Progress Report
NASA Grant NAG5-8989
Observations of the Pluto-Charon System

David J. Tholen, P.I.
Institute for Astronomy, University of Hawaii

Reporting Period

This report covers 2003 April 1 to 2004 March 31, which corresponds to the second year of this project.

Personnel

No individuals received any salary support from this grant. Two persons participated in research activities related to the project. In addition to the P.I., an undergraduate student from the University of Maryland, Jeremy Miller, applied for a position as an REU student (Research Experiences for Undergraduates) at the Institute for Astronomy during the summer of 2003. Analysis of the adaptive optics data acquired for this project had been proposed as a potential project to the various REU applicants who had expressed interest in planetary science. Having done some dynamical work in a class taught by Doug Hamilton at Maryland, Jeremy Miller was intrigued by the project, and so he accepted the offer of an REU position.

Data Analysis

Prior to the summer of 2003, only a subset of the images acquired on eight different nights had been examined. Jeremy Miller learned how to process infrared array detector images, dealing with the matter of bad pixels, and reduced all 384 images that had been obtained. Next, he determined the image scale and position angle of J2000 north by measuring the motion of an asteroid relative to a reference field star. The direction and speed of a numbered asteroid is extremely well-known from its orbit, providing a much better calibration than double stars of known separation and position angle. The results of the calibration work are shown in Table 2 of the attached document, which is a copy of Jeremy's poster presentation at the 2003 DPS meeting in Monterey. The calibration was repeated for each observing run, because we could not expect the instrument to be mounted on the telescope at precisely the same position angle each time. The image scales are more consistent, as expected, but show some evidence for variability that is almost certainly due to thermal effects on the telescope focal length. To minimize the amount of telescope time that was spent on calibration observations, asteroids moving fast enough to cross the 20 arcsec field of view of the detector in less than a half hour were chosen. As a result, the motion is fast enough to leave noticeable trails during the exposure. To derive accurate centroids for those trails, Jeremy used the same software that had been developed for doing astrometry of near-Earth asteroids. One limitation that we encountered is that the start times of the exposures were recorded in the image headers to a precision of only 1 second (truncated, not rounded). The motion of the asteroid in 1 second exceeds the accuracy with which we can determine the location of the centroid. For now, we are treating the precision of the times as a source of noise in the centroids, one that we hope averages out over the many images obtained during the calibration sequence.

With the calibration in hand, the next step was to perform the relative astrometry on the images of Pluto and Charon. Jeremy experienced first-hand the known problem that adaptive optics systems do not produce a typical point-spread function. Instead, they tend to have a narrow core surrounded by extended wings. We attempted to deal with this problem by using a double Gaussian to fit the images of Pluto and Charon. Both Gaussians have the same centroid but different peak values and widths. One Gaussian would attempt to reproduce the narrow core while the second Gaussian would attempt to reproduce the extended wings of the image. The increase in the number of free parameters slowed down the computations, but did improve the results.

It should be noted that at no time did we achieve diffraction-limited imaging, despite the expectation that we could prior to the observing runs. Had we obtained diffraction-limited images (0.05 arcsec in the infrared H band when observed with an 8-m telescope), then the disk of Pluto (0.11 arcsec in diameter) could have been resolved. A major source of uncertainty in the earlier determinations of the orbital eccentricity for Charon is due to the poorly known offset between the location of the center of light and the location of the center of the disk, which we assume coincides with the center of mass. Resolving the disk would allow the center of disk (and presumably mass) to be determined independently of the center of light. Unfortunately, our best images achieved only about 0.09 arcsec FWHM, presumably because Pluto simply isn't bright enough to allow the adaptive optics system to achieve full correction, even on an 8-m telescope, so we still have the same problem of not knowing where our center of light measurements fall on the disk of Pluto. The known contrast on the surface of Pluto makes this a significant issue, but the more uniform surface of Charon helps, which is fortunate, because the disk of Charon cannot be resolved from the ground with current technology.

