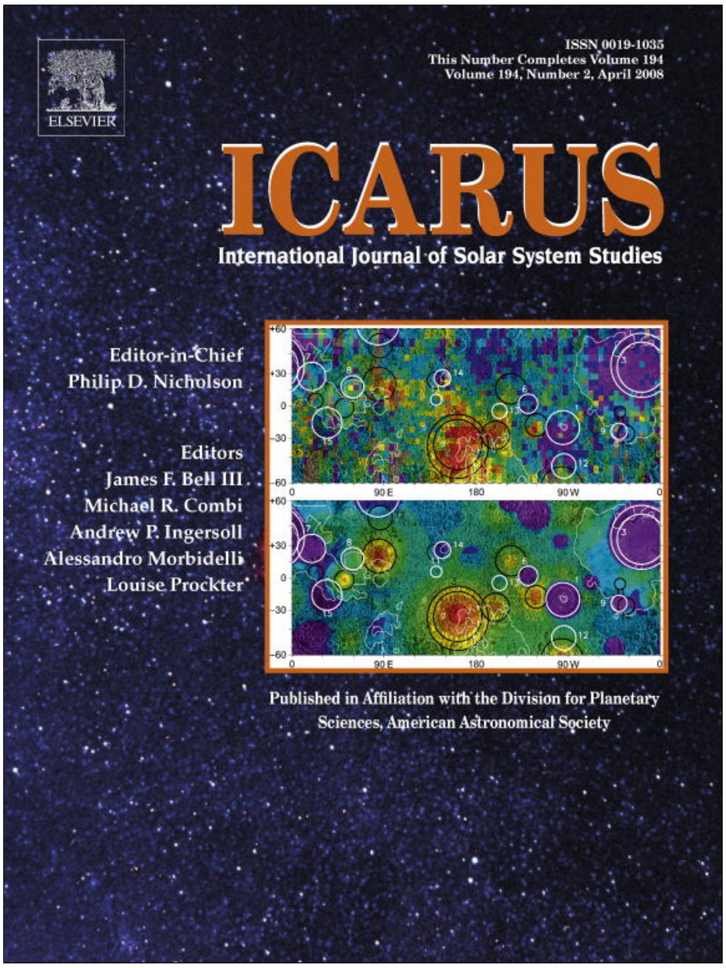
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Note

Tidal evolution of Dysnomia, satellite of the dwarf planet Eris

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Abstract

The past tidal evolution of the satellite Dysnomia of the dwarf planet Eris can be inferred from the current physical and orbital properties of the system. Preliminary considerations, which assumed a circular orbit for the satellite, suggested that the satellite formed close to the planet, perhaps as a result of a giant impact, and that it is thus unlikely that smaller satellites lie further out. However, if the satellite's orbit is eccentric, even if the eccentricity is very small, a qualitatively different past tidal evolution may be indicated. Early in the Solar System's history, the satellite may have been on a highly eccentric orbit much farther from the planet than it is now, suggestive of a capture origin. Additional satellites farther out cannot be ruled out.

Keywords: Kuiper Belt; Satellites, dynamics; Satellites, formation; Tides; Trans-neptunian objects

1. Introduction

The dwarf planet Eris (the Kuiper Belt Object formerly known as the non-planet Xena) is orbited by its satellite Dysnomia at a distance of about 37,400 km, or 31 dwarf-planetary radii (Brown et al., 2006; Brown and Schaller, 2007). The satellite's orbit is nearly circular with a best-fit eccentricity value of 0.007, although that value is not statistically more meaningful than a perfectly circular orbit (Brown and Schaller, 2007).

