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CVF Spectrophotometry of Pluto: Correlation of Composition with Albedo

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Time-resolved spectrophotometry of the Pluto–Charon system was obtained on 6 nights in March and April of 1988. The observations include about one-third of the 6.4-day lightcurve, centered around minimum light, and span the wavelength region from 0.96 to 2.65 μm. The spectra reveal night-to-night variations in depths of methane absorptions throughout this region. Band depths vary such that their equivalent width is least near minimum light. One obvious interpretation is that dark regions on the planet are depleted in methane relative to bright areas, at least for the hemisphere observed. Our results are consistent with the observations of M. W. Buie and U. Fink (1987, *Icarus* 70, 483–498) but in conflict with those of S. R. Sawyer (1989, *Bull. Amer. Astron. Sci.* 21, 986, Abstract). The near-infrared spectrum of Pluto appears to be dominated by surface frost; atmospheric methane contributes much less to the overall spectral signature. We see evidence that Pluto's dark equatorial regions tend to be redder than those of more moderate albedo. © 1991 Academic Press, Inc.

1. INTRODUCTION

Infrared spectrophotometry of Pluto by Cruikshank *et al.* (1976), Lebofsky *et al.* (1979), and Cruikshank and Silvaggio (1980), along with visual/near-infrared spectroscopy by several groups (e.g., Fink *et al.* 1980; Soifer *et al.* 1980), has demonstrated conclusively the existence of methane in the combined light of the Pluto–Charon system. The mutual events allowed Marcialis *et al.* (1987) to determine that the spectral signature of methane could be attributed wholly to Pluto; Charon's surface is consistent with that of water frost. These observations subsequently were confirmed by Buie *et al.* (1987).

CCD spectrophotometry of the Pluto–Charon system in 1983 (Buie 1984, Buie and Fink 1987) shows methane absorption bands at 6190 and 8900 Å that seem to vary with rotational phase. However, similar observations spanning many nights in the period 1983–1989 (Sawyer 1986, 1989, Sawyer *et al.* 1987) apparently are in conflict with the results of Buie and Fink.

To resolve these discrepant results regarding rotational variability of Pluto's methane, and to test whether albedo and composition are correlated, we undertook a program to observe Pluto during the 1988 apparition.

2. OBSERVATIONS

To increase the sensitivity of our observations to methane, Pluto was observed in the 1.0- to 2.6-μm region of the spectrum. As for most other cosmically abundant frosts, the spectral activity of methane is much greater at near-infrared wavelengths than in the visual region of the spectrum.

Observations reported here were made with the liquid He-cooled InSb infrared photometers RC1 and PRIMO at NASA's 3-m Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. Dates, times, and detector systems used for the observations are reported in Table I. The University of Hawaii double CVF (circularly variable filter) was used to step through 22 different wavelengths in the spectral region from 1 to 2.65 μm. This CVF has spectral resolutions ($\Delta\lambda/\lambda$) of 3 and 5% in the short- and long-wavelength halves, respectively. The switch from short half to long half was made at about 1.5 μm, with one channel of overlap to ensure that both halves had a common zero point. The telluric water absorption at 1.40 μm, along with the "CVFCAL" program written by M. Buie, was used to calibrate the wavelength scale for the shorter half.

Based upon previous experience, it was assumed that both halves of the CVF were mounted rigidly with respect to one another. On the night immediately following our April run, we assisted Buie in an independent calibration of the long-wavelength half, using the 1.86-μm telluric absorption. Encoder offsets to the center of this feature were virtually identical for all three runs, so we have confidence in our long-wavelength calibrations as well.

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TABLE I
Log of IRTF Pluto Observations, 1988

Date	UT Times	No. Scans	r (AU)	Δ (AU)	α (deg)	$\theta_{\rm rot}$	Dewar	Comments
March 08	1540 - 1620	1	29.669	29.098	-1.59	0.85	RC1	cloudy < 1300
March 09	1130 - 1500	3	29.669	29.086	-1.57	0.00	RC1	
March 10	1110 - 1350	3	29.669	29.073	-1.55	0.15	RC1	occ. cirrus
March 11		0					RC1	winded out
April 15	0845 - 1320	4	29.668	28.740	-0.75	0.78	PRIMO	
April 16	1230 - 1330	1	29.668	28.735	-0.73	0.94	PRIMO	cloudy < 1200
April 17	0820 - 1130	3	29.668	28.732	-0.71	0.08	PRIMO	superb night

Note. Listed are times and circumstances of the observations. r, Δ, α, and $\theta_{\rm rot}$ are heliocentric and geocentric distance, solar phase angle, and rotational phase, respectively.

Each scan of Pluto's spectrum required 40–45 min to complete. At each wavelength step, one measurement of Pluto was taken as the mean of 10 separate 4-sec integrations. Measurements were made through a 4-mm aperture (7″.8 in the sky plane), relative to sky reference areas 20″ north and south of the object.

The nearby star SAO 120107 (= HD 120050) was used as the primary comparison object. This solar-type star has been used as a flux standard at many wavelengths for study of Pluto throughout the mutual event season, and defines the zero point (at least at visual wavelengths) to which the "Johnson Pluto system" is referenced (cf. Tholen *et al.* 1987b). SAO 120107 typically was observed both before and after each scan of Pluto. As a check on the nightly extinction coefficient determinations, we also observed the solar analog 16 Cyg B. Reproducibility was found to be excellent. The derived extinction coefficients almost always agreed to better than 5% (in the telluric H_2O bands), and to better than a few percent at other wavelengths.

