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Spectral variability of Charon's 2.21-μm feature

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ABSTRACT

The clear angular separation of Pluto and Charon from ground-based telescopes has been enabled by improved technology, particularly adaptive optics systems. Near-infrared spectral data have revealed Charon's surface to be rich in crystalline water ice and ammonia hydrates. In this work, we search for spectral differences across Charon's surface with new near-infrared spectral data taken in the *K*-band (2.0–2.4 μm) with SINFONI on the VLT and NIRI on Gemini North as well as with previously published spectral data. The strength of the absorption band of ammonia hydrate is dependent on the state of the ice, concentration in H_2O, grain size, temperature and exposure to radiation. We find variability of the band center and band depth among spectra. This could indicate variability of the distribution of ammonia hydrate across Charon's surface. If the spectral variation is due to physical properties of Charon, the New Horizons flyby could find the concentration of ammonia hydrate heterogeneously distributed across the surface. Comparison between this work and New Horizons results will test the limits of ground-based reconnaissance.

1. Introduction

Charon is the largest moon of the dwarf planet Pluto, located at Neptune's 3:2 mean-motion resonance in the Kuiper Belt. At the time of the Pluto–Charon mutual eclipse events (while the orbital plane of Pluto and Charon was aligned with the line-of-sight from Earth from 1985 until 1990), observers were able to distinguish color and compositional differences between Pluto and Charon, identifying H_2O-ice on Charon's surface (Buie et al., 1987; Marcialis et al., 1987; Binzel, 1988). The first spectra that could clearly separate Charon's light from Pluto without the aid of occultation revealed a surface rich in crystalline water–ice (Brown and Calvin, 2000; Buie and Grundy, 2000; Dumas et al., 2001). A weak feature detected at 2.21 μm is also present on the surface and is suggested to be due to ammonia hydrate (Brown and Calvin, 2000; Buie and Grundy, 2000; Dumas et al., 2001; Cook et al., 2007; Verbiscer et al., 2007). An additional weak feature at 2.0 μm assumed to also be due to the presence of ammonia hydrate was detected by Merlin et al. (2010).

Charon can be compared with mid-size Transneptunian Objects (TNOs) in the 1000 km diameter size range. A handful of TNOs display prominent features at 1.5, 1.65, and 2.0 μm indicating a surface dominated by crystalline water–ice including Orcus (Fornasier et al., 2004; de Bergh et al., 2005), Quaoar (Jewitt and Luu, 2004), and Haumea (Trujillo et al., 2007; Dumas et al., 2011). Many icy satellites of the outer planets also have water–ice features (e.g., Calvin et al., 1995; Grundy et al., 1999, 2006; Clark et al., 2013). The best spectral analogs to Charon are the medium-sized TNO Orcus and the Saturnian satellite Tethys that, like Charon, have a distinct absorption feature at 2.21 μm (de Bergh et al., 2005; Barucci et al., 2008; Verbiscer et al., 2008).

Each spectrum that has been measured thus far provides a glimpse of the characteristics of a specific part of Charon's surface. Cook et al. (2007) find differences in the band position at 2.21 μm suggesting different ammonia hydration states across the surface. Dumas et al. (2001) detect the feature associated with ammonia

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on the leading side of Charon, but not the trailing side. Buie and Grundy (2000) measure four spectra across the surface and find weak spatial variation of H_2O ice, with stronger absorption on the leading hemisphere. They also note a neutrally absorbing component past 2 μm similar to that seen on icy outer Solar System satellites.

In this work we present new near-infrared spectral data at 3 locations on Charon's surface from SINFONI on the Very Large Telescope (VLT) and 1 from the Near InfraRed Imager (NIRI) on Gemini North. We compare all high spectral resolution, high signal-to-noise ratio data available of Charon to determine how the 2.21 μm feature varies across the surface.

2. Observations

Here we present new near-infrared spectral data at 4 locations on Charon's surface, 3 from SINFONI on the VLT and 1 from NIRI on Gemini North. Previously published data included in this work are from Brown and Calvin (2000), Buie and Grundy (2000), Dumas et al. (2001), Cook et al. (2007), Verbiscer et al. (2007), Merlin et al. (2010). Observing and reduction information is contained therein. Below we describe observation and data reduction procedures for unpublished data.

2.1. SINFONI, VLT

Observations of Charon and Pluto were performed using the SINFONI instrument (Spectrograph for INtegral Field Observations in the Near Infrared), installed at the 8.2-m European Southern Observatory (ESO) VLT, Unit 4 at Paranal Observatory. As described in Dumas et al. (2007) SINFONI is an image slicer integral field spectrometer (Eisenhauer et al., 2003; Bonnet et al., 2004) with a field-of-view split into 32 image-slitlets that reflect onto small plane mirrors before being re-directed toward the selected grating. The 32 spectra are then re-imaged on a 2048 × 2048 pixel Hawaii 2RG (1–2.5 μm) near-infrared detector. We used the $H + K$ spectral grating (resolving power $R \sim 1500$) covering both H and K bands simultaneously (1.4–2.4 μm), and a spatial scale of 12.5 × 25 mas/spaxel (0.8″ × 0.8″ field-of-view). With this small field-of-view, we were able to take separate observations of Pluto and Charon.

