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FIRST ULTRAVIOLET REFLECTANCE SPECTRA OF PLUTO AND CHARON BY THE *HUBBLE SPACE TELESCOPE* COSMIC ORIGINS SPECTROGRAPH: DETECTION OF ABSORPTION FEATURES AND EVIDENCE FOR TEMPORAL CHANGE

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ABSTRACT

We have observed the mid-UV spectra of both Pluto and its large satellite, Charon, at two rotational epochs using the *Hubble Space Telescope* (*HST*) Cosmic Origins Spectrograph (COS) in 2010. These are the first *HST*/COS measurements of Pluto and Charon. Here we describe the observations and our reduction of them, and present the albedo spectra, average mid-UV albedos, and albedo slopes we derive from these data. These data reveal evidence for a strong absorption feature in the mid-UV spectrum of Pluto; evidence for temporal change in Pluto's spectrum since the 1990s is reported, and indirect evidence for a near-UV spectral absorption on Charon is also reported.

Key words: planets and satellites: surfaces

1. INTRODUCTION

Pluto has not yet been visited by any spacecraft, so our knowledge of it is necessarily limited to remote sensing observations from Earth and Earth's orbit. Obtaining remote sensing ultraviolet spectra of Pluto is of interest because they can potentially constrain Pluto's surface and atmospheric composition, and can inform observation planning for the upcoming July 2015 *New Horizons* flyby of Pluto (e.g., Weaver & Stern 2008).

The first published UV spectrum of the Pluto system was obtained by *IUE* (Stern et al. 1989) using its Long Wavelength Prime camera in low dispersion with maximum signal-to-noise ratio (S/N) per exposure of 6 at 2800 Å. A geometric albedo of 0.35 ± 0.05 smoothed over 100 Å near 2700 Å was also reported, along with a blue spectral slope that suggested an albedo minimum occurs between 3000 and 3500 Å. Additional *IUE* spectra were obtained during 1988 and 1989 spanning about 30% of the rotational light curve range (Stern et al. 1991). Over this limited wavelength range, an opposite variation of the UV and visible light curves was found, suggesting a UV absorption feature on the surface of either Pluto or Charon. This behavior was confirmed for Pluto's light curve by the *HST* results reported by Trafton & Stern (1996), but was revealed to occur only near Pluto's light curve maximum.

The *Hubble Space Telescope*'s (*HST*'s) sensitivity is far superior to *IUE*'s, and its resolution is capable of splitting Pluto from Charon (<1 arcsec apart), which *IUE* could not do. Using *HST*'s Faint Object Spectrograph, Trafton & Stern (1996) reported spectra of Pluto without Charon extending down to 2500 Å. Among their findings was that Pluto's geometric albedo averaged over rotational phases declines in brightness down to ∼2600 Å, where a minimum, possibly representing an absorption feature, was inferred.

Here we explore the UV reflectance spectra of Pluto and its largest satellite, Charon, using *HST*'s Cosmic Origins Spectrograph (COS; Osterman et al. 2011). COS is a considerably more sensitive far-ultraviolet spectrograph than any previously installed on board *HST*; the observations we report are the first Pluto and Charon observations made using COS.

2. OBSERVATION DESCRIPTION AND DATA REDUCTION

The Pluto and Charon system was observed with *HST*/COS in four separate visits from 2010 August to October, all using the G230L grating of the COS near-UV (NUV) channel. Each of these observations covered one of two wavelength ranges and one of two Pluto longitudes.

COS is able to spatially resolve targets about 1″ apart, aligned in the cross-dispersion direction. In order to obtain distinct spectra of Pluto and Charon, we targeted Pluto longitudes near 90° and 270°E, which present the largest possible current-day Pluto–Charon angular separation of 0.″86. With angular diameters of about 0.″1 and 0.″05, respectively, these two bodies are effectively point sources for COS.

In each visit, Pluto (the brightest object in the field) was centered in the COS aperture using an acquisition sequence of images and pointing adjustments. *HST*'s roll angle was then specified to align Charon in the cross-dispersion direction. Acquisition images verified the final positions of Pluto and Charon in the COS field. Two visits used an instrument "central wavelength" setting of 3000 Å, obtaining spectral coverage from 1715 to 2150 Å and 2810 to 3250 Å, while two other visits used a 3360 Å central wavelength, obtaining coverage from 2080 to 2520 Å and 3170 to 3600 Å. Our spectra therefore exhibit a gap in coverage from 2525 to 2810 Å. Additional details of these four observations are presented in Table 1.

