

RESOLVED CCD PHOTOMETRY OF PLUTO AND CHARON*

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ABSTRACT

Highly-resolved CCD images (0.7–0.9 arc sec FWHM) of Pluto and Charon near maximum separation are measured with PSF fitting techniques to determine independent magnitudes and an accurate separation for Pluto and Charon. A measured separation of 0.923 ± 0.005 arc sec at position angle $173^{\circ}3 \pm 0.3$ on 1987 June 18 UT led to a value of 19558.0 ± 153.0 km for the radius of Charon's orbit. An apparent B magnitude of 14.877 ± 0.009 and $(B - I)$ color of 1.770 ± 0.015 are found for Pluto, while Charon is fainter with $B = 16.826 \pm 0.011$ and slightly bluer with $(B - I) = 1.632 \pm 0.018$. Using the radii determined by Tholen and Buie (1987) along with the new value for Charon's orbital radius from our data, we can determine the geometric albedos of Pluto and Charon in the B and I bandpasses for the hemisphere observed at rotational phase ~ 0.50 (Binzel 1988). Using the magnitudes as corrected to zero phase these albedos are: $p_B(0^{\circ})_{\text{Pluto}} = 0.55 \pm 0.03$, $p_B(0^{\circ})_{\text{Charon}} = 0.32 \pm 0.03$, $p_I(0^{\circ})_{\text{Pluto}} = 0.73 \pm 0.04$, $p_I(0^{\circ})_{\text{Charon}} = 0.37 \pm 0.02$. We hope that the data presented here will help constrain the physical and dynamical parameters determined from the study of the mutual eclipse events which are now under way.

Key words: Pluto–Charon–planets–photometry

I. Introduction

With the advent of the series of mutual eclipse phenomena between Pluto and its moon Charon, predicted by Andersson (1978) and first observed by Binzel *et al.* (1985), many of the physical and dynamical parameters of the Pluto-Charon system could be investigated firsthand. In order to refine the orbit so that these mutual eclipse phenomena could be better predicted and observed, Tholen (1985) used speckle interferometric observations of the Pluto system since the small maximum separation of 0.9 arc sec almost precluded using normal imaging techniques. Analysis of these mutual events has already begun to constrain the parameters of the Pluto system (Dunbar and Tedesco 1986; Tholen *et al.* 1987a; Reinsch and Pakull 1987), and as the eclipse series continues a much more accurate characterization of this system will result. We present here some rather unique data which

we feel will complement the mutual event studies and help bring about a more rapid convergence of the parameters of the system to the best measured values.

In June of 1987, during an engineering run intended to characterize a new RCA CCD at the Canada-France-Hawaii Telescope (CFHT), several images of the Pluto-Charon system were taken in an attempt to resolve the system while it was near its maximum separation. While the separate images of Pluto and Charon were still blended in most of the frames, we felt they were resolved enough to use Point Spread Function (PSF) fitting techniques to measure the individual magnitudes and the separation between the two bodies. The photometry program DAOPHOT (Stetson 1987) was used, assuming that the images of Pluto and Charon were essentially stellar, and the results were quite satisfactory, as can be seen from the further analysis in this paper.

II. Observations and Calibrations

The last night of a three-night engineering run, allo-

*Based on observations obtained at the Canada-France-Hawaii Telescope Corporation.

cated to test a new RCA CCD at CFHT, coincided with a maximum elongation of the Pluto-Charon system. Images were obtained in the *B* and *I* passbands with a double-density CCD (640×1024 , $15^2 \mu\text{m}^2$ pixels; "RCA4") on the 3.6-m telescope on Mauna Kea. This device is similar in characteristics to another double-density CCD ("RCA2") in regular use at CFHT (cf. Waddell and Christian (1987) for description). However, RCA4 is mounted to a glass substrate which necessitated a complete evaluation of efficiency and calibration characteristics of this CCD in an astronomical environment.

The night of observation, 1987 June 17/18 (1987 June 18 UT), was characterized by good seeing (0.9 arc sec FWHM), and since the Pluto-Charon system was to be near maximum separation an attempt was made to resolve the system. This attempt produced four *B* CCD frames with an average star image FWHM of 0.94 arc sec and three *I* CCD frames with an average star image FWHM of 0.76 arc sec. The best-resolved frame was the 10 sec *I* frame with a FWHM of 0.68 arc sec. Table I lists the journal of observations and FWHM of the individual CCD images.