Brown and Schaller (2007) considered the tidal evolution history of the satellite, and used those considerations, combined with observational limits, to suggest that there are no satellites, larger or smaller, farther out from Eris than Dysnomia. The argument goes as follows. Given Eris' measured brightness (Brown et al., 2005) and measured radius $R_E = 1200$ km (Brown et al., 2006), Dysnomia's radius can be estimated, assuming a similar albedo, to be $R_D = 75$ km. The orbit of Dysnomia yields a mass for Eris of about 1.66×10^{22} kg and corresponding density of about $2.3\ \text{gm}/\text{cm}^3$. Assuming a similar density allows an estimate of the satellite's mass. Brown and Schaller considered the tidal evolution, assuming that the tidal dissipation parameter Q is $\sim$100 and the Love number k is $\sim$1.5 for both the planet and the satellite. They calculated that, if the satellite formed near the Roche limit (semi-major axis $\sim 2R_E$) 4.5 Byr ago, tidal evolution would have brought it to orbits near the observed one. The interpretation was that the satellite had formed close to the planet after a giant impact into Eris. Any other satellites formed in that way, if smaller than Dysnomia, would not have evolved outward further than Dysnomia is now, and any satellites larger than Dysnomia would have been observed.

This chain of logic led to two conclusions. The satellites formed from a giant impact and there are no other satellites beyond its orbit. A key component of the calculations of tidal evolution is that the orbital eccentricity e has always been very small. Brown and Schaller based the assumption on the very short tidal damping time for e, which they estimated to be $\sim$50 Myr. In fact, it would have been even shorter when the satellite was closer to the planet. Thus, implicit in the calculations is the idea that any early eccentricity would have damped away quickly, so subsequent tidal expansion of the semi-major axis occurred with a circular orbit.

That approach is appropriate for considering the evolution of a satellite from the Roche limit. Here, rather than assume an initial condition, we evaluate the tidal evolution backwards in time from the present condition. From this perspective, the implication of the short eccentricity-damping time is not that e has always been small, but rather that it may have been much greater in the not-too-distant past. For example, with the damping timescale of 50 Myr, a current eccentricity $e_o = 0.007$ would roughly suggest that e was $\sim$1 only $1/4$ Byr ago if we assume the same tidal parameters as Brown and Schaller did. Thus, looking back in time, we cannot assume that e has been negligible.

2. Tidal evolution of Dysnomia

In order to calculate the changes in the orbital elements a and e over time, we use the conventional formulae for tidal evolution (Kaula, 1960; Goldreich and Soter, 1966), as combined by Jackson et al. (2008):

$$\frac{1}{e}\frac{\mathrm{d}e}{\mathrm{d}t} = \left(\frac{57}{8}(G/M_E)^{1/2}\frac{k_E R_E^5 M_D}{Q_E} - \frac{21}{2}\left(GM_E^3\right)^{1/2}\frac{k_D R_D^5}{Q_D M_D}\right)a^{-13/2},$$

$$\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} = \left(3(G/M_E)^{1/2}\frac{k_E R_E^5 M_D}{Q_E} - 21\left(GM_E^3\right)^{1/2}\frac{k_D R_D^5}{Q_D M_D}e^2\right)a^{-13/2}.$$

Here subscripts E and D refer to the planet Eris and satellite Dysnomia, M is the body's mass, R is its radius, Q is its dissipation parameter, and k is the Love number. With the values considered by Brown and Schaller, $\mathrm{d}e/\mathrm{d}t$ is dominated by the second term in the first equation, which is why they found that e is damped on a short timescale.

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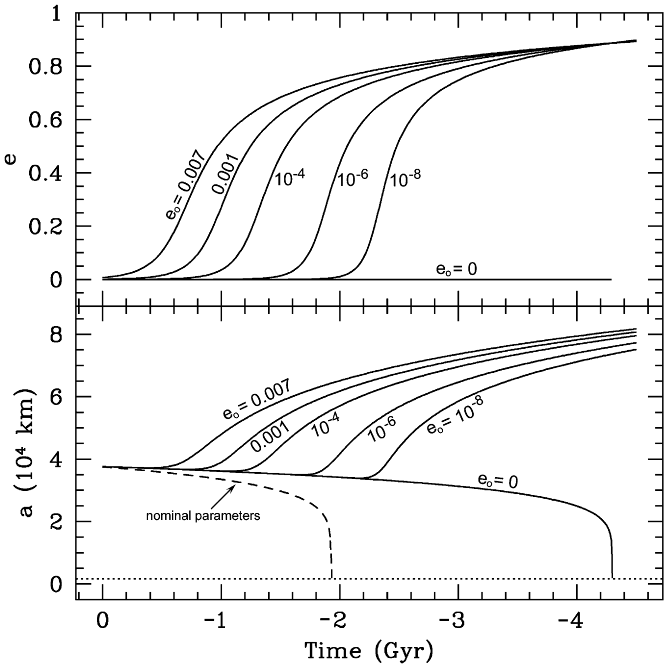

