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Water frost on Charon

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The current series of mutual eclipses between Pluto and its satellite, Charon, provides a very powerful means of probing the most distant known planet in our Solar System. Observations from 1985 and 1986 have already dramatically improved our knowledge of the sizes, albedos, and the orbital parameters of the system[1-3]. One experiment that we had been waiting to perform is to observe Pluto during a total eclipse of its satellite. This geometry provides a direct means to study the planet without contamination from the satellite. Once the spectrum of the planet is known, it is then possible to subtract it from the spectrum of the planet plus satellite and thus discern the properties of the satellite. Here we present new spectra of the Pluto–Charon system taken just before and during a total eclipse of the satellite. From these data we have extracted the spectrum of the satellite, Charon, which reveals the spectral signature of water ice. There is no evidence for any methane or ammonia frost on the surface of Charon. This observation places important constraints on the composition and origin of this planetary system.

On 3 March 1987 UT Marcialis *et al.* obtained observations[4] of a total eclipse of the satellite at four discrete wavelengths, 1.5, 1.75, 2.0 and 2.35 μm. Their observations provided a tentative identification of water ice on Charon through the excellent placement of the chosen wavelengths. Our efforts at Mauna Kea on the same date were hampered by high winds and we could not provide simultaneous observations.

The observations reported here were made by one of us (M.W.B.) at the IRTF (infrared telescope facility) on Mauna Kea, Hawaii, on the night of 23 April 1987 UT. The detector was an InSb diode used in a spectrometer in which a circular variable interference filter (CVF) provided the wavelength separation. The sensitivity of this system was such that we could obtain a CVF spectrum of Pluto with a signal-to-noise ratio of ~100 in one hour.

We used an 8-arc s aperture with a 5% resolution, high-throughput CVF covering the wavelength range 1.5-2.5 μm. A single spectrum consists of 13 different points equally spaced across this wavelength range. With the resolution of this CVF a 13-point spectrum is slightly undersampled. The chopping distance was 20 arc s to the north, with a chopping frequency of 6 Hz. The comparison star for these observations was SAO120599. This G0 star should match the near-infrared spectrum of the Sun very closely so that a ratio spectrum of Pluto to the star will be a close approximation of its spectral reflectance. The same star was used by Marcialis *et al.*[4].

The predicted event timing was 11:13 UT for first contact, 13:07 UT for second contact, 13:59 UT for third contact, and 15:44 UT for fourth contact[5]. It is between second and third contact that the satellite is completely hidden from view. Before the event, D. J. Tholen provided an updated prediction that second contact would be ten minutes early and third contact five minutes late.

The out-of-eclipse spectrum was started at 9:20:09 UT and completed at 10:20:52 UT. The spectrum during totality was taken between 13:00:35 UT and 14:00:04 UT, thus matching the predicted geometry very closely. In all cases, a spectrum of the comparison star was taken before and after each spectrum of Pluto. Throughout the observations the tracking of the telescope on Pluto was checked about every five or ten minutes to ensure that there were no systematic drifts of Pluto out of the aperture.

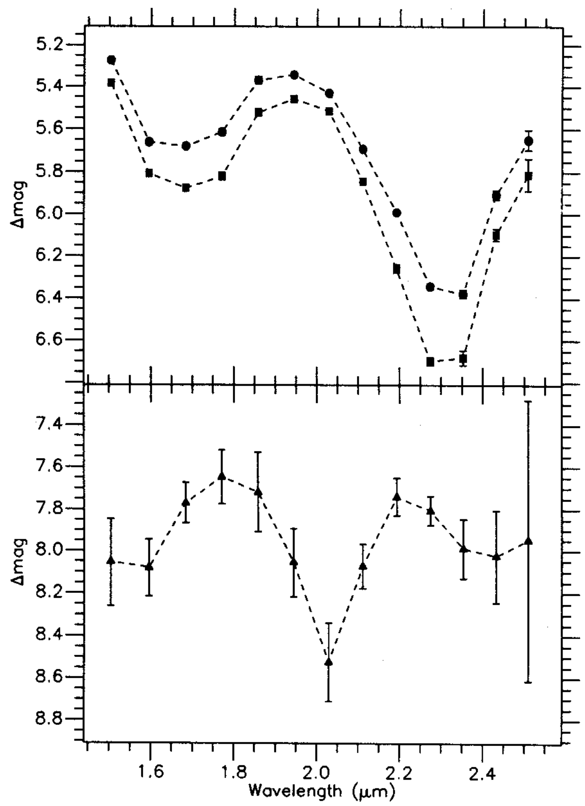

Fig. 1 *a*, Magnitude plot of spectra of the Pluto–Charon system before and during the total eclipse of the satellite. *b*, Spectrum of Charon derived from subtracting the two spectra in *a* after correcting for lightcurve effects. The stellar magnitudes are relative to SAO120599. ●, Pluto and Charon; ■, Pluto, ▼, Charon.