Considering that the main purpose of the run was to characterize RCA4, a large number of standard-star cluster fields (Christian *et al.* 1985) were observed over the three-night run. This allowed excellent calibration of the photometry in both *B* and *I*. Photometry was performed on the standards using the synthetic aperture routine PHOT within DAOPHOT (Stetson 1987). The apertures ranged from 3 pixels (0.6 arc sec) to 30 pixels (6.3 arc sec). An aperture of 24 pixels (5 arc sec) was selected as optimum for the reductions since it was the smallest aperture which still contained almost all the star light. In all, 139 measured points in *B* and 113 in *I* from the clusters M 92 and NGC 4147 covering the three nights were used to set the color term. For the third night, 15 points in *B* and 24 in *I* were available to set the zero points and extinction coefficients. Figure 1 shows the fits to the color terms and zero points for all three nights in *B* and *I*. Although there is an apparent slope in the *I* zero point for the third night

(for which there is no NGC 4147 data), it is clear from the other zero-point plots that the stars in M 92 which contribute to the appearance of the figure are systematically discrepant on all nights. The systematic errors for the two offending stars are nearly equal but opposite in sign and so cancel out in the zero-point determination. However, these errors are reflected in the larger zero-point error for the *I* fit.

The final transformation equations are

$$B = b + 26.848 - 0.217 X + 0.095 (B - I)$$

and

$$I = i + 25.704 - 0.055 X - 0.041 (B - I),$$

where X is the air mass and the instrumental magnitudes b and i are normalized to 10 sec. The total zero-point error which results from the fit of these data and the aperture corrections of the individual frames is about ± 0.0087 for *B* and ± 0.0117 for *I*.

III. Use of PSF Techniques

In crowded field photometry, one of the best techniques to measure magnitudes is PSF fitting. This is not the first time such a method has been applied to the Pluto-Charon system. A similar technique was used on lower resolution CCD images by Reitsema, Vilas, and Smith (1983) to derive a Pluto/Charon brightness ratio of 5.5 (1.85 magnitudes) in *V*. In order to find the individual magnitudes of the blended images of Pluto and Charon, we used a version of DAOPHOT (Stetson 1987).

The PSF can be defined as the system response to a point source represented by a stellar image. At issue is whether or not the apparent diameter of Pluto, which is much larger than that of a star but still small compared to the pixel size, changes significantly the detected image profile of Pluto so that a PSF derived from stellar images might not be applicable to the planet.

To test this, consider an estimated diameter of 2300 km for Pluto and a distance from Earth of 29.039 AU (Tholen, private communication) during our observations; then the apparent diameter of Pluto was about 0.1 arc sec or 0.5 pixel. The best seeing image was the 10-sec *I* frame with 0.68 arc sec FWHM (3.2 pixel). Treating the disk of Pluto as a FWHM and convoluting this with the seeing gives a probable FWHM of the Pluto image of 3.24 pixel, or approximately a 1.3% increase in FWHM. The poorer seeing of the *B* frames produces only a 0.5% increase in FWHM for these images and we expected the PSF to model them nicely, but the $\sim 1\%$ increase of the best-seeing *I* frames might have been large enough to cause a systematic error in the magnitude measurement.

DAOPHOT returns a statistic, called χ (Stetson 1987), which is indicative of the goodness of the PSF fit. For a good fit, χ will be close to 1.0, and for all the measurements done on these frames this is the case. The best-see-

TABLE I
Journal of Observations

Frame ID	UT start (18 June 1987)	Exp. time (sec)	Airmass	FWHM (arcsec)	Filter
Pluto022	8:13:09.3	10.0	1.081	0.96	<i>B</i>
Pluto023	8:15:30.5	30.0	1.084	0.91	<i>B</i>
Pluto024	8:17:38.7	60.0	1.086	0.91	<i>B</i>
Pluto025	8:19:16.0	90.0	1.088	0.96	<i>B</i>
Pluto026	8:23:30.3	10.0	1.093	0.68	<i>I</i>
Pluto027	8:25:15.4	15.1	1.096	0.74	<i>I</i>
Pluto028	8:26:09.1	20.0	1.098	0.88	<i>I</i>

