Reports

Hemispherical Color Differences on Pluto and Charon

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Time-resolved multicolor photometric observations of Pluto-Charon mutual events have been used to derive individual colors for these two bodies and to investigate the degree of color differences between their synchronous facing and opposite hemispheres. Pluto is significantly redder than Charon, where direct measurements of the anti-Charon hemisphere of Pluto and the Pluto-facing hemisphere of Charon yield B-V magnitudes of 0.867 ± 0.008 and 0.700 ± 0.010, respectively. Both Pluto and Charon are found to have relatively uniform longitudinal color distributions with 1σ upper limits of 2% and 5%, respectively, for any large-scale hemispherical color asymmetries. Thus, a previous suspicion of a significant color asymmetry on Charon is not confirmed. Instead the data may be attributed to a direct detection of polar caps on Pluto.

SINCE THE DISCOVERY OF THE ONSET of the once-per-century series of mutual events ("eclipses") between Pluto and Charon in 1985 (*1*), photometric measurements of these events have allowed us to make major advances in our knowledge of this remote system. This paper reports the results of time-resolved multicolor photometric observations of the mutual events. Individual colors for Pluto and Charon are derived from these observations during the unique geometry of the 1987 events. In addition, upper limits are determined for the degree of hemispherical color asymmetry for both bodies. Although, previous data (*2*) led to the suspicion that Charon might have hemispheres of significantly different colors, more complete observations presented here rule this out. An alternative explanation is that the transit observations may be revealing the presence of polar caps on Pluto.

Figure 1 presents photometric observations of the 4 April 1987 total occultation of Charon by Pluto. These data were obtained simultaneously in the standard astronomical Johnson blue (B) and visual (V) wavelengths by means of a two-channel photometer attached to the University of Texas McDonald Observatory 2.7-m telescope. The top panel shows the light curve as observed in B and the lower panel depicts the color change during the event as measured by the B-V color index. As Charon was being obscured behind the planet, the color of the system became increasingly red by about 0.024 magnitude. Between 0906 and 1018 UT, Charon was totally occulted behind Pluto and the measured color leveled off at a value of B-V = 0.867 ± 0.008 magnitude, corresponding to the color index of the anti-Charon hemisphere of Pluto (*3, 4*). Qualitatively, the color change during the event implies that the obscured hemisphere of Charon is bluer (less red) than the observed hemisphere of Pluto.

Observations of the other hemispheres of both bodies were obtained during the 22 May 1987 transit of Charon in front of Pluto. Figure 2 presents photometric observations in B and B-V, which were taken with the same instrumentation attached to the University of Texas McDonald Observatory 2.1-m telescope. The greater depth (in B) of the transit event is primarily attributable to Charon's lower albedo (*2*) and also shadowing. Deviations from a smooth curve in the B light curve (top) may be due to small-scale surface features on Pluto and separate work to further investigate this possibility is under way. The bottom panel shows that as Charon transited the disk of Pluto, the measured color index shifted toward the blue by a maximum of 0.022 magnitude from the mean out of eclipse value. This color change is qualitatively consistent with a bluer hemisphere of Charon obscuring a large fraction of a redder hemisphere of Pluto.

From the observations on 4 April 1987, I can quantitatively derive the color of the Pluto-facing hemisphere of Charon. Let P_B, P_V, C_B, and C_V represent the intensities of Pluto and Charon as measured in B and V, respectively. At the time of mid-event we have:

$$-2.5 \log (P_B/P_V) = 0.867 \qquad (1)$$

From the depth of the event as measured in B (0.180 ± 0.004 magitude), I obtain (*5*):

$$-2.5 \log [(P_B + C_B)/P_B] = -0.180 \qquad (2)$$

The measured B-V of the system before the onset of the event was 0.843 ± 0.008 magnitude. This allows me to write:

$$-2.5 \log \left[\frac{P_B + C_B}{P_V + C_V}\right] = 0.843 \qquad (3)$$

Using Eqs. 1 and 2 to derive values for P_V/P_B and C_B/P_B, I obtain from Eq. 3.