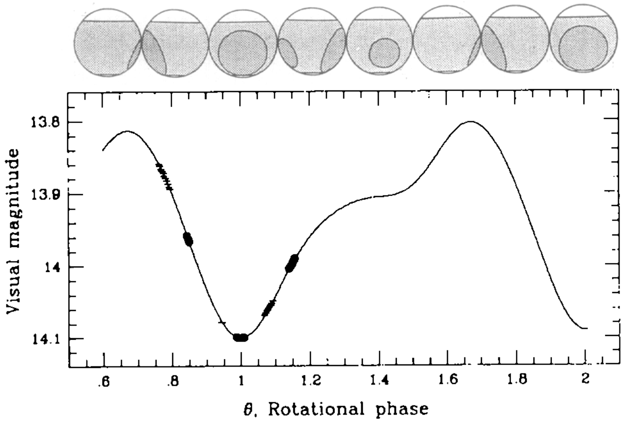

FIG. 1. Portions of lightcurve sampled on the 6 nights data were obtained. Solid regions: 1988 March 8, 9, and 10; hatched regions: 1988 April 15, 16, and 17. Corresponding images of the two-spot model are included for reference.

Figure 1 depicts the mean rotational phase of Pluto on those 6 nights when data were obtained.

3. RESULTS

To present the data in a reasonably compact form, we tabulate in Tables II–V only the mean UT for each scan, uncorrected for light-travel time. Columns labeled "Δm" are differential magnitudes in the usual sense (Pluto–SAO 120107), but have been reduced to mean distance on the night of April 17 using values of r and Δ in Table I. No solar phase coefficient β has been applied to the data.

The March and April observations are plotted in Figs. 2 and 3, respectively, with nightly mean rotational phase indicated on each panel.

It must be remembered that the combined lightcurve of the Pluto–Charon system changes systematically in intensity by as much as several (3–10) mmag hr^{-1} (see Fig. 3, last panel). Such variations should be taken into account when using the data for very detailed light curve or spectral analysis, as the spectrum does vary during the ~1 hr of elapsed time it takes to make a scan. Stated another way, each wavelength of each scan was made at a specific time which, for the sake of brevity and clarity, has not been included as part of the tabulation.

Bearing this in mind, marginally significant lightcurve slopes can be calculated (at each wavelength) on those nights when multiple scans were obtained. These can be used to reduce each scan to a truly common epoch, and to combine scans to produce a more accurate nightly mean. However, these corrections are small (<1%). As they have no significant bearing on the present analysis, they have not been applied to the data.

TABLE II
Summary of Observations, 1988 March 8–9

$\lambda(\mu m)$	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ
0.963	4.531	0.019	4.509	0.021	4.489	0.017	4.576	0.008
1.034	4.491	0.034	4.543	0.060	4.526	0.029	4.592	0.014
1.105	4.489	0.027	4.492	0.015	4.566	0.040	4.576	0.011
1.176	4.710	0.045	4.785	0.033	4.760	0.030	4.793	0.017
1.248	4.419	0.037	4.469	0.028	4.523	0.011	4.504	0.026
1.319	4.546	0.045	4.679	0.039	4.739	0.015	4.621	0.036
1.392	4.814	0.106	5.025	0.145	5.017	0.156	5.000	0.033
1.428	4.610	0.030	4.616	0.042	4.561	0.055	4.685	0.233
1.464	—	—	4.632	0.029	4.690	0.043	4.617	0.031
1.537	—	—	4.646	0.047	4.686	0.037	4.710	0.019
1.540	4.612	0.018	4.664	0.014	4.681	0.012	4.672	0.022
1.649	4.991	0.017	4.991	0.026	4.982	0.012	4.964	0.021
1.756	4.854	0.028	4.925	0.025	4.920	0.005	4.888	0.010
1.862	4.620	0.022	4.779	0.030	4.769	0.020	4.783	0.040
1.966	4.683	0.012	4.766	0.014	4.762	0.010	4.782	0.016
2.069	4.836	0.011	4.894	0.023	4.893	0.009	4.898	0.020
2.169	5.151	0.019	5.117	0.022	5.142	0.015	5.111	0.021
2.268	5.425	0.029	5.393	0.025	5.448	0.016	5.430	0.024
2.365	5.487	0.044	5.537	0.025	5.487	0.023	5.551	0.031
2.460	5.208	0.043	5.239	0.078	5.205	0.043	5.287	0.062
2.554	4.813	0.097	4.504	0.191	4.864	0.108	4.705	0.089
2.646	4.153	0.555	3.782	0.479	3.569	0.675	4.571	0.948
Date:	March 08		March 09		March 09		March 09	
(UT):	15.96		11.97		13.16		14.13	
corr:	$-0\overset{\mathrm{m}}{.}0276$		$-0\overset{\mathrm{m}}{.}0267$		$-0\overset{\mathrm{m}}{.}0267$		$-0\overset{\mathrm{m}}{.}0267$	

Note. Tabulated are spectra obtained on 1988 March 8 and 9. Date and mean geocentric UT of each scan appear at the bottom. Also tabulated are the distance corrections applied (in magnitudes) in order to bring all data to the geometry of the 1988 April 17 observations.

