Icarus 319 (2019) 312–333

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Impact excitation of a seismic pulse and vibrational normal modes on asteroid Bennu and associated slumping of regolith

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ARTICLE INFO

Keywords:
Asteroids
Surfaces – asteroids
Individual
Bennu – impact processes

ABSTRACT

We consider an impact on an asteroid that is energetic enough to cause resurfacing by seismic reverberation and just below the catastrophic disruption threshold, assuming that seismic waves are not rapidly attenuated. In asteroids with diameter less than 1 km we identify a regime where rare energetic impactors can excite seismic waves with frequencies near those of the asteroid's slowest normal modes. In this regime, the distribution of seismic reverberation is not evenly distributed across the body surface. With mass-spring model elastic simulations, we model impact excitation of seismic waves with a force pulse exerted on the surface and using three different asteroid shape models. The simulations exhibit antipodal focusing and normal mode excitation. If the impulse excited vibrational energy is long lasting, vibrations are highest at impact point, its antipode and at high surface elevations such as an equatorial ridge. A near equatorial impact launches a seismic impulse on a non-spherical body that can be focused on two additional points on an the equatorial ridge. We explore simple flow models for the morphology of vibration induced surface slumping. We find that the initial seismic pulse is unlikely to cause large shape changes. Long lasting seismic reverberation on Bennu caused by a near equatorial impact could have raised the height of its equatorial ridge by a few meters and raised two peaks on it, one near impact site and the other near its antipode.

1. Introduction

Impact induced seismic waves and associated seismic shaking can modify the surface of an asteroid. Impact induced seismicity is a surface modification process that is particularly important on small asteroids due to their low surface gravity and small volume which limits vibrational energy dispersal (Cintala et al., 1978; Cheng et al., 2002; Richardson et al., 2004). Seismic disturbances can destabilize loose material resting on slopes, causing downhill flows (Titley, 1966; Lambe and Whitman, 1979), crater degradation and crater erasure (Richardson et al., 2004; Thomas and Robinson, 2005; Richardson et al., 2005; Asphaug, 2008; Yamada et al., 2016) and particle size segregation or sorting (Miyamoto et al., 2017; Matsumura et al., 2014; Tancredi et al., 2015; Pereraa et al., 2016; Maurel et al., 2017). Flat deposits at the bottom of craters on Eros known as "ponds" can be explained with a seismic agitation model (Cheng et al., 2002), though electrostatic dust levitation may also be required to account for their extreme flatness and fine grained composition (Robinson et al., 2001; Colwell et al., 2005; Richardson et al., 2005). Regions of different crater densities on asteroid 433 Eros are explained by large impacts that erase craters (Thomas and Robinson, 2005). Seismic shaking accounts for slides, slumps, and creep processes on the Moon (Titley, 1966) and on Eros (Veverka et al., 2001), particle size segregation or sorting on Itokawa (Miyamoto et al., 2017; Tancredi et al., 2015) and smoothing of initially rough ejecta on Vesta, a process called 'impact gardening' (Schröder et al., 2014).

During the contact-and-compression phase of a meteor impact, a hemispherical shock wave propagates away from the impact site

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https://doi.org/10.1016/j.icarus.2018.09.032
Received 6 April 2018; Received in revised form 1 September 2018; Accepted 24 September 2018

(Melosh, 1989). As the shock wave attenuates, it degrades into normal stress (seismic) waves (e.g., Richardson et al., 2004; Richardson et al., 2005; Jutzi et al., 2009; Jutzi and Michel, 2014). The seismic pulse, sometimes called 'seismic jolt' (Nolan et al., 1992) or 'global jolt' (Greenberg et al., 1994; 1996), travels as a pressure wave through the body. Seismic agitation is most severe nearest the impact site and along the shortest radial paths through the body because of radial divergence and attenuation of the seismic pulse (Thomas and Robinson, 2005; Asphaug, 2008). After the seismic energy has dispersed through the asteroid, continued seismic shaking or reverberation of the entire asteroid may continue to modify the surface (Richardson et al., 2005). Small impacts could excite seismic waves that overlap in time as they attenuate, causing continuous seismic noise known as 'seismic hum' (Lognonné et al., 2009). The regime that is important for a particular impact and surface modification process depends on the frequency spectrum of seismic waves launched by the impact and the frequency dependent attenuation, scattering and wave speed of the seismic waves (Richardson et al., 2005; Michel et al., 2009).

The size of an impactor that catastrophically disrupts an asteroid exceeds by a few orders of magnitude the size of one that causes sufficient seismic shaking to erase craters (Richardson et al., 2005; Asphaug, 2008). In a rarer event, an asteroid could be hit by a projectile smaller than the disruption threshold but large enough to significantly shake the body. It is this regime that we consider here. We explore the nature of shape changes caused by vibrational oscillations excited by a subcatastrophic impact. With the imminent arrival in 2018 of the OSIRIS-REx mission at Bennu (Asteroid 101955), we investigate the possibility that the unusual shape of Bennu's equatorial ridge is due to a energetic but subcatastrophic impact.