$$C_V/C_B = 1.906 \qquad (4)$$

which yields a B-V color of 0.700 ± 0.010 magnitude for the inward-facing hemisphere of Charon. Charon is therefore a relatively neutrally colored body because it reflects nearly the same color as the incident sunlight (B-V of the sun is 0.65 magnitude). The redder color of Pluto with respect to Charon derived here is consistent with other observations, and has been attributed to the loss of methane ice from Charon's surface (*6, 7*).

Having derived color measurements for

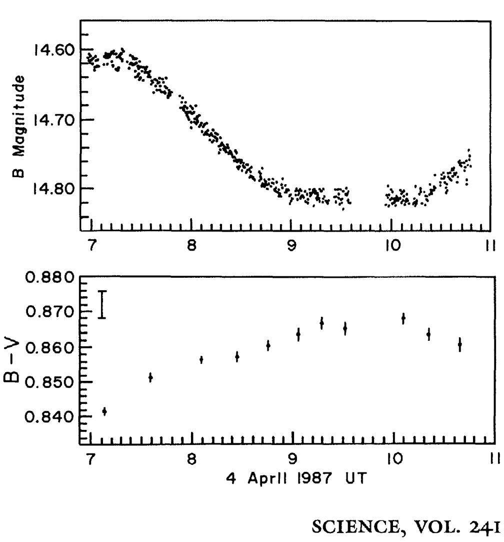

Fig. 1. Total occultation of Charon behind Pluto (4 April 1987). (UT times are as observed and have not been corrected for light time.) (**Top**) Event light curve as measured in blue (Johnson B) light. The average uncertainty for each measurement is 0.005 magnitude. The flat portion between 0906 and 1018 UT represents the interval when Charon was totally obscured behind Pluto. (**Bottom**) Observed color change during the event as measured by the standard Johnson B-V color index. The error bars for each measurement denote internal 1σ uncertainties. The larger error bar (upper left) denotes the uncertainty in the overall calibration of the B-V scale to the standard system. With Charon totally occulted, the measured B-V of Pluto is 0.867 ± 0.008 magnitude.

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one hemisphere of each body, I can now use the observations of 22 May 1987 to compute upper limits on the uniformity of color for the opposite hemispheres. Before the onset of the 22 May 1987 event, the B-V magnitude of the system was measured to be 0.856 ± 0.008, which is in agreement within the observational uncertainties of the 4 April 1987 pre-event measurements (*8*). By attributing to Pluto (which dominates the light of the system) the entire difference in color between the 22 May 1987 and 4 April 1987 measurements, I can set a 1σ upper limit of 2% to the degree of large-scale longitudinal color variation as measured by the color index between the Charon-facing and anti-Charon hemispheres of Pluto.

To compute the B-V of the anti-Pluto hemisphere of Charon, I choose the time when Charon made its largest contribution to the total light of the system: mid-event on 22 May 1987. Based on the measured B-V magnitude = 0.834 ± 0.008 I can write:

$$-2.5 \log \left[\frac{P_B(1-f) + C_B}{P_V(1-f) + C_V}\right] = 0.834 \quad (5)$$

where f is the fraction of Pluto's surface covered by Charon and its shadow at the time of mid-event. With the observed 0.430 ± 0.003 magnitude depth of the event in B, a value for f can be derived from:

$$-2.5 \log \left[\frac{P_B + C_B}{P_B(1-f) + C_B}\right] = -0.43 \quad (6)$$

where the solution for f contains a correction to the value of C_B/P_B determined in Eq. 2 owing to Pluto's rotational light curve variation (*9*). Equations 5 and 6 can then be solved to obtain:

$$C_V/C_B = 1.950 \quad (7)$$

which yields a B-V color of 0.725 ± 0.025 magnitude for the outward-facing hemisphere of Charon, where the error estimate includes the uncertainty due to the previously derived upper limit for color asymmetry on Pluto. With these factors taken into account, I can place a 1σ upper limit of 5% on the degree of large-scale hemispherical color variation on Charon.

