating a combination of pyroxenes and olivines), and are consistent with other spectral data sets obtained in this wavelength region (Lowry et al. 2005). Spectra from all three nights also show a broad, weak feature centered near 0.65 μm, a region in which absorption features have been previously identified in S-class asteroid spectra (Hiroi et al. 1996).

## Near-Infrared (NIR) Observations

Near-infrared observations of asteroid (25143) Itokawa were obtained using the SpeX instrument (Rayner et al. 2003), which is a medium-resolution near-infrared spectrograph, developed by the Institute for Astronomy for the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawai‘i. The low-resolution (or asteroid) mode of SpeX combined with a 0.5-arcsecond-wide slit provides a spectral resolution of ~150 over the entire ~0.7 to 2.5 μm wavelength range. High signal-to-noise data can be attained with SpeX even down to wavelengths of ~0.7 μm, which aids the mineralogical identification and interpretation of features that are present in this region of a spectrum.

Table 3. Sub-Earth latitude and rotation phase for the NIR data.

| Observing date (2001) | Start time (UT) | End time (UT) | Sub-Earth latitude (°) | Rotation phase |
|---|---|---|---|---|
| March 11 | 10:44 | 11:05 | −68.0 | 0.01 |
| | 11:49 | 12:14 | −68.0 | 0.10 |
| | 12:50 | 13:30 | −67.9 | 0.20 |
| | 14:13 | 14:38 | −67.9 | 0.31 |
| March 12 | 10:42 | 11:22 | −66.8 | 0.89 |
| | 12:00 | 12:40 | −66.7 | 0.00 |
| March 23 | 11:00 | 11:25 | −39.8 | 0.66 |
| | 11:42 | 12:07 | −39.7 | 0.72 |
| | 12:30 | 12:55 | −39.6 | 0.78 |
| | 13:22 | 13:47 | −39.4 | 0.85 |
| | 14:01 | 14:16 | −39.3 | 0.90 |
| March 24 | 11:35 | 11:50 | −35.4 | 0.68 |
| | 12:28 | 12:53 | −35.2 | 0.76 |
| | 14:08 | 14:33 | −34.9 | 0.90 |
| | 15:00 | 15:25 | −34.8 | 0.97 |
| March 28[a] | 13:48 | 14:35 | −16.3 | 0.87 |

[a]Observation obtained by Binzel et al. (2001).

Asteroid (25143) Itokawa was observed during the March 2001 apparition over an *Mv* range of 14.10 to 14.96 and a phase angle range of approximately 24 to 52° (Table 2). There were 234 120 s near-infrared spectra were taken of this object between 1.00 and 1.30 airmass on March 10, 11, 12, 23, and 24 UT (Table 2). The observing conditions on Mauna Kea were good to excellent for all but the first night, which enabled the collection of the high signal-to-noise spectra necessary for detailed compositional analysis. Data obtained on March 10 UT are not as good as the other four nights due

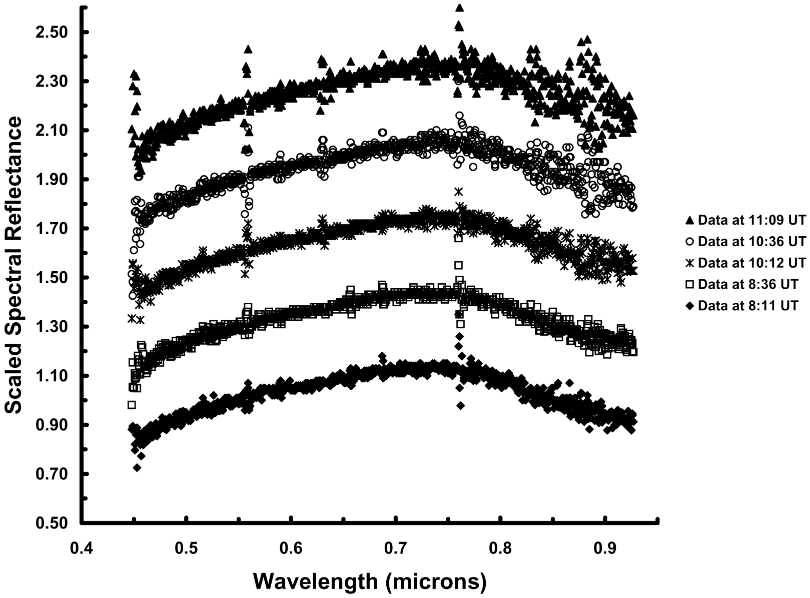

Fig. 1. VNIR reflectance spectra of (25143) Itokawa taken on March 24, 2001 UT. Spectra are scaled to 1.0 at approximately 0.55 μm, and are offset by 0.2 in reflectance for clarity.

