Improved Orbital and Physical Parameters for the Pluto-Charon System

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Analysis of the observations of several Pluto-Charon occultation and transit events in 1985 and 1986 has provided a more detailed knowledge of the system. The sum of the radii of Pluto and Charon is 1786 ± 19 kilometers, but the individual radii are somewhat more poorly determined; Pluto is 1145 ± 46 kilometers in radius and Charon is 642 ± 34 kilometers in radius. The mean density of the system is 1.84 ± 0.19 grams per cubic centimeter, implying that more than half of the mass is due to rock. Charon appears to have hemispheres of two different colors, the Pluto-facing side being neutral in color and the opposite hemisphere being a reddish color similar to Pluto.

TWO YEARS HAVE NOW ELAPSED since the beginning of the orbital alignment that causes Pluto to occult its satellite Charon and Charon to transit Pluto (the so-called mutual events) (*1*). We report here successful observations of several of these events and present new model parameters for the system based on these data.

Telescopes at Maúna Kea Observatory on the island of Hawaii and McDonald Observatory in west Texas were equipped with photoelectric detectors to monitor changes in the brightness of the Pluto-Charon system. Figure 1 shows plots of the system brightness as a function of time ("light curves") for six mutual events observed in 1986. In all cases, the measurements were made differentially with respect to a nearby comparison star with a color similar to Pluto's (*2*). Most of the Mauna Kea observations were made through a standard blue filter (Johnson B) with the 2.24-m telescope. A few events were observed with the No. 1 0.61-m telescope, but, to increase the light-gathering power to the level necessary to obtain useful data, a much broader filter (hereafter called "yellow") was utilized (*3*). The McDonald observations were made through either standard blue or green filters (Johnson B and V) with the 2.1-m telescope.

We used nonlinear least-squares techniques to determine the best possible values for both the orbital and physical parameters. The orbits of Earth, Pluto, and Charon are used to compute the three-dimensional geometry of the system, which is then projected onto the plane of the sky as three disks, one for Pluto, one for Charon, and a third to represent either the shadow of Pluto or Charon. During an inferior event (Charon passing in front of Pluto), Charon casts its shadow on Pluto; likewise, during a superior event (Charon passing behind Pluto), Pluto casts its shadow on Charon. For the geometry at any given time, the theoretical brightness of the system is computed on the basis of the model reflectivity of the surface (the "albedo"), the occulted area (derived from the radius and orbital model parameters), and the known behavior of the system's rotational light curve; this model brightness is then compared with the observations. The model orbital radius was fixed at the value determined from the high-resolution imaging technique known as speckle interferometry (*4*). The eccentricity of Charon's orbit is assumed to be zero. To avoid potential problems that might be introduced by the use of different filters, the model parameters were derived from only the more extensive blue filter data. The overall fit of the model to the data is excellent, with the average residual exceeding the average measurement uncertainty by less than 0.002 mag. Table 1 contains a list of resulting orbital and physical parameters. The tabulated quantities without error bars were held constant. With the exception of the density, which is a derived result, all the other numerical quantities were determined from the least-squares fit.

The uncertainties in the model parameters were determined by taking the standard deviation of the mean of nine sets of model parameters. Each set was determined from one-ninth of the entire collection of observations. Therefore, the uncertainties should be reliable. We did assume, however, that the albedos of the occulted areas are uniform; departure from the assumed uniformity would increase the uncertainties.

Note that the sum of the radii has been determined with smaller relative uncertainty than either of the individual radii because the mutual events to date have been only partial events. The duration of an event is determined by the length of time that the center-to-center separation is less than the sum of the individual radii, thus implying object-object or object-shadow overlap. Separating this sum into individual radii requires additional information that does not come from the shape of the ingress and egress portions of the light curve. These portions are remarkably insensitive to the individual radii. In this case, the augmentation of the depth of an event produced by the shadow (which is a function of the Earth-Pluto-sun illumination angle) helps. The depth also depends on the albedo, however, and the dependencies between the various parameters limit the precision with which they can be determined. The higher the correlation between two variables, the poorer each variable can be determined independently of the other.