Between the start and end of the science exposures comprising each individual observation, Pluto and Charon each rotated between 5° and 9°; therefore, in Table 1 the central sub-Earth longitudes specified for each observation give the approximate longitude at the midpoint of observation. We use east longitudes and adopt the convention in which Pluto's north pole corresponds to its angular momentum vector, following the right-hand rule (and, we note, contrary to the IAU definition which violates angular momentum conventions).

Spectra were extracted from the raw event lists recorded by COS, using the COS pipeline software *calcos*, version 2.16. In general, we used the default extraction parameters, with two notable modifications.

Table 1
Observing Circumstance

Observation Date	*HST* Program ID	Central Wavelength (Å)	Pluto Longitude (°E)	Total Exposure (s)
2010 Aug 28	12042	3000	94	4860
2010 Aug 31	11540	3360	273	7912
2010 Sep 26	12042	3000	273	7912
2010 Oct 31	11540	3360	96	4860

1. *Cross-dispersion locations of spectral stripes and detector background regions*. Pluto was centered in the COS aperture during all observations, with Charon very nearly aligned in the cross-dispersion direction. Default extraction parameters would pick up Pluto's spectrum only (perhaps with faint contamination from the wings of Charon's illumination pattern) and would include Charon flux in the region used to measure background. Extraction of Charon's spectrum required identifying the location of Charon's spectral stripe in detector images and choosing background regions not contaminated by Pluto or Charon. Extraction of Pluto's spectrum required similar adjustment of the background locations.
2. *Cross-dispersion height of the extraction regions*. The default extraction region height for NUV spectra is 57 pixels, well beyond the NUV channel's PSF-core cross-dispersion spatial resolution (about 4 pixels with the G230L grating). Given our UV-faint targets, detector background is the largest contributor to statistical uncertainty in our results. We sought to minimize the included background and its noise by reducing the area of the region from which each spectrum is tallied; based on examination of the shapes and heights of the spectral stripes of both targets on the detector, we adopted a height of 27 pixels for all spectral extraction regions. This extraction width includes >95% of the signal, while suppressing noise that would be included with a wider extraction width.

After pipeline extraction of the spectra of Pluto and Charon, one additional correction was required, i.e., the adjustment of Charon's wavelength scale to correct for Charon's imperfect alignment with Pluto in the dispersion direction. The wavelength scale generated by the pipeline assumes a target perfectly centered in the dispersion direction. We used the measured horizontal (dispersion direction) offset of Charon from Pluto in the COS acquisition images, in integer pixels, and the G230L system dispersion of 0.39 Å pixel^{-1} to generate this correction. Offsets of –9 to + 12 pixels were found; these yielded corrections of –3.5 to 4.7 Å to our observations.

The COS NUV channel illuminates its detector with three separate spectral stripes, each capturing a different portion of the full wavelength coverage of a given grating. With grating G230L, stripes A and B cover non-overlapping wavelengths in first order, and stripe C is primarily second-order illumination, partly overlapping with the spectral coverage of stripe A. Because the extracted spectra from stripe C had noise levels many times greater than the other two stripes, we used only stripes A and B in our analysis.

We binned the COS flux spectra in 40 Å bins to achieve an improved S/N. We excluded wavelengths shortward of 2000 Å, where S/N was very poor, and longward of 3200 Å, beyond which the flux calibration of the G230L spectrograph configuration is unreliable due to second-order grating contamination.

Table 2
Solar Spectrum Choices

Pluto COS Observation Date	Solar SORCE Spectrum Date
2010 August 28	2010 September 2
2010 August 31	2010 September 5
2010 September 26	2010 September 23
2010 October 31	2010 September 23

To compute albedo spectra for Pluto and Charon, we adopted daily average solar UV spectra from the Solar Radiation and Climate Experiment (SORCE) mission. We used spectra from dates corresponding to the dates of Pluto observations, appropriately adjusted for solar Carrington rotation, such that Pluto and SORCE viewed approximately the same solar longitude. However, spectra from the SORCE archive were unavailable for two of the adjusted dates, corresponding to September 26 and October 31, due to SORCE technical problems. A comparison of several SORCE daily solar spectra from the relevant time period revealed minimal solar flux variations (maximum flux difference at any wavelength between these dates was under 3%) in the wavelength range of interest. We therefore adopted solar spectra from the closest dates for which they were available for these Pluto observations; this technique reduces possible errors introduced by not having simultaneous solar spectra of the hemisphere of the Sun facing Pluto. Table 2 summarizes the SORCE solar spectra adopted for each of our Pluto observation dates.

