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Subsurface failure in spherical bodies: A formation scenario for linear troughs on Vesta's surface

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ABSTRACT

Many asteroids in the Solar System exhibit unusual, linear features on their surface. The Dawn mission recently observed two sets of linear features on the surface of the asteroid 4 Vesta. Geologic observations indicate that these features are related to the two large impact basins at the south pole of Vesta, though no specific mechanism of origin has been determined. Further, the orientation of the features is offset from the center of the basins. Experimental and numerical results reveal that the offset angle is a natural consequence of oblique impacts into a spherical target. Here we demonstrate that a set of shear planes develops in the subsurface of the body opposite to the point of first contact. These subsurface failure zones then propagate to the surface under combined tensile-shear stress fields after the impact to create sets of approximately linear faults on the surface. Comparison between the orientation of damage structures in the laboratory and failure regions within Vesta can be used to constrain impact parameters (e.g., the approximate impact point and likely impact trajectory).

1. Introduction

Comets and asteroids represent survivors of original planetary building blocks that record conditions of the early Solar System. Nevertheless, nearly all asteroids observed close-up today have impact craters with diameters comparable to the body itself (e.g., Bottke et al., 2002). The size of these craters implies that the interior of these asteroids must be highly fractured and damaged. Consequently, most small bodies underwent collisional, dynamical and thermal processes over the last 4.5 Ga.

Previous experimental and numerical work examined failure of spherical targets to better understand asteroid evolution, damage structures seen on asteroids, and limits for catastrophic disruption. Impact-induced failure within a spherical target contrasts with failure in a planar target due to curvature of the surface that focuses shock waves toward the center with incipient (if not total) failure at the farside (e.g., Rinehart, 1960; Gault and Wedekind, 1969). This phenomenon is important even for planetary bodies such as the Moon and Mercury (Schultz and Gault, 1975; Hughes et al., 1977; Schultz and Crawford, 2011), and Saturnian satellites (Bruesch and Asphaug, 2004; Moore et al., 2004).

Laboratory impacts into spherical targets have been used to better understand the effects of material properties on collisional outcomes of asteroids (e.g., Fujiwara et al., 1989; Nakamura and Fujiwara, 1991; Martelli et al., 1994; Holsapple et al., 2002). Impact experiments indicate that impact angle, in conjunction with material properties and impact velocity, significantly affects collisional outcomes (Gault, 1973; Gault and Wedekind, 1978; Fujiwara and Tsukamoto, 1980). Previous experimental studies show that catastrophic disruption of basalt and glass targets resulted in an intact fragment at the center of the original target (called the "core") (Gault and Wedekind, 1969; Fujiwara, 1986; Nakamura and Fujiwara, 1991). This phenomenon is also observed in PMMA targets when they are struck at high velocity.

Laboratory experiments, however, are orders of magnitude smaller than collisions throughout the Solar System. Thus, numerical modeling or scaling relationships (e.g., Housen et al., 1983; Holsapple, 1993; Davis et al., 1994) become increasingly important for understanding collisional histories of asteroids and larger terrestrial bodies. Hydrocode simulations of asteroid disruption were originally benchmarked by comparison with disruption of laboratory-scale spherical targets (e.g., Melosh et al., 1992; Benz and Asphaug, 1994, 1999; Asphaug, 1997; Melosh and Ryan, 1997; Ryan and Melosh, 1998). Two-dimensional simulations were generally successful in reproducing fragment size distribution and mean ejecta speeds from laboratory experiments into basalt

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(Takagi et al., 1984; Hartmann, 1980; Nakamura and Fujiwara, 1991) and weak and strong mortar targets (Davis and Ryan, 1990).

Hydrocode simulations also revealed subsurface damage caused by impacts on asteroids (e.g., Asphaug, 1997; Nolan et al., 2001; Buczkowski et al., 2012; Bowling et al., 2013a, 2013b; Ivanov and Melosh, 2013). Asphaug et al. (1996) used the hydrocode SALE2D (Amsden et al., 1980) to examine subsurface damage on the asteroid Ida, and Asphaug (1997) provided similar analysis for the asteroid 4 Vesta. Their results indicated that stresses from large events into curved, finite target surfaces focus in regions far from the impact point, causing fracture throughout the body; this can be exacerbated by a non-spherical target (Asphaug et al., 1996). Further, Asphaug et al. (1996) showed that the impactor responsible for the Vienna Regio region of Ida may have caused fracturing in Pola Regio. Spacecraft images of Pola Regio reveal sets of parallel to sub-parallel troughs and linear features in this region. The authors concluded that these linear features may be the result of the Vienna Regio impact, and that later impacts may have created stress waves that reactivated these ancient flaws such that the grooves appear fresh on the surface of Ida.