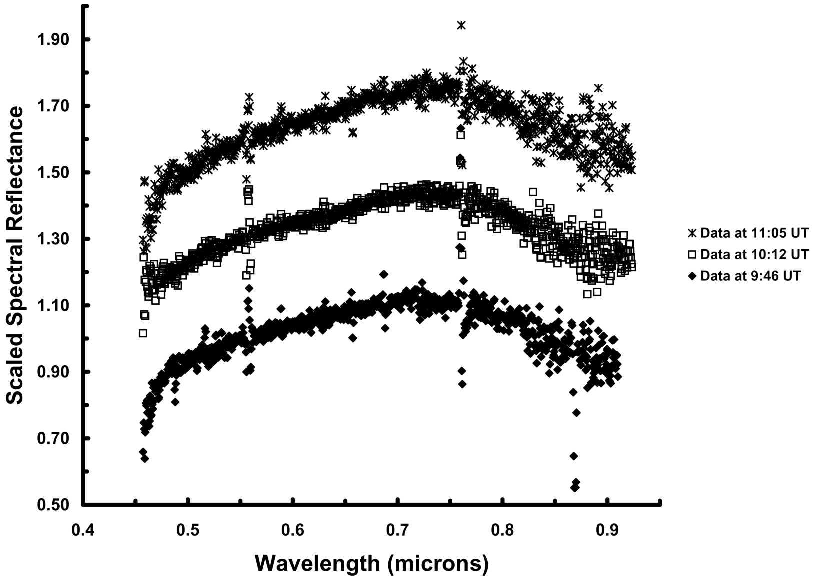

Fig. 2. VNIR reflectance spectra of (25143) Itokawa taken on March 26, 2001 UT. Spectra are scaled to 1.0 at approximately 0.55 μm, and are offset by 0.2 in reflectance for clarity.

to large variations in local humidity and the presence of high-altitude cirrus clouds associated with a weather system moving through the Hawai‘ian Islands. Hence, the data from this night are not included in this study, but have been examined and are generally consistent with the other data obtained of (25143) Itokawa.

Observations of standard stars SAO 120107 and SAO 83786 were obtained in addition to spectra of (25143) Itokawa, over a similar airmass range as the asteroid in order to model the atmosphere at Mauna Kea. This allows for a more accurate determination of extinction coefficients over the entire spectral interval obtained by the SpeX instrument. These data are also used to correct spurious artifacts in the spectra due to strong telluric water vapor features, especially at ~1.4 and ~1.9 μm, in regions where most of the common materials found in rocky Solar System objects have near-infrared absorptions. Additional observations of a solar analogue star were not required given that SAO 120107 is a well-known standard and has been used as a solar analogue star in the past. In addition, each of the object and standard

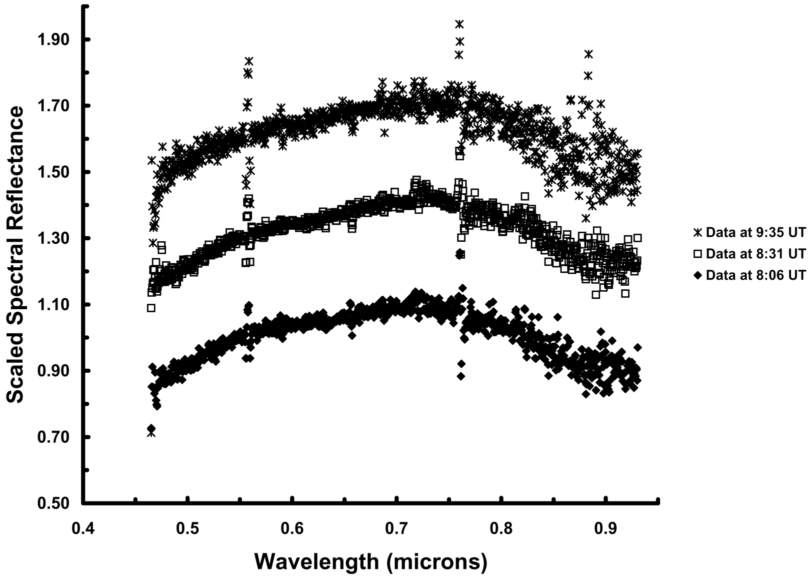

Fig. 3. VNIR reflectance spectra of (25143) Itokawa taken on March 27, 2001 UT. Spectra are scaled to 1.0 at approximately 0.55 μm, and are offset by 0.2 in reflectance for clarity.

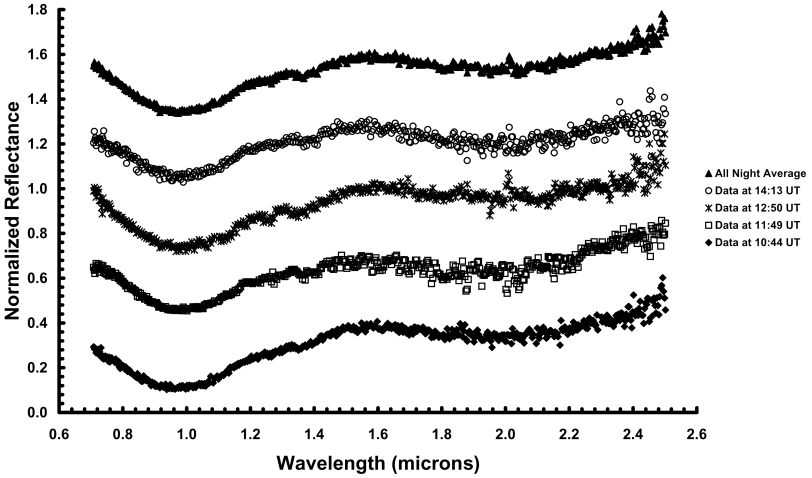

Fig. 4. Near-infrared spectra of (25143) Itokawa from the NASA IRTF taken on March 11, 2001 UT. These data have larger errors than those from subsequent dates due to weather at the summit of Mauna Kea during this night, but the 1.0 and 2.0 μm features are clearly present. Data are taken in groups and then averaged together to increase the signal-to-noise. One all-night average is also calculated and displayed here for comparison with the rest of the individual sets of spectra. All spectra are normalized and offset for clarity.

star spectra were channel-shifted to a registered reference spectrum in order to account for any slight instrument flexure due to the changing orientation of the telescope as it tracked the object or star over the course of the night.

