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Near-infrared spectral monitoring of Pluto's ices: Spatial distribution and secular evolution

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ABSTRACT

We report results from monitoring Pluto's 0.8 to 2.4 μm reflectance spectrum with IRTF/SpeX on 65 nights over the dozen years from 2001 to 2012. The spectra show vibrational absorption features of simple molecules CH_4, CO, and N_2 condensed as ices on Pluto's surface. These absorptions are modulated by the planet's 6.39 day rotation period, enabling us to constrain the longitudinal distributions of the three ices. Absorptions of CO and N_2 are concentrated on Pluto's anti-Charon hemisphere, unlike absorptions of less volatile CH_4 ice that are offset by roughly 90° from the longitude of maximum CO and N_2 absorption. In addition to the diurnal variations, the spectra show longer term trends. On decadal timescales, Pluto's stronger CH_4 absorption bands have been getting deeper, while the amplitude of their diurnal variation is diminishing, consistent with additional CH_4 absorption at high northern latitudes rotating into view as the sub-Earth latitude moves north (as defined by the system's angular momentum vector). Unlike the CH_4 absorptions, Pluto's CO and N_2 absorptions appear to be declining over time, suggesting more equatorial or southerly distributions of those species. Comparisons of geometrically-matched pairs of observations favor geometric explanations for the observed secular changes in CO and N_2 absorption, although seasonal volatile transport could be at least partly responsible. The case for a volatile transport contribution to the secular evolution looks strongest for CH_4 ice, despite it being the least volatile of the three ices.

1. Introduction

Reflectance spectroscopy has had a remarkable record of revealing the surface compositions of icy Solar System bodies, ranging from satellites of the four giant planets to icy dwarf planets beyond Neptune's orbit (see reviews by Cruikshank et al. (1998a,b), Clark et al. (2013), and de Bergh et al. (2013), and references therein). In addition to nearly ubiquitous water ice, more exotic ices of methane, ethane, nitrogen, oxygen, hydrogen cyanide, ammonia, carbon monoxide, carbon dioxide, and sulfur dioxide have been identified on outer Solar System bodies from their characteristic patterns of absorption bands imprinted on visible to infrared reflectance spectra. Several of these ices are highly volatile (e.g., Brown and Ziegler, 1980; Fray and Schmitt, 2009) and could be mobilized on seasonal timescales, even at the cryogenic temperatures prevalent in the outer Solar System (Hansen and Paige, 1996; Spencer et al., 1997; Trafton et al., 1998; Young, 2012a). In addition to discovering the existence of such ices, spectroscopy can be a powerful tool for monitoring their evolution over time. This prospect is especially enticing for Pluto's surface, where volatile N_2, CH_4, and CO ices are all known to exist (Owen et al., 1993; Douté et al., 1999). Having passed through both perihelion and equinox within the past few decades, Pluto's surface and atmosphere are thought to be undergoing seasonal evolution at an especially rapid pace, at least compared with aphelion. Stellar occultations indicate that the atmospheric pressure has been increasing (Elliot et al., 2003; Sicardy et al., 2003; Young, 2012b and references therein) and photometric lightcurves and Hubble Space Telescope imagery show that Pluto's surface albedo patterns are not static (Buratti et al., 2003; Schaefer et al., 2008; Buie et al., 2010a,b). NASA's New Horizons spacecraft will return a detailed, up-close look at the system in 2015 (e.g., Young et al., 2008). Understanding how that brief snapshot fits into the broader, seasonal context is crucial for getting the most scientific understanding out of the New Horizons flyby.

Various teams have been spectroscopically monitoring the Pluto system at near-infrared wavelengths to help constrain the spatial distribution and long term evolution of its surface ices (e.g., Rudy et al., 2003; Verbiscer et al., 2007; Merlin et al., 2010). From 1995 to 1998, we collected Pluto spectra on 83 nights at Lowell Observatory's 72″ Perkins telescope (Grundy and Buie, 2001).

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Over the past dozen years, our spectroscopic monitoring campaign has continued at NASA's InfraRed Telescope Facility (IRTF). This paper presents the ensemble of the IRTF data and discusses some patterns seen in the data. Companion papers will go into greater detail with radiative transfer models fitted to the Pluto spectra.

2. Data acquisition and reduction

Spectra were recorded during a series of observing runs from 2001 through 2012 at NASA's 3 m IRTF, located at an altitude of 4168 m on the summit of Mauna Kea. Most observing was done remotely by observers situated on the mainland as described by Bus et al. (2002), during scheduled telescope time allocations of typically 2–4 h duration, although longer allocations were occasionally requested in order to obtain higher quality data. We used the short cross-dispersed mode of the SpeX spectrograph (Rayner et al., 1998, 2003). This mode divides the 0.8–2.4 μm wavelength range across five spectral orders, recorded on a 1024 × 1024 InSb detector array. Usable data were obtained on 65 nights, with circumstances described in Table 1. A few of the resulting spectra have been shown previously (Olkin et al., 2007; Protopapa et al., 2008; Tegler et al., 2012; plus several conference presentations), but this paper presents most of them for the first time, along with a full description of data acquisition and reduction procedures.

