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Detectability of hydrous minerals using ONC-T camera onboard the Hayabusa2 spacecraft

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Abstract

The Hayabusa2 spacecraft has three framing cameras (ONC-T, ONC-W1, and ONC-W2) for optical navigation to asteroid 1999 JU_3. The ONC-T is a telescopic camera with seven band-pass filters in the visible and near-infrared range. These filters are placed on a wheel, which rotates to put a selected filter for different observations, enabling multiband imaging. Previous ground-based observations suggesting that hydrous materials may be present on the surface of 1999 JU_3 and distributed in relatively limited areas. The presence of hydrous minerals indicates that this asteroid experienced only low to moderate temperatures during its formation, suggesting that primordial materials are preserved. In order to find the best sampling sites, we will perform reflectance spectroscopic observations using the ONC-T near the asteroid after arrival. Finding regions rich in hydrous minerals is the key for this remote sensing observation. In preparation for this, we conducted ground-based experiments for the actual ONC-T flight model to confirm the detectability of the absorption band of Fe-rich serpentine. As a result, we detected the absorption band near 0.7 μm by reflectance spectroscopy of CM2 chondrites, such as Murchison and Nogoya, which are known to contain the Fe-rich serpentine, and did not detect any 0.7 μm absorption in Jbilet Winselwan CM2 chondrite with decomposed Fe-rich serpentine.

Keywords: Hayabusa2; Spectroscopy; ONC; Chondrites; Asteroid

1. Introduction

Hayabusa2 is a sample-return mission to the asteroid 162173 1999 JU_3 (Tsuda et al., 2013; Ishiguro et al., 2014). The spacecraft was launched on December 3,

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2014, and is expected to arrive at the asteroid in 2018, and return to Earth in 2020. Asteroid 1999 JU_3 is one of the near-Earth C-type asteroids (Binzel et al., 2001; Campins et al., 2013). Vilas (2008) found that the reflectance spectrum has an absorption feature centered near 0.7 μm, which indicates the presence of iron-bearing phyllosilicates and primordial or aqueously altered early solar system material on the surface of the asteroid. The objective of the Hayabusa2 mission is to return samples from 1999 JU_3. On the other hand, only the July 2007 spectrum has a 0.7 μm absorption feature, and the other reflectance spectra in the visible and near-infrared range obtained by the ground-based observations do not exhibit a clear indication for 0.7 μm feature Moskovitz et al. (2013), Lazzaro et al. (2013) and Sugita et al. (2013). The signal to noise ratio (S/N) of their observation may not high enough for detection of a 3–4% absorption near 0.7 μm, which is typical for Murchison and Murray CM2 chondrites including iron-bearing phyllosilicates (Cloutis et al., 2011). If any hydrous minerals with 0.7 μm absorption are present, they may be distributed only in relatively limited areas and/or during a limited time period.

To locate hydrous minerals, Hayabusa2 has a multi-band imager. The optical navigation camera (ONC) system onboard the Hayabusa2 spacecraft consists of one telescopic camera (T) and two wide-angle cameras (W1 and W2). These cameras are similar to those installed on the Hayabusa spacecraft (Ishiguro et al., 2010). Table 1 shows the specifications of ONC-T and Fig. 1 shows the transmittance spectra of the band-pass filters. The ONC-T has a wheel with seven band-pass filters and one panchromatic glass window for correction of the light path length. The center wavelengths of the filters are 0.39 μm (ul-band), 0.48 μm (b-band), 0.55 μm (v-band), 0.59 μm (Na), 0.70 μm (x-band), 0.86 μm (w-band), and 0.95 μm (p-band). These filters were selected based on the filters on the Hayabusa spacecraft. In the design phase of ONC for the Hayabusa mission, the filters were selected based on the 8 filters used by the Eight Color Asteroid Survey (ECAS) (Zellner et al., 1985). The names of the filters except for 0.59 μm (Na) are the same in 6 cases as the ECAS filters. The zs-band filter (1.05 μm) used in Hayabusa was changed to Na filter for Hayabusa2 and the center wavelengths of ul- and b-bands have been slightly shifted to longer wavelength because the sensitive spectral range of the CCD image sensor is from ~0.39 μm to ~0.95 μm. Na filter would be not only useful for detecting possible Na atmosphere around the asteroid and also for characterizing the 0.7 μm absorption band. More specifically, reflectance peak of some CM chondrites exhibit around 0.59 μm, not 0.55 μm (e.g., Cloutis et al., 2011).