The above results from extensive multicolor data in 1987 clearly show that Charon is fairly uniform in color, which contrasts with preliminary conclusions from 1986 data that Charon had hemispheres of significantly different colors (*2*). The much more limited 1986 multicolor data showed a measurable B-V shift during occultation events whereas transit events displayed no measurable change, thus giving rise to the color asymmetry conclusion.

With the above solutions for Pluto and Charon B-V magnitudes, it can be seen that a larger observed color change during partial occultation events is expected. During the 1986 partial occultations, Pluto's fractional contribution to the total light of the system increased from ~ 0.85 before the event to ~ 0.92 at mid-event. Thus Pluto's "red" component to the color of the system increased by about 8%, yielding a computed B-V color change of +0.012 ± 0.006 magnitude. During the transit events, Pluto's fractional contribution decreased from ~ 0.84 to ~ 0.80, corresponding to a decrease in the "red" component of about 5% and a computed B-V color change of −0.007 ± 0.006 magnitude.

Although small, the computed B-V color changes during the 1986 transit events are marginally within the limit of detectability in the available data (*2*). Therefore, possible explanations for the lack of observed color variations during partial transits still need to be investigated. The original explanation of color asymmetry on Charon appears to have been ruled out by the present results.

An alternative explanation is now offered. During 1986, Charon and its shadow were transiting across the northern latitudes of Pluto, whereas in 1987 the transits were occurring near the equator. If the high latitudes of Pluto contain polar caps, as has been proposed (*11, 12*), and if these polar caps are bluer in color than the equatorial region, then little or no color change might be observed as Charon transited in front of the north polar cap. Thus the transit observations may be yielding direct detections of polar caps on Pluto. Further investigations of these polar caps and other latitudinal color variations will be possible through precision multicolor photometry of the partial transit events during 1989 and 1990.

As a final note, both the 4 April 1987 and 22 May 1987 events were observed simultaneously in blue light by M. L. Frueh with the McDonald Observatory 0.91-m telescope using the same photomultiplier and B filter combination. The measured depths of the events between the 0.91- and 2.7-m and the 0.91- and 2.1-m, respectively, were in agreement to within 0.01 magnitude, the limiting precision for this comparison. These observations do not confirm the prediction (*13*) that diffraction effects would cause the measured depth to depend significantly on telescope aperture. Recent work (*14*) argues that such effects should indeed be absent (*15*).

