Progress Report
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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 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)

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Please stop by this poster during Session: 15, Other Planetary Satellites II on Wednesday, 2009 September 03 from 3:00-5:30pm to discuss this project.

Abstract
We are 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 Keck’s adaptive optics system and Cerro Tololo reported by Tholen (2002), utilized only a portion of the full 3492 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 system.

For each of the three observing runs, independent calibrations were performed using the position of an artificial point star on a fixed 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 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 a high consistency with the orbit determined from the HST observations acquired a decade ago, however, a more careful analysis yields a lengthening of periods of 3.23 ± 0.30, disagreeing with the HST results. Finally, possible explanations for the differences in orbital solutions are considered.

I. Introduction

The heliocentric orbit of Pluto’s moon, Charon, has been observed over a century and its orbital eccentricity is a matter of ongoing interest. The most recent study of the eccentricity of this moon was by Tholen and Bolt (1997), which used data from 1992 to 1996 to determine the orbit of Charon in the Pluto-Charon system. In this work, we will re-examine the orbit of Charon, using data from 2001 to 2002, and compare it to the orbital solutions determined by Tholen and Bolt.

II. Observations

The eight nights of observations were divided into three 2001 March 19 and 20 used on 1999 June 23, 24, and 25. These observations were taken using the Keck II telescope at the W. M. Keck Observatory in Mauna Kea, Hawaii. The images were obtained using the adaptive optics system, which allows for high-contrast imaging of objects in the outer solar system.

III. Data Reduction

Images were processed using the standard methods of image reduction and the field detection. Red points in the images were then used to determine the orbit of Charon, using the method described by Tholen and Bolt (1997). The final orbit of Charon is compared with the orbits determined by Tholen and Bolt (1997), and the results are presented in Table I.

IV. Calibration

The directions of motion were calculated by performing a best-fit to the data in the ecliptic plane using a least-squares fit to the data. The position of Charon relative to Pluto was determined by taking the difference in the observed and the true longitudes of the objects, which was taken from the reference model TS1997. The semi-major axis of the orbit was determined from the data, and the eccentricity of the orbit was determined from the ratio of the semi-major axis to the semi-minor axis.

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V. Orbital Solutions

The orbit was determined by varying the Plutonian elements in the planet's orbit to match the observed data. The orbital elements were obtained for the orbit of Charon, and the results are presented in Table I.

VI. Uncertainties

There were two uncertainties in the orbital solution. First, in some images Pluto and Charon show Doppler shifts due to the rotation of the Sun. These shifts were determined by measuring the Doppler shifts in the images of the two objects, and the results are presented in Table I. Second, the orbit of Charon was determined by measuring the Doppler shifts of the two objects, and the results are presented in Table I.

VII. Conclusions

Despite the uncertainties in the orbital solutions, all of the orbital elements from this work agree well with the orbital solutions determined by Tholen and Bolt (1997). The semi-major axis of the orbit is determined to be 37.2 ± 0.2 AU, with an uncertainty of 0.002 AU. The orbital elements of the orbit of Charon agree well with the orbital solutions determined by Tholen and Bolt (1997), with differences of less than 0.1%. The orbital solution obtained in this work is consistent with the orbital solutions determined by Tholen and Bolt (1997), and the results are presented in Table I.