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Crustal failure on icy Moons from a strong tidal encounter

Alice C. Quillen[a,*], David Giannella[a], John G. Shaw[b], Cynthia Ebinger[c]

[a] Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[b] Laboratory for Laser Energetics, 250 East River Rd., Rochester, NY 14623, USA
[c] Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY 14627, USA

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ABSTRACT

Close tidal encounters among large planetesimals and Moons should have been more common than grazing or normal impacts. Using a mass spring model within an N-body simulation, we simulate the deformation of the surface of an elastic spherical body caused by a close parabolic tidal encounter with a body that has similar mass as that of the primary body. Such an encounter can induce sufficient stress on the surface to cause brittle failure of an icy crust and simulated fractures can extend a large fraction of the radius of body. Strong tidal encounters may be responsible for the formation of long graben complexes and chasmata in ancient terrain of icy Moons such as Dione, Tethys, Ariel and Charon.

1. Introduction

A number of large surface features in the Solar System have origins potentially due to giant impacts that occurred between planet-sized bodies or planets and large planetesimals. These include the crustal dichotomy of Mars (Frey and Schultz, 1988; Marinova et al., 2008; Wilhelms and Squyres, 1984) and the Moon (Jutzi and Asphaug, 2011), jumbled terrain on Mercury (Schultz and Gault, 1975) and numerous impact craters throughout the Solar System (Melosh, 1989). Because of their larger cross-section, grazing impacts among planets and planetesimals are more likely than normal angle impacts (Asphaug, 2010). Likewise, strong *tidal encounters*, those involving close encounters between two large bodies that do not actually touch, are more likely than grazing impacts. A fraction of a body's gravitational binding energy can be dissipated during a close tidal encounter (Press and Teukolsky, 1977). While some large surface features on planets and Moons have proposed origins due to large impacts, so far none have been linked to single close and strong tidal encounters.

Strong tidal encounters are unlikely now, but would have occurred in the past, during the late-heavy bombardment era and beforehand. Orbits of closely packed Moons can become unstable (e.g., Cheng et al., 2014; French and Showalter, 2012) and this too could cause close encounters between similar mass bodies. Impacts primarily cause compressive stress (Melosh, 1989), but tidal stress can be tensile and many materials are weaker when subjected to tensile stress than a comparable magnitude of compressive stress (for ice see Fig. 1 by Petrovic, 2003 and Fig. 7.2 by Collins et al., 2010 and for the Earth's lithosphere see failure envelopes in Fig. 6.24 and Yield Strength envelopes in Fig. 6.27 by Watts, 2001 or Fig. 9.6 by Kohlstedt and Mackwell, 2010). Ancient regions of planets and Moons exhibit features such as chasmata, grooves, grabens or graben complexes that are associated with extension and tensile deformation (Collins et al., 2010), and some of these may have been caused by strong tidal encounters with large bodies.

Many studies of tidal encounters between two planetesimals or between a planetesimal and a planet have focused on tidal disruption (e.g., Boss, 1994; Dobrovolskis, 1990; Holsapple and Michel, 2008; Richardson et al., 1998; Sharma et al., 2006). But tidal stresses due to close encounters between bodies can affect body rotation and shape (Bottke et al., 1999) and disturb weathered surfaces of asteroids, exposing fresh surface materials (Binzel et al., 2010; Nesvorny et al., 2010). Simulations of granular materials have predicted resurfacing in weak regions where tidal stresses cause avalanches or landslides (Yu et al., 2014).

Some icy Moons exhibit global tectonic features, such as grooves or long fractures, that could be caused by varying tidal stresses exerted by their host planet (e.g., Helfenstein and Parmentier, 1985; Hurford et al., 2015; 2007; McEwen, 1986; Smith-Konter and Pappalardo, 2008; Wahr et al., 2009). The patterns and individual morphologies of parallel sets of grooves and troughs on satellites and asteroids such as Phobos, Eros, Ida, Gaspra, Epimetheus and Pandora (see Thomas and Prockter, 2010 for a review) can be attributed to fracturing in weak materials caused by oscillating tidal stresses associated with orbital eccentricity

* Corresponding author. Tel.: +1 5752759625.
E-mail address: alice.quillen@gmail.com, aquillen@pas.rochester.edu (A.C. Quillen).

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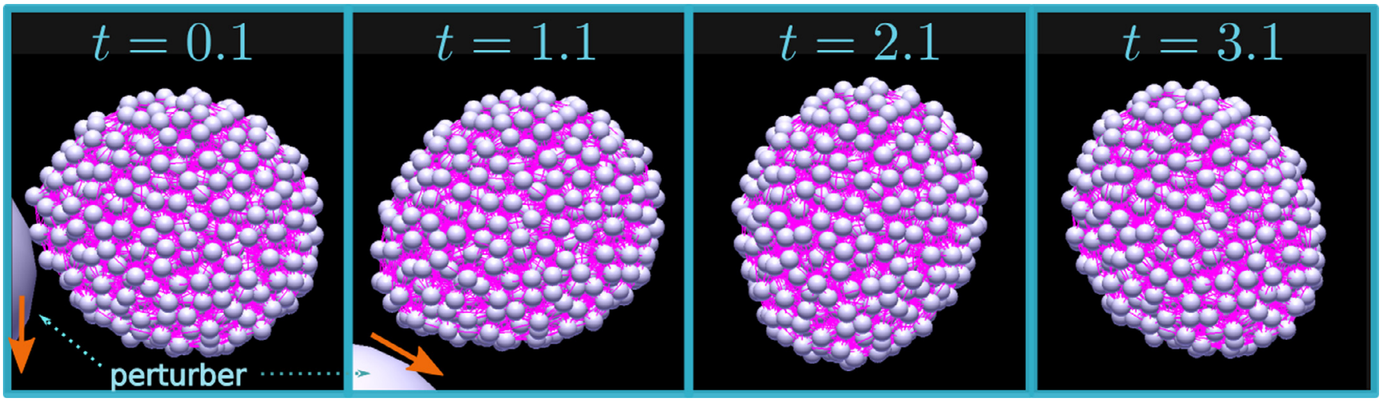