During the time between arriving at 1999 JU_3 and the first touchdown, the Hayabusa2 spacecraft will stay at the home position (HP) altitude of 20 km and obtain the global multi-band spectral image, which is useful for determination of the first touchdown point. Vilas (1994) detected a 0.7 μm absorption feature in the ground-based observations of C-class asteroids using the ECAS filters. In order to demonstrate the ability of the spectroscopic mapping observations in a laboratory before launch, we performed multi-band spectral imaging of CM2 chondrites (Murchison, Nogoya, and Jbilet Winselwan) using the ONC-T flight model and examined its detectability of hydrous minerals.

Table 1
ONC-T specification.

Optics	Focal length	120 mm
	F#	8
	Effective aperture	φ15 mm
	Field of view	6.35° × 6.35°
	Pixel resolution	22 arcsec/pixel
	Depth of field	100 m ~ infinity
	Transmittance of ND filter	30%
Filter wheel	Band pass filter	#1:ul 0.39 μm, #2:wide*, #3:v 0.55 μm, #4:w 0.70 μm, #5:x 0.86 μm, #6:Na 0.59 μm, #7:p 0.95 μm, #8:b 0.48 μm
	Filter wheel driving rate	9.6°/s (4.69 s/filter)
CCD	CCD	e2v CCD47-20 (AIMO)
	Pixel format	1024(H) pixel × 1024(V) pixel
	Pixel pitch	13 μm × 13 μm
Electronics	Dynamic range	10 bit
	A/D bit length	12 bit

* "Wide" is a panchromatic glass window for light path length correction.

2. Experiment

The absorption of hydrous minerals near 0.7 μm is only ~3%, and its full width of half maximum is ~0.1 μm (Cloutis et al., 2011). ONC-T has filters centered at 0.55 μm, 0.70 μm, and 0.86 μm. To detect the absorption at 3%, S/N for each band should be higher than ~122. ONC-T has a 1 K × 1 K-pixel (13-μm square pixel) CCD with a 12-bit analog-to-digital converter. One analog-to-digital unit (ADU) corresponds to 21 electrons. We set the exposure time so that the intensity of the light is more than 2000 ADU, which corresponds to ~42,000 e, and the S/N is more than 200. The exposure times were 2.8 s (ul), 131 ms (b), 87 ms (v), 131 ms (Na), 33 ms (w), 87 ms (x), and 348 ms (p). The electrical random noise generated by the detector and the electronics in readout is negligible (~2 ADU). The dark current is smaller than ~50 ADU in ul-band and ~5 ADU in other bands in the room temperature during the exposure time. After dark noise correction, the random noise caused by a statistical fluctuation of the dark current is ~1.5 ADU. Therefore, the photon noise is dominant in this experiment. The bias offset can be subtracted using the blind region of CCD pixels.

To examine the detectability of the absorption near 0.7 μm, we used CM2 chondrites: Murchison (pellet), Nogoya (chip), and Jbilet Winselwan (slab). Fig. 2a shows

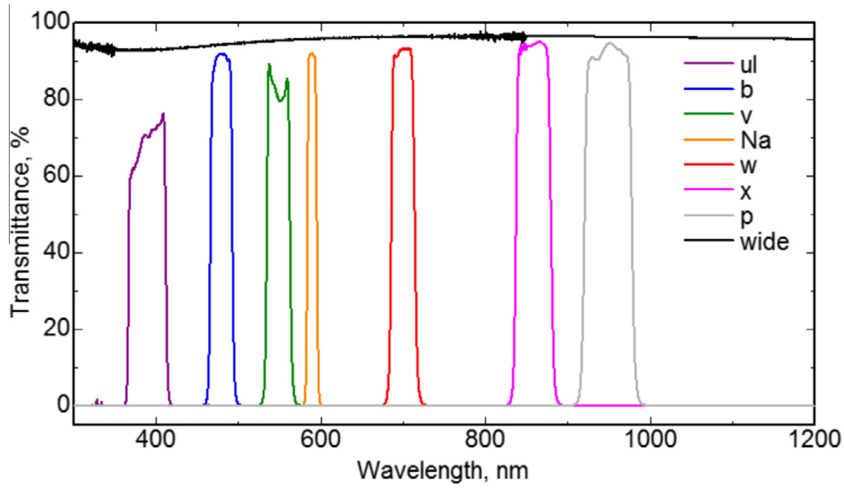


Fig. 1. The transmittance spectra of the band-pass filter installed on the wheel in ONC-T. ONC-T has 7 filters (ul, b, v, Na, w, x, p) and a panchromatic glass window. The center wavelengths of the filters are 390 nm, 480 nm, 550 nm, 589 nm, 700 nm, 860 nm, and 950 nm, respectively. The accuracy of the transmittance is less than 1%.

the configuration of our experiment. Because the depth of field of ONC-T is more than 100 m, we set an achromatic lens with a focal distance of 150 mm in front of ONC-T. The focal length of ONC-T is 120 mm; consequently, the magnification ratio is 1.25. The angular resolution is 0.1 mili-radian. Without the achromatic lens, the spatial pixel resolution at the asteroid surface is 2 m/pix when the spacecraft is at the HP altitude (20 km). The phase angle of the light-source sample camera was set at 30°.