All of the (25143) Itokawa and standard star spectra were extracted using the Image Reduction and Analysis Facility (IRAF) program, which was written and distributed by the National Optical Astronomy Observatories (NOAO). The raw spectra files were imported into the Spectral Processing Routine (SpecPR) program for processing and analysis where the atmospheric and channel-shifting corrections were conducted (Clark 1980; Gaffey et al. 2002; Gaffey 2003). More details concerning the observing and reduction procedures for these types of near-infrared measurements can be found in Hardersen et al. (2004, 2005) and Abell et al. (2005).

Individual averages of groups of spectra and all-night averages, except those from March 10, 2001 UT, are shown in Figs. 4–7. All of the spectra demonstrate substantial 1.0 and 2.0 μm absorption features with the 1.0 μm feature showing some asymmetry in the longer wavelength wing out to 1.5 μm. Smaller scale features at ~1.4 and ~1.9 μm seen in some of the spectra are as a result of incomplete correction of the telluric water bands. The overall reflectance of the

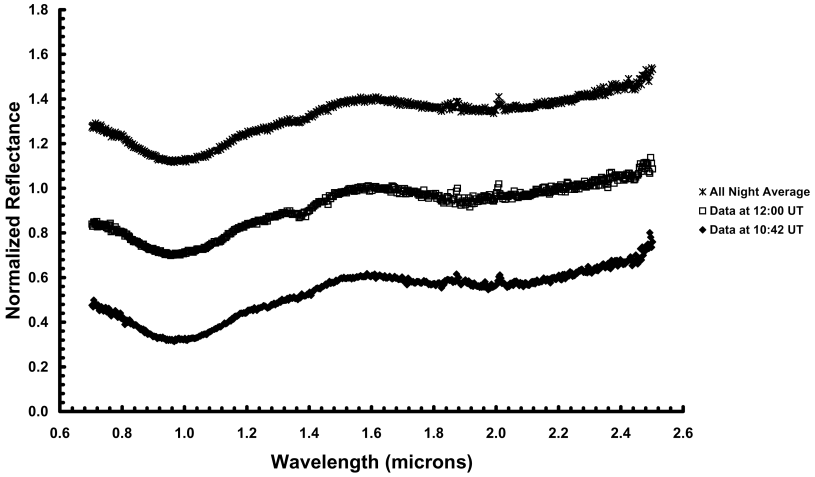

Fig. 5. Near-infrared spectra of (25143) Itokawa from the NASA IRTF taken on March 12, 2001 UT. Data are taken in groups and then averaged together to increase the signal-to-noise. One all-night average is also calculated and displayed here for comparison with the rest of the individual sets of spectra. All spectra are normalized and offset for clarity.

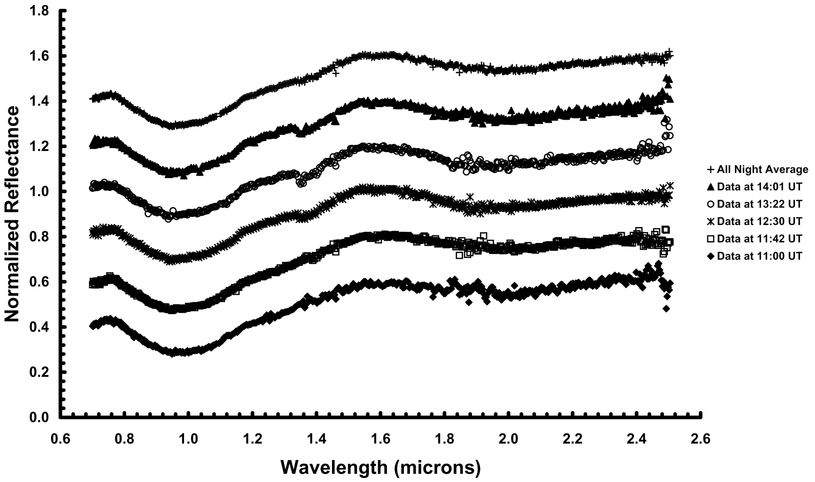

Fig. 6. Near-infrared spectra of (25143) Itokawa from the NASA IRTF taken on March 23, 2001 UT. Data are taken in groups and then averaged together to increase the signal-to-noise. One all-night average is also calculated and displayed here for comparison with the rest of the individual sets of spectra. All spectra are normalized and offset for clarity.

spectra in this portion of the near-infrared region appears to gradually increase with wavelength, and is consistent with that of asteroids with similar absorption features in this wavelength region (cf. Gaffey et al. 1993a).

The relative point-to-point scatter in each of the all-night data averages shown in Figs. 4–7 provides a good estimate of the uncertainty associated with these measurements. However, more accurate error analyses using the standard error of the mean indicate that the average uncertainty in the March 11 UT data is roughly 1–2% at wavelengths shorter than 2.4 μm and approximately 2–4% for those points longer than 2.4 μm. For the data from March 12, 23, and 24 UT, the errors are 0.5–0.8% at wavelengths shorter than 2.4 μm and about 1–2% for data points longer than 2.4 μm. The noise increases at wavelengths greater than 2.4 μm in each of these nights due to the decreased response of the SpeX detector beyond this wavelength interval. Note that in most of the data sets, the last few channels are quite noisy, and therefore are omitted from the analysis for compositional interpretations. Data from March 11 and 12 UT have greater point-to-point scatter than data from March 23 and 24 UT, probably due to the remnants of the weather front that was passing over Mauna Kea on the night of March 10 UT. Data near to the 1.4 and 1.9 μm regions in all the spectra appear to have slightly higher errors than the rest of the data due to the imperfect corrections of the telluric atmosphere contribution. However, these are still relatively minor and do not interfere with the compositional analysis of the spectra obtained from asteroid (25143) Itokawa.