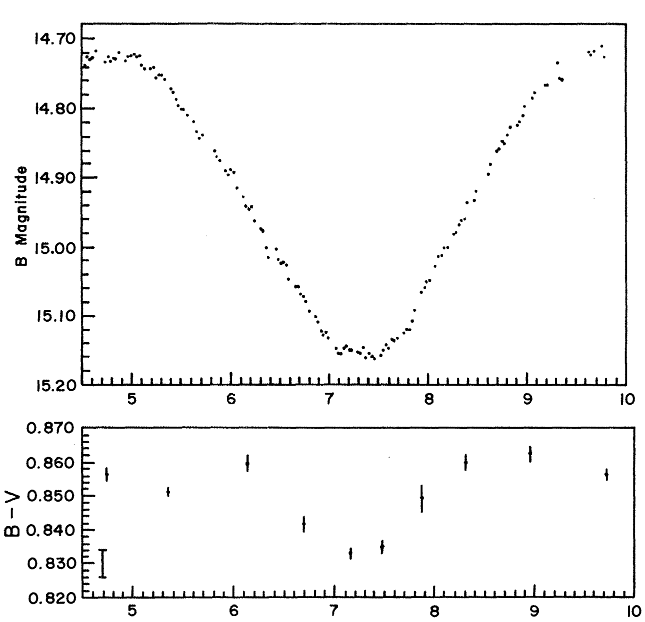

Fig. 2. Transit of Charon in front of Pluto (22 May 1987). (UT times are as observed and have not been corrected for light time.) (**Top**) Event light curve as measured in blue (Johnson B) light. The average uncertainty for each measurement is 0.005 magnitude. (**Bottom**) Observed color change during the event as measured by the standard Johnson B-V color index. The error bars for each measurement denote internal one-sigma uncertainties. The larger error bar (lower left) denotes the uncertainty in the overall calibration of the B-V scale to the standard system.

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3. Charon is in a synchronous orbit around Pluto, where its 6.4-day orbital period is equal to the planet's rotation period. Thus one hemisphere of Pluto is permanently "locked" facing Charon. Similarly, one hemisphere of Charon permanently faces Pluto. Because Charon's orbit is circular, transit and occultation events occur at intervals equal to one-half the synchronous period.
4. In this case and throughout this report, unless otherwise noted, all uncertainties listed are formal 1σ errors resulting from taking the mean of several independent observational measurements. Uncertainties listed with calculated values are also 1σ errors resulting from the formal propagation of the observational errors.
5. The depth of this event (as measured from the mean out of eclipse level to the level at mid-event) has been corrected for the ~0.0055 magnitude per hour background slope in Pluto's rotational light curve at this rotational phase. A careful inspection of the mid-event portion of the B light curve in Fig. 1 reveals this decreasing slope and indicates that its cause is attributable to the rotation of surface features on Pluto and is not due to Charon.

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8. The photometric color calibrations for 4 April 1987 and 22 May 1987 were made with respect to the 1987 Primary Comparison star by using the magnitudes listed by D. J. Tholen, M. W. Buie, and C. E. Swift, [*Astron. J.* **94**, 1681 (1987)].
9. Occultation events occur near rotational phase 0.75 whereas transits occur near phase 0.25, at which time Pluto's background rotational light curve displays no slope but is at a level 0.09 magnitude fainter as measured in B (*10*). It is assumed that this entire light curve variation is attributable to the rotation of surface features on Pluto and is not due to Charon (*5*). The assumption of a uniform albedo for Charon is supported by the analysis of eclipse observations (*2*).
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15. This research was supported by NASA Planetary Astronomy Contract NASW 4264. The author was a guest observer at the McDonald Observatory, University of Texas. I thank Marian L. Frueh and J. Derral Mulholland for their assistance with Pluto observations during the 1987 season. This is PSI contribution number 246. The Planetary Science Institute is a division of Science Applications International Corporation.

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Effect of a Coordination Change on the Strength of Amorphous SiO_2

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Measurements of the yield strength of SiO_2 glass to pressures as high as 81 gigapascals at room temperature show that the strength of amorphous silica decreases significantly as it is compressed to denser structures with higher coordination. Above 27 gigapascals, as the silicon in amorphous SiO_2 is continuously transformed from fourfold to sixfold coordination, the strength of the glass decreases by more than an order of magnitude. These data confirm theoretical predictions that the mechanical properties of polymerized amorphous silicates are sensitive to pressure-induced structural transformations and suggest that the viscosity of silica-rich liquids decreases significantly at high pressures. Such a change in melt rheology could enhance the processes of chemical differentiation with depth in the Earth's mantle.