With the plots laid out on facing pages, rotational phase increases in the normal reading sense (left to right, top to bottom). Due to the large dynamic range inherent in the spectra (~1.5 mag), it is only barely possible to discern night-to-night spectral variations. However, careful study of the absorptions at 1.6–1.8 and 2.0–2.5 μm in particular shows that the depths and/or shapes do in fact vary systematically. It happens that at the core of the 1.7-μm absorption there is only a very small lightcurve during about 1 day to either side of visual lightcurve minimum. The increase in continuum level is almost totally negated by a simultaneous increase in absorption depth.

One convenient technique for depicting the variable nature of the absorptions is to take flux ratios of the various nightly mean spectra. Were there no inherent variation, then all absorptions might be expected to divide out to within a constant. This constant is due to the nightly variation in mean brightness. Conversely, if the band depths vary, then a systematic deviation from a constant value would be encountered as an absorption is traversed. We present two different normalizations to demonstrate different effects. Figure 4 depicts the March ratios. Although the spectra do vary over the 3 nights, there is remarkable symmetry in shape around minimum light. Within a zero-point correction of about 2%, deviations from the normalization track each other rather well.

The April ratios (Fig. 5) use the 0.94 rotational phase data as divisor. Variation is very apparent between rotational phases 0.78 and those close to the lightcurve minimum. As expected from Fig. 4, the differences between phases 0.94 and 0.08 are once again much less pronounced. The deviation at any one wavelength is barely significant when considering the zero-point correction, but we feel the *systematic* variation seen as a band is traversed lends credence to the claim that differences are real.

TABLE III
Summary of Observations, 1988 March 10

$\lambda(\mu m)$	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ
0.963	4.565	0.045	4.403	0.017	4.540	0.036
1.034	4.802	0.042	4.512	0.023	4.544	0.010
1.105	4.622	0.035	4.454	0.027	4.521	0.023
1.176	5.005	0.046	4.733	0.034	4.862	0.060
1.248	4.552	0.023	4.413	0.013	4.557	0.045
1.319	4.518	0.019	4.570	0.009	4.724	0.043
1.392	4.672	0.078	4.751	0.182	4.842	0.121
1.428	4.550	0.153	4.560	0.071	4.694	0.032
1.464	4.561	0.037	4.699	0.059	4.641	0.081
1.537	4.539	0.024	4.540	0.020	4.642	0.049
1.540	4.570	0.019	4.596	0.016	4.669	0.027
1.649	5.009	0.019	4.996	0.029	5.050	0.032
1.756	4.893	0.019	4.935	0.022	4.967	0.047
1.862	4.660	0.015	4.770	0.048	4.629	0.036
1.966	4.441	0.017	4.583	0.024	4.750	0.026
2.069	4.956	0.017	4.883	0.022	4.937	0.008
2.169	5.269	0.031	5.228	0.016	5.285	0.043
2.268	5.577	0.034	5.439	0.055	5.519	0.029
2.365	5.740	0.042	5.602	0.025	5.575	0.047
2.460	5.483	0.080	5.326	0.024	5.340	0.031
2.554	5.996	0.133	5.127	0.057	5.249	0.138
2.646	3.433	0.411	5.572	0.915	3.995	0.419
Date:	March 10		March 10		March 10	
(UT):	11.50		12.67		13.42	
corr:	$-0\overset{m}{.}0257$		$-0\overset{m}{.}0257$		$-0\overset{m}{.}0257$	

Note. As for Table II, but for the 1988 March 10 observations.

4. DISCUSSION

Marcialis (1983, 1988a) constructed an albedo model for the surface of Pluto to explain the rotational and orbital light curve. This model invoked two static dark regions near Pluto's equator to modulate the 6.4-day rotational variation, and two bright, longitudinally symmetric polar caps as one means of explaining the observed dimming of Pluto over the last three decades. A reanalysis by Buie and Tholen (1989) gave basically the same results, although they had the advantage of data from three more apparitions. The only significant difference they found was admitting to a second solution where the smaller equatorial spot might be *bright* and, if so, was positioned in longitude *ahead* of the major dark region (Marcialis 1988b). At the observed rotational phases near minimum light, the two models are virtually identical.

The original albedo model was formulated only to explain the lightcurve of Pluto, and no a priori connection was implied between albedo and composition. However, if such a connection were to be assumed, there are two simple possibilities. That is, dark regions could be either enriched or depleted in methane relative to bright.

If bright regions are rich in methane relative to dark, then one would expect to see the planet's lightcurve in the band center to be *inversely correlated* with the continuum (visual) light curve. Conversely, if dark regions are rich in methane relative to bright, one would expect both continuum and band center lightcurves to vary in step with one another, particularly because when the dark regions face Earth, less continuum due to the bright areas can dilute the absorptions.

