Icarus 293 (2017) 94–113

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Obliquity evolution of the minor satellites of Pluto and Charon

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ARTICLE INFO

Article history:
Received 23 January 2017
Revised 21 March 2017
Accepted 17 April 2017
Available online 19 April 2017

ABSTRACT

New Horizons mission observations show that the small satellites Styx, Nix, Kerberos and Hydra, of the Pluto–Charon system, have not tidally spun-down to near synchronous spin states and have high obliquities with respect to their orbit about the Pluto–Charon binary (Weaver, 2016). We use a damped mass-spring model within an N-body simulation to study spin and obliquity evolution for single spinning non-round bodies in circumbinary orbit. Simulations with tidal dissipation alone do not show strong obliquity variations from tidally induced spin-orbit resonance crossing and this we attribute to the high satellite spin rates and low orbital eccentricities. However, a tidally evolving Styx exhibits intermittent obliquity variations and episodes of tumbling. During a previous epoch where Charon migrated away from Pluto, the minor satellites could have been trapped in orbital mean motion inclination resonances. An outward migrating Charon induces large variations in Nix and Styx's obliquities. The cause is a commensurability between the mean motion resonance frequency and the spin precession rate of the spinning body. As the minor satellites are near mean motion resonances, this mechanism could have lifted the obliquities of all four minor satellites. The high obliquities need not be primordial if the minor satellites were at one time captured into mean motion resonances.

1. Introduction

The five satellites of Pluto are Charon, Styx, Nix, Kerberos, and Hydra, in order of distance from Pluto (Weaver, 2006; Showalter et al., 2011; Showalter, 2012). The satellite system is nearly coplanar with orbital periods near ratios of 1:3:4:5:6, but sufficiently distinct from integer ratios relative to Charon's orbital period that the small satellites are not presently in mean-motion resonances with Charon (e.g., Buie et al. 2013). As the masses of Pluto and Charon vastly exceed the masses of the other satellites, we refer to Pluto and Charon as a binary (following Stern 1992) and Styx, Nix, Kerberos and Hydra as minor satellites of the Pluto–Charon binary.

Over 1–10 Myr, tidal evolution should have synchronized the rotation of Pluto and Charon and then circularized their orbit, expanding the binary to its present separation (Farinella et al., 1979). Tidal evolution of Pluto–Charon would lead to capture of the minor satellites into mean motion orbital resonances. However numerical integrations have shown that this often causes such wide-scale dynamical instability that resonant transport (migration) of minor satellites to their current location probably did not take place (Cheng et al., 2014). Alternatively the smaller satellites could have formed from a circumbinary disk, and after the formation of the Pluto–Charon binary (Lithwick and Wu, 2008; Kenyon and Bromley, 2014).

Prior to the arrival of the New Horizons mission at Pluto, Showalter and Hamilton (2015) explored possible spin states for the minor satellites. They speculated that the minor satellites would have tidally spun down and so would be slowly spinning, with angular spin rate w a similar size as the orbital mean motion n_o. Showalter and Hamilton (2015) speculated that the minor satellites would be chaotically wobbling or tumbling due to instability associated with spin-orbit resonances (Colombo, 1965; Goldreich and S. J. Peale, 1966; Wisdom et al., 1984; Celletti, 1990; Melnikov and Shevchenko, 2010) (resonances where $2w$ is a multiple of n_o). Showalter and Hamilton (2015) also suggested that perturbations from Charon could affect the rotation state of the minor satellites, contributing to chaotic tumbling, in analogy to how an orbital resonance between Titan and Hyperion could affect the rotational state of Hyperion. A dynamical mechanism for the chaotic behavior was proposed by Correia et al. (2015) who showed that for slowly spinning satellites, spin-binary resonances from Charon's periodic perturbations are sufficiently strong to cause chaotic tumbling. However, New Horizons observations showed that the low mass satellites are spinning faster than considered by

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http://dx.doi.org/10.1016/j.icarus.2017.04.012
0019-1035/

Showalter and Hamilton (2015) and Correia et al. (2015), with angular spin rates $w \gtrsim 6n_o$, many times greater than their orbital mean motions, implying that despinning due to tidal dissipation has not taken place (Weaver, 2016). At higher spin states, spin-orbit and spin-binary resonances may not be as strong, so chaotically tumbling is not assured.

1.1. Obliquities

The obliquity is the angle between the spin vector of satellite and its orbit normal. For the four minor satellites, Weaver (2016) measured the angle between minor satellite spin vector and the orbit normal of the Pluto–Charon binary and at low orbital inclination this angle is equal to the obliquity. Weaver (2016) found that all four minor satellites have obliquities near 90 degrees, with spin vector lying nearly in their orbital planes.

Are the high obliquities surprising? If the minor satellites have not tidally spun-down then tidal evolution may not have varied their obliquities. The high obliquities could be primordial and acquired during formation. The minor satellite orbital inclinations and eccentricities are all low, with all inclinations below 0.5° and eccentricities all below that of Hydra at 0.00554 (Brozovic et al., 2015). The low orbital inclinations and eccentricities suggest that the minor satellites were formed in situ, in a circumbinary disk. Postulated is minor satellite formation in ring of debris comprised of material ejected during the impact that formed the Pluto–Charon binary (see Kenyon and Bromley 2014).