CCD field coordinates:	
$\alpha = 14^{\text{h}}39^{\text{m}}42^{\text{s}}$	$\delta = 01^{\circ}58'14''$
Ephemeris:	
$r = 29.686 \text{ AU}$	$\Delta = 29.039 \text{ AU}$ $phase \ angle = 1^{\circ}53'$

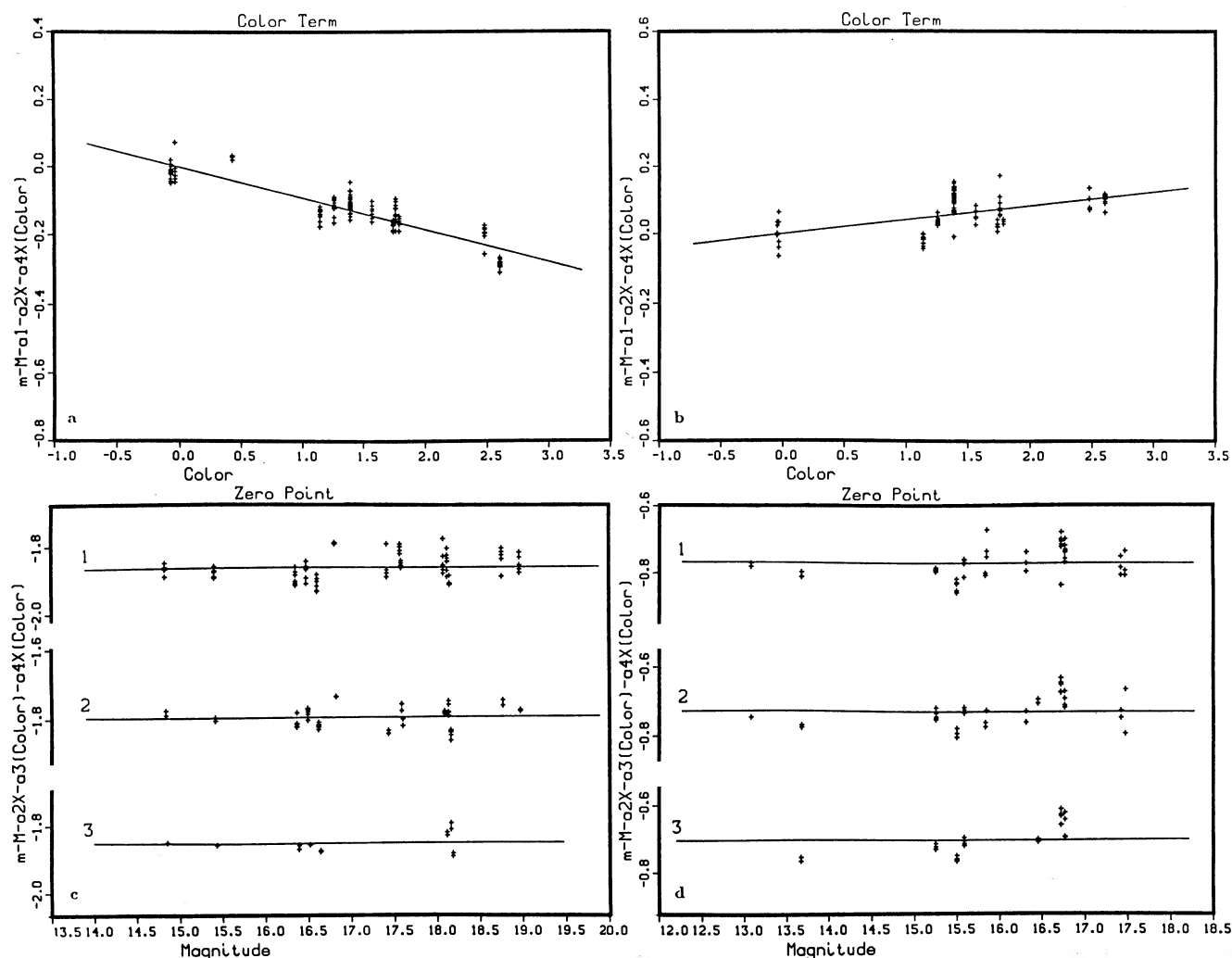


FIG. 1—(a) *B* color-term fit. (b) *I* color-term fit. (c) *B* zero-points fit. (d) *I* zero-points fit. In the figure above, m and M are, respectively, the instrumental and standard magnitudes in the filter indicated by the subcaptions, and Color indicates $(B-I)$ standard color. The coefficients are: a_1 = zero point, a_2 = extinction, a_3 = color term, and a_4 = cross term (color times extinction).

