# Active Seismology of Asteroids through Impact and/or Blast Loading

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**1. Overview and Motivation:** Though the NEAR and Hyabusa space missions to 433 Eros and 25143 Itokawa provided detail on the asteroid surfaces and on their gravitational distribution, still unknown is the interior structure. This state of affairs is true for all other asteroids studied to date: photographic or radar information about the exterior exists, but interior information has not been gathered (Huebner, et al., 2001, Greenberg and Huebner, 2002). Solar system formation and evolution theories have changed over the years, and in the last two or three years theory has leaned toward fragmented interiors for small bodies, but still no direct data is available. Hence, the determination of the interior structure is an extremely important scientific undertaking. In addition to understanding interior structure for scientific purposes, it is also important to know the interior structure in the event of a need to mitigate a potentially hazardous object. Scientific techniques developed answering the question of asteroid interiors could be applied to understanding the interior structure of the specific hazardous object.

**2. Scientific Questions and Seismology Technique:** Several categories of interior structure for asteroids have been proposed, and a spacecraft mission with a seismology experiment can determine which occur in nature. Specific questions that can be answered by performing seismology on asteroids are

1. What is the internal structure of the asteroid: monolithic, fractured, assemblages of fragmented rock held together only by self-gravity (“rubble piles”), highly porous, or “gravel piles”?
2. What are the material strength and/or cohesiveness of the surface regolith and interior materials of the asteroid?
3. Is the interior structure homogeneous or inhomogeneous? Isotropic or anisotropic?

4. Do these structures and strengths indicate origin of the asteroid from, say, a differentiated parent body or from dust and aggregate accumulation (i.e., from larger to smaller or from smaller to larger)?
5. If the terrestrial planets (such as Earth) were involved in large impacts, can surviving-fragment evidence be identified through inferring the asteroid's interior materials through its interior structure and strength?
6. Is there a correlation between interior structure and material strength and asteroid size and/or spectral type?
7. Is there a correlation between interior structure and material strength and asteroid size, rotation and rotation rate?

The latter two questions are aimed at the possibility of classifying objects so that we can infer interior structure based on external observations after having performed detailed studies on the interior of a handful of asteroids. In addition to the science questions above, the question of interior structure and strength is relevant to mitigation options for asteroids whose trajectory is found to intersect with Earth.

Seismology is the method by which the interior of bodies is studied through mechanical (sound) waves. Seismology has been an extremely important tool in answering questions about the Earth and its structure and interior composition. Without seismological information, there would be little known about the Earth composition and its history. Similarly, seismology will need to be an important tool in understanding asteroids, their structure, and composition. Specifically, seismology can identify material densities and sound speeds as well as infer cohesiveness; it can also identify interior boundaries and determine homogeneity of the interior material.

Through active seismology either through impact or explosive sources, it is also possible to infer the strength of material in the region of the source event by the amplitude of the transmitted seismic waves. Also, for small bodies, it may be possible to get them to "ring" with relatively small sources and then to subsequently study the decay of the normal modes. Examining the normal mode oscillations of the Earth has proven to be very fruitful in yielding information about internal structure. Asteroids, since they are of irregular shape, will not be able to rely on the techniques developed for Earth which assume near-spherical shape, but modern computing techniques have been shown to be capable of modeling normal mode behavior on an irregularly shaped body with various assumed interior structures (Walker, et al., 2003, 2004, 2006, Dahlen and Trump, 1998).

One of the difficulties with asteroid seismology is the seismometer attachment to the surface. However, topics such as this are being explored at various institutions. It should be possible to put a small to a large number (depending on their sophistication and battery life) of devices for measuring seismic disturbances on the surface of asteroids. Seismometer based devices can be extremely sensitive or possibly extremely light and compact, using MEMs technology for sensors. The technology is nearly ready for a mission that employs seismology on asteroids.

Various target asteroids (or comets) could be chosen for specific missions. In addition to questions of accessibility due to their orbits, other defining features of upcoming missions should be an attempt to perform interior investigation of a number of different spectral-type asteroids, as well as asteroids of differing size and rotation behavior. Such missions would begin to address the question of the bulk properties of different asteroids as well as whether it is possible to identify expected interior structures and compositions with outwardly observable remote sensing data.

**3. Successful Heritage: Apollo Seismology.** Seismology was successfully conducted on the Moon during the Apollo program (e.g., Kovach, Watkins, Landers, 1971, Kovach, Watkins, Talwani, 1972, 1973, Kovach and Watkins, 1973, Latham, Ewing, Press, et al., 1973, Goins, Dainty, Toksöz, 1981, Hood, 1986, Nakamura, 1983). Both passive seismology and active seismology were employed in lunar studies, passive meaning that the source of mechanical disturbance is nature while active meaning that the source of mechanical disturbance is man made. Of particular relevance is Apollo 17's active seismology experiment that involved the placement of explosives by the astronauts during their exploration of the site (Kovach, Watkins, Talwani, 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 meters of materials 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 m/s and 116 m/s, with respective thicknesses of 8.5 m and 12.2 m (Kovach, Watkins, Landers, 1971, Kovach, Watkins, Talwani, 1972).

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