The density of the system does not depend on the absolute linear scale for the system (that is, the density remains the same even if the orbital radius and planet-satellite radii are all doubled). It does, however, depend on the individual radii, so the uncertainty in the density is now rather large. The large value for the density would seem to indicate that the system is composed of more rock than water ice by weight. This conclusion assumes that the water has not been compressed to a higher density, as in the case of the Galilean satellite Europa. Given the smaller sizes of Pluto and Charon relative to Europa, such compression effects should be small. The uncertainty in the density does need to be reduced, however, before we can make any definitive statements about the ice-rock ratio.

These uncertainties will be reduced tremendously when total events are observed. The duration of totality yields the difference between the individual radii. Given the sum and difference, the individual radii will be well determined, with corresponding improvements in several other model parameters, as well as the derived density. Therefore, total events are extremely important, and they will be possible only during the 1987 and 1988 apparitions (*5*).

These results can be compared with those of Dunbar and Tedesco (*6*) and Reinsch and Pakull (*7*). The former group derived their model parameters by generating model light curves and by manually adjusting the parameters until the event depths matched two events observed in 1986 and three events observed in 1985 (*1*). The latter group used a least-squares approach on the three 1985 events plus two events they observed in 1986. Neither group explicitly reported their derived sum of the radii and its uncertainty, so no comparison can be made of this

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quantity. Only the more poorly determined individual radii are reported. The derived radii for Pluto are reasonably consistent (although the others' uncertainties are larger than ours), but the model radii for Charon differ substantially, with our result falling between the other two. It follows that our derived density also falls between the other groups' values. Their derived albedos should not be strictly compared with ours, given that their albedos represent the mean of the area swept out by the events they observed, and different events sweep out different areas; in addition, they used different filters from ours for most of their observations.

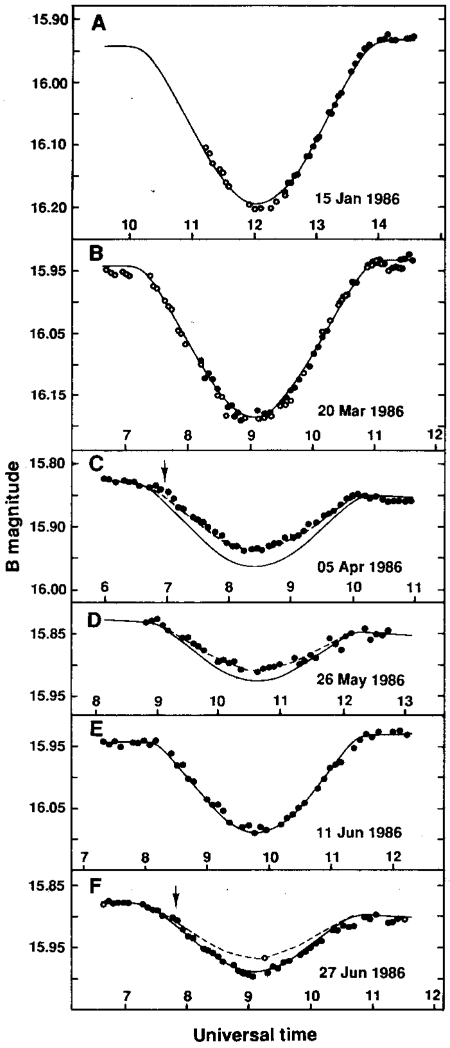

Fig. 1. Mean opposition B magnitude versus time for the Pluto-Charon system. (**A**) Inferior event observed on 15 January. The open circles are McDonald data observed with the green filter (V) transformed to blue (B), and the filled circles are Mauna Kea data observed in the B band. (**B**) Inferior event observed on 20 March. The symbols are the same as for (A), but in this case the McDonald data were observed in the B band. (**C**) Superior event observed on 5 April from McDonald in the V band. The arrow marks the location of a bump in the data that may correspond to a similar bump seen in the 27 June data. (**D**) Superior event observed on 26 May from Mauna Kea in yellow light. (**E**) Inferior event observed on 11 June from Mauna Kea in yellow light. (**F**) Superior event observed on 27 June from Mauna Kea. The filled circles are for blue light data, and the open circles are for yellow light data. The arrow marks the location of a bump in the data that may correspond to a similar bump seen in the 5 April data.