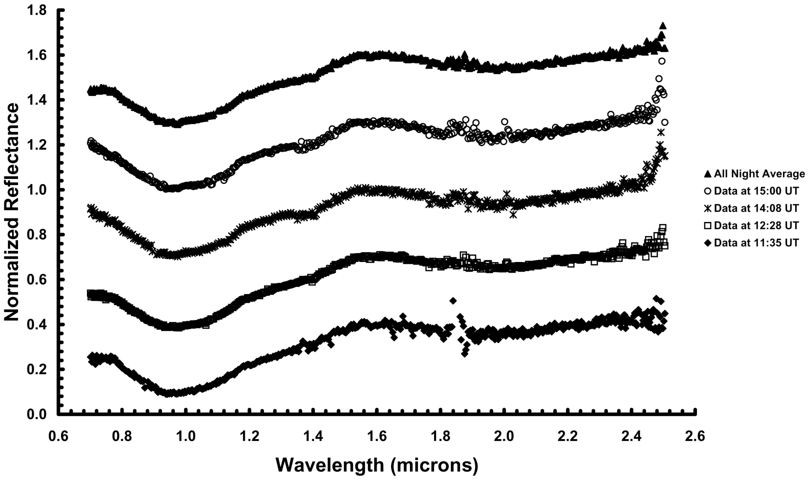

Fig. 7. Near-infrared spectra of (25143) Itokawa from the NASA IRTF taken on March 24, 2001 UT. Data are taken in groups and then averaged together to increase the signal-to-noise. One all-night average is also calculated and displayed here for comparison with the rest of the individual sets of spectra. All spectra are normalized and offset for clarity.

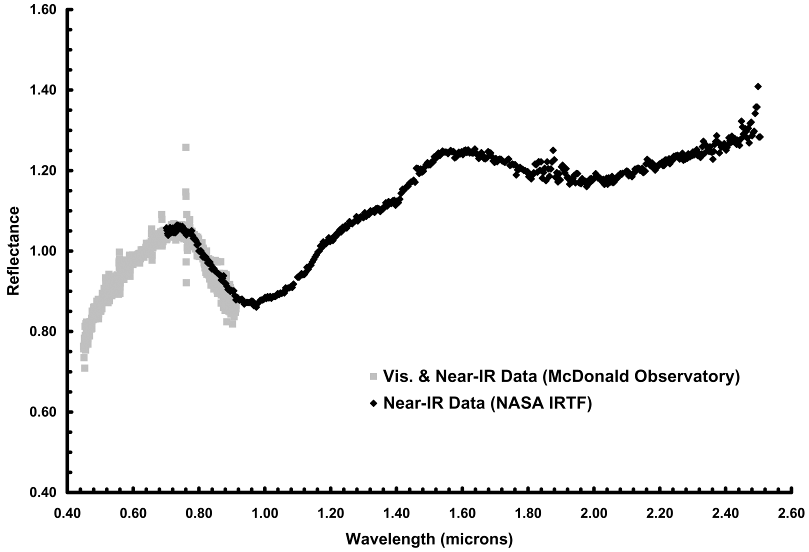

Fig. 8. The combined spectrum of visible and near-infrared data obtained of (25143) Itokawa on March 24, 2001 UT from McDonald Observatory and the NASA IRTF. Note the excellent agreement between the two datasets, particularly in the overlap region of the short wavelength wing of the 1.0 μm band.

## DISCUSSION AND ANALYSIS

Combining the data sets from the two telescopes described above gives the opportunity for a good compositional study of asteroid (25143) Itokawa. However, given that asteroid (25143) Itokawa is an NEO, any visible and near-infrared data should ideally be from observations of the object obtained relatively close in time, in order to minimize potential differences in the spectra due to rapidly changing phase angle effects and sub-Earth observation points. Fortunately, observations were obtained at both McDonald Observatory and the NASA IRTF on March 24 UT with very little difference in viewing geometry of the asteroid (Table 2). The data from this night have been combined together and scaled to unity at 0.8 μm, and are shown in Fig. 8.

The combined visible and near-infrared data show excellent agreement and match together well in the overlap region from ~0.7 to 0.8 μm. This suggests that any slight differences in viewing geometry of the asteroid at the time of the observations were minor and had little effect on the spectral response of the data obtained from the two telescopes. More importantly, this finding also suggests that near-infrared data obtained by SpeX is useful down to wavelengths significantly below 0.8 μm (Fig. 8). Given that the entire short wavelength wing of the 1.0 μm feature is