Fig. 1. The tidal evolution of Dysnomia's orbital eccentricity and semi-major axis, going back in time from the present ($t = 0$). The dashed line is for the nominal parameters reported by Brown and Schaller (2007), with current eccentricity $e_o = 0$ and tidal $Q = 100$ for the satellite and planet. It shows the satellite at the Roche limit near the planet (the horizontal dotted line) less than 2 Byr ago. With parameters adjusted within the range of observational uncertainty, but e_o still zero, this evolution can be extended back to near the age of the Solar System (solid curve). However, with small non-zero values of e_o, the evolutionary history is quite different, suggestive of an origin by capture, rather than formation near the planet.

We first consider the tidal evolution under Brown and Schaller's assumption that e has been effectively zero throughout the age of the Solar System. Inspection of the first equation shows that if e were precisely zero it would not change with time. Moreover, the change in a would be due entirely to tidal dissipation in Eris (the first term in the expression for da/dt). Using the current orbit from Brown and Schaller, e_o (the current value) assumed to be precisely zero, and their assumed k and Q (Section 1 above), integration of the tidal evolution equations back in time brings the satellite close to the planet about 1.9 billion years ago, following the dashed line in Fig. 1. This calculation appears to be inconsistent with Brown and Schaller's result that Dysnomia started at the Roche limit early in the history of the Solar System.

However, by selecting values of the various parameters from within the range of observational uncertainty, one can slow the evolution considerably to a rate consistent with formation of Dysnomia at the Roche limit, even with Q and k nearly the same as adopted by Brown and Schaller. We take $a = 37{,}600$ km, $M_E = 1.68 \times 10^{22}$ kg, $R_E = 1150$ km, $R_D = 75$ km, which are all values within the range of uncertainty (Brown and Schaller, 2007). We also reduce the satellite's mass to $M_D = 2.3 \times 10^{18}$ kg, corresponding to a density 1.3 gm/cm^3, about half that of Eris, which is one plausible case considered by Brown and Schaller (2007). With these parameters, and again assuming $e_o = 0$, we can extend the evolution back, putting a at the Roche limit about 4.3 billion years ago (Fig. 1). Slight adjustments in the assumed value of k or Q could make that figure 4.5 Byr, consistent with Brown and Schaller's hypothesis. Thus an origin near the Roche limit cannot be ruled out, assuming the tidal parameters adopted by Brown and Schaller.

However, contrary to the conclusion of Brown and Schaller, the history and origin might have been quite different (even with the same tidal parameters) if we consider a currently non-circular orbit, even if e_o is very small, because of the short eccentricity-damping timescale. Results of numerical integration of the above equations are shown in Fig. 1 for various assumed values of e_o. All of the solid curves in Fig. 1 were computed with the same suite of parameter values (other than e_o).

Consider the case (in Fig. 1) in which e_o has the observational best-fit value of 0.007. The short damping timescale means that in the past e must have been much greater. Accordingly, we see that only 0.5 Byr ago e was about 0.1. At that time, with such a large e, tidal dissipation in the satellite would have been significant, and the heat energy would have come out of the orbital energy. Its effect on a is described by the last term in the equation for da/dt. Its negative sign is opposite that of tides raised on the planet, which tend to increase the semi-major axis at the expense of the planet's rotational energy. Indeed, about 0.5 Byr ago the eccentricity would have been large enough that the two effects would have been equal and opposite, giving $da/dt = 0$.

Going back further in time, with even larger e, da/dt would have been negative. We see that a few billion years ago the satellite was significantly farther from the planet than it is now (with a over twice as large). Note that, due to the larger early values of a, the rates of change of both e and a would have been much slower prior to 1 Byr ago; The equations show that the rates of evolution have a strong inverse dependence on a.