On the basis of molecular dynamics simulations, Angell and co-workers (*1*) originally suggested that increases in pressure comparable to the range of values that occur in the Earth's mantle could dramatically change both the structure and viscosity of polymerized silicate melts (*2, 3*). These were important predictions because silicate melts are extremely mobile compared to crystalline rocks, and any changes in the density or viscosity of melts with depth could strongly influence the chemical differentiation and thermal evolution of the planetary interior through geologic time. In accord with the computer simulations, as well as with the interpretation of shock wave measurements on silicate melts (*4*), recent spectroscopic observations have indicated that the structures of noncrystalline silicates change markedly with pressure. Specifically, the SiO_4 tetrahedra making up the melt and glass structures at low pressures are transformed to SiO_6 octahedra (and distorted octahedra) at pressures of a few tens of gigapascals (*5*). We report measurements of the yield strength of silica glass to 81 GPa that confirm the second prediction from the molecular dynamics simulations: the mechanical properties of amorphous silicates are indeed sensitive to structural changes, such as a pressure-induced increase in coordination (*6*).

We determined the strength of amorphous silica at room temperature and high pressure by measuring the maximum shear stress supported by the glass in a diamond cell (*7–9*). We measured pressure in the samples with the ruby fluorescence technique and pressure gradients by comparing spectra from individual ruby grains distributed across the sample (*10*). The measured pressure gradient ($\partial P/\partial r$) and the sample thickness (h) closely approximate the maximum shear stress supported by the sample through the relation (*8, 9, 11*):

$$\sigma_{rz} = \frac{h \partial P}{2 \partial r} \quad (1)$$

where σ_{rz} is the shear stress acting on the plane of the diamond-sample interface and r is the radial distance from the center of the sample. The sample thickness was measured on decompressed samples at zero pressure (*12, 13*). We equate the shear stress expressed in Eq. 1 with the yield strength of the sample at high pressure (*8, 9, 11*).

All of our measurements were carried out above 8 GPa because the sample compaction is not reproducible below these pressures. At low pressures, extrusion of the sample and compaction of voids at grain boundaries control deformation. These processes occur at different rates in each sample (*14*). Also, irreversible compaction of silica glass increases the density by as much as 18% between 0 and 8 GPa (*15*), providing additional stress relaxation, which also varies between samples.

The strength of amorphous SiO_2 increases and then decreases with pressure as the glass is compressed from 8.6 to 81 GPa (Fig. 1 and Table 1). This behavior is unusual because most solids become stronger with increasing pressure and density (*8, 16*). The decrease in strength was reproducible in separate recompression experiments, which suggests that these results are independent of previous deformation and compaction (*17*). Indeed, transient effects of work hardening should not be important in the low-temperature deformation of the glass (*18*).

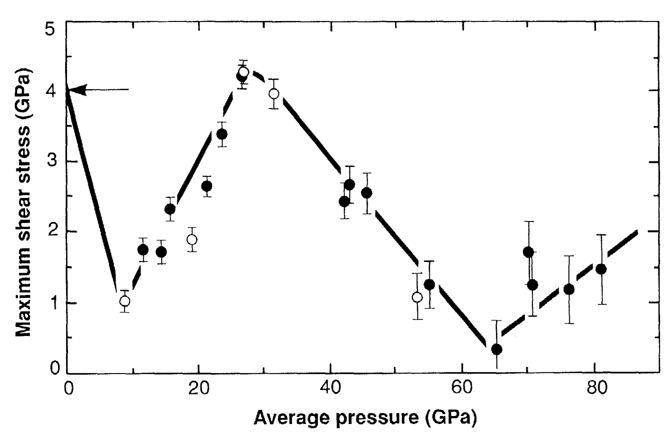

Fig. 1. Maximum shear stress in silica glass at room temperature and average pressures ($\bar{P}$) between 8.6 and 81 GPa. Each point corresponds to a separate sample, and the heavy line shows the general trend of the data. The shear stress is determined from Eq. 1, and it is a measure of the yield strength of the sample at high pressures. The error bars represent the combined uncertainties from the measurements of h and $\partial P/\partial r$. The open circles show the strength of samples that were initially compressed to 50 GPa, unloaded, and then recompressed. The arrow marks the zero pressure strength of silica glass (*19*).

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