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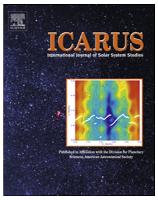

The orbits and masses of satellites of Pluto

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ABSTRACT

We present the numerically integrated orbits of Pluto's satellites. The orbits have been fit to a data set that includes Earth-based and Hubble Space Telescope (HST) astrometry of Charon, Nix, Hydra, Kerberos, and Styx, as well as the lightcurves from the Pluto–Charon mutual events. We also report new, 2010–2012 HST astrometry of all satellites including recently discovered Styx plus a pre-discovery detection of Kerberos in 2006. Pluto-relative data sets have been corrected for the center-of-light vs. center-of-mass offsets with the Pluto albedo model. The results are summarized in terms of the postfit residuals, state vectors, and mean orbital elements. Orbits of Charon, Styx, Nix, and Kerberos are nearly circular, while Hydra's shows a small eccentricity. All satellites are in near-resonance conditions, but we did not uncover any resonant arguments. Our model yields 975.5 ± 1.5 km^3 s^{-2}, 869.6 ± 1.8 km^3 s^{-2}, and 105.9 ± 1.0 km^3 s^{-2} for the system's, Pluto's, and Charon's GM values. The uncertainties reflect both systematic and random measurement errors. The GM values imply a bulk density of 1.89 ± 0.06 g cm^{-3} for Pluto and 1.72 ± 0.02 g cm^{-3} for Charon. We also obtain $GM_{Nix} = 0.0030 \pm 0.0027$ km^3 s^{-2} $GM_{Hydra} = 0.0032 \pm 0.0028$ km^3 s^{-2}, $GM_{Kerberos} = 0.0011 \pm 0.0006$ km^3 s^{-2}, and an upper bound on Styx's GM of 0.0010 km^3 s^{-2}. The 1σ errors are based on the formal covariance from the fit and they reflect only measurement errors. In-orbit (or along the track), radial, and out-of-plane orbital uncertainties at the time of New Horizons encounter are on the order of few tens of km or less for Charon, Nix, and Hydra. Kerberos and Styx have their largest uncertainty component of ~140 km and ~500 km respectively in the in-orbit direction.

1. Introduction

Dwarf-planet Pluto and its five currently known satellites (Charon, Nix, Hydra, Kerberos, and Styx) are the highly anticipated targets of NASA's New Horizons mission in 2015. Not only was Pluto once considered the ninth planet of the Solar System, but it is also the first discovered Kuiper belt object (KBO). New Horizons will be able to obtain unprecedented science data on the Pluto system that are likely to surprise and excite astronomers. Good-quality orbital solutions for Pluto and its satellites are the important prerequisites for the mission's success. Here, we provide the latest orbits and mass estimates for Pluto's satellites based on the most complete data set to date.

Charon was discovered in 1978 by James Christy (Christy and Harrington, 1978), and since then there have been multiple studies (Tholen et al., 1987, 2008; Foust et al., 1997; Tholen and Buie, 1997; Olkin et al., 2003; Buie et al., 2006; Lee and Peale, 2006; Sicardy et al., 2011; Beauvalet et al., 2013) to establish its orbit and mass ratio with respect to Pluto. Charon's orbit around Pluto is nearly circular, and the pair is tidally locked. Buie et al. (2012) reported that the upper limit to Charon's eccentricity is 7.5×10^{-5}. Early estimates of the Pluto–Charon mass ratio ($r = GM_{Charon}/GM_{Pluto}$) varied substantially, from $r = 0.0837 \pm 0.0147$ (Null et al., 1993) to $r = 0.1566 \pm 0.0035$ (Young et al., 1994). Two later estimates by Buie et al. (2006) and Tholen et al. (2008) have very consistent values: $r = 0.1165 \pm 0.0055$ and $r = 0.1166 \pm 0.0069$, respectively. The most recent analysis (Beauvalet et al., 2013) lists two ratios for the two sets of Pluto–Charon masses. Their more complete dataset gives $r = 0.1126 \pm 0.0001$, while the one that excludes the Buie et al. (2012) data gives $r = 0.1176 \pm 0.0022$. Two findings are apparent: Buie et al. (2012) data have significantly lowered the mass estimate for Charon (from $GM_{Charon} = 102.83 \pm 1.87$ km^3 s^{-2} to $GM_{Charon} = 98.33 \pm 0.11$ km^3 s^{-2}) and the added data have also significantly reduced the uncertainty on the mass of Charon. It is important to note that these uncertainties only reflect measurement errors as opposed to any systematic errors.

