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A preliminary analysis of seismological techniques to study Eros and other asteroids

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Abstract

The NEAR Shoemaker mission to near-Earth asteroid 433 Eros provided a great deal of information about the asteroid. Still to be learned are the interior structure and material properties: the local density, strength, and cohesiveness within Eros. Seismology is a way to determine such information. This paper numerically explores performing a seismological experiment on Eros, using an explosive as a seismic source. Computations with the explosive source were performed in an Eulerian hydrocode (CTH) and then results of those computations were transferred to a Lagrangian wavecode (LS-DYNA) to calculate the subsequent seismic wave propagation in the body. To verify the technique, computations were first carried out for two cases where analytical results are known: a uniaxial-strain bar and a sphere. Computations were then performed for a three-dimensional solid model of Eros with surface shape based on NEAR data. Initial computations assumed Eros was isotropic and homogeneous in its material properties. Modal frequency computations for the isotropic, homogeneous Eros were then compared with a model of Eros that included an interior fracture plane. Differences in seismic traces and in modal frequencies show that seismology can differentiate the interior of Eros in particular and other asteroids in general.

Keywords: 433 Eros; Asteroid seismology; Normal mode analysis; Seismic sources; Explosive loading

1. Introduction

The NEAR Shoemaker mission to 433 Eros provided a great amount of detail on the asteroid (e.g., Veverka et al., 2000). However, still unknown is the interior structure. This state of affairs is true for all other asteroids studied to date: photographic information about the exterior exists, but no detailed interior information has been gathered. Several categories of interior structure for asteroids have been proposed (Fig. 1), and it is desirable to determine which applies to Eros as well as to other asteroids.

There are two known ways to look inside a body. One is to radiate the body with electromagnetic radiation of various wavelengths – from radio to gamma rays – and examine the resulting scattering and absorption. The other approach is to study the interior through the use of mechanical (or sound) waves that transmit through the body and, in a similar fashion, study the resulting scattering and decay. The mechanical wave approach is referred to as seismology, and has been applied to the Earth with considerable success for over 100 years. This paper will demonstrate that tools presently exist that can be used to make seismology a method of determining interior discriminating information for irregular bodies such as asteroids.

Seismology was successfully conducted on the Moon during the Apollo program (e.g., Kovach et al., 1971,

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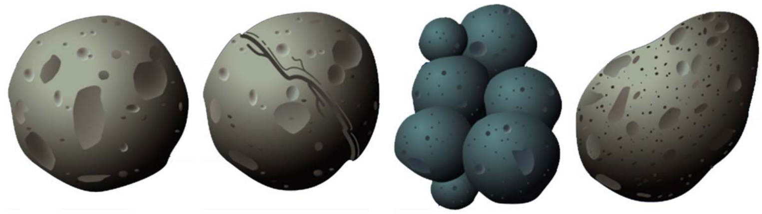

Fig. 1. Possible asteroid internal structures.

1972, 1973; Kovach and Watkins, 1973; Latham et al., 1973; Goins et al., 1981; Hood, 1986; Nakamura, 1983). Of particular relevance to the study performed in this paper is Apollo 17's active seismology experiment that involved the placement of explosives by the astronauts during their exploration of the site (Kovach et al., 1973; Kovach and Watkins, 1973). A small box was placed on the lunar surface and its location recorded. The box contained explosive and communications equipment to allow the explosive to be detonated from Earth. On three excursions the astronauts placed eight charges. An array of four geophones, with a maximal distance between geophones of 50 m, was placed on the lunar surface. Beginning the day after the astronauts' departure, over the next four days the explosives were detonated and the motion from the geophones recorded. Based on the results of these seismic experiments it was estimated that, directly under the Apollo 17 Taurus-Littrow landing site, the first 258 m of material has a sound speed 250 m/s. The next layer of material down has a sound speed of 1200 m/s. These three pieces of information (two sound speeds and one layer thickness) are based on the arrival time information: when the seismic wave arrived at the geophones after the charge detonation. After the Apollo 17 Lunar Module returned the astronauts to the Command Module for their return to Earth, the Lunar Module was impacted into the lunar surface at a distance of 8.7 km from the Apollo 17 landing site at a speed of 1.67 km/s. The ground motion from this impact was recorded on the geophones, and arrival times indicated there is an even deeper layer with roughly 4000 m/s wave speed. Layer boundaries appear to be sharp (rapid transitions in wave speeds). As to the surface regolith, experiments with hand-held thumpers on Apollos 14 and 16 landing sites determined the regolith layers there to have velocities of 104 and 116 m/s, with respective thicknesses of 8.5 and 12.2 m (Kovach et al., 1971, 1972).

The Apollo experience showed that information about the lunar surface could be obtained from seismological techniques. The best data came from well-characterized explosive charges and impacts, and most information relied on initial arrival times. The inferred wave speeds indicate the cohesiveness: the regolith has a very low sound speed, and is therefore not very cohesive, whereas the deeper rock has a higher sound speed and is likely to be cohesive. Determining whether asteroid or comet material is cohesive is important in both the science context of asteroid formation as well as the mitigation question in the event that one were found with an Earth intersecting course. Seismological experiments can determine material waves speeds and infer cohesiveness.

2. Computational approach

Earth seismological computations have been performed for many years. To determine the structure and material properties under the ground, essentially there are two types of computational geometries. In the first, a small volume of the Earth – on the order of kilometers – is studied and computations are performed to determine the local structure. These computations are used in oil exploration, for example. In the second, generally referred to as global seismology, the whole Earth is included in the computation to determine the structure of the Earth. In these global calculations, the Earth is assumed to be nearly spherical and comprised of spherical layers, an assumption that greatly reduces the computational size of the problem and computational resources required for its solution. In these calculations, rock is assumed to be nearly linearly elastic and, for small motions, it is elastic (elastic means that when the load is removed from the material, it returns to its original shape).

To study the interior of an asteroid, it is desirable to include the whole asteroid in the computational problem. In some cases, it is not only desirable but it is necessary to do so since, for small asteroids, reflections off the free surfaces affect motion at seismometers on very short time scales. To compute the global motion of the asteroid, the asteroid's irregular geometry requires a