ASTEROID SURFACES AS EXPRESSIONS OF SEISMIC INTERIORS. Erik Asphaug, Earth and Planetary Sciences Department, University of California, Santa Cruz, CA 95064, asphaug@pmc.ucsc.edu.

Summary: Asteroid surface morphologies are expressions of the acoustic properties of their interiors. That is an hypothesis which if proven true might allow us to one day know what an asteroid is all about just by looking at it. I explore the hypothesis and suggests how it might be tested by a small cratering experiment.

Background: Asteroid and comet interiors remain the subject of theoretical inference [1]. Bulk densities have been measured for a number of asteroids [2], and ~33x13x13 km asteroid 433 Eros appears to have a homogeneous mass distribution at km-scales [3]. That is about all we know beneath the optical (~μm) and thermal (~cm) skin depths. Densities of small asteroids are invariably lower than what is expected on the basis of the likely analog rocks. Ordinary chondrite meteorites are thought to come from the S asteroids, and carbonaceous chondrites from the C asteroids, but densities only agree if you allow for substantial porosity [2].

Mechanical Properties. How do porous asteroids behave, mechanically? Do they have landslides? How do their craters form? These are not trivial questions, for three reasons. One, we do not know the scale or structure of this porosity. It could be macroscopic fissures and voids, or it could be microscopic pores in a dust ball. Two, we do not very well understand the mechanical properties of granular media even under well-controlled laboratory conditions on Earth; there are as many new advances in this field as there are in asteroid science (e.g. [4]). Three, we especially do not understand the mechanical behaviors of granular materials when gravity is as low as a millionth that of Earth.

In a study of asteroid 243 Ida, it was argued [5] that an abundance of parallel surface fractures observed in one location resulted from a major cratering event in another, with acoustic stresses channeling and focusing through a somewhat competent interior. That work owed much to earlier work in this area by [6], who correlated the striking fracture patterns on the Martian satellite Phobos to its major impact crater Stickney, from which he could deduce an elastic Poisson ratio.

Crater erasure is probably a better seismic tool for small asteroids, since the stresses involved in an impact may be too weak to fracture rock, but might jumble the surface if it is loosely bound. (Or perhaps, paradoxically, it is the larger asteroids that are more intact, and the smaller asteroids that are preferentially rubble piles.) It is similarly argued [7] that seismic energy from the ~7 km diameter impact crater Shoemaker Regio preferentially erased craters in the terrains closest to it spatially, including on the back side. This requires mechanical coupling of some sort.

What emerges from these studies is a recognition that asteroid surfaces can give clues to their interiors. Perhaps structural properties of asteroids can be understood through simple flyby imaging.

Itokawa. Wherefore the paucity of craters on tiny Itokawa? Seismic shaking seems contradictory, considering that it appears to be a rubble pile [8]. Granular solids attenuate acoustic stress rapidly, so that an impact that would reset Itokawa's cratered surface would have to be relatively recent, and relatively large. As no large fresh craters are observed, it is problematic because this most recent resetting event must erase its own crater, or else be a very small cratering event.

Impacts on small bodies do not trigger global reverberations that last longer than the gravity regime crater formation timescale. On an asteroid this timescale can be more than an hour ($\sim 1/\sqrt{G\rho}$). Assume that Itokawa is a rubble pile, with acoustic velocity ~100 m/s, and a wave crossing timescale of several seconds. For a new impact crater to be erased by its own seismic energy, reverberations must persist to shake apart ejecta deposits after ~1000 wave crossings.

It is then logical to ask just how small of an impact can cause global vibrations that are sufficient to reset an asteroid's surface. If the answer is "very small", compared to the size of the asteroid, then asteroids that size are not expected to have large craters, since more frequent small impacts keep erasing them. It appears that large asteroids do not have their surfaces easily reset by seismic shaking – something as major as Shoemaker Regio is required to do this, and only partially, on Eros – and on a sample of 1, it may be that small asteroids are more easily reset. If the bombardment rate is known (not the crater production function, since that is the question being asked), and if the population of "smallest fresh craters" is known from a survey of asteroids, then one could perhaps derive the attenuation rate of shock and acoustic energy with distance from an impact, if seismic resurfacing is indeed the mechanism of landscape erasure on asteroids.

Asteroid as Geophone. Seismic experiments on asteroids have been proposed for some time, and most of these involve the development of surface packages containing accelerometers or geophones, plus an acoustic trigger (an impact or explosion, or a penetrator containing a thumper). But given the cost and complexity of surface packages, it is worth considering whether precarious surface features on an asteroid can serve as gratis geophones, responding to the reverberations by landscape evolution: toppling of boulders, shifting of rock fields, triggering of landslides and dust clouds. If an artificially induced seismic event on a small asteroid triggers global changes, then the asteroid is well-coupled mechanically; if only local (the crater and its ejecta) then it is poorly coupled. It is a basic and relatively easy measurement that casts light upon how a given asteroid responds to collisions – how it absorbs momentum, what size impact it can withstand before it shatters, how big a crater forms. The measurement also influences the science of asteroid hazard mitigation, since it allows for seismic modeling of an asteroid interior, and for the first directly scaleable cratering event observed in microgravity.