We performed the experiment inside a dark room installed in a clean room at JAXA. The stray light was carefully reduced because the reflectance of the samples is low (~5%). We used an adjustable aperture in front of the light source to illuminate only the sample surface and covered all the parts near the light path with black flock paper (Fig. 2b). We used a halogen lamp (LA-100USW) without a thermal filter as a light source. The stability of the output was confirmed to be less than required (0.3%) during the experiment.

We obtained seven-band images of each sample and used a standard reflective plate to estimate the reflectance of the sample. A white standard reflector called Spectralon (Labsphere SRS-99-20; $R \sim 100\%$) is commonly used for reflectance measurements. The absorption depth of 3% is relative to the reflectance averaged from 0.55 μm to 0.86 μm. The average reflectance is ~5% for 1999 JU_3 and CM2 chondrites, therefore, the absolute absorption depth with respect to the incident flux is very small (0.15%). To reduce the requirement for dynamic range of our experiment, we used a black standard reflector (SRS-05-020) for a reference, the reflectance of which was measured as ~5% in the visible and near-infrared ranges.

3. Results

Fig. 3a shows an image of a Murchison chondrite obtained with the v-band filter. The roughness of the sample surface is clearly seen in the obtained images because the spatial resolution at the sample surface is ~16 μm and the grain size is ~100 μm. Fig. 3b shows the reflectance spectra normalized at the wavelength of 550 nm, averaged in 70 × 70 pixels. The absorption depth (d_a) is calculated from the v-, w-, and x-band reflectances (R_v, R_w, and R_x) as given by the following equation:

$$d_a = 1 - \frac{3.1R_w}{1.6R_v + 1.5R_x} \quad (1)$$

The coefficients are determined by taking into account the difference of the center wavelengths of the v-, w-, and x-band filters (0.55 μm, 0.70 μm, and 0.86 μm). In the case that the spectrum is linear between v-band and x-band, d_a equals to zero.

For the Murchison chondrite (pellet), the absorption depth was measured as ~3%. We selected three regions without any hot pixels or glare due to specular reflection on grain surfaces. The reflectance spectra of the three regions conform to one another, although the reflectance at 0.86 μm and 0.95 μm is slightly variable. In the three regions shown in Fig. 3a, the average absorption depth is 2.9%, and the maximum deviation from the average is 0.3%. This suggests that the 0.7 μm absorption band caused by hydrous minerals can be detected by ONC-T.

Fig. 4a shows an image of a part of the Nogoya chondrite (chip) with the v-band filter. We can see a bright chondrule near the center of the field of view. We selected three regions again (Fig. 4a). Two are for the matrix, and one is for the chondrule. Fig. 4b shows the reflectance spectra normalized at the wavelength of 0.55 μm, averaged in 50 × 50 pixels. The absorption depth of the matrix is 3.8% (Fig. 4A) and 4.2% (Fig. 4B) and that of the chondrule is 0.0% (Fig. 4C). This result suggests that the matrix contains hydrous minerals and that a chondrule does not contain a detectable amount of Fe-rich serpentine.

An image of a part of the Jbilet Winselwan chondrite (slab) with the v-band filter is shown in Fig. 5a. Fig. 5b shows that the absorption depth is below zero in the three