A third possibility is that neither region is particularly enriched in methane with respect to the other. Ab initio, one would expect there to be no variation in absorption with rotational phase. As was first pointed out by Buie (1984), this is not the case. Any albedo distribution not longitudinally symmetric which underlies an optically thin atmosphere tends to modulate the "airmass factor" as the planet rotates. (Airmass factor, η_{eff}, may be defined as the one-way, globally averaged optical path length, expressed in units of the normal optical path length η_0.) For example, if a dark area constituting a substantial portion of a hemisphere were positioned at the sub-Earth point of a fully illuminated planet, then the long slant paths near the limb make the dominant contribution to the airmass factor, and η_{eff} would be maximized.

Note that the consequences of these three possibilities are completely general, and therefore immune to the specifics of the albedo model assumed in all but the most pathological or contrived cases.

For completeness, we mention a fourth possibility: the planet could be shrouded by a deep, optically thick atmosphere. In this case, one would expect little variation in the spectrum with rotational phase. However, this case is not acceptable for Pluto as it causes difficulty in explaining the observed 30% brightness modulation seen each 6.4 days. A transparent upper atmosphere with an optically thick basal haze layer (Elliot *et al.* 1989) causes similar problems, and therefore such layers with normal optical depth $\tau_0 \gtrsim 0.5$ also may be excluded, independent of theoretical considerations (Stansberry *et al.* 1989).

Based upon the results of our observations, the only scenario which gives a consistent explanation is the first one. The near-infrared spectrum is dominated by surface frost, not atmosphere. Albedo and composition (or at least spectral activity of the methane) do indeed seem to be correlated on the surface of Pluto. Bright regions show a more pronounced methane signature in a real and systematic manner. The deep bands at 1.7 and 2.35 μm dominate the substantial modulation of the continuum level. While the much narrower and shallower bands at 1.15 and 1.35 μm track the continuum variations, they do show some evidence for a variation in their depth, although much less conclusively so.

As always, when one observes Pluto, the effect of Charon must be considered as well. Although the pres-

TABLE IV
Summary of Observations, 1988 April 15

λ(μm)	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ
0.968	4.342	0.008	4.389	0.007	4.376	0.007	4.387	0.007
1.038	4.375	0.008	4.438	0.010	4.410	0.006	4.411	0.009
1.109	4.357	0.011	4.374	0.010	4.381	0.008	4.393	0.008
1.181	4.642	0.015	4.679	0.015	4.634	0.013	4.661	0.013
1.252	4.334	0.009	4.349	0.009	4.347	0.013	4.350	0.013
1.324	4.512	0.011	4.512	0.015	4.505	0.013	4.482	0.007
1.396	4.840	0.031	4.775	0.042	4.787	0.037	4.804	0.024
1.436	4.448	0.038	4.484	0.065	4.472	0.045	4.601	0.050
1.469	4.555	0.015	4.506	0.010	4.500	0.013	4.506	0.012
1.541	4.499	0.019	4.446	0.008	4.433	0.012	4.463	0.010
1.547	4.504	0.006	4.527	0.008	4.525	0.009	4.494	0.009
1.657	4.897	0.012	4.923	0.009	4.908	0.012	4.909	0.006
1.764	4.853	0.014	4.833	0.009	4.822	0.006	4.821	0.007
1.870	4.569	0.008	4.575	0.012	4.568	0.008	4.575	0.010
1.974	4.569	0.009	4.567	0.008	4.571	0.010	4.574	0.008
2.076	4.724	0.012	4.748	0.011	4.723	0.009	4.728	0.011
2.176	5.075	0.012	5.131	0.011	5.094	0.008	5.089	0.012
2.275	5.410	0.015	5.407	0.018	5.414	0.024	5.403	0.016
2.372	5.571	0.029	5.596	0.033	5.600	0.015	5.538	0.029
2.467	5.068	0.035	5.110	0.032	5.101	0.047	5.105	0.032
2.560	4.649	0.119	4.922	0.094	4.963	0.090	5.113	0.354
2.652	4.574	0.695	4.665	0.742	4.708	0.347	—	—
Date:	April 15		April 15		April 15		April 15	
(UT):	9.15		10.32		11.67		12.92	
corr:	$-0\overset{\mathrm{m}}{.}0006$		$-0\overset{\mathrm{m}}{.}0006$		$-0\overset{\mathrm{m}}{.}0006$		$-0\overset{\mathrm{m}}{.}0006$	

Note. As for Table III, but for the 1988 April 15 observations.

ence of water and the absence of detectable methane on Charon were demonstrated for only one hemisphere (not too far displaced from the April 15 observations), there are two reasons for believing its global spectrum should be free of methane.

The first argument is theoretical, and is discussed both in Marcialis *et al.* (1987) and in Trafton *et al.* (1988). Due to Charon's relatively feeble gravity, any surface methane should have escaped long ago. Observational evidence, though indirect, also exists. Mutual event observations of Charon in both transit and occultation (Binzel 1988) show that complementary hemispheres of the satellite are spectrally bluer than Pluto, and little color variation is seen throughout the orbit.

Note that the continuum in the April ratio of phases 0.78/0.94 has a slightly negative slope. We feel this is evidence for variation of color with rotational phase, in the sense that *dark* regions are *redder* than bright regions. If real, this effect is consistent with (but not unique to) the hypothesis that dark regions may be contaminated by the products of methane photochemistry and/or bombardment by high-energy particles (cf. Cheng *et al.* 1986, Cruikshank and Brown 1986, Johnson 1989, and references cited therein). It is known that the dark region causing minimum light has persisted for at least 35 years. Currently available theoretical models of seasonal methane migration have thus far not addressed quantitatively this longitudinal asymmetry.