Given the total light from the system and the depth of an event, we can divide the visible surface into two albedo domains. The first domain is the surface area that is blocked from view during the event; the second domain is the remainder. During an inferior event, we can therefore determine the albedo of the north polar region on Pluto and the average albedo of the remainder of Pluto plus Charon. (North is taken here to lie in the direction of the angular momentum vector.) During a superior event we can determine the albedo of the northern hemisphere of Charon and the average albedo of the remainder of Charon plus Pluto. We can decouple the albedo of the remainder of Pluto from the north polar region by making the assumption that the albedo of Charon is uniform over its entire surface. As will be explained below, such an assumption may very well be invalid, but, because Charon contributes a small fraction of the total light (about one-fifth), a serious error in this assumption will have a much smaller effect on the computed albedo for the remaining visible surface of Pluto.

The results of these calculations are shown in Fig. 2. The average albedo of the equatorial and south polar regions on the Charon-facing hemisphere of Pluto is much lower than the albedo of the north polar region. This albedo distribution would appear to predict that Pluto should be getting brighter as the northern hemisphere comes into view; in fact, the system has been getting fainter since its discovery in 1930. Therefore, we can assume that the south polar region also has an albedo about as high as the north polar region. This implies that the equatorial region is even darker. This result is consistent with the albedo distribution model derived from out-of-eclipse photometry (*8*). The opposite hemispheres of the two bodies would have the mean albedos as shown in the lower portion of Fig. 2.

Some color information was also obtained in 1986. The 27 June event was primarily observed through the blue filter, although the wide yellow filter was used to obtain three points: one before the event, one near maximum depth, and one after the end of the event. The event depth is obviously less in yellow light (Fig. 1F), which demonstrates that the Pluto-facing hemisphere of Charon is not as red as Pluto itself. The 26 May data (Fig. 1D), which were obtained exclusively through the yellow filter, confirm the event to be deeper in blue light; the solid curve is the blue light model, whereas the dashed curve is the model that reproduces the depth of the yellow light data on both 26 May and 27 June. The 5 April data (Fig. 1C) also show the same effect. Given the known reflectance spectrum of the Pluto system, the reflectance spectrum of the Pluto-facing hemisphere of Charon must be fairly neutral in color. On the other hand, the hemisphere of Charon facing away from Pluto must have approximately the same color as Pluto. If the entire surface of Charon were neutral in color, the depth of an inferior event should be deeper in yellow light than in blue light. The 11 June data show no such effect; Fig. 1E shows the yellow light data and the blue light model, which agree rather well. Thus it appears that we have yet another example of a solar

Table 1. Summary of Pluto-Charon orbital and physical parameters.

Semimajor axis (km)	19130.0 [from (*4*)]
Eccentricity	0.0 (assumed)
Inclination* (deg)	91.6 ± 1.6
Ascending node* (deg)	222.44 ± 0.15
Argument of periapsis* (deg)	0.0
Mean anomaly (deg)	259.59 ± 0.22
Epoch (Julian date)	2446600.5
Period (days)	6.387204 ± 0.000047
Pluto radius† (km)	1145 ± 46
Charon radius† (km)	642 ± 34
Sum of radii† (km)	1786 ± 19
Mean density of system (g cm^{-3})	1.84 ± 0.19
Pluto blue geometric albedo	0.612 ± 0.017
Charon blue geometric albedo	0.424 ± 0.018
Pluto reflectance spectrum	Reddish
Charon reflectance spectrum	Neutral (Pluto-facing) Reddish (anti-Pluto)

* Equator and equinox of 1950.0. †We emphasize that these values and uncertainties are relative to the assumed size of the semimajor axis. A preliminary analysis of the first observed total superior event (29 December 1986) indicates that Pluto is larger and Charon is smaller by about one standard deviation.