Attenuation of Stress in a Porous Asteroid. Consider a 500 m diameter small asteroid of density 2 g cm^{-3}, with surface escape velocity v_{esc}=50 cm/s. On such an asteroid, shaking the surface a mere 10 cm/s resets the landscape at a scale of at least 10 m. But powerful stress waves in geologic media attenuate rapidly, with peak particle velocity dropping as $\sim 1/r^{1.87+/-0.05}$ [9]; another report [10] finds a similar exponent for rocks and a steeper exponent (~2.2) for alluvium, corresponding to greater irreversible effects such as crushing and alteration.

One is tempted to infer that rubble piles are strongly attenuative, but this is not necessarily so. Intense short wavelength energy dissipates as mechanical heating and is also strongly scattered, until sharp pulses disperse to the scale of the medium's heterogeneity. There is at present no theory for the broadening and decay of a coherent wave in a granular material [12], but it seems possible that distal waves in a well-packed rubble pile could propagate almost elastically once they are broader than the rubble and weaker than the threshold of granular cohesion or friction.

Peak stress in an elastic stress wave is approximately $\sigma = \rho c u_p$, where u_p is the peak particle velocity. Now, a typical powdery soil has a cohesion of about 10^5 dyn/cm^2, and a sound speed c~100 m/s. Since we only need to wiggle a small asteroid a few cm/s to modify its landscape, stresses of only ~10-100 dyn/cm^2 need to be supported during compressive or surface or shear-wave loading. A powder-rich asteroid might behave elastically to these low stresses, allowing the asteroid to ring like a bell at very subtle velocities which may nevertheless trigger global geomorphic activity under ultra low gravity. When the compressive pulse reflects at the free surface it might act to shake loose (unload) and thereby mobilize material.

Shake Your Backside. Very low amplitude stress waves have not been measured for granular solids. The author is typing this sentence at about one cm/s, and net displacements needing measurement are also quite small. Assuming the attenuation exponent is 1.87, then the detonation of 10 kg of high explosive on the surface of an asteroid will cause 0.1 cm/s of antipodal motion on the same 500 m asteroid. This is only enough to cause ground motions of a few cm. In the elastic limit, $\langle v \rangle_{RMS}$ falls only as $\sim r^{-1}$. If $v \sim r^{-1.5}$, say, then the antipodal velocity is ~2 cm/s for the same scenario, enough to toss rocks a distance ~10 m. These are measurable differences, so it is a valid experiment to be performed at an asteroid.

There are finally some implications regarding artificial means of changing the momentum of an asteroid, because it is possible to shake more material off the back than off the front, causing it to move in the opposite direction as intended. If the exponent is 1.2, then the antipodal velocity is ~20 cm/s, almost equaling escape velocity. The same blast would cause the escape (and net momentum loss) of considerable material off the back side of a not-much-smaller asteroid, causing it to move in a direction opposite than intended, in the case of a hazard mitigation attempt.

[1] Asphaug, E. 2004. Interior structures for asteroids and cometary nuclei. In Belton et al. (eds.) Mitigation of hazardous comets and asteroids, Cambridge.

[2] Britt, D. et al. 2002. Asteroid density, porosity, and structure. In Bottke et al. (eds.), Asteroids III, Univ. Arizona Press.

[3] Yeomans, D. et al. 2000. Radio science results during the NEAR-Shoemaker spacecraft rendezvous with Eros. Science 289, 2085-2088.

[4] Asphaug, E. et al. 2001. Brazil nuts on Eros: size-sorting of asteroid regolith. LPSC XXXII, 1708.

[5] Asphaug, E. et al. 1996. Mechanical and geological effects of impact cratering on Ida. Icarus 120, 158-184.

[6] Fujiwara, A. 1991. Stickney-forming impact on Phobos – crater shape and induced stress distribution. Icarus 89, 384-391.

[7] Thomas, P. and Robinson, M. 2005. Seismic resurfacing by a single impact on the asteroid 433 Eros. Nature 7049, 366-369.

[8] Fujiwara, A., Kawaguchi, J. et al. 2006. The rubble-pile asteroid Itokawa as observed by Hayabusa. Science 312, 1330-1334.

[9] Perret, W. and Bass, R. 1975. Free-field ground motion induced by underground explosions. Sandia Report SAND74-0252.

[8] Rodionov, V. et al. 1971. Mechanical effect of an underground explosion. UCRL-Trans-10676.

[9] Somfai et al. 2005. Elastic wave propagation in confined granular systems. Physical Review E 72, 021301.