Tholen *et al.* (1987a) originally suggested that Charon might have hemispherical color differences. Subsequently, Binzel (1988) reported little color variation between conjugate hemispheres of Pluto and Charon. Although our tentative result is at odds with his findings, the two results are not necessarily inconsistent. Binzel's observations were limited to the visual region of the spectrum, and were at different rotational phases. However, we do point out that if Pluto is indeed redder at minimum light, this does cast doubt upon his conjecture that "the data may be attributed to a direct detection of polar caps on Pluto." If the (bright) polar caps are *bluer* than the mean of all equatorial regions, then at minimum light Pluto's color would be expected to be its bluest, not reddest, for that is when the equatorial regions contribute the least to the integrated global flux.

TABLE V

Summary of Observations, 1988 April 16–17

λ(μm)	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ	Δm (mag)	σ
0.968	4.559	0.010	4.517	0.007	4.505	0.018	4.476	0.010
1.038	4.547	0.011	4.564	0.009	4.534	0.009	4.528	0.009
1.109	4.525	0.014	4.511	0.008	4.501	0.013	4.483	0.010
1.181	4.731	0.017	4.791	0.013	4.743	0.015	4.737	0.015
1.252	4.464	0.012	4.479	0.012	4.467	0.013	4.431	0.009
1.324	4.598	0.012	4.599	0.013	4.599	0.016	4.624	0.014
1.396	4.751	0.047	4.841	0.020	4.814	0.072	4.789	0.025
1.436	4.640	0.070	4.517	0.040	4.650	0.050	4.577	0.041
1.469	4.634	0.026	4.653	0.017	4.592	0.024	4.577	0.014
1.541	4.607	0.022	4.569	0.012	4.564	0.013	4.456	0.010
1.547	4.639	0.011	4.656	0.014	4.637	0.013	4.630	0.009
1.657	4.913	0.011	4.980	0.014	4.969	0.163	4.976	0.012
1.764	4.835	0.010	4.895	0.013	4.880	0.014	4.874	0.010
1.870	4.545	0.013	4.718	0.011	4.661	0.036	4.656	0.018
1.974	4.737	0.017	4.742	0.009	4.701	0.023	4.677	0.014
2.076	4.852	0.008	4.881	0.011	4.847	0.010	4.833	0.010
2.176	5.079	0.018	5.114	0.018	5.121	0.012	5.134	0.014
2.275	5.297	0.028	5.360	0.015	5.375	0.020	5.386	0.021
2.372	5.410	0.023	5.425	0.024	5.509	0.020	5.522	0.042
2.467	5.175	0.054	5.203	0.045	5.231	0.042	5.200	0.041
2.560	5.025	0.170	5.160	0.114	5.122	0.172	5.111	0.139
2.652	4.078	0.694	—	—	4.907	0.611	4.483	0.479
Date:	April 16		April 17		April 17		April 17	
(UT):	13.03		8.71		9.86		10.96	
corr:	$-0^{\mathrm{m}}0002$		$-0^{\mathrm{m}}0000$		$-0^{\mathrm{m}}0000$		$-0^{\mathrm{m}}0000$	

Note. As for Table IV, but for the 1988 April 16 and 17 observations.

In addition, Charon is spectrally *bluer* than Pluto. Therefore, even in the absence of any color variation over each object's surface, the combined color of the system should be bluer at minimum light than at maximum light. Our result that the system appears *redder* at minimum light than at maximum light presents an even stronger argument for regional color variation on Pluto itself due to the diluting effects of Charon (much the same way that Pluto's lightcurve must have a higher amplitude than the system's).

We emphasize that the entire problem can be made to disappear and the observations form a self-consistent scenario if *darker* equatorial regions of Pluto are *redder* than those low-latitude areas of more moderate albedo. Clearly, this reddening should be confirmed for the longitudes observed, and extended to those regions not yet probed.

With respect to known continuum wavelengths, there is little evidence in our observations for variability at either 1.5 or 2.0 μm, wavelengths where water frost is known to absorb. This implies the combined disk-integrated Pluto + Charon water abundance is fairly constant. Now, the Pluto-facing hemisphere of Charon is known to have a spectrum consistent with water frost (Marcialis *et al.* 1987). A little thought reveals two obvious scenarios. Assume, purely for the sake of conjecture, that globally Charon has a spectrally uniform coat of water frost. This immediately implies water frost on Pluto (should any exist at the surface) is likely to be rather evenly distributed as well, or covered. An alternative is to admit to spatial (longitudinal) variability of water on Charon. However, any such variation on Charon must be exactly canceled by an opposite variation on Pluto, so that their integrated light shows no net change. Although possible, we find this solution much less tenable.