The orbit fitted to the observations looks consistent with earlier work to first order. The position angle calibration primarily affects the fitted orbital inclination, and we are pleased to see results that are consistent, to within the stated uncertainties, with earlier work. The determination of the ascending node depends on the ratio of the minor and major axes of the projected ellipse of Charon's orbit, as well as Pluto's location in the sky, and is therefore relatively immune to calibration effects. Again, our results are quite consistent with earlier work. The semimajor axis of Charon's orbit is uncomfortably on the small side, which could be an artifact of our scale calibration. Note that the absolute diameters of Pluto and Charon, as determined from the mutual events observed between 1985 and 1990, scale with the semimajor axis. A smaller orbit therefore implies smaller sizes for Pluto and Charon, but the 1980 stellar occultation data place a lower limit on the size of Charon, and the new semimajor axis makes a tight fit even more uncomfortably tighter.

Numerically, the resulting eccentricity appears compatible with earlier work. However, the longitude of periapsis is nearly orthogonal to the previous result. We considered the possibility that the orbit of Charon could be precessing at a rate sufficient to move periapsis by 90 degrees in one decade; however, calculations by Jeremy with assistance from Doug Hamilton during the following academic year appear to have ruled out this possibility.

The residuals shown in Fig. 3 of the attached document are not randomly distributed, however. Clearly there is still a small source of systematic error that we have not yet identified and removed from the measured centroids, therefore any conclusions about the orbit of Charon are still premature at this time.

Remaining Tasks

Our top priority is to reexamine the double Gaussian centroiding procedure to see if the source of the systematic error is there. We do know that on some of the images, the solutions were unstable. The original intent was to perform this reexamination during the fall of 2003. ~~However, a death in the family put a sudden hold on those plans, one that has persisted for the~~ last year. Academic matters took priority, and the remainder of the academic year was needed to remove the backlog that accumulated during the bereavement period. The summer of 2004 and the current academic year have gone to removing the backlog of observational work for NASA's NEOO program.

In addition to the adaptive optics observations acquired by this project, there are newly published observations from *Hubble Space Telescope* obtained with the Fine Guidance Sensor (Olkin *et al.*), which were used to reexamine the matter of the Charon/Pluto mass ratio. We would like to incorporate those data into our orbit solutions. Even more *HST* observations of the Pluto-Charon system were acquired by Buie using the Advanced Camera for Surveys for purposes of mapping the surface albedo distribution. He is nearly ready to release the astrometric data for inclusion in our orbit solutions.

So although the fall 2003 hiatus in progress was both unanticipated and unfortunate, it has delayed work long enough to permit the inclusion of these other new sources of data, if the Planetary Astronomy program would grant a no-cost extension to this project.

Schedule

If a no-cost extension is allowed, we expect the remaining tasks to be addressed during the first half of 2005. Because of prior commitments to the Hayabusa (née MUSES-C) mission, there would be substantial motivation for the P.I. to complete the work prior to a planned sabbatical, the first portion of which would be spent in Japan during the encounter phase with the near-Earth asteroid Itokawa, and the remainder of which would be spent working on the analysis of the Hayabusa imaging data.

Revisiting the Question of Charon's Orbital Eccentricity (Abstract 470)

Authors:

Jeremy A. Miller – University of Maryland – millerja@wam.umd.edu

David J. Tholen – University of Hawaii – tholen@ifa.hawaii.edu

Please stop by this poster during Session: 15, Other Planetary Satellites II on Wednesday, 2003 September 03 from 3:00-5:30pm to discuss this proje

Abstract

We are continuing the analysis of adaptive optics observations of the Pluto-Charon system, with the goal of confirming the orbital eccentricity reported by Tholen and Buie (1997). Previous work on these data, obtained with the Hokupa'a adaptive optics system and Gemini North and reported by Tholen (2002), utilized only a portion of the full set of 348 images taken on 8 nights between 2001 and 2002, and was based on a preliminary calibration of the image scale and position angle of the detector.

For each of the three observing runs, independent calibrations were performed using the motion of an asteroid past a fixed stellar source to remove any minor differences in the way the instrument was mounted on the telescope for each run. The image scales determined for each run are good to better than 1 part in 1000, while the individual position angle determinations are good to at least 0.1 deg.