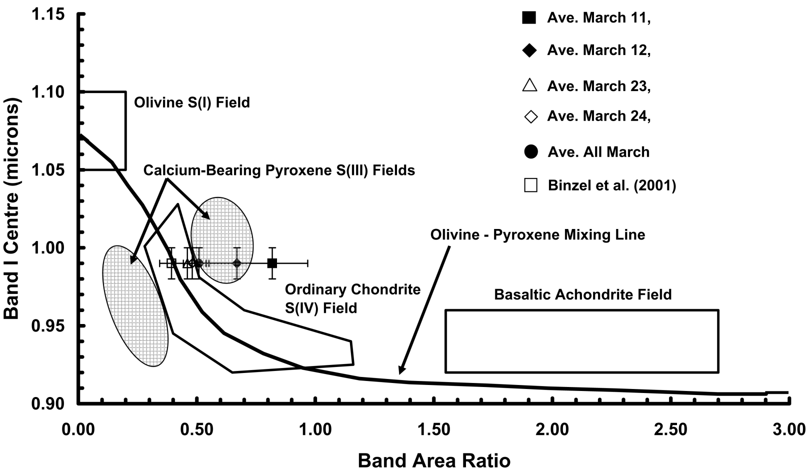

Fig. 9. A plot of Band I center versus Band area ratio for (25143) Itokawa. The average data point for Itokawa lies within the S(III) field, but individual values overlap into the S(IV) field. Based on determinations described in Cloutis et al. (1986) and later modified by Gaffey et al. (1993a), the asteroid most probably has a mineralogy dominated by a calcium-bearing Fe-rich pyroxene assemblage.

covered over the spectral interval obtained by SpeX in this study, the NIR data set can be used to do a complete band parameter analysis to determine the composition of (25143) Itokawa. Such assumptions have been made in the past with regard to similar analyses of other objects based solely on SpeX near-infrared data (e.g., Kelley et al. 2003; Hardersen et al. 2004, 2005). However, there has always been some question concerning the analysis of these objects given that there was no contemporaneous VNIR data set with which to verify whether the entire short wavelength wing of the 1.0 µm feature was covered. Now with the confirmation of SpeX's capabilities down to such wavelengths by the McDonald Observatory VNIR data in this study, such analyses can be viewed with more credibility and confidence.

A preliminary analysis of the two absorption features, based on approximate band position and shape, suggests that this is an assemblage containing olivine and pyroxene. Pyroxene has absorption features centered near these regions, and the presence of an olivine component would contribute to the asymmetric shape of the absorption feature centered near 1.0 µm (e.g., Gaffey et al. 1993b), as is seen in the Itokawa near-infrared spectra shown in Figs. 4–7. Taxonomically, asteroid (25143) Itokawa would be classified as a member of the S-type asteroids on the basis of this preliminary analysis (Tholen 1984; Tholen and Barucci 1989).

More detailed analyses of the band centers and areas are conducted by isolating the absorption features and removing a linear continuum from the near-infrared spectra. This type of analysis was first used and described by Cloutis et al. (1986) in laboratory studies, and has been further developed by Gaffey et al. (1993a, 2002) to extract mineralogical compositions from asteroids with 1.0 and 2.0 µm features. This technique provides a better constraint on the actual mineralogy of a particular object, rather than relying on the taxonomic classification scheme alone. The entire SpeX data set from March 2001 has been averaged together to produce a combined spectrum with increased signal-to-noise. Individual spectra were included in an averaging routine that eliminated data points greater than 2 sigma from the overall mean. Detailed analyses of this entire SpeX data set indicate that the value of the Band I center is 0.99 ± 0.01 µm, the Band II center is 2.02 ± 0.02 µm, and the band area ratio (BAR) is 0.51 ± 0.03. These error bars are estimates of the uncertainty in each band parameter that are determined by selecting different continua for each absorption band multiple times and comparing the results. This provides a more conservative estimate of the uncertainty associated with these data than a 1-sigma error.

A plot of Band I versus BAR places this determined value of (25143) Itokawa within the S(III) field, which is described as a region where the assemblage may bear a significant calcic pyroxene component (Gaffey et al. 1993a) (Fig. 9). However, it should be noted that although the BAR places Itokawa within the S(III) field, this value is located near the boundary, and the error bars extend into the S(IV) ordinary chondrite field (Fig. 9). In addition, BARs obtained from March 23 and 24 UT are placed within the S(IV) field, but have error bars that extend into the S(III) field. BAR values from March 11 and 12 UT are well outside the S(IV) field. Note that BAR values from March 11 and 12 have larger error bars compared to the other March values due to the greater uncertainty in defining a continuum for the Band II feature from these data, but do not extend into the S(IV) field (Fig. 9).

The BAR value can be used as an approximate measure of the abundance of the spectrally dominant mineral phases located on the surface of (25143) Itokawa. The BAR value of 0.51 ± 0.03 from the average of the entire data set indicates that the abundance of the olivine and pyroxene phases on the

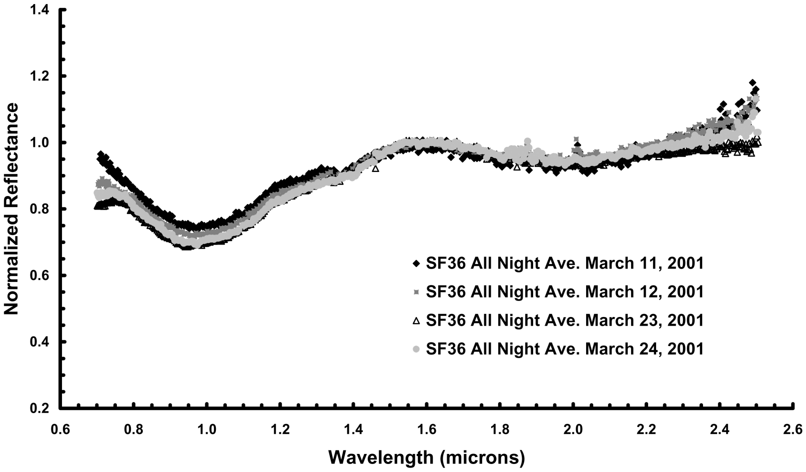

Fig. 10. A plot showing the all-night average NIR data from March 11, 12, 23, and 24, 2001 UT. Note that all the spectra have similar Band I and Band II positions, and differ only slightly in terms of depth. There are no significant changes in spectral slope that can be attributed to phase angle effects.