On each night, sets of Pluto observations lasting from 30 min up to an hour were sandwiched between sets of nearby solar analog star observations. Each set of observations, star or Pluto, consisted of at least three spectra taken in an "A" beam position and at least three more taken in a separate "B" beam position, interleaved according to an ABBAAB... pattern. Star integration times were set to a minimum of 30 s to ensure that the spatial profile in each star integration was averaged over numerous telescope guiding updates, in order to be as similar as possible to the longer 2 min Pluto integrations, while still leaving the majority of available time for Pluto integrations. In cases where the star was too bright to integrate for 30 s without saturating, multiple, consecutive, shorter integrations were combined through co-addition to synthesize 30 s integrations. A and B spectral images were subtracted pairwise to remove most telluric sky emission features. Spectral extraction of the A and B components from each such subtracted pair was accomplished using the Horne (1986) optimal extraction algorithm. Details of our implementation have been described previously and, for the sake of brevity, interested readers are referred to Grundy et al. (2010) and references therein. However, it is worth mentioning here that the spatial profiles used to extract Pluto spectra were constructed from the bracketing star observations, rather than from the Pluto frames themselves.

Pluto's motion along its heliocentric orbit required a new nearby solar analog star to be selected every few years. Stars used for this purpose (and the years they were used) were SAO 160066 (2001), HD 153631 (2003), HD 160788 (2005–2009), and HD 170379 (2010–2012). Spectra of these stars were compared with additional observations of established solar analogs 16 Cyg B, BS 5968, BS 6060, SA 112-1333, Hyades 64, and SA 105-56. The nearby solar analogs were found to be spectrally consistent with these better known analogs, with the exception of HD 170379, which was found to have an effective temperature of ~6500 K, somewhat hotter than the Sun. To account for the temperature difference, a correction based on the ratio of two Planck functions was applied to observations using that star. Pluto spectra were divided by spectra of bracketing nearby solar analogs to remove most instrumental and telluric effects. During 2002 we tried a different procedure of observing an ensemble of well known solar analogs over a broad range of airmasses to construct an extinction model for the night. After correcting all Pluto and star spectra to a common airmass, the Pluto average was divided by the star average. This procedure was hampered by wavelength shifts from instrument flexure, leading us to rely on a nearby solar analog in all subsequent years. Because the observed Pluto flux is entirely due to reflected sunlight over this wavelength range, the Pluto/solar analog ratio produced spectra proportional to the reflectance of Pluto. It is not possible to quote absolute albedos from our narrow-slit spectra, since variable slit losses (e.g., due to changes in guiding, seeing, or focus) undermine the photometric fidelity of comparisons between targets and standards. Residual telluric features remain near 1.4 and 1.9 μm, where strong and narrow H_2O vapor absorptions make sky transparency especially variable in time. Example spectra from some representative nights are plotted in Fig. 1, showing how data quality varies from relatively short total integration times, such as the 2007 June 23 spectrum, to much longer total integrations with multiple interleaved Pluto and star observations as on 2005 May 24.

We selected one of two different slit widths for use during a night's observations. An 0.5″ slit provided a reasonable match to near-infrared seeing at Mauna Kea, resulting in a typical spectral resolving power of $R = 1200$ (wavelength divided by measured full width at half maximum for an unresolved line). A narrower 0.3″ slit boosted the resolution to around $R = 1900$, at a cost of increased slit losses. SpeX's internal integrating sphere, illuminated by a low-pressure argon arc lamp, was observed at similar sky positions as Pluto so as to duplicate instrument flexure conditions experienced during the Pluto observations. A quadratic wavelength calibration curve was derived for each spectral order from the ensemble of arc lamp spectra obtained over the course of the Pluto observations. For additional protection against flexure effects, the derived wavelengths of telluric sky emission lines extracted from the Pluto frames themselves were checked against their published wavelengths (Rousselot et al., 2000; Hanuschik, 2003). Occasionally, this check called for a shift in the constant term of the wavelength calibration relative to what was measured for the argon spectra. Spectral profiles of both arc lamp and sky emission lines were well approximated by Gaussians having full width at half maximum (FWHM) of ~2 pixels for the 0.3″ slit and ~3 pixels for the 0.5″ slit. Wavelength uncertainty, primarily due to flexure and to a few sparse regions in the argon spectrum, is generally less than a pixel. Flexural shifts over the course of a night's observations degraded the spectral resolution of final nightly average spectra, especially for nights with longer total integration times. On such nights, measured resolutions of $R \approx 1600$ and 1100 were more typical for the 0.3″ and 0.5″ slits, respectively.

As seen from Earth, Pluto and its largest satellite Charon are never separated by more than about 1″ on the sky, so light from both objects can enter the spectrograph slit and be blended in our spectra. Unfortunately, the amount of light received from Charon is highly variable, depending on the separation between the two objects, seeing conditions, slit width, and the orientation of the slit relative to the Pluto-Charon position angle. At higher airmasses we would try to orient the 15″ long slit near the parallactic angle to minimize effects of differential refraction by the Earth's atmosphere, while at lower airmasses we would try to place it along the Pluto-Charon line. However, over the past decade Pluto has been passing through a highly crowded region near the galactic center, so the need to keep background sources out of the slit often left us with little choice of slit orientation. Our use of point-source spatial profiles based on the star observations helped reduce the Charon contribution on nights of better seeing, but on poor seeing nights, signal from the two bodies was highly blended. Charon accounts for about a fifth of the total surface area in the Pluto system so it could contribute up to a fifth of the observed signal, if its albedo was the same as Pluto's. Charon's albedo is actually lower than Pluto's at most wavelengths between 0.8 and 2.4 μm (Fink