Data were taken on May 13, June 9, and August 9, 2005. Total exposure times for each night were 5 min for Pluto and 25 min for Charon (the analysis of Pluto was published in DeMeo et al. (2010)). Observations were taken under clear sky conditions, at airmasses less than 1.15 and seeing generally one arcsecond or less. Solar analogs were observed each night to correct for telluric features. The detector was aligned in the Pluto–Charon direction. For observational conditions and circumstances, see Table 1. For the coordinates reported, the north pole follows the angular momentum vector and the sub-Earth longitude is zero at the sub-Charon (or sub-Pluto) point and decreases in time, following the IAU recommendation (Archinal et al., 2011).

Reduction was performed using the ESO SINFONI pipeline combined with custom IDL procedures. First the data were corrected for bad lines created from bad pixels located among the four non-illuminated edge pixels at the beginning and end of each row. Master darks, master flats, bad pixel maps, and wavemaps were created within the SINFONI pipeline. We improved the master bad pixel map by combining the pipeline output with a more sensitive map created from an IDL routine. Xe–Ar–Kr lamps were used for wavelength calibration, and as part of the SINFONI pipeline, a wavelength map was computed to derive a direct correspondence between pixel position and wavelength. Determining the orientation and position of each spectrum on the detector enabled the reconstruction of an image-cube of the original field-of-view. A sky spectrum was taken nearby before or after observing the object to correct for sky background.

The slices within each image cube were then realigned using an IDL routine that calculated the location of the maximum signal using a 2-D gaussian and shifting it to a center pixel. This alignment allows a smaller aperture to be used when extracting the spectra. We extracted test spectra before and after alignment to be confident that the alignment did not introduce artifacts to the data. A second sky correction was performed by finding the median sky value for each slice within an annulus after rejecting the highest and lowest 10%, and subtracting that median value from the entire slice. The spectra were then extracted from the individual data cubes using QFitsView, the 3D-visualisation tool developed at the Max Planck Institute for Extraterrestrial Physics (MPE) for SINFONI.[1] The individual spectra were corrected for the remaining bad pixels and divided by the solar analog spectra. The Charon data, having more than one spectrum per night, were then combined and normalized to the mean value between 1.7 and 1.75 μm.

2.2. NIRI, Gemini

Charon was also observed with the 8-m Gemini telescope on Mauna Kea. K-band (2.0–2.4 μm, $R \sim 600$) spectra were obtained on 2008 May 30, June 5, and June 18 UT with NIRI (Hodapp et al., 2003) with the Altair adaptive optics (AO) system. The data were reduced using in-house IDL programs. Prior to extracting the 1-D spectrum, the data were pretreated to remove several electronic patterns. These patterns become more apparent when the data are read-noise limited. We removed three patterns: (i) bias offsets, (ii) banding and (iii) striping. The bias differences were estimated by taking the median of the unilluminated portion of each quadrant. The four median values were averaged and a constant was added to each quadrant so the median background equals the average value. Banding is a 16-pixel wide pattern seen in the spectral images that runs perpendicular to the spectrum. The pattern is measured in each quadrant and removed. Striping is an alternating pattern that is parallel to the spectrum. The intensity of the alteration is sensitive to the flux incident on a given pixel. This striping pattern was measured in each quadrant and removed.

The extraction of the 1-D spectrum generally followed the method of optimal extraction by Horne (1986). This method is most useful in the extraction of low signal-to-noise (SNR) data and can result in a final SNR that is equivalent to a 70% increase in the exposure time. Our optimal extraction routine used estimates for the read-noise (10 e^-), dark current (0.75 e^-/s/pix) and gain (12.3 e^-/ADU) to produce errors for each point of the array. The errors were then used to weight each pixel and then the spectrum was extracted from the image.

The method of extraction diverged from Horne (1986) for sky subtraction. Instead of modeling the sky after masking out the objects' spectral beam, we used a 2-D spectrum of the objects at the opposite dither position. By analyzing image differences, we accurately removed dark current and most of the sky flux. However, the difference image had a read-noise $\sqrt{2}$ greater than a single spectral image. Since the data were not read-noise limited, the greater read noise had a minor adverse impact on the final spectrum.

To maximize the effect of optimal extraction, it is important to map out the location of the spectral beam, known as the trace, in the 2-D image. We estimated the trace of the object by finding the maximum signal in each column, and fit a third order polyno-

[1] http://www.mpe.mpg.de/~ott/QFitsView.