asteroid are roughly 75:25 ± 5, respectively, based on the BAR calibration determined from Equation 4 in Gaffey et al. (2002). Taking the data at face value, the BAR values for the entire data set suggests that there is a possible 10% variation across the asteroid's surface, so the range of abundance ratios could be from 60:40 to 80:20, accounting for the error inherent in the calibration. However, the largest BAR value, which corresponds to an olivine to pyroxene ratio of 60:40, is based on data from March 11, which is also the noisiest spectral data set. Data from the all night spectral averages of March 12, 23, and 24 give abundance ratios of 67:33, 76:24, and 75:25, respectively. These values agree quite well, given the approximate 5% uncertainty of the calibration from Gaffey et al. (2002). Therefore, the lower limit on the olivine to pyroxene ratio of 60:40 is probably not accurate and may be closer to 70:30.

Given that the rotation period of this object is 12.132 h and the pole position is at ecliptic longitude and latitude of 355°, −84° (Kaasalainen et al. 2003), the NIR observations were obtained of two different portions of the asteroid's surface during the March 2001 apparition. If the BAR values calculated from the March 12, 23, and 24 data are accurate, this suggests that significant mineralogical heterogeneity cannot be confirmed on Itokawa's surface at large regional scales. March 11 and 12 data were taken at sub-Earth latitudes (SELs) of approximately −68° to −67° and at relative rotation phases of 0.89 to 0.31, whereas the March 23 and 24 data were obtained at SELs of approximately −40° to −35° and at 0.66 to 0.97 rotation phase (Table 3). BAR values would be expected to align well with one another given the similar viewing geometry of Itokawa on March 11 and 12. These BAR values do not match particularly well, which may be further indication of the uncertainty associated with the March 11 data set due to the atmospheric conditions at the time (Fig. 4). Conversely the BAR values obtained from the March 23 and 24 data demonstrate a narrower range, which is consistent with observations obtained of the same hemisphere (Fig. 9).

The data from the March 2001 run all appear to have similar Band I and Band II positions, and differ only slightly in terms of depths. These differences are small and, as discussed above, suggest that little or no significant heterogeneity of asteroid (25143) Itokawa appears to exist in terms of the relative abundances of the olivine and pyroxene phases at large regional scales. The similarity in the band positions also suggests that Itokawa's pyroxene composition is homogenous over hemisphere scales. In addition, there do not appear to be any significant differences in slope of the spectra that could be contributed to observations due to phase angle effects (Fig. 10).

Gaffey et al. (2002) have developed equations for determining pyroxene chemistries based on the band center position of laboratory data. The two band center positions determined from the spectral analysis of asteroid (25143) Itokawa are 0.99 ± 0.01 μm and 2.02 ± 0.02 μm, respectively. Given that the Band I position is a composite of both olivine and pyroxene absorption features, the olivine contribution must be removed before any pyroxene chemistry can be determined. Therefore a correction factor to the Band I position is applied based on the estimated olivine contribution from the BAR value. In this case, the determined BAR value for Itokawa is 0.51 ± 0.03. The BAR component of any Band I position can be estimated based on calibrations developed by Cloutis et al. (1986) (see Fig. 4 of Gaffey et al. 2002). A BAR value of 0.51 corresponds to a Band I adjustment factor of approximately 0.05 μm. Therefore the olivine-removed Band I position for asteroid (25143) Itokawa is 0.94 μm.

The olivine-removed Band I and the Band II values can now be applied to the calibrations found in Gaffey et al.

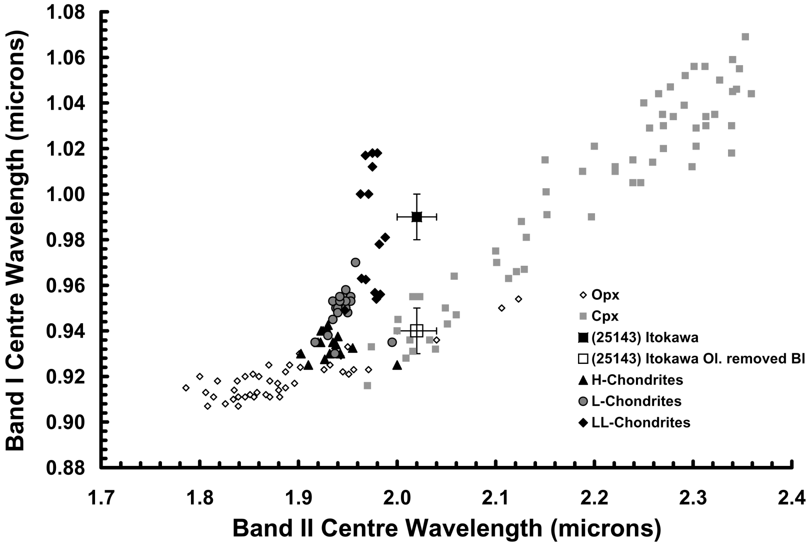

Fig. 11. A plot of Band I center versus Band II center adapted from the work by Adams (1974). The band centers for (25143) Itokawa place this asteroid well off the pyroxene trend, which is indicative of a significant amount of olivine present in its composition, and outside the range of values for ordinary chondrites. The olivine removed Band I value of 0.94 μm for Itokawa is plotted and falls along the calcic-bearing pyroxene trend. The long wavelength of Band II at 2.02 ± 0.02 μm suggests that an appreciable amount of calcium bearing Fe-rich pyroxene must also be present in the mineralogical assemblage of this asteroid, which places Itokawa outside the range of known LL ordinary chondrites.

