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Tidal disruptions: A continuum theory for solid bodies

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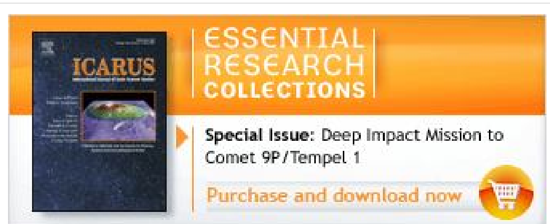
Abstract

Although the theory of Roche 1847 for the tidal disruption limits of orbiting satellites assumes a fluid body, a length to diameter of exactly 2.07:1, and a particular body orientation, the theory is commonly applied to the satellites of the Solar System and to small asteroids and comets passing nearby a planet. Clearly these bodies are neither fluid nor generally are that elongated, so a more appropriate theory is needed. Here we present exact analytical results for the distortion and disruption limits of solid spinning ellipsoidal bodies subjected to tidal forces, using the Drucker–Prager strength model with zero cohesion. It is the appropriate model for dry granular materials such as sands and rocks, for rubble-pile asteroids and comets, and for larger satellites, asteroids and comets where the cohesion can be ignored. This study uses the same approach as the studies of spin limits for solid ellipsoidal bodies given in [Holsapple, K.A., 2001. Icarus 154, 432–448; Holsapple, K.A., 2004. Icarus 172, 272–303]. It is a static theory that predicts conditions for breakup and predicts the nature of the deformations at the limit state, but does not track the dynamics of the body as it comes apart. The strength is characterized by a single material parameter associated with an angle of friction, which can range from zero to 90°. The case with zero friction angle has no shear strength whatsoever, so it is then the model of a fluid or gas. The case of 90° represents a material that cannot fail in shear, but still has zero tensile strength. Typical dry soils have angles of friction of 30°–40°. Since the static fluid case is included in the theory as a special case, the classical results of Roche [Roche, E.A., 1847. Acad. Sci. Lett. Montpelier. Mem. Section Sci. 1, 243–262] and Jeans [Jeans, J.H., 1917. Mem. R. Astron. Soc. London 62, 1–48] are included and re-derived in their entirety; but the general solid case has much more variety and applicability. We consider both the spin-locked case, appropriate for most satellites of the Solar System; and the zero spin case, a possible case for a passing stray body. Detailed plots of many special cases are presented, in terms of shape, orientation and mass densities. A very typical result gives a closest approach $d=1.5(\rho/\rho_P)^{1/3}R$ in terms of the planet radius R, and the satellite and planet mass densities ρ and ρ_P. We also use the theory to distinguish between conditions allowing global shape changes leading to new equilibrium states, or those leading to complete disruption. We apply the theory to the potentially hazardous Asteroid 99942 Apophis due to pass very near the Earth in 2029, and conclude it is extremely unlikely to experience any tidal readjustments during its passage. The states of many of the satellites of the Solar System are compared to the theory, and we find that all are well within their tidal disruption



limits for expected values of the internal friction.

Keywords: Asteroids; Asteroids, rotations; Comets; Planetary rings; Tides, solid body; Satellites, general

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