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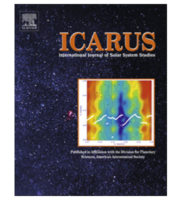

Complete tidal evolution of Pluto–Charon

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ABSTRACT

Both Pluto and its satellite Charon have rotation rates synchronous with their orbital mean motion. This is the theoretical end point of tidal evolution where transfer of angular momentum has ceased. Here we follow Pluto's tidal evolution from an initial state having the current total angular momentum of the system but with Charon in an eccentric orbit with semimajor axis $a \approx 4R_P$ (where R_P is the radius of Pluto), consistent with its impact origin. Two tidal models are used, where the tidal dissipation function $Q \propto 1/\text{frequency}$ and $Q = \text{constant}$, where details of the evolution are strongly model dependent. The inclusion of the gravitational harmonic coefficient C_{22} of both bodies in the analysis allows smooth, self consistent evolution to the dual synchronous state, whereas its omission frustrates successful evolution in some cases. The zonal harmonic J_2 can also be included, but does not cause a significant effect on the overall evolution. The ratio of dissipation in Charon to that in Pluto controls the behavior of the orbital eccentricity, where a judicious choice leads to a nearly constant eccentricity until the final approach to dual synchronous rotation. The tidal models are complete in the sense that every nuance of tidal evolution is realized while conserving total angular momentum—including temporary capture into spin–orbit resonances as Charon's spin decreases and damped librations about the same.

1. Introduction

Pluto has five known satellites: Charon, Nix, Hydra, Keberos, and Styx, with the latter four much smaller than Charon. Listed in Table 1 are the physical and orbital parameters of Pluto–Charon from Buie et al. (2012), unless otherwise specified. The Charon-Pluto mass ratio ($q = 0.1165$) is large when compared with others in the Solar System (1/81 for Moon–Earth and <1/4000 for the other satellites and their planets). The barycenter of the Pluto–Charon system lies outside the surface of Pluto. Hence, some astronomers regard the pair as a binary system (Stern, 1992). The total angular momentum L of the Pluto–Charon system is so large that the combined pair would be rotationally unstable (Mignard, 1981a; Lin, 1981).

The Pluto–Charon system is currently in a dual synchronous state (Buie et al., 1997; Buie et al., 2010), which is the endpoint of tidal evolution. As such the expected zero orbital eccentricity has been recently verified (with a 1-σ upper limit of 7.5×10^{-5}), after taking into account the effects of surface albedo variations on Pluto (Buie et al., 2012; see Table 1).

As Pluto–Charon is similar to Earth–Moon, the feasible origin of this system may be chosen from the proposed schemes for the origin of the Earth–Moon system. A giant impact of a Mars-sized body is thought to be the only viable origin of the Moon (e.g., Cameron and Ward, 1976; Boss and Peale, 1986; Canup, 2004) to account for the large angular momentum of the system. McKinnon (1984) proposed a similar origin for Charon. If Charon accumulated from a debris disk resulting from such an impact, the initial eccentricity of Charon's orbit would be near zero. Dobrovolskis et al. (1997, hereafter DPH97) were thereby motivated to determine the tidal evolution of Charon in a circular orbit to the current dual synchronous state in a time short compared to the age of the Solar System (see also Farinella et al., 1979) as the only possible outcome of the dissipative process. In a circular orbit, Charon would reach synchronous rotation very quickly (e.g., DPH97), and this has generally been assumed (e.g., Peale, 1999). However, smoothed particle hydrodynamic (SPH) simulations by Canup (2005) showed that the results of a nearly intact capture in a glancing encounter surround the (q, L) region of the system much more completely than those of disk-forming impacts. Therefore, capture where Charon comes off nearly intact after a glancing impact is favored and non-zero eccentricity would be more probable.

We are not aware of any previous attempts to examine the tidal evolution of Charon's orbit incorporating finite eccentricity. As we

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shall see, Charon in an initially eccentric orbit avoids the almost immediate synchronous rotation heretofore assumed, and the varied and interesting evolutionary sequences that were suppressed in the circular orbit evolution are revealed. Depending on the ratios of rigidity μ and tidal dissipation function Q between Pluto and Charon, the eccentricity of Charon's orbit may either grow or decay during most of the evolution (Ward and Canup, 2006). Permanent quadrupole moments of the bodies may also lead to spin–orbit resonance, and such resonances can have a significant effect on the orbital evolution.