(2002, p. 188) by using Equations 2c and 3b to determine a pyroxene chemistry of $\sim Wo_{14 \pm 5}Fs_{43 \pm 5}$. This chemistry is atypical for an ordinary chondrite S(IV) assemblage because of the high Fe content of the pyroxene. The full range of observed Fs values found in ordinary chondrites is $Fs_{14-26}$, with LL chondrites spanning the upper end of this range from $Fs_{22-26}$ (Brearley and Jones 1998). Therefore any meteoritic assemblage containing pyroxene with Fs values outside this range would be considered non-chondritic. The mean pyroxene composition for a typical LL chondrite contains $Fs_{24}$ (Gomes and Keil 1980; Brearley and Jones 1998). Measured Band II positions for known LL chondrites in the laboratory range from 1.95 to 1.99 μm with a mean center position located approximately at 1.97 μm with a standard deviation of 0.01. Itokawa's Band I center position is consistent with similar values found among the LL chondrites (Gaffey 1976), but the corresponding Band II position at 2.02 ± 0.02 μm is outside the range that is observed for these meteorites (Gaffey 1976; Gaffey et al. 2002) (Fig. 11). However, it should be noted that the error bars for the Band II measurement are close to the upper end of laboratory values for known LL chondrites, but do not overlap.

Pyroxene Band II positions are sensitive to the presence of Fe and Ca (Burns 1970; Adams 1974), so any increase in Fe or Ca would distort the crystal structure of the pyroxene and push the observed band center to longer wavelengths. The observed Band II position for (25143) Itokawa gives a mean pyroxene composition of $Fs_{43 \pm 5}$, which is much higher than Fs values observed in LL chondrites, as discussed above (Brearley and Jones 1998). This suggests that Fe (and most likely Ca) is enriched in some portion of the pyroxene found on the asteroid. Hence the data suggest that at least two pyroxenes are present: a low-Ca orthopyroxene accompanied by a spectrally significant (~15–20%) high Fe-rich pigeonite phase.

Previous interpretations of other (25143) Itokawa VNIR and NIR data have stated that this object could be a space-weathered LL ordinary chondrite (Binzel et al. 2001). Preliminary analyses of the data presented in a paper by Kelley et al. (2001) suggested that the asteroid is either an olivine-dominated restite or an olivine-rich L or LL ordinary chondrite. More complete analyses of the data presented here suggest that (25143) Itokawa has pyroxene compositions that are suggestive of phases crystallized from partial melts (Hess 1989; McCoy et al. 1997; Mittlefehldt et al. 1998). This would indicate that the parent body of (25143) Itokawa reached temperatures sufficient to initiate partial melting (~1050–1250° C), but that it did not attain the degree of melting required for significant melt mobilization and efficient segregation of the basaltic melt component from the unmelted residual olivine portion (Keil 2000).

Most ordinary chondrites have textures that indicate they experienced some degree of heating, probably due to radioactive decay of elements such as $^{26}Al$, or electromagnetic induction heating. Analyses of metamorphosed LL-chondrite textures (LL4 to LL6) show evidence that these assemblages probably experienced peak temperatures below 950° C, and therefore could not have produced eutectic melts (Brearley and Jones 1998). If the interpretation concerning the high olivine content and the

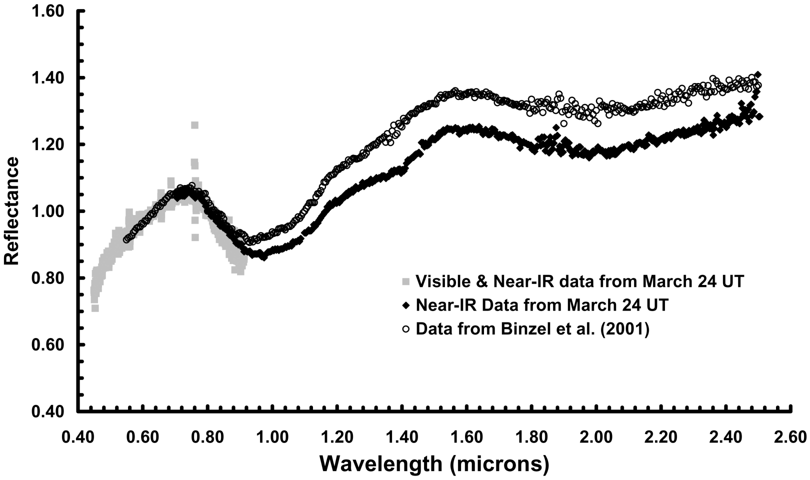

Fig. 12. A comparison of the spectra obtained by Binzel et al. (2001) and this study. All spectra are normalized to 0.8 μm. Note that the spectrum of Binzel et al. (2001) is redder than the one in this study, but still demonstrates mafic silicate absorption bands due to olivine and pyroxene.

pyroxene chemistry is correct, then (25143) Itokawa's parent body most probably was an olivine-rich L or LL ordinary chondrite that started to produce eutectic melts, which did not adequately mobilize. Hence, the composition of this asteroid would most likely resemble an olivine-rich primitive achondrite similar to those described in Gaffey et al. (1993b), but which is not contained within our terrestrial collections of meteorites. Alternatively, it is possible that Itokawa may be a rare atypical type of LL chondrite, or a previously unsampled oxidized Fe-rich chondritic-like assemblage.