In fact, a similar large early distance from Eris is obtained even if the current eccentricity e_o is orders of magnitude smaller than the best-fit value. For example, as shown in Fig. 1, if $e_o = 10^{-4}$, the past history is similar to that with the best-fit value. The only difference is that, going back in time, it takes longer for the e values to exponentially reach values great enough to reverse the evolution of a. As shown in Fig. 1, even for e_o as small as 10^{-8}, the evolution is similar. For any plausible value of e_o other than 0, the orbit 4.5 Byr ago is approximately the same: highly eccentric and with a approximately twice the current value a_o.

This scenario is precisely opposite the tidal evolution envisioned by Brown and Schaller. In this case the satellite originated much farther out, rather than close to the planet.

3. Discussion

The values shown at the right side of Fig. 1 should not be taken as precise descriptions of the initial orbit because tidal theory depends on details of the geophysical response of the planet and satellite to the continually changing tidal potential. The classical equations for tidal evolution were derived assuming modest orbital eccentricities, because inclusion of higher-order effects would require information about the dependence of the tidal lag on frequency and amplitude, which is not currently available. Nevertheless, the general trends and the magnitude of the changes given by the evolution equations are probably correct and consistent with the requirements of reasonable rates of energy dissipation and angular momentum conservation.

Consideration of tidal evolution alone would suggest that only if the current eccentricity is shown to be smaller than $\sim 10^{-10}$ could one conclude that Dysnomia's initial orbit around Eris was initially near the Roche limit. Any larger e_o would seem (from Fig. 1) to require that Dysnomia moved inward from much farther out. On the other hand, such a value of the current e could also be the result of more recent events, rather than simply a relic of a primordial orbit. For example, some eccentricity could have been introduced by perturbations from another still-undetected satellite, by spin–orbit resonance effects, or by an encounter with another Kuiper Belt object. The latter might have stepped the value up to ~ 0.001, but probably not much larger, extrapolating from calculations by Stern et al. (2003). Whether any of these non-tidal effects contributed substantially to the "best-fit" value of $e_o = 0.007$ is uncertain. In any case, an original orbit that was highly eccentric with a semi-major axis $\sim 50 R_E$, as shown in Fig. 1, is consistent with the current orbit.

In that case, the initial orbit of Dysnomia may have extended as far out as $\sim 100 R_E$ at "apodwarf," but that distance is still small compared with the Hill sphere of Eris, which has a radius about 40 times larger. Nevertheless this large extended orbit is suggestive of an origin by capture, rather than the origin by giant impact that seemed to be implied by an original orbit near the Roche limit. If Dysnomia entered the Hill sphere of Eris at a time when one or more other bodies were nearby, their effects could have allowed Dysnomia to become trapped, while the others escaped. Goldreich et al. (2002) pointed out that capture of satellites in the Kuiper Belt could be aided by the gravitational effect of a single large perturber, or the cumulative gravitational scattering of many small bodies (dynamical friction). The probability that a specific body like Dysnomia could be captured in the type of initial orbit inferred here from tidal evolution remains to be computed. However, capture is certainly possible and would be more consistent with the initial conditions implied by tidal evolution than an origin close to the planet.

Here we have demonstrated a range of possible alternative histories to that reported by Brown and Schaller using the same tidal parameters Q and k as they used, in order to show that an origin close to the planet is not the only possibility. In fact, an even wider range of possibilities exists if we consider the great uncertainty in the tidal parameters. For example, if either body behaves effectively as a solid, rigid body, with the rigidity of ice, their k values could be much smaller than the value 1.5 (adopted by Brown and Schaller). The actual physical properties are uncertain. For example, Eris might have a liquid layer (Hussmann et al., 2006) and Dysnomia could be relatively fractured or unconsolidated. Evolutionary scenarios that take into account the possibility of various models of internal structures and tidal properties could be quite diverse.

Observers should not be discouraged from looking for additional outer satellites of Eris on the grounds that they could not have evolved there from initial close-in orbits. If other satellites were captured, or in some other way started out far from Eris (as Dysnomia may have), then some could remain on orbits beyond Dysnomia.

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