Asteroids are often modeled as either fractured monoliths or rubble piles. In dry granular media on Earth, pressure waves propagate through particles and from particle to particle through a network of contact points, called 'force chains' (Cundall and Strack, 1979; Ouaguenouni and Roux, 1997; Geng et al., 2001; Clark et al., 2012). Laboratory experiments find that the elastic wave speed tends to scale with the classic speed $\sqrt{E/\rho}$ where E is the Young's modulus and ρ is the density, and is not usually dependent on the particle size, but is weakly dependent on the constraining pressure and porosity (Duffy and Mindlin, 1957). Thus a continuum elastic material model can approximate the seismic behavior of granular materials and has been used to model seismicity in asteroids (e.g., Murdoch et al., 2017). However, if the force chains are dependent on gravitational acceleration, terrestrial and lunar granular materials may not provide good analogs for asteroids which have low surface gravity. Rubble pile asteroids may have a small, but finite, level of tensile strength (Richardson et al., 2009) due to van der Waals forces between fine particulate material (Sánchez and Scheeres, 2014; Scheeres and Sánchez, 2018), so both compressive and tensile restoration forces may be present allowing seismic waves to reflect. Even without cohesion, contacts under pressure allow seismic waves to propagate (e.g., Sánchez and Scheeres, 2011; Tancredi et al., 2012). Ballistic contacts also allow a pressure pulse to propagate, as illustrated by the classic toy known as Newton's cradle.

Unfortunately, little is currently known about how seismic waves are dispersed, attenuated and scattered in asteroids. The rapidly attenuated seismic pulse or jolt model (Thomas and Robinson, 2005) is consistent with strong attenuation in laboratory granular materials at kHz frequencies (O'Donovan et al., 2016), but qualitatively differs from the slowly attenuating seismic reverberation model (Cintala et al., 1978; Cheng et al., 2002; Richardson et al., 2004; 2005), that is supported by measurements of slow seismic attenuation in lunar regolith (Dainty et al., 1974; Toksöz et al., 1974; Nakamura, 1976). While both seismic jolt and reverberation processes can cause crater erasure and rim degradation, size segregation induced by the Brazil nut effect relies on reverberation (e.g., Miyamoto et al., 2017; Tancredi et al., 2012; Matsumura et al., 2014; Tancredi et al., 2015; Pereraa et al., 2016; Maurel et al., 2017).

Despite the poorly constrained seismic wave transport behavior in asteroids, a linear elastic material simulation model may describe the propagation of impact generated seismic waves (e.g., Murdoch et al., 2017). To model the propagation of seismic waves, we use the mass-spring and N-body elastic body model we have developed to study tidal and spin evolution of viscoelastic bodies (Quillen et al., 2016a; Frouard et al., 2016; Quillen et al., 2016b; 2017). As shown by Kot et al. (2015), in the limit of large numbers of randomly distributed mass nodes and an interconnected spring network comprised of at least 15 springs per node, the mass spring model approximates an isotropic continuum elastic solid. We use our mass-spring model to examine the surface distribution of vibrational energy excited by an impact. In this respect we go beyond previous works which have primarily focused on simulation of rubble piles (e.g., Walsh et al., 2012; Holsapple, 2013; Schwartz et al., 2013; Schwartz et al., 2014; Pereraa et al., 2016) and transmission of seismic pulses in planar sheets or spherical bodies (e.g., Tancredi et al., 2012; Murdoch et al., 2017).

In the following Section (2), we summarize properties of Bennu. Normalized units for the problem are discussed in Section 2.1 and we estimate frequencies for its vibrational normal modes (Section 2.2). In Section 3 we discuss excitation of seismic waves by an impact. We identify a regime where low frequency normal modes are likely to be excited by an impact. In Section 4 we describe our mass/spring model simulations. We simulate impacts by applying a force pulse to the simulated asteroid surface and the strength and duration of the applied force pulse are estimated from scaling relations described in Section 3. Normal modes are identified in the spectrum of the vibrationally excited body. We examine the pattern of vibrational kinetic energy on the surface for three different shape models. In Section 5 we explore how impact excited seismic vibrations could induce granular flows on Bennu's surface. A summary and discussion follows in Section 6.

2. Bennu

The OSIRIS-REx mission, launched in 2016, (Lauretta et al., 2017) to Bennu (Asteroid 101955), aims to fire a jet of high-purity nitrogen gas onto Bennu's surface so as to excite at least 60 g of regolith that can be collected and returned to Earth. A C-complex asteroid, Bennu is interesting due to its primitive nature. Spectroscopic measurements are consistent with CM-carbonaceous-chondrite-like material and Bennu's thermal inertia implies that its surface supports a regolith comprised of sub-cm-sized grains (Emery et al., 2014). A suite of remote sensing observations during 2018 and 2019 will be used to create a series of global maps to characterize the geology, mineralogy, surface processes, and dynamic state of Bennu. These maps will also be used to choose a sample selection site and place the returned sample in geological context. Measurements from the OSIRIS-REx rendezvous will be used to test theories for the formation of Bennu's equatorial ridge (Scheeres et al., 2016).

Ground-based radar has been used to characterize Bennu's shape, spin state, and surface roughness (Nolan et al., 2013). Bennu's shape is nearly spherical but like 1999 KW4 (Scheeres et al., 2006), Bennu has an equatorial ridge. The shape model consists of 1148 vertices, with a spacing of 25 m between vertices and two subdivided regions with additional resolution where there are protruding features that could be boulders. The shape model was generated by using the vertex locations, estimated Doppler broadening and the radar scattering function, to match the radar images and enforced a uniform mass distribution and principal-axis rotation (Nolan et al., 2013). In Figs. 1 and 2 we show the geometric height (distance from geometric center of body). Fig. 1 shows 4 orthographic projections. The left two panels show polar views and the right two panels show equatorial views. The polar axis is aligned with the axis of rotation. We use latitude λ and longitude ϕ angles of the body with respect to the center of mass and spin axis, which we assume is aligned with a principal body axis (following Nolan et al., 2013). The body spin and higher equatorial elevation reduce the radial