ing *I* image of the Pluto-Charon system with Pluto subtracted in Figure 2 shows a very clean fit with only slight noise in the very core as is typical of such subtractions. However, the largest deviations from 1.0 do occur in the good seeing *I* frames where the average χ value of the PSF fits to other star images is 1.02 compared to the fit to Pluto-Charon with $\chi = 1.36$. In *B* there is essentially no difference between the fit to the stellar images with an average χ of 1.05 and the Pluto-Charon images with $\chi = 1.02$.

It seems clear that the effect of Pluto's disk size is detectable in the *I* frame fits, but how much effect does this have on the measured magnitude? As a check, Charon was subtracted from the two best *I* frames assuming that it was modeled well by the PSF, since its apparent diameter would be about half that of Pluto. Aperture photometry was then done on the lone Pluto image and compared to the PSF fit magnitude returned from

DAOPHOT. The average difference was only 0.003 magnitude, well below the final estimated errors. We conclude that while the nonzero apparent diameter of Pluto does seem to have a measurable effect on the PSF fitting parameters, its effect on the measured magnitude is minimal and the use of PSF fitting methods for the Pluto-Charon system is acceptable.

IV. Results

The results of the PSF fitting photometry are presented in Table II. The magnitude errors include the zero-point errors of the transformation to the standard *B* and *I* filters. Photometry for several stars imaged on the same CCD frame are also included. Figure 3 shows the deepest *I* CCD image with the Pluto-Charon system and these field stars labeled for identification. Using the measured magnitudes for Pluto and Charon and the known zero points of the photometry, the total *B* and *I* magnitudes for the

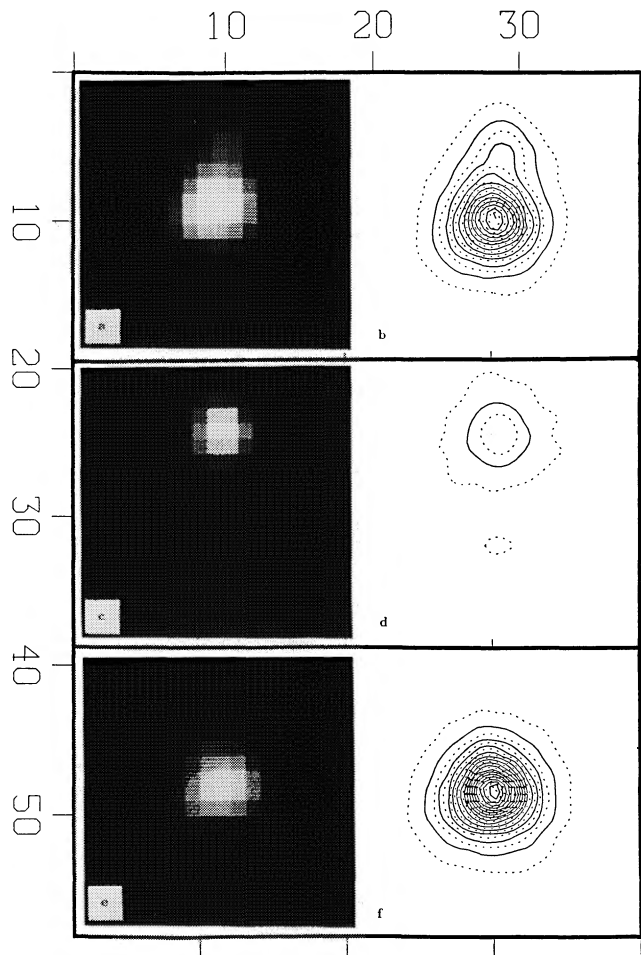


FIG. 2—(a) Pluto-Charon CCD image. (b) Contour of Pluto-Charon CCD image. (c) Charon CCD image (Pluto subtracted). (d) Contour of Charon image. (e) Star image (ID = 2). (f) Contour of Star image. (All images are from the best-seeing 10-sec I frame.)

system were calculated to be 14.710 ± 0.009 and 12.959 ± 0.012 , respectively. This implies a $(B - I)$ color for the system of 1.751 ± 0.015 .

