Progress Report
NASA Grant NAG5-8989
Observations of the Pluto-Charon System
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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, 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 the reexamination during the fall of 2003. However, a death in the family put a sudden hold on these 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)

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

Abstract

We are re-examining the analysis of adaptive optics observations of the Pluto-Charon system, with the goal of confirming the orbital eccentricity reported by Tholen and Bolt (1997). Previous work on these data, obtained with the Hubble Space Telescope's adaptive optics system and Gemini North and reported by Tholen (2003), 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 estimate of the image scale and position angle of the data.

For each of the three observing runs, independent calibrations were performed using the motion of an artificial star in a faint stellar source to remove any angular differences in the way the instrument was scanned on each run. The image scales determined for each run are good to better than 1 arcmin in 2003, while the independent position angle determinations are good to about 0.1 degree.

The preliminary analysis reported at last year's DPS meeting indicated consistency with the orbit determined from the HST observations reported a decade ago; however, a more careful analysis yields a biaxiality of 132.2 ± 9.5°, disagreeing with the HST results. Finally, possible explanations for the differences in orbital solutions are considered.

I. Introduction

Today's astrophotographer should consider Charon's orbit in 1-5 million years. A new-look eccentricity would then suggest something happen to the system in the past 1-5 million years to excite its eccentricity. The most plausible means for the eccentricity to a recent impact by a fairly large (600km-diameter) Kuiper Belt Object (KBO) such an impact would be important implications for the population density and semi-major-axis distribution in the outer solar system (Weissman et al. 1999).

Plot, the Independent Motion of Charon's orbit was found, while spectral motion plaed in the secularly. The discovery of a new eccentricity in Charon's orbit in 1994 by Tholen and Bolt (1997), however, was a popular discovery given the dwarf planet's conspicuous tail and its position in the Kuiper Belt. However, efforts to reproduce the Hubble Space Telescope (HST) results were not successful. Instead, these results were revised with the advent of new HST observations in 1995 and 1997 to determine the Hamiltonian of observations from just over 20 years ago to about 50 years ago, providing the opportunity to further understand the Hamiltonian of observations.

II. Observations

The eight nights of adaptive optics data were divided into two sets, April 19 and 20, made on v. 1999, v. 33, v. 34, and v. 35; and April 21 and 22, made on v. 34, v. 35, and v. 36. All observations were made with the same observing conditions. In 1999, multiple HST observations were taken on 7 nights, each with 1-5 arcsec resolution, to examine the Hamiltonian of observations.

Table 1. Observed images of Pluto-Charon system

<table>
<thead>
<tr>
<th>Date</th>
<th>Seeing (arcsec)</th>
<th>Exposure Time (sec)</th>
<th>Magnitude</th>
<th>Phase Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999-04-20</td>
<td>1.0</td>
<td>150</td>
<td>14.0</td>
<td>0</td>
</tr>
<tr>
<td>1999-04-22</td>
<td>1.4</td>
<td>120</td>
<td>14.3</td>
<td>0</td>
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III. Data Reduction

Images were processed using the standard techniques of bias subtraction and the flat-fielding. Red pixels in the images were then determined automatically by flagging any pixels more than 3 standard deviations away from the mean value in the same image. All remaining bad pixels were then removed by comparing the flattened differences of the images. These pixels were then set to the mean of the detector and were excluded from analysis.

Acknowledgments

This work is supported in part by NSF Research Experiences for Undergraduates (REU) Grant 9955396 and NASA Grant NAG3-8909 to the University of Hawaii.

References


IV. Calibrations

The detector of motion was determined by performing a point-source image at the v. 7 position of Charon and the central image of Charon. The position angle of Charon relative to Pluto was determined to be consistent with the absence of the observed and the actual positions of Charon, which was taken from the occultations. In the third run, the adaptive optics system field FWHM constant, causing the stars to streak rather than to measure. The effect produced a position angle shift of 180 degrees, which is a source of error.

The image was determined by performing an equivalent point-source image at the v.7 position of Charon and the central image of Charon. Since the position of Charon is determined from the positions of the inner planets in the last image, the average angular velocity of the outer planets was used to determine the image scale in seconds of arc.

V. Observational Results

The orbit was determined by solving all the Pluto-Charon system in the plane of the sky and enhancing the residuals. Mean longitude was computed for the epoch Julian date 24500017 with the average longitude in the 2003-2004 time-span. The results show the presence of a significant orbital solution.

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VI. Uncertainties

There are two main sources of uncertainties in the data. First, a new model of Pluto-Charon's variability is used to fit the model to the observed data. Second, the model is fit to the observed data. These models are fit to the data using a least-squares fitting method.

VII. Discussion

Despite the mean-absolute magnitude, all the data of the published solutions from this work agree with the Tholen and Bolt (1997) model with a 1.2 degree, including the orbital eccentricity of 0.045. Our model consistently fits better than the published model. The 0.1 degree difference between the models is due to the difference in the orbital elements. The orbital elements are fit to the published model using a least-squares fitting method.