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Weaver et al. (2006) were the first to attempt to determine orbital parameters for Nix and Hydra (originally S/2005 (134340) 2 and S/2005 (134340) 1) based on a few discovery data points. Although the data set turned out to be too sparse to allow definite determination of the orbits, they concluded that the two satellites appeared to be moving in circular orbits in the same orbital plane as Charon. Orbital periods were estimated to be ~25 days for Nix and ~38 days for Hydra. Buie et al. (2006) followed with a two-body orbit solution in the Pluto–Charon barycentric frame. They confirmed that the orbits of all three satellites are nearly coplanar, and they found that the orbit of Hydra has an eccentricity of $e_{\mathrm{Hydra}} = 0.0052 \pm 0.0011$.

Lee and Peale (2006) presented a theoretical study of the orbits of Nix and Hydra. They first discussed an analytic theory, which they followed with integrated orbits for various considerations of the satellites' masses. The range of masses was calculated based on the assumption that the geometric albedo is either similar to that of Charon (high-albedo–low-mass) or to that of a comet (low-albedo–high-mass). For the case where the masses of Nix and Hydra were low, Lee and Peale (2006) predicted that Hydra has a significant epicyclic eccentricity and that the prograde precession of its longitude of periapsis has a period of ~5300 days. At the high end of the albedo-derived masses (a geometric albedo of few percent), Lee and Peale (2006) found that Nix and Hydra could be in the 3:2 mean-motion resonance (the resonant parameter $\theta_{\mathrm{Hydra}} = 2\phi_{\mathrm{Nix}} - 3\phi_{\mathrm{Hydra}} + \varpi_{\mathrm{Hydra}}$ librating about 180 deg) with the Hydra's longitude of periapsis (ϖ_{Hydra}) in retrograde precession with a 500-day period.

Tholen et al. (2008) were the first to attempt a four-body orbital fit to the data and they obtained order-of-magnitude GM estimates for Nix and Hydra: $\mathrm{GM}_{\mathrm{Nix}} = 0.039 \pm 0.034\ \mathrm{km}^3\ \mathrm{s}^{-2}$ and $\mathrm{GM}_{\mathrm{Hydra}} = 0.021 \pm 0.042\ \mathrm{km}^3\ \mathrm{s}^{-2}$. Their analysis also ruled out the high end of Nix and Hydra masses that Lee and Peale (2006) found as a necessary condition in order to have 3:2 mean-motion resonance. Beauvalet et al. (2013) reported the most recent integrated orbital fit to the astrometry of the satellites in the Pluto system. Their results placed tighter constraints on the masses of Nix and Hydra ($\mathrm{GM}_{\mathrm{Nix}} = 0.014 \pm 0.011\ \mathrm{km}^3\ \mathrm{s}^{-2}$ and $\mathrm{GM}_{\mathrm{Hydra}} = 0.069 \pm 0.014\ \mathrm{km}^3\ \mathrm{s}^{-2}$), although the dataset that they used was still relatively sparse and potentially sensitive to the systematic effects in the data.

The latest additions to the Pluto family are satellites Kerberos (S/2011 (134340) 1) (Showalter et al., 2011) and Styx (S/2012 (134340) 1) (Showalter et al., 2012). Not much is known about these satellites, except that they orbit Pluto in nearly circular orbits with $a_{\mathrm{Styx}} \sim 42{,}000$ km (Showalter et al., 2012) and $a_{\mathrm{Kerberos}} \sim 57{,}900$ km (Buie et al., 2013). Their respective periods are $P_{\mathrm{Styx}} \sim 20.1$ days and $P_{\mathrm{Kerberos}} \sim 32.2$ days. Together with Nix and Hydra, Styx and Kerberos complete the continuous sequence of near-resonant orbits (1:3:4:5:6) with respect to Pluto–Charon orbital period.