5. FUTURE INVESTIGATION

Although our observations cover one-third of Pluto's lightcurve, investigation into the observed variability in methane and nonvariability in water needs to be extended over the opposite hemisphere. We feel that a similar data set for those regions may provide evidence with which the two existing albedo models of Pluto may be tested. If

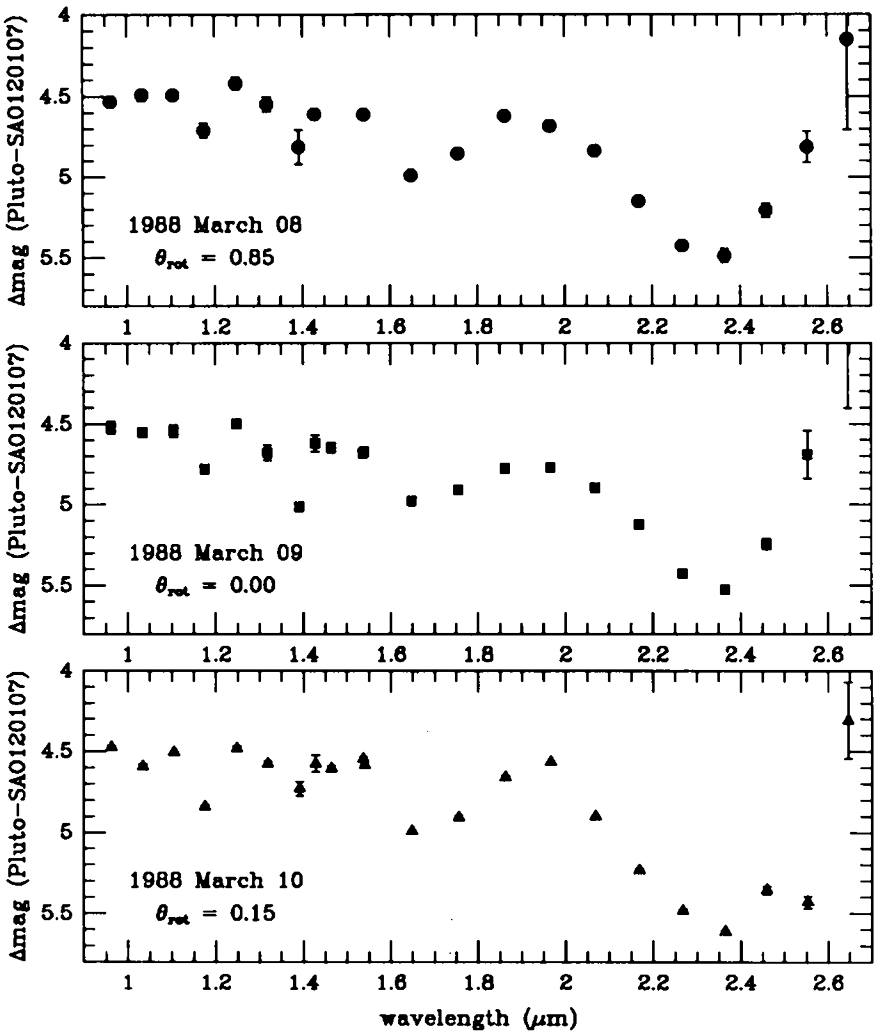

FIG. 2. Nightly mean Pluto spectra for1988 March 8, 9, and 10. All absorptions are due to methane. Formal error bars include any variation between scans due to Pluto's lightcurve.

the albedo/composition trend is a global one, discrimination between the Two Spot Model (TSM) and Twenty-Four Parameter Model (TPM) might be within reach.

With infrared array detectors coming into more widespread usage, the multiplexing advantage can be used to increase the spectral resolution, allowing band shapes as well as depths to be measured. This additional information can be used to construct models of methane distribution and to test those derived from mutual event observations (Buie *et al.* 1989, Young and Binzel 1990).

Finally, the data presented here serve as a caution to those planning synoptic measurements of Pluto. Some have suggested (cf. Cruikshank and Silvaggio 1980, Marcialis 1983, Stern and Trafton 1984) that as Pluto recedes from perihelion, a portion of its atmosphere may condense onto the surface. This should result in a slow evolution in the spectrum over a span of a few decades. Such long-term observations should be planned at a *specific sampling* of representative rotational phases, given the impracticality of detailed observation over the entire lightcurve. Much care should be devoted to tracking the evolution of continuum slope (color) during this period. Pluto would be expected to become slightly bluer if an optically thick layer of fresh frost coats what is now the surface.

Even then, it must be remembered that the sub-Earth latitude on Pluto currently is varying by approximately 2.2° year^{-1}. The resulting change in aspect is approximately equivalent to that produced during ~1 hr of rotation, a time scale over which the spectrum has been demonstrated to vary (see Fig. 3). The combination of the present results with *either* of the spot models might actually predict that, over the next decade or two, Pluto's methane absorptions might actually *strengthen* as the northern polar cap swings into view. Without spatial reso-