The PSF fit in DAOPHOT also returns the best-fit positions of all the measured star images. Since the relative positions of the Pluto system and the field stars may be of some astrometric interest, we present these data for all seven CCD frames in Table III. The coordinates are given in CCD pixels.

Perhaps of more immediate interest is the separation and position angle of Charon relative to Pluto. Table IV gives the relative separation in pixels and the position angle relative to the positive x axis (rows) of the CCD for all seven frames. To find the separation in arc seconds, the known plate scale of 0.20596 ± 0.001 arc sec pixel $^{-1}$ ($15 \mu\text{m pixel}^{-1}$) is applied to the average value of the separation giving 0.923 ± 0.005 arc sec toward the south. The formal error comes from the standard deviation of the mean of the seven measured separations and from the

TABLE II
Pluto-Charon Field Photometry

ID	B	$B \text{ err}^*$	I	$I \text{ err}^*$	$B - I$	Name
3	14.877	0.009	13.107	0.012	1.770	Pluto
7	16.826	0.011	15.194	0.014	1.632	Charon
1	17.728	0.010	16.070	0.014	1.658	
2	14.709	0.009	12.752	0.012	1.957	PSF 1
4	15.790	0.009	13.791	0.012	1.999	PSF 2
5	18.625	0.012	17.574	0.027	1.051	
6	18.890	0.013	16.692	0.015	2.198	

* The I and B errors include zero point errors from the transformation to the standard filter system of 0.0117 and 0.0087 respectively, added in quadrature.

plate scale error. This separation is larger than predicted by an ephemeris using the value for the orbital radius given by Tholen (1985); however, it is consistent with a more recent predicted separation of 0.934 arc sec based on newer speckle data (Beletic *et al.*, private communication).

The plate scale which we use comes from a value of $72.83 \pm 0.01 \mu\text{m arc sec}^{-1}$ measured at prime focus on a CCD with $30 \mu\text{m}$ pixels. The plate scale error is derived using the given error above and a somewhat conservative estimate of the pixel spacing error for RCA4 of $\pm 0.1 \mu\text{m pixel}^{-1}$. By overestimating the pixel spacing error, we hope to include other possible errors in the plate scale which might be caused by changes in focus, different filters, or off-axis deviations. It might be noted that the separation and position angle derived here refer to the optocenters of Pluto and Charon, which might not be the same as the geometric centers if the albedo distributions are unusual. This is probably quite a small effect, as the actual angular diameters of Pluto and Charon are much smaller than a single pixel on the CCD.

The true position angle is not as well determined, since we had no accurate measurement of the orientation of the CCD for the night of the observations. The transformation to the true position angle was determined by a three-step process. First, the angle between the positive x axis and equatorial north was found a few nights after these observations by trailing a star image in a north-south direction using the telescope hand paddle. Then the angle between the x axis on that night and the night of the Pluto observations was determined by comparing the M92 standard cluster field imaged on both nights. Finally, by trailing a star image north-south with the hand paddle, and then stopping the telescope drive for a few seconds to get a true east-west trail, we have determined the paddle-driven north-south trail to be within $0^{\circ}02 \pm 0^{\circ}19$ of the true north-south line. The result is that the true position angle was found to be $173^{\circ}25 \pm 0^{\circ}28$. The error includes the error in the measurement of the orientation of Charon, the error in the measurement of the orientation of the north-south trailed star image, the error