The adopted SORCE solar flux spectra were then binned in the same manner as the Pluto and Charon spectra, and geometric albedo spectra were calculated for Pluto and Charon separately according to $p = (D^2\Delta^2/R^2) f(F_{\rm body}/F_{\rm sun})$, where D is the distance between Earth and the target body at the time of the observation, Δ is the distance between the Sun and the target body at the time of the observation, R is the radius of the target body, $F_{\rm body}$ is the binned COS flux spectrum of the body, $F_{\rm solar}$ is the binned SORCE solar spectrum, and f represents the solar phase function correction function. We adopted consensus radii of 1170 km and 604 km for Pluto and Charon, respectively. For the phase function corrections to zero-phase geometric albedos, we adopt Buie et al.'s (1997) V-band phase coefficients, as did previous *HST* Pluto/Charon UV spectral analysis papers; these coefficients are 0.0294 mag deg^{-1} and 0.0866 mag deg^{-1}, respectively, for Pluto and Charon.

3. RESULTS AND DISCUSSION

We have analyzed the albedo spectra of Pluto and Charon obtained by COS in 2010 and present key results in Figures 1 and 2, respectively; Table 3 further quantifies some of these results; it presents albedo averages in the 2250–2450 Å and 2850–3150 Å regions, and slopes in the 2850–3150 Å region.

Table 3
Pluto and Charon UV Albedo Results

Regions	Average Geometric Albedo		Geometric Albedo Slope	
(Å)	Pluto 95 deg	Charon 95 deg	Pluto 95 deg	Charon 95 deg
2250–2450	0.20 ± 0.01	0.24 ± 0.04	. . .	. . .
2850–3150	0.23 ± 0.002	0.24 ± 0.01	17% ± 3%/1000 Å	1.1% ± 14%/1000 Å
	Pluto 273 deg	Charon 273 deg	Pluto 273 deg	Charon 273 deg
2250–2450	0.19 ± 0.01	0.28 ± 0.03	. . .	. . .
2850–3150	0.27 ± 0.002	0.25 ± 0.01	14% ± 2%/1000 Å	1.5% ± 7%/1000 Å

Note. Pluto albedo slopes are not meaningful in the 2250–2450 Å region owing to the reported absorption feature there.

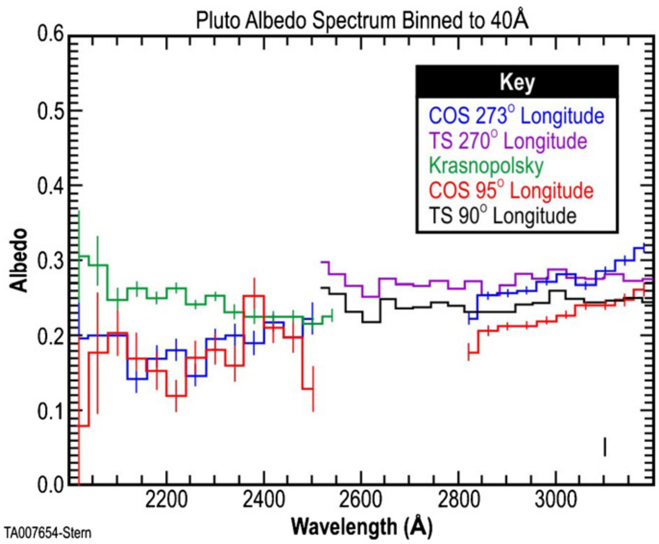

Figure 1. Pluto's mid-UV geometric albedo spectrum obtained by COS at longitudes 95 and 273 deg, compared to previous *HST* Pluto mid-UV reflectance datasets. TS = Trafton & Stern (1996) average geometric albedo spectra at each longitude.