Over the last two decades, missions to asteroids and comets have become increasingly common (e.g., NEAR, Galileo, Deep Impact, Stardust, Hayabusa, EPOXI, Stardust-NExT, Dawn, Rosetta, OSIRIS-REx). These missions reveal a great deal about the nature of small bodies in the Solar System, including surface properties, morphologies, and shapes. Because internal structure and damage can be manifested on the surface of bodies (e.g., Asphaug et al., 1996; Buczkowski et al., 2008; Schultz and Crawford, 2011), an understanding of subsurface damage caused by impact is important for fully understanding data returned by these missions.

The present study first describes a new time-resolved experimental approach for assessing damage in spherical targets. This description is followed by a detailed comparison between subsurface damage in laboratory experiments and small-scale CTH simulations. We then discuss the results of CTH simulations on the scale of a particular asteroid: 4 Vesta. We finish with discussion of the damage structures in spherical targets, including formation mechanisms, differences with planar targets, and implications for asteroid evolution and future study.

2. Methods and approach

Previous studies focused on planar polymethylmethacrylate (PMMA) targets in order to track the evolution of subsurface damage following oblique impacts for both impacts directly into PMMA (Stickle and Schultz, 2011, 2014) and impacts into layered PMMA and geologic targets (Stickle and Schultz, 2012, 2013). At planetary scales, however, target curvature creates shock-wave interactions that significantly change the damage pattern (and process). Here, impacts into transparent PMMA spheres are directly compared with three-dimensional CTH models. These results, and the intuition gained from comparing small-scale models to experiments, then provide insights into extrapolations to large-scale planetary models.

2.1. Laboratory experiments

A suite of laboratory experiments was performed at the Ames Vertical Gun Range (AVGR) at the NASA Ames Research Center in Mountain View, California. The AVGR is a two-stage light gas gun that achieves impact velocities from ~0.5 to 7 km/s (depending on projectile size). The barrel can rotate from 0 to 90°, in 15° increments, allowing the target to stay oriented correctly with respect to gravity, which is especially important when studying impacts into granular or fluid targets. The targets are set up inside a 2.5-m diameter vacuum chamber, so a wide variety of shapes and sizes can be accommodated. The vacuum chamber can be maintained at a vacuum level below 0.3 torr, or filled with different gasses to simulate various environments. High-speed cameras (up to 1 million frames per second) are used to record the impact events.

For this study, transparent PMMA spheres were used as the target. PMMA is a transparent acrylic that becomes opaque under high strain and allows tracking the evolution of impact-induced damage. At room temperature and high-strain rates, PMMA is brittle and has mechanical properties similar to that of the upper crust of the Earth, which makes it an ideal rock analog in high-rate laboratory experiments (de Joussineau et al., 2003; Rosakis et al., 1999, 2004, 2008; Rittel and Brill, 2008; Nasraoui et al., 2012). PMMA, along with some other transparent polymeric materials, also exhibits birefringence, making it useful for studies of dynamic failure processes because stress fields can be mapped using photoelasticity techniques (e.g., de Joussineau et al., 2003; Rosakis et al., 1999; Rosakis, 2002; Misra et al., 2009). While not a perfect match to a differentiated, rocky body, the brittle fracture processes that occur within these targets are the same that would be expected in brittle rock targets. Thus, this choice of target material allows the best of both worlds: brittle damage processes, and the ability to track those processes and the resulting damage evolution with time.

For this study, spherical targets with a 10-cm diameter were placed on top of a thin (0.3 cm) plastic cylinder protruding from a sand surface. Pyrex spheres (0.635-cm in diameter) impacted the target at ~5.5 km/s with impact angles ranging from 40° to 65°. The downward direction of impact minimized interactions with the thin cylinder supporting the sphere (evident in imaging and in lack of surface damage to the sphere). The evolution of

Table 1
EOS and strength model parameters used in the CTH calculations.

Parameter	Pyrex[a]	PMMA[b]	Basalt	Dunite	Iron
Density (g/cc)	2.23	1.186	2.86	3.32	7.85
Sound speed (km/s)	2	2.3	5.17	6.59	4.99
Linear coefficient of the Us-up Hugoniot curve: S1	1.5	1.75	–	–	–
Quadratic coefficient of the Us-up Hugoniot curve: S2	0	−0.13	–	–	–
Gruneisen parameter: Γ	1	0.91	–	–	–
Cv (erg/g/eV)	1×10^{11}	3.5×10^{11}	–	1.35×10^{11}	5.16×10^{10}
Yield strength (MPa)	1000	120	1000	1000	1000
Yield strength at $P = 0$ (MPa)	2	–	2	2	
Poisson's ratio	0.26	0.37	0.26	0.26	0.28
Strain to failure	–	10%	–	–	–
Slope of the yield surface at $P = 0$: dy/dp	0.5	–	0.5	0.5	–
Melting temperature, T_m (eV)	0.25	0.25	0.25	0.25	0.16

[a] Marsh (1980).

[b] EOS parameters are library coefficients; strength parameters are based on a parameter study in Stickle and Schultz (2011).