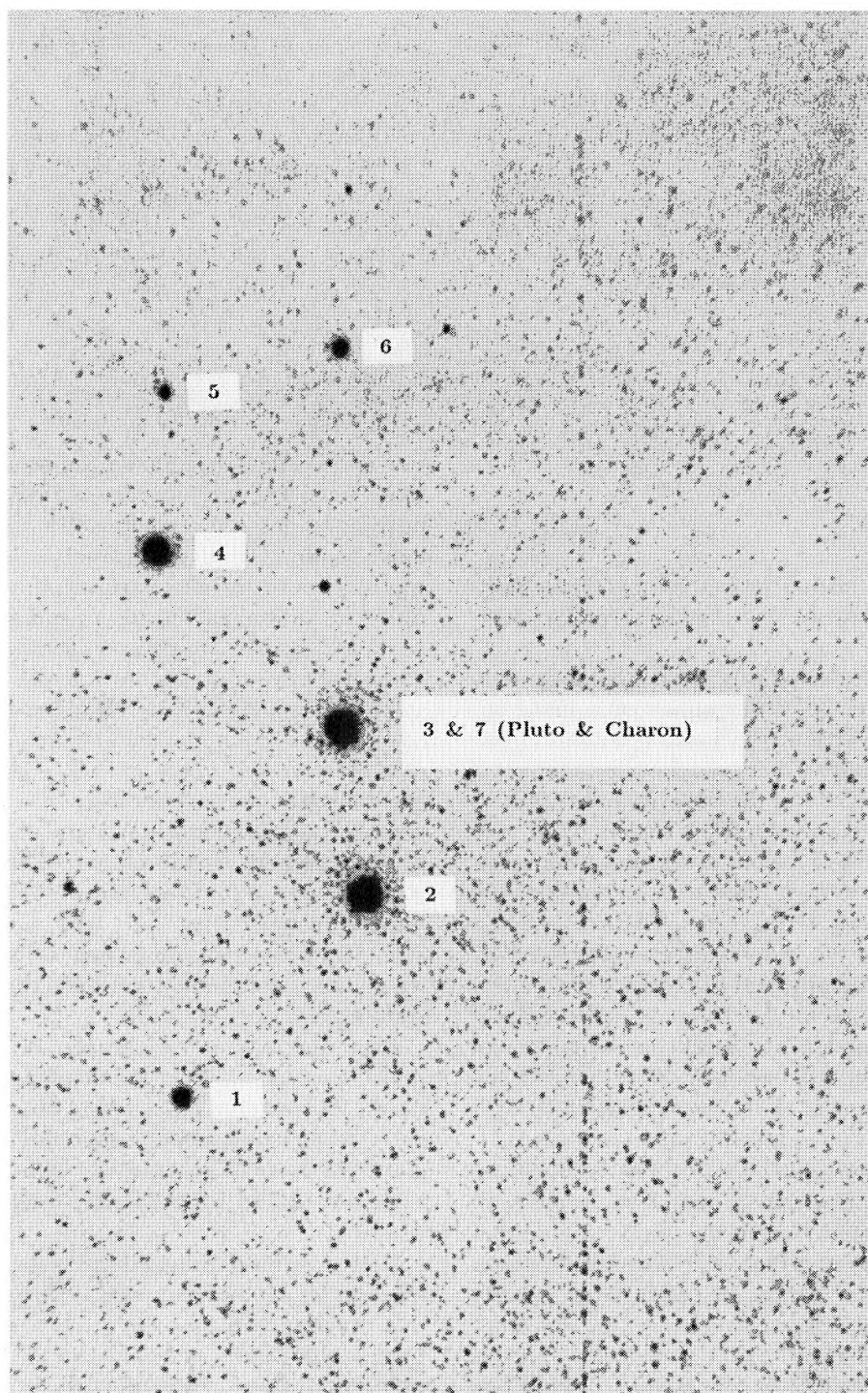


FIG. 3-1 20-sec exposure CCD frame finder chart. In this high-contrast image, background noise shows up as individual dark pixels scattered throughout the frame.

in the transformation from the night of the star trail to the night of the observations of the Pluto system, and, finally, the error of the north-south trail with respect to the true north-south line.

