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Implications of Tidal Dissipation in the Inner Uranian Satellites

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Abstract

Uranus hosts a system of at least 13 small ($R \sim 10 - 80$km) satellites orbiting near the planet ($a \sim 1.9 - 3.7R_u$). Dynamical scaling arguments and orbital integrations have shown that mutual gravitational interactions drive some of the inner satellites to crossing orbits on timescales of 10^5 to 10^7 years [1, 2]. Using a simple model for tidal dissipation in rubble piles, scaling arguments and numerical simulations, we are investigating how tidal dissipation in the uranian satellites affects their orbital evolution. We will present initial results of this study and discuss the implications for the orbital history and stability of the system, the interior structure of the satellites and the nature of tidal dissipation within them.

Introduction

The orbits of the inner uranian satellites are nearly circular and effectively coplanar ($e \sim I \sim 10^{-3}$). They are also very densely packed. For example, the pairs Cupid-Belinda and Cressida-Desdemona approach each other within 1000km, distances $\sim$ 10 times their diameters. This results in repeated close approaches and substantial orbital evolution. Indeed, orbital integrations of the system starting with the system's observed orbital parameters and assuming a density of 1g/cc (comparable to that of the innermost large satellite, Miranda, 1.2g/cc) have shown that the system evolves to crossing orbits on timescales much less than the age of the solar system [1, 2]. (See also Figure 1 where Cupid and Belinda cross orbits in <300,000 years.)

Duncan & Lissauer (1997) conducted a large number of orbital integrations of the uranian satellites to explore the relation between the system stability and satellite masses. They found that the time to orbit crossing t_c is a power-law function of the satellite mass of the form $t_c = \beta m_f^\alpha$ where m_f is the satellite mass relative to the value calculated using a density of 1.2 g/cc [1]. The constants α and β are de-

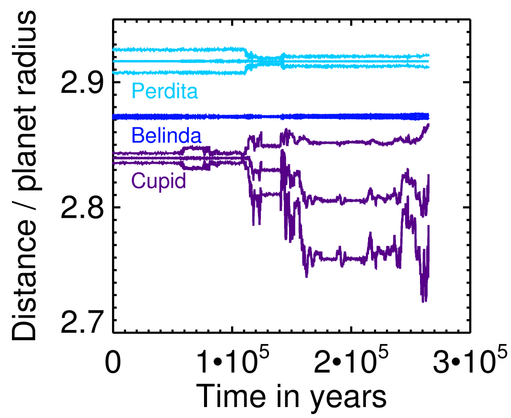

Figure 1: Evolution of semi-major axis, pericentre and apocentre of selected satellites, from a simulation including all 18 regular satellites, with density 1.0 g/cc assumed for the 13 inner ones. This result is similar to those reported by [1]&[2].

termined by fitting the values of t_c and m_f from a large number of orbital integrations. Including more recently discovered satellites and updated properties of the uranian system, French & Showalter (2012) confirmed this power-law relation between orbit crossing time and satellite mass. They also showed that the Cupid-Belinda-Perdita grouping of satellites may be dynamically coupled through resonant interations and unstable on timescales shorter than previously studied satellite groupings in the uranian system.

The inner uranian satellites are curious. How is it that we find such a dynamically active system in a relatively quiescent, nearly circular and coplanar state?

Our Study

We are examining the evolution of the inner uranian satellite system. To provide examples of the baseline behaviour of the system for our study, we have conducted a series of orbital integrations using the Swifter WHM integrator [4]. Our initial results confirm the general instability of the system, the nature of dynamical coupling and the power law relation between the time to orbit crossing and density reported by previous works [1, 2]. Example results are shown in Figures 1 and 2.

Tidal dissipation within satellites is known to damp orbital eccentricities. Standard models of tidal dissipation assume a satellite interior of monolithic material (see e.g., [5] for a description). In the uranian system the timescales to damp orbital eccentricity (i.e., $\tau_e = e/\dot{e} \sim \mathcal{O}(10^8 - 10^9 \text{ yr})$) are much longer than the time to reach crossing orbits (t_c) suggesting that tidal eccentricity damping is unlikely to play an important role. However, if the satellites have rubble pile interior structure then their shapes may be more susceptible to deformation by the planet and the global rate of tidal dissipation may be greatly enhanced by small scale granular friction.

Goldreich & Sari (2009) developed an order of magnitude description for the scaled rigidity ($\tilde{\mu}_s$) of rubble-piles [3] that facilitates a simple and quantitative analysis of the problem. When applied to the inner uranian satellites it predicts that their rigidity as rubble piles may be reduced by factors of order ∼10-100 over the monolithic values. In addition tidal dissipation within rubble piles may also be enhanced over monoliths, leading to reduced tidal quality factors (Q_s). Using this rubble pile tidal model we find that for satellite densities $\lesssim 1.0$ g/cc and $Q_s \lesssim 10$ the tidal eccentricity damping timescale τ_e of some satellites becomes comparable to the orbit crossing times t_c of the undamped satellite system.

We are examining the tidal evolution of the uranian system using orbital integrations including tidal eccentricity damping with a rubble pile rigidity model [3]. Our initial results and scaling arguments indicate that tidal evolution may play an important role in the evolution of this system. Eccentricity damping has the potential to alter the dynamical structure of the system and may increase the time to orbit-crossing by as much as two orders of magnitude. At the meeting we will present these results and discuss how the properties of the inner uranian satellites may inform their orbital histories.

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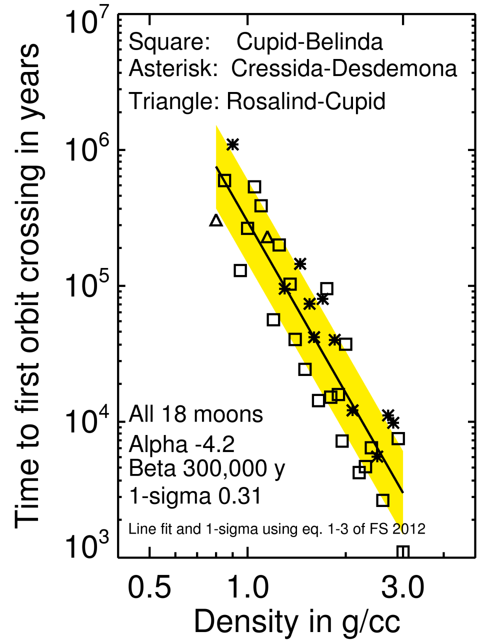

Figure 2: Times to orbit crossing as a function of satellite density. These simulations included the 18 innermost satellites. The pair of satellites that reach crossing orbits first is denoted by the symbol shape. The best fit to the power-law is also shown with the shaded region indicating the 1-σ variation of the fit.

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