The spectra from this study and that of Binzel et al. (2001) are very similar in that each shows definite absorption bands centered near 1.0 and 2.0 μm, but they differ significantly in spectral slope (Fig. 12). The data presented in this study show a less reddened spectrum than what is seen in Binzel et al. (2001). Possible reasons for these differences could be due to different standard star effects or differences in asteroid sub-Earth latitude. Also, the data from Binzel et al. (2001) were obtained from a completely different viewing geometry, which may have contributed to the observed differences in spectral slope (Table 3).

Binzel et al. (2001) suggest that the red spectral slope may be due to space-weathering effects. The determined albedos for Itokawa from various ground-based observations range from 0.19 to 0.55 (Dermawan et al. 2002; Ishiguro et al. 2003; Sekiguchi et al. 2003; Cellino et al. 2005; Lederer et al. 2005; Müller et al. 2005). If the true Itokawa albedo value is 0.19 to 0.30, and if the actual asteroid composition is an LL chondrite, then alteration effects cannot be ruled out. However, if the albedo value for Itokawa ranges from 0.35 to 0.55, it will be difficult to reconcile these brightness values for an object that is space-weathered. In order to be space-weathered, the starting material of the object must have originally been significantly brighter than an albedo of 0.35. This seems to be inconsistent with the proposed composition of (25143) Itokawa of a possible ordinary chondrite assemblage given the observed albedo range of these meteorites (Gaffey 1976).

A more quantitative analysis of the spectrum obtained from Binzel et al. (2001) reveals a Band I center of 0.99 ± 0.01 μm, a Band II center of 2.02 ± 0.02 μm, and a BAR of 0.39 ± 0.05. These values agree well with the previously reported Itokawa Band I and BAR parameters, 0.99 ± 0.01 μm and 0.40 ± 0.02, respectively (Binzel et al. 2001). In addition, the spectral parameters from Binzel et al. (2001) agree with the parameters derived from the spectra obtained in this investigation. The only real discrepancy noted between the two data sets is the differing BAR values 0.39 ± 0.05 and 0.51 ± 0.03, which places Itokawa either in the S(IV) or S(III) fields respectively (Fig. 9). Given the BAR calibration formula from Gaffey et al. (2002), this corresponds to relatively small differences in olivine to pyroxene abundance ratio: 79:21 as opposed to 74:26. Since the formula has an uncertainty of approximately 0.05, these results agree within the estimated error bars.

Binzel et al. (2001) did not report a Band II center from their data, but the extracted result demonstrates an exact match to those determined from this study of the March 2001 data using identical analytical procedures. The Itokawa band center data determined from analyses of spectra obtained in this study and Binzel et al. (2001) plot in the same location on a Band I versus Band II plot and lie outside the nominal range for LL ordinary chondrites (Gaffey 1976; Gomes and Keil 1980) (Fig. 11). Even though both data sets have similar spectral parameters, and either lie in the S(IV) or S(III) fields, the Band II data indicates that Itokawa does not have pyroxene chemistries of a typical LL ordinary chondrite assemblage.

## CONCLUSIONS

Combined VNIR and NIR spectral data of asteroid (25143) Itokawa suggest that this asteroid has a mineralogy that is dominated by olivine and pyroxene. Analyses of the absorption bands indicate that 1) there seem to be a minimum of two pyroxenes present on the surface of this asteroid, with one component having a high Fe content ($Fs_{43 \pm 5}$) that is significantly above the values observed in ordinary chondrites ($Fs_{14–26}$) (Gomes and Keil 1980; Brearley and Jones 1998), and 2) that there seems to be an average olivine to pyroxene abundance ratio of 75:25 ± 5 with no verifiable rotational variation observed at the detection limit of the data. The preferred taxonomic classification for this asteroid is S(III), but there is some overlap within the S(IV) field. Itokawa's location near the S(III)/S(IV) boundary and its long Band II center position suggest that this asteroid probably has an assemblage with a significant Ca-bearing Fe-rich pyroxene and therefore is not analogous to a typical LL chondrite. It should be noted that this detailed interpretation is heavily based on the accurate determination of the Band II center position. Therefore, it is essential that future asteroid spectra are obtained with high signal-to-noise, and cover a wavelength range out to 2.5 μm to fully illuminate the Band II position in order to adequately characterize these objects.

If there is a high concentration of Fe and Ca in the pyroxene of Itokawa, this suggests partial melting without significant mobilization, and so the parent body of (25143) Itokawa would have probably only reached temperatures of 1050 to 1250 °C (Keil 2000). Given the high olivine content and the location of its average spectral parameters within the S(III) field near the S(IV) boundary, this asteroid probably originally had a composition similar to an L or LL chondrite. Therefore, the meteorite analogue that most closely matches the composition of (25143) Itokawa is an olivine-rich primitive achondrite, and would represent a mineral assemblage not found within the terrestrial meteorite collections. However, an alternative possibility is that given the limited number of suitable unweathered LL chondrites for laboratory analysis, and the sample bias of the meteorite flux to Earth, it is possible that Itokawa may be a rare atypical type of LL chondrite or a previously unsampled oxidized Fe-rich chondritic-like assemblage. These alternatives are less likely given the range of Fs values found in ordinary chondritic meteorites, but cannot be completely omitted from consideration.

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