V. Discussion

Using the values determined for the separation and magnitudes of Pluto and Charon from the June observa-

TABLE III
 Image Coordinates

B Frame:		Pluto022		Pluto023		Pluto024		Pluto025	
ID	X (pixels)	Y (pixels)	X (pixels)	Y (pixels)	X (pixels)	Y (pixels)	X (pixels)	Y (pixels)	X (pixels)
3*	250.89	501.60	250.39	500.94	250.31	501.08	249.53	501.12	
7*	251.46	506.06	250.96	505.39	250.83	505.51	250.04	505.58	
1	134.96	753.21	134.97	752.45	135.36	752.45	134.99	752.41	
2	263.61	617.09	263.62	616.39	264.03	616.39	263.64	616.40	
4	121.17	380.90	121.21	380.24	121.62	380.29	121.24	380.29	
5	126.56	272.46	126.62	271.47	127.02	271.57	126.55	271.60	
6	247.89	242.05	247.93	241.70	248.31	241.81	247.89	241.79	

I Frame:		Pluto026		Pluto027		Pluto028	
ID	X (pixels)	Y (pixels)	X (pixels)	Y (pixels)	X (pixels)	Y (pixels)	
3*	250.67	503.35	250.28	503.28	250.12	503.31	
7*	251.18	507.80	250.79	507.75	250.63	507.74	
1	136.99	754.45	136.91	754.37	136.96	754.36	
2	265.57	618.46	265.56	618.35	265.60	618.35	
4	123.10	382.36	123.07	382.21	123.12	382.21	
5	128.33	273.45	128.38	273.66	128.36	273.58	
6	249.58	244.00	249.61	243.80	249.72	243.85	

* 3 = Pluto, 7 = Charon

tions along with information derived from previous light-curve analyses, it is possible to constrain several parameters of that system.

Perhaps the best measured parameter is the separation of Pluto and Charon. Our observations were made approximately 2.5 hours before the greatest southern separation of Charon from Pluto between the inferior event of 1987 June 16, 20:40 UT and the superior event of 1987 June 20, 00:59 UT as predicted by Tholen, Buie, and Swift (1987). The value of the projected separation calculated from this observation gives a lower limit to the orbital radius of Charon. Using the known distance to the Pluto system during the observations as calculated by Tholen (private communication) and including a conservative error of 0.001 AU for that distance and an error of 10 km in the definition of 1 AU, a projected separation of 19439 ± 104 km may be determined. Most of the formal error comes from the error of the measured angular separation and that error depends on the plate scale error.

Using the ephemeris for our observations calculated by Tholen (private communication), and by assuming all other orbital parameters remain the same, we find that the maximum separation of Pluto and Charon (and therefore the orbital radius) should be 1.0061 times our observed value. It is unclear how changes in the other orbital parameters might effect the scale factor, but it is safe to assume that the ultimate scale factor will not be less than unity. Therefore, in an attempt to assign a reasonable error to the scale factor, we will use the difference between the minimum and the ephemeris-derived values of the scale factor as the error estimate. This results in a scale factor error of ± 0.006 , which gives us a value of 19558 ± 153 km for the orbital radius of Charon.

Other significant measurements from these observations are the individual magnitudes of Pluto and Charon

 TABLE IV
 Relative Position Angle and Separation

Frame ID	Pluto (pixels)		Charon (pixels)		Angle (degrees)	Separation* (pixels)	
Pluto022	250.89	501.60	251.46	506.06	82.717	4.496	
Pluto023	250.39	500.94	250.96	505.39	82.701	4.486	
Pluto024	250.31	501.08	250.83	505.51	83.305	4.460	
Pluto025	249.53	501.12	250.04	505.58	83.477	4.489	
Pluto026	250.67	503.35	251.18	507.80	83.462	4.479	
Pluto027	250.28	503.28	250.79	507.75	83.491	4.499	
Pluto028	250.12	503.31	250.63	507.74	83.433	4.459	
					mean:	83.226	4.480
					std. dev.:	0.359	0.017
					std. err.:	0.136	0.006

* plate scale = 0.206 ± 0.001 arcsec/pixel

in *B* and *I*. The *B* magnitudes can be used along with the blue geometric albedos determined from light-curve analysis to determine photometric diameters for Pluto and Charon. Or, given diameters measured from the mutual events, the geometric albedos can be estimated. Since it is known that there are major albedo variations on Pluto and perhaps on Charon (Tholen *et al.* 1987a) and since the measured albedos refer to hemispheres with sub-Earth longitudes almost 90 degrees from the present observations, it is not practical to determine photometric diameters using the current data. Therefore, we will use the diameters determined from light curves along with our new value of Charon's orbital radius to determine the *B* and *I* albedos of the observed hemisphere. Pluto's rotational phase for these observations has been calculated by Binzel (1988) to be ~ 0.50 , and he points out that since Pluto is near maximum light at this rotational phase, the albedos determined here are the maximum hemispherically-averaged albedos.