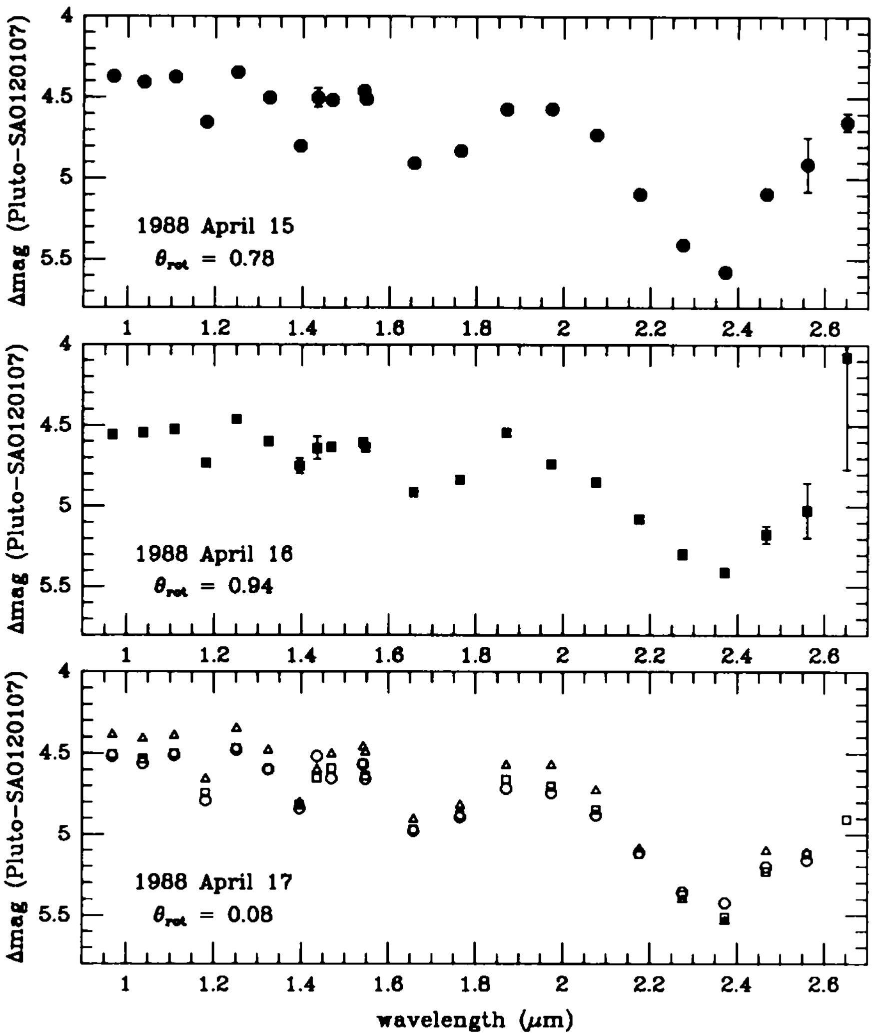

FIG. 3. Same as Fig. 2 for Pluto spectra obtained 1988 April 15, 16, and 17. In lieu of error bars, individual scans are plotted for April 17. Approximately 70 min elapsed between scans. Systematic scan-to-scan variation is apparent on April 17 and is due to the rotational lightcurve of Pluto. Note the "negative" lightcurve in the core of the 2.35-μm band.

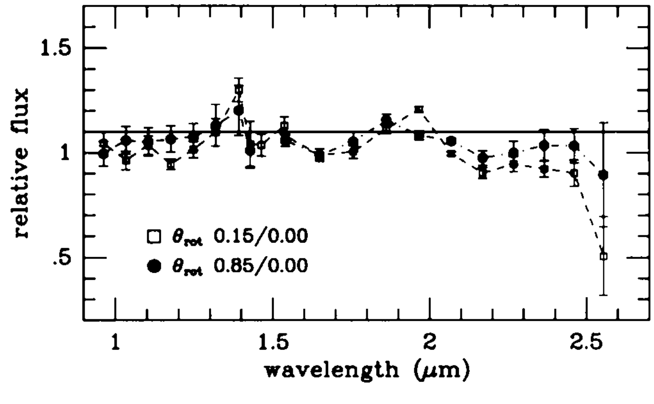

FIG. 4. Flux ratios for March 8/9 and 10/9 show systematic deviation from a straight line. Probable errors from the divisor have been propagated to the other nightly means, and therefore represent true deviation from a flat line. For clarity, the horizontal line has been shifted upward by 10%, which corresponds approximately to the change in continuum lightcurve between the three nights. Deviation from a constant ratio is only marginally significant at any one datum; however, these deviations are systematic across the 1.7- and 2.35-μm absorptions of methane. The ratios are much more similar to each other than to the normalization, demonstrating symmetry about lightcurve minimum.

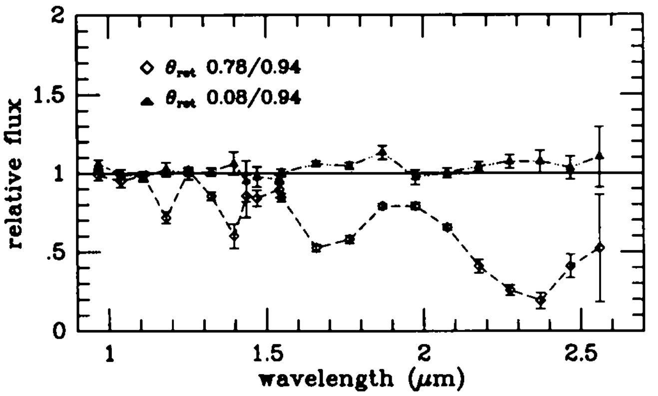

FIG. 5. As for Fig. 4, but for the April observations. For clarity, the April 15/16 ratio has been shifted downward by 20%, which corresponds to the approximate change in continuum lightcurve between the two nights. Systematic differences in the April 15 observations demonstrate an unquestionable variation in depth of methane absorptions with rotational phase. A slightly bluish slope in this ratio is evidence that Pluto may be redder at minimum light.

lution much in excess of that which Hubble Space Telescope could provide (even at its design specifications), disentangling viewing geometry effects from seasonal ones may prove to be a formidable task indeed.