Perhaps we can compare the obliquities of Pluto and Charon's minor satellites with other satellites that have high spin rates. Among satellites with known rotation states (Melnikov and Shevchenko, 2010) found only seven rapidly rotating satellites, with periods less than a day. All of them are irregular satellites, with a possible exception of Nereid (Sheppard et al., 2006). Peale (1977) showed that irregular satellites should reside close to their initial (and rapid) rotation states. We make the distinction between regular and irregular satellites as an irregular satellite can be a captured object whereas a regular satellite could be formed in a circum-planetary disk. We would expect the primordial spin of a captured object to be randomly oriented whereas a regular satellite, like a planet, could be formed at zero obliquity (we will discuss this assumption for Pluto and Charon's minor satellites below). Nereid with eccentricity 0.75 has a low inclination (7° with respect to Neptune's Laplace plane). However, a multiple year photometric study of Nereid's light curve (Shaefer et al., 2008) suggests that the rotation rate is not as fast as originally measured (at 0.48 days; Grav et al. 2003) but could be much slower and the body could be tumbling. Even if Nereid was originally a regular satellite, it may not currently be rapidly spinning.

The majority of regular planetary satellites with known rotation states rotate synchronously. The remaining regular satellites with known rotation states are tumbling with spin similar in magnitude (within a factor of a few) as the orbital mean motion (Peale, 1977; Melnikov and Shevchenko, 2010). Thus the solar system lacks rapidly spinning *regular* satellites. Placed in this context the minor satellites of Pluto and Charon are unique (though see Hastings et al. 2016 on Haumea's satellites). Styx, Nix, Kerberos and Hydra are similar to regular satellites of planets as they have low eccentricities and inclinations, yet their spin periods are much shorter than their orbital periods and so they can be considered rapid rotators (as classified by Melnikov and Shevchenko 2010).

What primordial obliquity distribution is predicted for Pluto and Charon's minor satellites? A proto-planet that forms in a disk via accretion of gas and small planetesimals is expected to form at low obliquity (Lissauer and Kary, 1991; Johansen and Lacerda, 2010). However, if planets accrete at late stages from a distribution of massive non-interacting planetesimals, their obliquity distribution can be consistent random spin orientations (Dones and Tremaine, 1993; Kokubo and Ida, 2007). The low inclinations and eccentricities of Pluto and Charon's minor satellites and inferred epoch of radial migration suggest that a circumbinary ring of small particles was present after minor satellite formation (Kenyon and Bromley, 2014) and implying that some fraction of accreted material incorporated into these satellites originated from low mass particles. We cannot rule out the possibility that the primordial spin states were randomly oriented, but neither is this assured.

We consider the possibility that four randomly oriented spinning bodies have obliquity distribution similar to Pluto and Charon's minor satellites. Weaver (2016) measured obliquities of $\epsilon = 91, 123, 96, 110°$ for Styx, Nix, Kerberos and Hydra, respectively, with an estimated error of $\pm$ 10°. The probability distribution for randomly oriented spin directions peaks at an obliquity of 90° and obeys probability distribution $P(\epsilon) = \frac{1}{2}\sin\epsilon$. All four obliquities are within an equatorial band $\epsilon \in [90, 123]$. Integrating the probability distribution between the two boundaries gives a probability of $0.5\cos 123° = 0.272$. The probability that 4 randomly oriented objects are all found in this same band is $P \sim 0.272^4 = 0.0055$. In an ensemble of 1000 systems of four randomly oriented minor satellites only 6 systems would have all four satellite obliquities in the band between 90 and 123°. Pluto and Charon's minor satellites are a single system so this is not a meaningful statistical result. Nonetheless the low probability does motivate study of mechanisms for tilting the spin axes after formation, away from their primordial values.

1.2. Evolution of spin states

As a satellite despins due to tidal dissipation, it may be captured in spin-orbit resonant states (Colombo, 1965; Goldreich and S. J. Peale, 1966; Peale, 1977; Wisdom et al., 1984; Celletti, 2010). However a body that is only very slowly spinning down due to tidal dissipation could cross spin-orbit resonances or spin-binary resonances if there is a drift in the satellite's semi-major axis, known as 'orbital migration'. Attitude instability, leading to obliquity variations and chaotic behavior, is common within spin-orbit resonance (Wisdom et al., 1984; Melnikov and Shevchenko, 2008; 2010) and expected in spin-binary resonance (Correia et al., 2015). There may be a connection between the minor satellite obliquities and previous episodes of spin-orbit or spin-binary resonance crossing or capture.

External to spin-orbit resonance, tidal dissipation causes a spherical body initially at low obliquity and $w/n_o \gtrsim 6$ to slowly increase in obliquity (Goldreich and S. J. Peale, 1970; Ward, 1975; Gladman et al., 1996), unless the viscoelastic relaxation timescale and eccentricity are both high (Boué et al., 2016). However, the obliquity drift rate due to tidal dissipation is slower than but a similar size as the tidal spin-down rate (Goldreich and S. J. Peale, 1970). Our numerical integrations have confirmed that this remains true for elongated non-spherical bodies. If the minor satellites have not spun down, then neither should their obliquities have approached 90°. As long as minor satellite primordial obliquities were not all near 90°, then it is unlikely that the current near 90° minor satellite obliquities in the Pluto–Charon system are due to tidal secular (non-resonant) obliquity evolution alone.

With near integer orbital period ratios between satellites, the Pluto–Charon satellite system is near orbital mean motion resonances and may have crossed or been captured into these resonances in the past. Migration could have taken place due to tidal evolution of Pluto and Charon but also due to interactions with a previous and now absent circumbinary disk (Lithwick and Wu, 2008; Cheng et al., 2014; Kenyon and Bromley, 2014). The minor satellites themselves could have been embedded in a disk and migrated by driving spiral density waves into the disk. Inwards or