Fig. 1. Simulation of a near parabolic tidal encounter of a random spring elastic model with parameters listed in Tables 3 and 4 for the N simulation. The perturbing body approaches from the top left, and is seen in the leftmost two panels. Different times in the simulation are shown from left to right, separated in time by 1 in units of t_{grav} (Eq. 9) and labelled by time from pericenter. The leftmost panel shows a time just after closest approach. The primary body is simulated with a mass-spring model and springs are shown as pink connecting lines between particles. The body is initially spherical but is elongated by the tidal force of the perturber. Vibrational oscillations are excited in the body by the tidal encounter. The rendered spheres are shown to illustrate the random distribution of node point masses, not imply that the body behaves as a granular rubble pile (e.g., Richardson et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

(Morrison et al., 2009) or an increase in tidal stress resulting from the orbital decay of the body itself (Hurford et al., 2015; Soter and Harris, 1977). For Phobos, the length of the grooves is perpendicular to the oscillating tensile stress (Morrison et al., 2009). Long (130 km) linear fractures termed "tiger stripes" on Enceladus are connected to diurnal tidal stress variations (Hurford et al., 2007; Nimmo and Matsuyama, 2007; Smith-Konter and Pappalardo, 2008).

Dione, Tethys, Rhea (Moons of Saturn), Titania (Moon of Uranus) and Charon (Moon of Pluto) have heavily cratered surfaces and also display long faults extending a significant fraction of the Moon radius, and chasma and faults in pairs interpreted as graben or graben complexes (for a review see Section 6.4 by Collins et al., 2010 and for recent results on the Pluto system see Stern et al., 2015). The Ithaca Chasma on Tethys is interpreted to be a large graben complex (Giese et al., 2007) and crater counts indicate that it is older than the large Odysseus impact basin (with radius 0.4 times that of the Moon itself). On Dione, Cassini imagery revealed that some fault networks have vertical offsets that dissect craters, confirming their extensional tectonic origin and suggesting that they were formed early (Jaumann et al., 2009). These studies suggest that the formation of chasmata and graben complexes can take place before or during an epoch of large impacts and so during an epoch when strong tidal encounters would have occurred. Explanations for the graben complexes include heating and expansion of the interior (e.g., Hillier and Squyres, 1991) and stresses induced by reorientation following a large impact (Nimmo and Matsuyama, 2007). Strong tidal encounters have not yet been explored as a possible explanation for the formation of surface features such as chasmata and graben complexes on icy Moons.

In this study we focus on the intersection between the works introduced above. We consider rare and close tidal encounters, that might have occurred billions of years ago, between large bodies that are not gravitationally bound (not in orbit about each other). The time of a parabolic or hyperbolic tidal encounter can be a few hours, so tidal encounters are extremely fast compared to the time scales of most geophysical processes. On such a short time scale rock and ice should deform in a brittle-elastic mode rather than a ductile, plastic or visco-elastic mode (e.g., Bürgmann and Dresen, 2008; Turcotte and Schubert, 2002). To numerically simulate tidal deformation we use a mass-spring model to simulate both elastic response and gravity (see Frouard et al., 2016). Brittle failure is modeled by allowing springs on the surface to fail if they exceed a critical tensile strain value. Our simulations allow to us to visualize brittle crustal failure following a hypothetical strong tidal encounter. Our approach differs from the granular flow simulations by Schwartz et al. (2013) with spring-like forces between neighboring soft spheres that mimic cohesion and can simulate bulk tensile failure.

1.1. Tidal encounters

Following Press and Teukolsky (1977) (also see Ogilvie, 2014) the response of a body during a tidal encounter can be estimated using an impulse approximation. The maximum tidal force, F_T, on body M from body m during the encounter is approximately

$$F_T \sim \frac{GmR}{q^3} \quad (1)$$

where q is the distance between body centers at closest approach (pericenter), m is the mass of the tidal perturber, R is the radius of the primary body with mass M, and G is the gravitational constant. The time scale of the encounter is

$$t_{enc} \sim 2q/V_q \quad (2)$$

where V_q is the velocity at pericenter. Together F_T and t_{enc} cause a velocity perturbation on the surface of the primary body

$$\Delta v \sim \frac{2\,GmR}{q^2 V_q} \quad (3)$$

If the orbit is parabolic then $\Delta v/\sqrt{GM/R} = \eta$, a dimensionless parameter used to characterize parabolic tidal encounters (Press and Teukolsky, 1977), that is the ratio of acceleration due to self-gravity and the tidal acceleration at the body's surface.

The extent of the tidal deformation of body M can be estimated by balancing the kinetic energy per unit mass due to the tidal impulse with elastic energy per unit mass

$$\Delta v^2 \sim \epsilon^2 E/\rho \quad (4)$$

with E the Young's modulus and ρ the density of body M, giving a strain of

$$\epsilon \sim \left(\frac{e_g}{E}\right)^{\frac{1}{2}} \left(\frac{R}{q}\right)^2 \left(\frac{m}{M}\right) \left(\frac{v_c}{V_q}\right), \quad (5)$$

where

$$v_c = \sqrt{GM/R} \quad (6)$$