The fluxes were recorded in units of stellar magnitude, and the instrumental magnitudes for each point in the spectrum were converted to colours by subtracting each magnitude in a given spectrum from a reference wavelength, 2.03 μm. The colour data were then reduced as standard photometry using the comparison star to provide the extinction correction at each wavelength. By reducing the data as colours, errors in the extinction correction were minimized. The colour spectra were then converted back to magnitude spectra for analysis by adding the magnitude at the reference wavelength. The errors derived are in units of a standard deviation.

Since the comparison star is similar in colour to the Sun, the reduced spectra should closely represent the spectral reflectance of the system. Figure 1*a* shows the out-of-eclipse spectrum of Pluto and Charon together with the eclipse of Pluto alone. Strong absorptions due to methane, centred at 1.7 and 2.3 μm, dominate both spectra. The error bars shown for each point reflect the known random errors from all stages of the data reduction. The signal-to-noise ratio is ~100, representing the highest signal-to-noise spectra of this system ever published for this wavelength range. These spectra are plotted on a magnitude scale so that any changes in brightness will not affect the shape of the spectral features. Any change in the shape of the spectrum on this plot is due entirely to the loss of the light from Charon. Note that the methane bands are clearly deeper when the light from Charon is removed.

Before the spectrum of Charon can be extracted, the effect of the underlying lightcurve of the system must be removed. At this rotational phase the slope of the background lightcurve of the system is 0.0055 mag per hour (D. J. Tholen and E.F.T., in preparation; M.W.B. and D. J. Tholen, in preparation). In the 3.67-h interval between taking the spectra, the system faded by

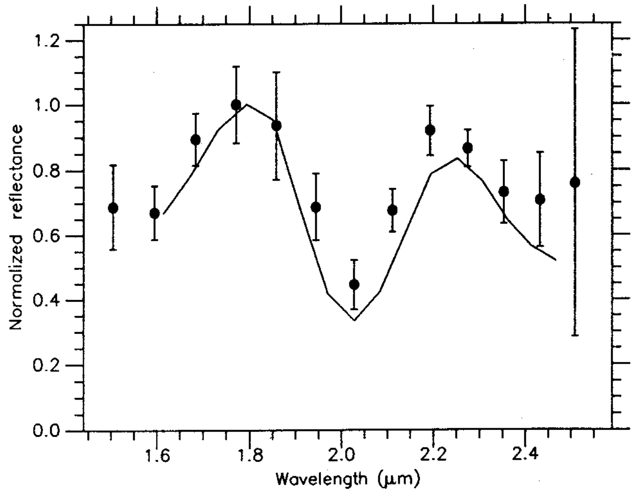

Fig. 2 Infrared spectrum of Charon compared to a laboratory water frost. The solid curve is a laboratory spectrum of a medium-fine-grained H_2O frost. The plot shows the data from Fig. 1*a* as relative reflectance, normalized to 1 at 1.8 μm.

0.020 mag. Here we have assumed that all of the lightcurve slope is due to Pluto. Therefore the out-of-eclipse spectrum was reduced by 0.020 mag before subtracting the Pluto spectrum. As Pluto contributes most of the light (~80%), we would expect most of the slope to be due to Pluto; though the precise contributions of Pluto and Charon to the lightcurve are not known. Furthermore, the slope of the lightcurve is well determined only at visual wavelengths. By using the visual lightcurve slope, we are extrapolating the lightcurve behaviour from 0.4 to 2.0 μm, on the assumption that the slope is independent of colour. As it has already been proved that the methane spectrum of Pluto varies with rotational phase[6,7], we know that this assumption is flawed.

Figure 1*b* shows the spectrum of Charon obtained by subtracting the two spectra shown in Fig. 1*a* after the lightcurve correction is applied. The characteristic 2-μm water frost absorption feature seen in the spectrum of Charon is unmistakable. Shown for comparison in Fig. 2 is a laboratory spectrum of a medium-fine-grained H_2O frost[8]. The spectrum of Charon is very different from that of Pluto alone, as can be seen in Fig. 1. In fact, the lack of any residual spectral signature due to methane (the spectrum of Pluto) gives us confidence that the lightcurve correction is accurate.

The spectrum of Charon is quite similar to those of other satellites in the outer solar system. Europa, Ganymede, Callisto, most of the saturnian satellites, and the uranian satellites all have spectra dominated by water frost absorptions[9]. The spectrum of Miranda is perhaps the closest match[10].

The most interesting result is that the spectra of Pluto and Charon are so different. If both bodies have the same origin, then the methane Charon originally had on its surface must have sublimated and escaped. In addition, the lack of a water frost signature on Pluto implies that any water frost there has been covered with methane. Both the lower albedo of Charon relative to Pluto and the lower surface gravity could have combined over the age of the solar system to remove all traces of methane from at least the near surface layers on Charon. If this is the case, we can now begin to set some limits on the composition and origins of the two bodies. The difference in the surface composition makes the measurement of the relative densities within the system much more important. Fortunately, this is a problem within the range of the Hubble Space Telescope.

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