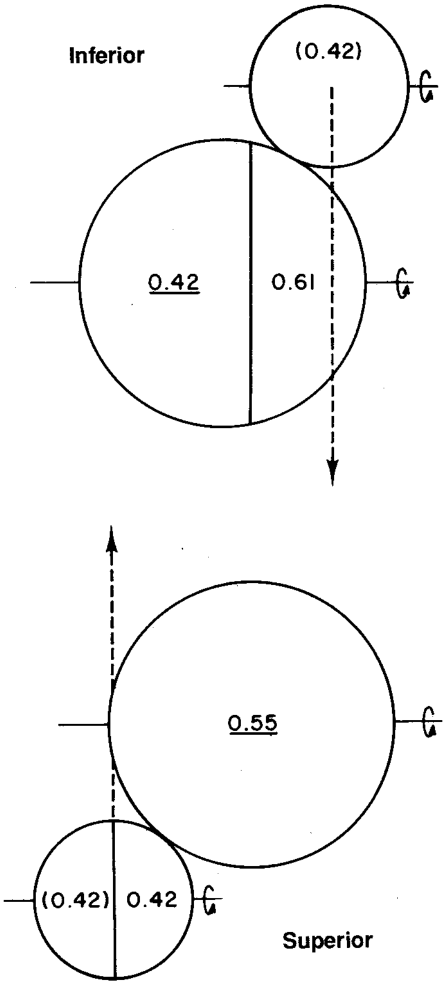

Fig. 2. Surface albedo distribution of the Pluto-Charon system. The unmarked albedo values were determined from the least-squares fit to the observations. If the values in parentheses are assumed, the underlined values can be derived.

system object with strikingly different hemispherically sized geologic units. The existence of this hemispherical color difference does not necessarily imply an albedo difference, which would invalidate the uniform surface albedo assumed earlier, but the possibility does admittedly exist (*9*).

Small-scale surface albedo features on either object should manifest themselves as small deviations from a smooth event light curve. A comparison of the 5 April and 27 June superior events shows a bump early in both events. The relative times of these bumps are shifted slightly, but this effect is expected, because the orientation of the limb of Pluto was different for these two events. The time shift information is essential to localize the albedo feature; given only one event, the location could be anywhere along the intersection of Charon's disk and Pluto's limb at the corresponding time. We feel confident that real albedo features have been detected on Charon. Although similar deviations have been seen in some high-quality inferior event data, which would indicate albedo features on Pluto, these deviations have yet to be confirmed.

In conclusion, we have already learned a great deal about the Pluto system from just the first 2 years of events. The next 2 years are critical for determining the individual radii of Pluto and Charon and the mean density of the system. Total superior events offer the opportunity to study Pluto uncontaminated by the light of Charon with both spectroscopic and colorimetric techniques. Similar observations of the combined light of Pluto and Charon immediately preceding or following a total event can be differenced with the observations of Pluto alone to yield the corresponding information on Charon alone.

REFERENCES AND NOTES

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2. D. J. Tholen, *Astron. J.* **90**, 2639 (1985). Because atmospheric absorption is a function of the color of an object at ultraviolet and blue wavelengths, the use of a comparison star with similar color eliminates any systematic error due to this effect.
3. This filter passes all light with wavelengths longer than about 5300 Å. The photoelectric detector used is sensitive out to 9300 Å, so the bandpass is about 4000 Å. This can be compared to the 900-Å bandpass of the blue filter used at the larger telescope.
4. D. J. Tholen, *Astron. J.* **90**, 2353 (1985).
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8. M. W. Buie and D. J. Tholen, *Bull. Am. Astron. Soc.* **18**, 821 (1986).
9. New observations obtained by several investigators in 1987 have further confirmed these color findings.
10. We thank the telescope allocations committee at the Institute for Astronomy for their support of this project. Because of the timing of these mutual events, the telescope scheduler faces a difficult task, and we also thank him for his patience. We acknowledge the assistance of F. Cheigh and B. Barnes at the 2.24-m telescope. The work at the University of Hawaii is supported by NASA grant NGL 12-001-057, and that at the University of Texas by NASA grant NGR 44-012-152. A portion of the computations done in the course of this research were performed with the facilities of the San Diego Supercomputer Center, which is supported by the National Science Foundation.

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