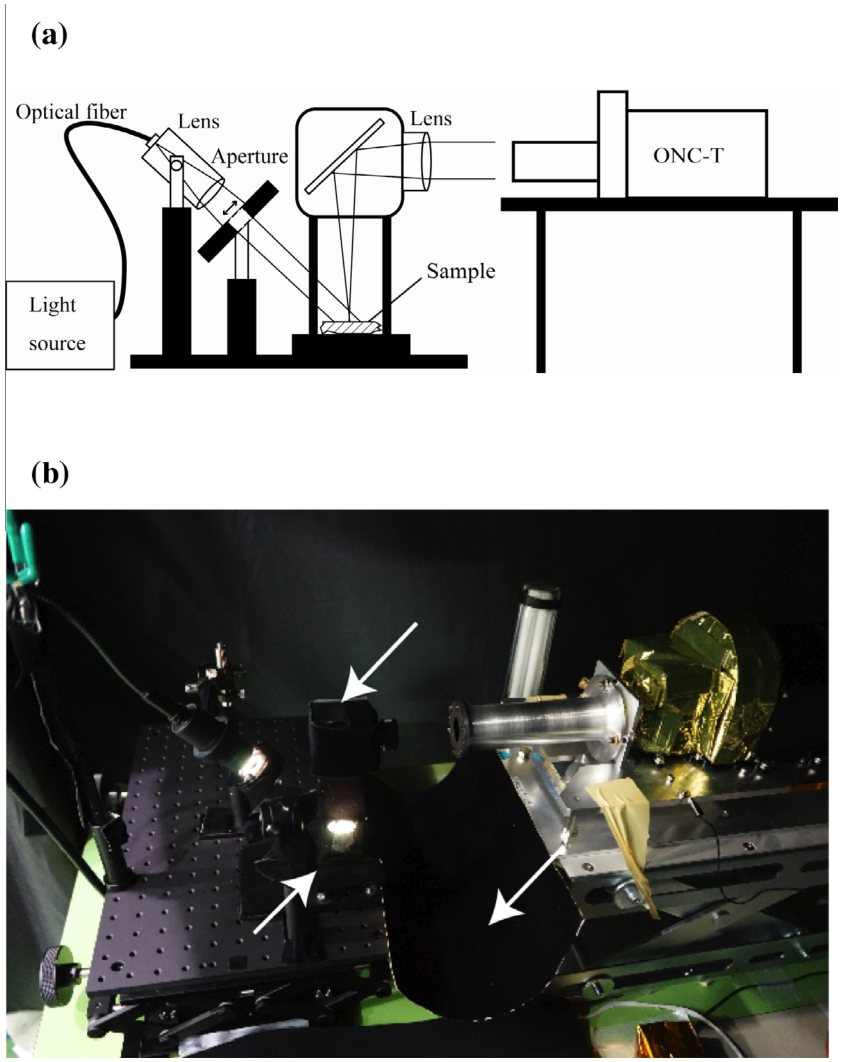


Fig. 2. (a) Schematic diagram for the experimental configuration. An achromatic lens with a focal distance of 150 mm was set in front of ONC-T. The phase angle of the light-source sample camera was set at 30°. (b) Inside the black room. The parts near the light path were covered with black flock paper (arrows).

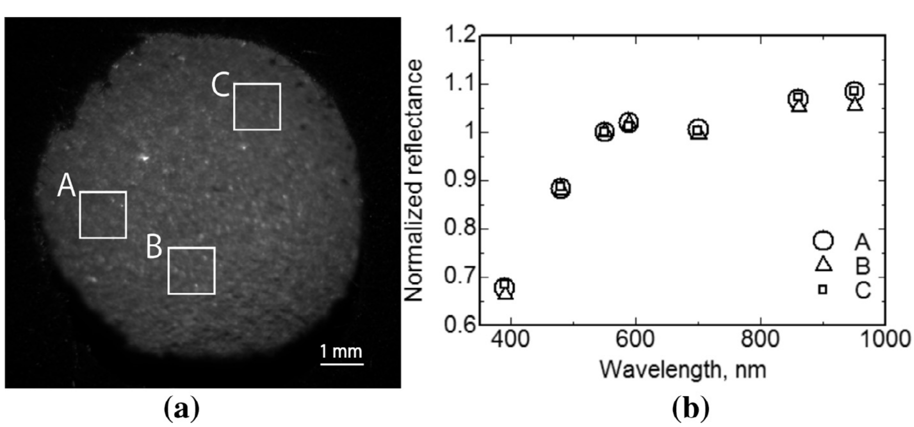
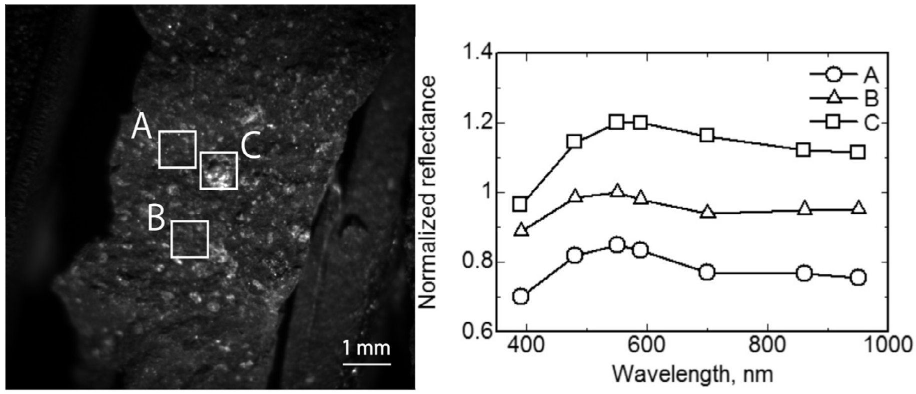