First, the absolute magnitudes of Pluto and Charon must be calculated from the measured apparent magnitudes. With no correction to zero phase included, Pluto's and Charon's *B* absolute magnitudes are 0.199 ± 0.009 and 2.148 ± 0.011 , respectively. In *I* the absolute magnitudes are -1.571 ± 0.012 for Pluto and 0.516 ± 0.014 for its moon.

Now in order to estimate the real albedo the absolute magnitudes must be corrected to zero-phase angle. To do this, some information about the phase function of the bodies must be known to estimate the magnitude correction to zero phase. Using the prescription of Bowell and Lumme (1979), the geometric albedos determined by Tholen and Buie (1987) for the other hemispheres, and assuming that Pluto and Charon have scattering properties similar to asteroids, an estimate of the phase correction can be made. For Pluto a rough correction of -0.11 magnitude to the absolute magnitude is found by using Table II and Figure 4 in Bowell and Lumme's (1979) discussion. For Charon, with its slightly lower albedo, a

correction of -0.13 mag results from this procedure. A better procedure might be to use a measured linear-phase coefficient to determine the zero-phase correction for the Pluto-Charon system and then use this value to correct both Pluto and Charon individually. Using his value for the linear-phase coefficient of 0.037 mag deg $^{-1}$, Tholen (1987) has calculated a phase correction of -0.057 mag for these data. A similar value of -0.063 ± 0.005 mag for the phase correction results from using the linear-phase coefficient of 0.041 ± 0.003 mag deg $^{-1}$ determined by Binzel and Mulholland (1984). When the albedos resulting from using the corrections from the linear-phase coefficients are compared to the albedos derived from the method of Bowell and Lumme (1979), the differences are within the range of the estimated errors. Therefore, in the following discussion a zero-phase correction of -0.057 magnitude is used for Pluto and Charon in both colors.

Using the values of the diameters determined by Tholen and Buie (1987), but scaling them by 1.022 ± 0.026 , according to our new value of the orbital radius, we have 2296 ± 59 km for Pluto and 1226 ± 33 km for Charon. These values plus our photometry in B , but without a correction to zero phase, give minimum B geometric albedos for Pluto of 0.518 ± 0.027 and for Charon of 0.302 ± 0.032 . Correcting to zero phase gives $p_B(0^\circ)_{\text{Pluto}} = 0.546 \pm 0.029$ and $p_B(0^\circ)_{\text{Charon}} = 0.318 \pm 0.034$. We can use the same procedure to determine the I albedos. The minimum I geometric albedo for Pluto is 0.689 ± 0.037 , and for Charon this minimum albedo is 0.353 ± 0.020 . Using the same corrections for zero phase as before gives $p_I(0^\circ)_{\text{Pluto}} = 0.726 \pm 0.039$ and $p_I(0^\circ)_{\text{Charon}} = 0.372 \pm 0.021$. These albedos indicate that the hemisphere of Charon sampled by these observations (the trailing hemisphere relative to its orbital motion) is fairly neutral in color as compared to the observed hemisphere of Pluto, which is reddish in color. This is evidenced in the redder ($B-I$) color of Pluto compared to Charon and supports the analysis of Tholen *et al.* (1987a).

VI. Summary

We have presented independent photometry of Pluto

and its moon Charon confirming that Pluto is redder than Charon, at least on the observed hemisphere. Along with the photometry, an accurate separation between the two bodies was measured, implying a slightly larger semimajor axis for Charon's orbit than previously measured. Using the diameters determined by the mutual-event observations, we derive values for the B and I geometric albedos of Pluto and Charon and find that the observed hemisphere of Pluto is reddish in color while Charon's observed hemisphere is more neutral.

We hope that the data presented here will serve as a check on the mutual-event observations and help to converge some of the dynamic and physical parameters of the Pluto-Charon system to their final values.

We wish to thank D. Tholen very much for advice concerning these observations and for providing excellent ephemeris and orbital data. We also wish to acknowledge the allocation of engineering time from the directors which allowed these observations.

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