The preliminary analysis reported at last year's DPS meeting indicated consistency with the orbit determined from the HST observations acquired a decade ago; however, a more careful analysis yields a longitude of periapsis of 132.2° ± 9.3°, disagreeing with the HST results. Finally, possible explanations for the differences in orbital solutions are considered.

I. Introduction

Tidal dissipation should circularize Charon's orbit in 1-10 million years. A non-zero eccentricity would then suggest something happened to the system in the past 1-10 million years to excite the eccentricity. The most plausible reason for eccentricity is a recent impact by a fairly large (tens of kilometers) KBO. Such an impact would have important implications for the population density and size-frequency distributions in the outer solar system (Weissman et al. 1989).

First, an independent determination of Charon's orbit was found, with special interest paid to the eccentricity. The discovery of a non-zero eccentricity in Charon's orbit in 1994 by Tholen and Buie (1997, henceforth TB1997) came as a surprise, given the tidal evolution of the system, and confirmation of this result would warrant further exploration into the Pluto-Charon system. Second, these results were combined with the aforementioned HST observations in 1992 and 1993 to increase the baseline of observations from just over one year to almost 10 years, decreasing the uncertainties in Pluto's orbital period by almost an order of magnitude.

II. Observations

The eight nights of observations were divided into 3 runs: 2001 April 19 and 28 made up run 1; 2001 June 23, 25, and 26 made up run 2; and 2002 April 23, 24, and 26 made up run 3. All observations were done as "service observing," except for 2001 April 19, so we are forced to assume that all observations were done as reported.

Table 1. Observing information. Note that information on the observing conditions was not reported.

Location	Mauna Kea
Telescope	Gemini North
Camera	QUIRC infrared camera
Detector	1024 x 1024 Marchead Telleride array
Filter	Only H-band images used
AO System	Hokupa'a, a 36 element system using the curvature method
Dates	4/01 - 4/02 (eight nights)
Objects	348 images of Pluto-Charon system Calibration asteroids (Smetana, Katanga, Phocaea)

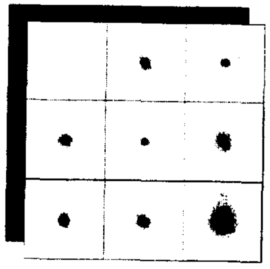

Figure 1: Examples of images from each of the 8 observing nights. Image centroids were weighted according to the quality of seeing on a given night.

III. Data Reduction

Images were processed using the standard method of bias subtraction and flat field division. Bad pixels in the images were then determined automatically by flagging any pixels more than 8 standard deviations away from the mean value in the flat images. All remaining bad pixels near the Pluto-Charon system were located by manually searching the dithered positions of the system. These pixels account for less than 0.1% of the detector and were excluded from analysis.

Acknowledgements

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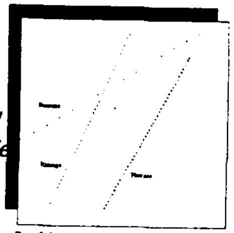

Figure 2. Location of all calibration asteroids on the detector with respect to the central star. For the third run, Phocaea was held center, while the background stars drifted across the field.

IV. Calibration

The directions of motion were calculated by performing a least-squares linear fit on the y vs. x position of the asteroid centroids and taking the arctangent of the slope. The position angle of Charon relative to Pluto was determined by taking the difference of the observed and the actual angles of motion, which was taken from the ephemeris. In the third run, the adaptive optics system held Phocaea constant, causing the stars to streak rather than Phocaea. This effect produced a position angle shift of 180 degrees, which is not a source of error.

The image scales were determined by performing an equivalent least squares linear fit of distance vs. time, where distances were measured from the position of the asteroid in the first frame. The average angular speed of each asteroid was then calculated from the ephemeris and divided out to determine the image scale in arcseconds per pixel.

Run	Asteroid Name	Position Angle	Image Scale
1	Smetana	0.2434 ± 0.0069°	0.02000651 ± 0.000014 "/pixel
2	Katanga	0.2100 ± 0.0052°	0.02004583 ± 0.000004 "/pixel
3	Phocaea	0.1977 ± 0.0112°	0.02003637 ± 0.000007 "/pixel

Table 2. Position angle and image scale calibrations for the three observing runs. On 19 April 2001, the detector was rotated 180° off the position angle for run one

V. Orbit Solution

The orbit was determined by rotating all the Pluto Charon vectors to the plane of the sky and minimizing the residuals. Mean longitude was computed for the epoch Julian date 2449000.5 for consistency with TB1997 data. With such high uncertainties in this work, the TB1997 data carries about eight times more weight in the combined solution.