In the following we tidally evolve the Pluto–Charon system with two tidal models distinguished by the dependence of the dissipation function Q on frequency $f: Q \propto 1/f$ and Q = constant. The tidal model developed in Section 2.1 has the tidal distortion of a body responding to the perturbing body a short time Δt in the past. Constant Δt leads to $Q \propto 1/f$, so we call the $Q \propto 1/f$ model the constant Δt model. In Section 2.2 we develop the equations of evolution for the constant Q model. Although neither of these frequency dependences represent the behavior of real solid materials (e.g., Castillo-Rogez et al., 2011) and although the evolutionary tracks are model dependent, most if not all of the possible routes from probable initial configurations to the current equilibrium state are demonstrated. In Section 2.3 we develop the contributions of rotational flattening J_2 and permanent quadrupole moment C_{22} to the equations of motion. We describe the adopted system parameters and initial conditions in Section 3 and the numerical methods in Section 4. The results from both the constant Δt and constant Q models with zero J_{2P} for Pluto and zero C_{22} for both bodies are shown in Section 5.1, and the effects of non-zero J_{2P} and C_{22} in Section 5.2, respectively. The results are discussed in Section 6, and the conclusions are summarized in Section 7.

2. Tidal models

Tides are raised on Pluto and Charon by each other. Friction delays the response of the tidal bulge to the tide raising potential and causes tidal lag. The lagged bulge leads to angular momentum exchange between itself and the tide raising body, which leads to rotational and orbital evolution.

2.1. Constant Δt tidal model

The idea of approximating tidal evolution with a single bulge that lags by a constant Δt was introduced by Gerstenkorn (1955), and developed and used by Singer (1968), Alexander (1973), Mignard (1979, 1980, 1981b), Hut (1981), and Peale (2005, 2007). The advantage of assuming a single, lagged bulge is that the tidal forces and torques can be calculated in closed form for arbitrary eccentricity and inclination. Either instantaneous or orbit-averaged tidal forces and torques can be used to determine the evolution.

The geometry is illustrated in Fig. 1, where ψ_P and ψ_C are the angular displacements of the axes of minimum moment of inertia from the inertial x axis for Pluto and Charon, respectively, ϖ is the longitude of periapse, f is the true anomaly, and ϕ_P and ϕ_C are the azimuthal spherical coordinates appearing in the potentials for Pluto and Charon, respectively. The x and y coordinates are those of Charon relative to Pluto with the x–y plane being the Pluto–Charon orbit plane. Both spin axes are assumed to be perpendicular to the orbit plane (see Section 3). The motion is thereby two dimensional, and the z coordinate is ignorable.

The tidal contributions to the equations of motion for Charon for this model are found from the gradient of the tidal potential expanded to first order in Δt (Mignard, 1980; Peale, 2007):

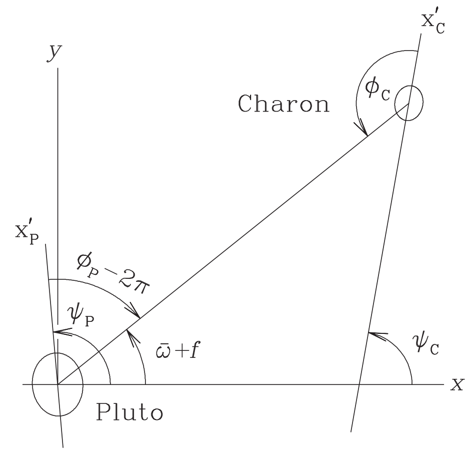

Fig. 1. Geometry of the Pluto–Charon system with orbit and equator planes being coplanar. ψ_i are the angles between the axes of minimum moment of inertia and the inertial x axis, and the ϕ_i are the azimuthal angles locating respectively M_P and M_C in the other's x'–y' plane measured counterclockwise from the x'_i axes of minimum moment of inertia.