The question of dynamical stability and the number of satellites in the Pluto system was discussed long before the Nix and Hydra discovery (Stern et al., 1994). Stern et al. (1994) showed that there is a region of space around Charon (so-called instability strip) that is unlikely to contain any other satellites because their orbits would be unstable. However, the regions interior and exterior to the Charon's instability strip were not excluded for the existence of small satellites (masses up to 10^{-4} of the Pluto–Charon GM). Furthermore, Stern et al. (1994) found that at two Pluto–Charon separation distances, it is possible to consider the existence of even more massive satellites (masses up to 10^{-2} of the Pluto–Charon GM). The discovery of Nix and Hydra in the same orbital plane as Charon and in the proximity of 4:1 and 6:1 mean motion resonances with Pluto–Charon orbital period led to some interesting studies on the stability of their orbits. Süli and Zsigmond (2009) used the spatial elliptic restricted three-body problem to study the dynamical structure of the phase space around Nix and Hydra and they found that Nix could be in 4:1 resonance for a certain selection of arguments of periapsis and longitudes of node, but that there are no combinations that could put Hydra in 6:1 resonance. Pires dos Santos et al. (2011) have analyzed the dynamical stability of the region beyond Charon in the light of Nix and Hydra perturbations. They concluded that the potential satellites would have to reside either as coorbitals of Nix and Hydra or between their orbits. The discovery of Styx and Kerberos in 3:1 and 5:1 near-resonance further raised the complexity of the Pluto system's dynamical architecture, but it also provided some tighter constraints for the masses in the system. For example, Youdin et al. (2012) used the orbit of the newly discovered Kerberos to explore the system's long-term stability in 4 + N body integrations (the four massive bodies are Pluto, Charon, Nix, and Hydra). This analysis constrained the masses of Nix and Hydra to an upper limit of 5×10^{16} kg ($0.0033\ \mathrm{km}^3\ \mathrm{s}^{-2}$) and 9×10^{16} kg ($0.0060\ \mathrm{km}^3\ \mathrm{s}^{-2}$), respectively. Furthermore, Youdin et al. (2012) have also predicted that the orbit of Kerberos lies just exterior to the 5:1 resonance. Most recently, Kenyon and Bromley (2014) did a numerical study of how the small satellites coagulated and migrated in a disk of debris particles around the newly formed Pluto–Charon binary and one of the conclusions was that there could be more small satellites (with radii between 1 and 3 km) beyond the orbit of Hydra.

2. Observations and data reduction

2.1. Old astrometry

We used the most complete set of Charon, Nix, Hydra, Kerberos, and Styx astrometry to date. The data include both Earth-based and HST observations as well as the lightcurves from Pluto–Charon mutual events. Table 1 shows that the earliest Charon data (Harrington and Christy, 1980) originated from photographic plates taken between 1965 and 1979. Charon's position (in position angle $\Delta\theta$ and separation $\Delta\rho$) is given relative to Pluto. The data before June 22, 1978 predate Charon's discovery (Christy and Harrington, 1978). Speckle interferometry provided early-to-mid-1980s measurements of the relative positions of Pluto and Charon (Bonneau and Foy, 1980; Hege et al., 1982; Hege and Drummond, 1984; Hetterich and Weigelt, 1983; Baier et al., 1982; Baier and Weigelt, 1987; Beletic et al., 1989). Beletic et al. (1989) measured Charon's position as separation in right-ascension ($\Delta\alpha$) projected onto a tangential plane (thus multiplied by cosine of declination) and separation in declination ($\Delta\delta$). All other measurements were position angle and separation from Pluto. Both photographic plates and speckle interferometry data have accuracies of ~100 milliarcseconds (mas).

The first HST astrometry was obtained in 1991 by Null et al. (1993); they measured absolute positions of Charon and Pluto in terms of samples and lines with the Wide-Field/Planetary Camera (WFPC). Follow up HST astrometry was obtained by Null and Owen in 1992–1993 (Null and Owen, 1996). At the same time, Tholen and Buie (1997) used HST to measure relative positions of Pluto and Charon in terms of $\Delta\theta$ and $\Delta\rho$. These data were later corrected with Pluto's albedo model (Buie et al., 2012) and expressed in terms of $\Delta\alpha\cos(\delta)$ and $\Delta\delta$.

Earth-based measurements of the Pluto system resumed in 1992 when Young et al. (1994) obtained Charon's location relative to Pluto ($\Delta\alpha$, $\Delta\delta$) with Mauna Kea's Observatory (MKO) 2.2 m telescope. The accuracy of these measurements is on the order 10–30 mas. Olkin et al. (2003) used HST in 1998 to determine absolute positions (α, δ) of Pluto and Charon. Buie et al. (2006) obtained an extensive HST dataset of relative positions of Pluto and Charon ($\Delta\theta$ and $\Delta\rho$) during 2002–2003. They reported 384 data points measured over 12 separate HST "visits" that were scheduled to map out the surface features as Pluto rotates. The stacked HST images also contain 12

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