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REFERENCES

Binzel, R. P. 1988. Hemispherical color differences on Pluto and Charon. *Science* **241**, 1070–1071.

Buie, M. W. 1984. *Lightcurve CCD Spectrophotometry of Pluto*. Ph.D. dissertation, University of Arizona, Tucson.

Buie, M. W., D. P. Cruikshank, L. A. Lebofsky, and E. F. Tedesco 1987. Water frost on Charon. *Nature* **329**, 522–523.

Buie, M. W., and U. Fink 1987. Methane absorption variations in the spectrum of Pluto. *Icarus* **70**, 483–498.

Buie, M. W., Lebofsky, L. A. Tedesco, and D. P. Cruikshank 1989. Methane map for Pluto based on mutual events. *Bull. Amer. Astron. Soc.* **21**, 985 (Abstract).

Buie, M. W., and D. J. Tholen 1989. The surface albedo distribution of Pluto. *Icarus* **79**, 23–37.

Cheng, A. F., P. K. Haff, R. E. Johnson, and L. J. Lanzerotti 1986. Interactions of planetary magnetospheres with icy satellite surfaces. In *Satellites* (J. A. Burns and M. S. Matthews, Eds.), pp. 403–436. Univ. of Arizona Press, Tucson.

Cruikshank, D. P., and R. H. Brown 1986. Satellites of Uranus and Neptune, and the Pluto–Charon system. In *Satellites* (J. A. Burns and M. S. Matthews, Eds.), pp. 836–873. Univ. of Arizona Press, Tucson.

Cruikshank, D. P., C. B. Pilcher, and D. Morrison 1976. Pluto: Evidence for methane frost. *Science* **194**, 835–837.

Cruikshank, D. P., and P. M. Silvaggio 1980. The surface and atmosphere of Pluto. *Icarus* **41**, 96–102.

Elliot, J. E., E. W. Dunham, A. S. Bosh, S. M. Slivan, L. A. Young, L. H. Wasserman, and R. L. Millis 1989. Pluto's atmosphere. *Icarus* **77**, 148–170.

Fink, U., B. A. Smith, D. C. Benner, J. R. Johnson, H. J. Reitsema, and J. A. Westphal 1980. Detection of a CH_4 atmosphere on Pluto. *Icarus* **44**, 62–71.

Johnson, R. E. 1989. Effect of irradiation on the surface of Pluto. *Geophys. Res. Lett.* **16**, 1233–1236.

Lebofsky, L. A., G. H. Rieke, and M. J. Lebofsky 1979. Surface composition of Pluto. *Icarus* **37**, 554–558.

Marcialis, R. L. 1983. *A Two-Spot Model for the Surface of Pluto*. Master's thesis, Vanderbilt University, Nashville.

Marcialis, R. L. 1988a. A two-spot albedo model for the surface of Pluto. *Astron. J.* **95**, 941–947.

Marcialis, R. L. 1988b. Spotting Pluto. *Sky and Telescope* **75**, 6 (Letter to the Editor).

Marcialis, R. L., G. H. Rieke, and L. A. Lebofsky 1987. The surface composition of Charon: Tentative identification of water ice. *Science* **237**, 1349–1351.

Sawyer, S. R. 1986. *Time Resolved Spectrophotometry of Pluto*. Master's thesis, University of Texas, Austin.

Sawyer, S. R. 1989. Reflectance spectroscopy of the surface and atmosphere of Pluto–Charon. *Bull. Amer. Astron. Soc.* **21**, 986 (Abstract).

Sawyer, S. R., E. S. Barker, A. L. Cochran, and W. D. Cochran 1987. CCD spectrophotometry of Pluto–Charon mutual events. *Bull. Amer. Astron. Soc.* **19**, 859 (Abstract).

Soifer, B. T., G. Neugebauer, and K. Matthews 1980. The 1.5–2.5 micron spectrum of Pluto. *Astrophys. J.* **85**, 166–167.

Stansberry, J. A., J. I. Lunine, and M. L. Tomasko 1989. Upper limits on possible photochemical hazes on Pluto. *J. Geophys. Res.* **16**, 1221–1224.

Stern, S. A., and L. M. Trafton 1984. Constraints on bulk composition, seasonal variation, and global dynamics of Pluto's atmosphere. *Icarus* **57**, 231–240.

Tholen, D. J., M. W. Buie, R. P. Binzel, and M. L. Frueh 1987a. Improved orbital and physical parameters for the Pluto–Charon system. *Science* **237**, 512–514.

Tholen, D. J., M. W. Buie, and C. E. Swift 1987. Circumstances for Pluto–Charon mutual events in 1987. *Astron. J.* **93**, 244–248.

Trafton, L. M., S. A. Stern, and G. R. Gladstone 1988. The Pluto–Charon system: Escape of Charon's primordial atmosphere. *Icarus* **74**, 108–120.

Young, E. F., and R. P. Binzel 1990. A singular value decomposition map of Pluto based on mutual event data. *Bull. Amer. Astron. Soc.* **22**, 1128 (Abstract).