Fig. 3. (a) A v-band image of Murchison (pellet). (b) The multi-band spectra of the three region shown in (a). Spectra are scaled to 1.0 at 550 nm.

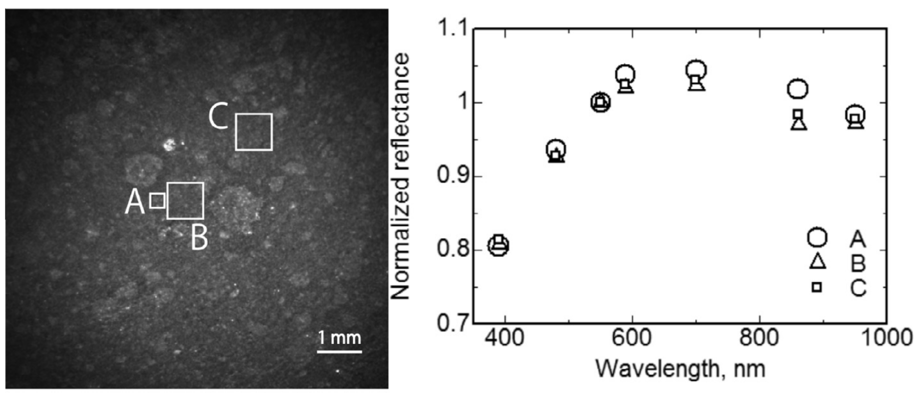
regions, which suggests that this chondrite does not contain crystalline Fe-rich serpentine, consistent with a previous mineralogical and optical study of this chondrite (Nakamura et al., 2014).

The systematic error of our measurement in the laboratory is difficult to assess. However, it is also difficult to explain that systematic differences in the measurements cause the detection of absorption in Murchison and



(a) **(b)**

Fig. 4. (a) A v-band image of Nogoya (chip). (b) The multi-band spectra of the three region shown in (a). Spectra are offset by a reflectance of 0.2 for clarity.



(a) **(b)**

Fig. 5. (a) A v-band image of Jbilet Winselwan (slab). (b) The multi-band spectra of the three region shown in (a).

Nogoya and no absorption in Jbilet Winselwan. We concluded that the ONC-T can detect the 0.7 μm absorption band caused by hydrous minerals and some additional in-flight and ground-based measurements are necessary for qualitative evaluation.

4. Summary and future work

We performed experiments using the ONC-T instrument to demonstrate its ability to detect and locate the hydrous minerals on the asteroid 1999 JU_3. The three CM2 chondrites are used, Murchison (pellet), Nogoya (chip), and Jbilet Winselwan (slab). As a result, the absorption of hydrous minerals centered near 0.7 μm was detected for Murchison and Nogoya, which contain Fe-rich serpentine, and was not detected for Jbilet Winselwan with decomposed Fe-rich serpentine.

For observation of the asteroid, we must take into account the spin of the asteroid. The exposure time is 0.1–0.3 s and it takes approximately 5 s for rotation of the filter wheel to change bandpass filters. The field of view at the asteroid surface significantly changes during this operation. To obtain the correct reflectance spectrum, we have to coregister the position of the field of view of the images of different bands. The sensitivity uncertainty due to temperature change will be small because the total time for 7-color imaging is short (∼100 s). We should conduct experiments to evaluate and compensate for the systematic error caused by this imperfect coregistration, taking into account the flat field correction imperfection. For in-flight calibration, instead of a black standard reference, we should use the standard solar spectrum (e.g., ASTM E-490) and sensitivity calibration data via in-flight standard star observation and pre-flight flat field measurements using an integration sphere. Though lens degradation in space is estimated to be low, standard star observations should be performed shortly before and after the asteroid observations, or frequently enough to confirm that the degradation is negligible.

Additionally, the phase angle was fixed to be 30° in our experiment. However, the actual phase angle for Hayabusa2 varies from 0° to 40°. We are planning an additional reflectance spectroscopy experiment with the various phase angles using the laboratory test model of ONC-T.

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