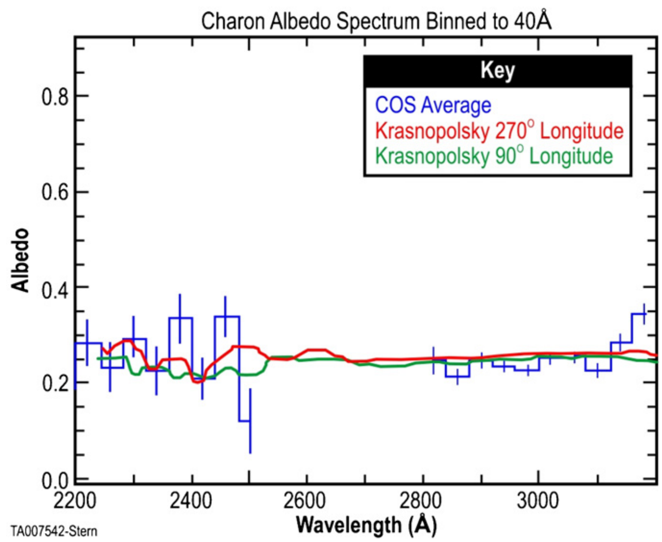

Figure 2. Charon's mid-UV geometric albedo spectrum obtained by COS at longitudes 95 and 270 deg, compared to previous *HST* Charon mid-UV reflectance work by Krasnopolsky (2001).

In Figure 1, we depict the COS UV spectra of Pluto at 95° and 273° east longitude, with comparison to both Krasnopolsky's (2001) short-wavelength (1800–2500 Å) global average spectrum and Trafton and Stern's data spanning 2550–3200 Å.

Examining Figure 1, we find generally good agreement between the 2800 and 3200 Å COS spectra at 95° and 273° longitude with the earlier data. However, the agreement is not fully complete: at both of our sampled longitudes the COS data show a red slope beginning near ∼3000 Å, which was not seen in the Trafton and Stern data at these wavelengths. Interestingly, this red slope may be slightly steeper at 273° longitude than at 95° longitude, but the difference is statistically weak. Except for this red slope, the 2600–3200 Å reflectance spectra as measured by COS are featureless.

We interpret this steeper 2800–3200 Å slope than that seen in previous data as the first evidence of temporal change in Pluto's mid-UV spectrum. This change could be related to effects of Pluto's atmospheric pressure increase over the past 20+ years (e.g., Gulbis 2006; Elliot et al. 2007). Alternatively, this could be due to our sampling of a different range of latitudes than older data, owing to Pluto's motion around the Sun and the consequent aspect angle change associated with its high obliquity (specifically, the sub-Earth latitude on Pluto has changed from –9° at the mid-point of the 1992–1993 Trafton & Stern data set, to −43° at our observing epoch in 2010).

Concerning the shorter wavelength COS Pluto data spanning 2000–2500 Å, we first point out that the error bars shortward of 2100 Å make these reflectance data unreliable, so they will not be discussed. Otherwise, we find the COS 95° and 273° longitude results are in good agreement with one another. However, they reveal significantly (i.e., ∼20%) lower albedos than Krasnopolsy's results, which could also be the result of a change in Pluto's spectrum that took place between the time these two data sets were taken, though the lower signal level at these bluer wavelengths makes this result less secure than the temporal change reported above at longer UV wavelengths.

Most importantly, the new data reveal evidence for an absorption feature centered between 2100 and 2400 Å. This feature is clearly detected in the 95° longitude data, and may be present in the 273° longitude spectrum as well, though it is clearly less distinct there. This is the first ultraviolet absorption feature unambiguously detected in Pluto's spectrum. Although we cannot uniquely identify a specific absorber with this feature, numerous hydrocarbons and nitriles produce absorptions in this wavelength range; such species are expected photochemical byproducts of the photolysis of Pluto's atmosphere and the radiolysis of its surface (Moore & Hudson 2003).

Now consider the COS Charon reflectance data, which we present in Figure 2. Here we find good agreement with

Krasnopolsky's albedos at 90° (southern elongation) and 270° (northern elongation); this good agreement strengthens the case that the differences between the COS and Krasnopolsky Pluto data are real and not instrumental. Continuing, the flat (i.e., gray, near zero) slope of our Charon UV spectra is very much like the flat visible reflectance spectra of Charon (Brown & Calvin 2000). However, because our albedos are lower than Charon's ∼0.35 reflectance at visible wavelengths, we infer that there must be some decline in Charon's albedo in the near-UV, longward of our reddest data but shortward of ground-based limits. Such a result calls for *HST* or ground-based data to directly confirm.

4. CONCLUSIONS

Using the *HST*/COS in 2010, we observed the mid-UV spectra of both Pluto and its large satellite, Charon, at two rotational epochs, 95° and 273° east longitude. These data yielded albedo spectra, average albedos, and albedo slopes in the mid-UV spectra of Pluto and Charon. In turn, the albedo spectra reveal:

1. evidence for an absorption feature in the mid-UV spectrum of Pluto,
2. evidence for temporal change in Pluto's UV spectrum since the 1990s, and
3. indirect evidence for a near-UV spectral absorption on Charon.

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