	This Work	*TB1997*	*Combined Solution*
semimajor axis (km)	19524 ± 46	19636 ± 8	19620 ± 9
eccentricity	0.0069 ± 0.0013	0.0076 ± 0.0005	0.0048 ± 0.0006
inclination (deg)	96.019 ± 0.144	96.168 ± 0.032	96.166 ± 0.028
ascending node (deg)	223.153 ± 0.130	222.993 ± 0.024	223.014 ± 0.038
long. periapsis (deg)	132.2 ± 9.3	219.1 ± 2.2	207.2 ± 6.0
mean longitude (deg)	33.115 ± 0.167	32.975 ± 0.047	32.963 ± 0.081
period (days)	6.387368 ± 0.000079	6.387223 ± 0.000017	6.387231 ± 0.000003

Table 3. Orbital elements of Pluto in Charon for this data set, Tholen et al. 1997, and the combined solution.

VI. Uncertainties and errors

There were two main sources of systematic error. First, in some images Pluto and Charon show elongation due to high frequency motions of the telescope. Low frequency errors were removed by the adaptive optics system. The size of this error varies from frame to frame and was addressed by down-weighting images showing elongation. Second, the non-Gaussian nature of the Pluto and Charon PSFs due to the adaptive optics system fit Charon's centroids too close to Pluto using a Gaussian fit. To account for this error, a Gaussian was fit to the core of Pluto and Charon, and another to the light wings.

Random errors arose from instrumental limitations, such as the truncation of the time of exposure to the nearest second, and from poor seeing on the final night of observations. To account for the seeing, 26 April 2003 was down-weighted.

Uncertainties in orbital elements were calculated by adding random Gaussian noise to the calculated centroids. Thirty such orbits were created, and the standard deviations of their elements were taken as orbital uncertainties.

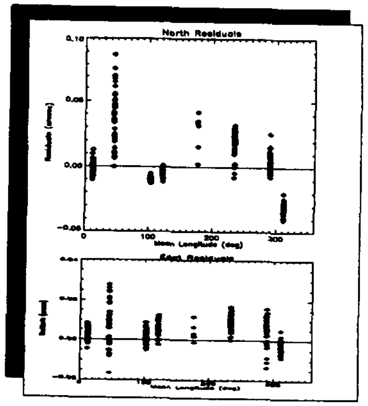

Figure 3: North and East Residuals for the 348 Charon locations. Notice how the systematic errors still permeate the data. The systematic errors are larger north than east because of the larger northern separation. Column 2 corresponds to 2002 April 26.

VII. Discussion

Despite the unresolved systematic errors, all but two of the orbital elements from this work agree with TB1997 to within 1.8 sigma, including the computed eccentricity of 0.0069. Our smaller semimajor axis may be due to overlap in the Pluto and Charon PSFs. While the double Gaussian improved the fit over the single Gaussian, no formal fit check was performed. The 86.9 degree difference between longitude of periapsis, however, is not so simply explained, and warrants further consideration.

There are a few possible explanations for the disagreements in the fits. First, Pluto is known to have a very large albedo gradient in optical wavelengths, however these data were taken from infrared wavelengths. If albedo difference is wavelength dependent, both this solution and TB1997 could both be correct for their respective wavelength. Second, precession of the Pluto Charon system could have caused the system physically rotate, and thus both solutions would be correct for their respective time. Finally, the unresolved systematic errors could be introducing eccentricity and mean longitude fluctuations into the system. This third possibility can be confirmed or refuted by finding a way to reduce the systematic errors.

The combined results showed good agreement with TB1997, especially in inclination where the uncertainty actually decreased. The uncertainty in the orbital period improved by almost 6 times, as expected with the larger base line of observation. This new value for orbital period holds, despite differences in the two sets of orbital elements. Agreement in the other orbital elements has less meaning since the two combined solutions were in disagreement to begin with.