$$\begin{aligned} M_{PC}\ddot{x} = &-\frac{3k_{2P}GM_C^2R_P^5}{r^8}\left[x+\frac{2\mathbf{r}\cdot\dot{\mathbf{r}}x\Delta t_P}{r^2}+(\dot{\psi}_P y+\dot{x})\Delta t_P\right] \\ &-\frac{3k_{2C}GM_P^2R_C^5}{r^8}\left[x+\frac{2\mathbf{r}\cdot\dot{\mathbf{r}}x\Delta t_C}{r^2}+(\dot{\psi}_C y+\dot{x})\Delta t_C\right], \\ M_{PC}\ddot{y} = &-\frac{3k_{2P}GM_C^2R_P^5}{r^8}\left[y+\frac{2\mathbf{r}\cdot\dot{\mathbf{r}}y\Delta t_P}{r^2}+(-\dot{\psi}_P x+\dot{y})\Delta t_P\right] \\ &-\frac{3k_{2C}GM_P^2R_C^5}{r^8}\left[y+\frac{2\mathbf{r}\cdot\dot{\mathbf{r}}y\Delta t_C}{r^2}+(-\dot{\psi}_C x+\dot{y})\Delta t_C\right], \end{aligned} \tag{1}$$

where G is the gravitational constant, $\mathbf{r}$ and $\dot{\mathbf{r}}$ are the position and velocity of Charon relative to Pluto, M_i, R_i, $\dot{\psi}_i$, and k_{2i} are the mass, radius, spin angular velocity, and second order potential Love number, respectively, of body i ($= P$ for Pluto and $= C$ for Charon), and $M_{PC} = M_P M_C/(M_P + M_C)$ is the reduced mass. The first term on the right hand side of the first (second) equation in Eq. (1) is the x-component (y-component) of the force due to the tides raised on Pluto by Charon, and the second term is the force due to the tides raised on Charon by Pluto. The equations of motion for the spins are found from the negative of the torques on the bodies determined from the tidal forces:

$$\begin{aligned} \mathcal{C}_P\ddot{\psi}_P &= -\frac{3k_{2P}GM_C^2R_P^5\Delta t_P}{r^6}\left[\dot{\psi}_P+\frac{-\dot{y}x+y\dot{x}}{r^2}\right], \\ \mathcal{C}_C\ddot{\psi}_C &= -\frac{3k_{2C}GM_P^2R_C^5\Delta t_C}{r^6}\left[\dot{\psi}_C+\frac{-\dot{y}x+y\dot{x}}{r^2}\right], \end{aligned} \tag{2}$$

where $\mathcal{C}_i$ is the moment of inertia of body i about its spin axis.

Eqs. (1) and (2) can be used directly in numerical integration of the equations of motion in Cartesian coordinates. Alternatively, one can average the tidal forces and torques over an orbit to obtain the orbit-averaged equations for the variation of the spin rate $\dot{\psi}_i$, orbital semimajor axis a, and eccentricity e (Mignard, 1980, 1981b):

$$\frac{1}{n}\left\langle\frac{d\dot{\psi}_i}{dt}\right\rangle = -\frac{3G}{\mathcal{C}_i a^6}k_{2i}\Delta t_i M_j^2 R_i^5\left[f_1(e)\frac{\dot{\psi}_i}{n}-f_2(e)\right], \tag{3}$$

$$\frac{1}{a}\left\langle\frac{da}{dt}\right\rangle = \frac{6G}{M_{PC}a^8}k_{2P}\Delta t_P M_C^2 R_P^5\left[f_2(e)\left(\frac{\dot{\psi}_P}{n}+A_{\Delta t}\frac{\dot{\psi}_C}{n}\right)-f_3(e)(1+A_{\Delta t})\right], \tag{4}$$

$$\frac{1}{e}\left\langle\frac{de}{dt}\right\rangle = \frac{27G}{M_{PC}a^8}k_{2P}\Delta t_P M_C^2 R_P^5\left[f_4(e)\frac{11}{18}\left(\frac{\dot{\psi}_P}{n}+A_{\Delta t}\frac{\dot{\psi}_C}{n}\right)-f_5(e)(1+A_{\Delta t})\right], \tag{5}$$