Workshop summary on physical and chemical properties of potential Earth impactors

Abstract–From 2001 June 17 to 25, we held the first international workshop in Erice, Italy, dedicated to the determination of geological and geophysical properties of near-Earth objects (NEOs). The goal was to develop a roadmap for determining the physical and chemical properties of NEOs in the coming decades to meet the scientific requirements for development of Earth collision avoidance technology. We identified many properties that are desired, but four measurements are needed most critically for any potentially hazardous NEO: (1) its mass, (2) its mass distribution, (3) its material strengths, and (4) its internal structure. Global (whole-body) properties, such as material strengths and internal structure, can be determined best from the analyses of permeating waves: artificially initiated seismology and multifrequency reflection and transmission radio tomography. Seismology provides the best geophysical (material strengths) data of NEOs composed of consolidated materials while radio tomography provides the best geological data (*e.g.*, the state of fracture) of electrically nonconducting media. Thus, the two methods are complementary: seismology is most suitable for stony and metallic asteroids, while radio tomography is most appropriate for comet nuclei and carbonaceous asteroids. The three main conclusions are (1) remote sensing for physical characterization should be increased, (2) several dedicated NEO missions should be prepared for geophysical and geological investigations, and (3) that it is prudent to develop and prove the technology to make geophysical measurements on NEOs now.

INTRODUCTION

The first international workshop dedicated to the determination of geological and geophysical properties and physical characterization of near-Earth objects (NEOs) was held in Erice from 2001 June 17 to 25. The NEO impact hazard is a planetary emergency that deserves a major international collaborative effort. For this reason we call special attention to the support given by the European Space Agency (ESA), the Italian Ministry of University Scientific Research and Technology, the Italian Space Agency (ASI), the USA National Aeronautics and Space Administration (NASA), the Japan Institute of Space and Astronautical Science (ISAS), the Japan Society for the Promotion of Science (JSPS), and the Sicilian Regional Government. We also acknowledge the efforts made by participants who came from China, Germany, Italy, Japan, The Netherlands, Poland, and USA.

Presentations covered the areas of NEO research in Earth collision avoidance and mitigation, properties of asteroid surfaces and internal structure, geophysical properties, space missions to determine physical properties, laboratory and computer simulation experiments to determine physical and chemical properties of NEO materials, and links between comets, asteroids, meteorites, and dust.

We know little about the geophysical properties of NEOs. We are still far from developing a credible defense system against collisions with Earth. Before we can develop realistic collision avoidance strategies, we must investigate the properties of NEOs to assess their response to the appropriate application of forces. Currently, theoretical and laboratory activities are insufficient to provide plausible orbital deflection techniques. Some properties can be determined through remote sensing from visible and infrared facilities, but *in situ* exploration will be essential for determining the internal properties.

Craters on the planets and their moons are the evidence of asteroid and comet impacts throughout the history of the planetary system. The evidence from the craters on the Moon and on Mars is overwhelming. The Earth has also suffered such collisions even in very recent times. On 1908 June 30 a small celestial object, probably <100 m in size, exploded in the atmosphere over Tunguska, Siberia, north-northwest of the town of Vanavara (~101° E, 62° N). Although the object was too small to form a crater, it flattened the trees radially outward from the center below the explosion over an area of ~2000 km^2. More recently, in July 1994 astronomers witnessed telescopically the collisions of 21 fragments of comet Shoemaker–Levy 9 with Jupiter. The comet had been torn apart by the gravitational forces of Jupiter in a prior orbit around the planet. Many of these collision fragments left "black eyes" on Jupiter, each larger than the Earth. Collisions of asteroids and comets with Earth have occurred in the past. They will again occur in the future. Several reports and books (Morrison, 1992; Rather *et al.*, 1992; Canavan *et al.*, 1993; Gehrels, 1994; The Chelyabinsk-70 Workshop, 1994; The Planetary Defense Workshop, 1995) document the probability of such collisions. We will not dwell further on these issues.

For the first time in human history, we may consider a defense against collisions of NEOs with Earth. Finding NEOs has become an important task for modern planetary astronomy. Space agencies of several countries and the International Astronomical Union (IAU) have recognized the importance of detecting NEOs, following them up to determine their orbital parameters, and cataloging them (see, for example, the web site of the IAU Minor Planet Center at http://cfa-www.harvard.edu/cfa/ps/mpc.html). As important as these objectives are, they are only a first step in the preparations to avoid NEO collisions with Earth. To mitigate an Earth collision, we must know how and where to apply the required forces on an NEO without splitting it. Splitting an incoming object may not significantly reduce the damage of a collision and may actually increase it. To avoid wasting costly energy by spinning the object, we must direct forces through its center of mass (Huebner, 1999). We must decide whether to use gradual, long-term applications of small forces or sudden but large impulsive forces. The material properties of the object and its internal structure (*e.g.*, the state of fracture) play an important role in such decisions. Thus, determinations of geophysical properties and geological structures as well as physical characterization of NEOs are very important (Huebner and Greenberg, 2000). This was the first workshop in which these topics relevant to "know your enemy" were of prime consideration.

PRIMARY GOALS

The primary goals of the workshop were to determine which geophysical properties of asteroids and comet nuclei we need to better understand in order to implement NEO collision mitigation. We have developed a roadmap for determining the geological and geophysical properties. Specifically, we have outlined methods to determine these properties and relate them in a database to other observational, laboratory, and theoretical data and to procedures, instrumentation, and mission requirements for data acquisition. We also must expand methods for characterization and search and develop dedicated space missions and instrumentation.

We assessed the status of the NEO program by the following four categories:

In progress:	Finding NEOs, follow them up with observations to determine their orbits, and catalog their orbits.
Falling behind:	Physical characterization, which includes remote sensing to determine the sizes of objects and their albedo independently. The rate of characterization by remote sensing is not keeping pace with the rapid increase in the rate of new NEO discoveries (Tedesco *et al.*, 2000).
Discussed here:	Determination of geological and geophysical properties such as mass and mass distribution, moments of inertia, material strengths, internal structure, and relationship of global properties to surface properties. Determination of the geological and geophysical properties also relates to the secondary goals discussed below.
Final goal:	Develop techniques for Earth-collision mitigation based on geological and geophysical properties. This was left for future discussions.

SECONDARY GOALS

Closely related to the determination of geophysical properties and geological structure are the formation and evolution of small bodies in the solar system: origins of asteroids, comet nuclei, and transition objects between comet nuclei and asteroids, collision and orbital history of these objects, their relationship to meteorites, *etc.* were all topics of the workshop. Since asteroids and comet nuclei are the building blocks of planets, they are the most representative samples of the entire pre-accretionary solar system. They contain far more directly accessible information about the early solar system then any other planetary body. Thus, the science of formation and evolution of the planetary system played an important part in the workshop.

However, not only science benefits from the approach to address the collision mitigation problems so do resources exploitation of asteroids and comet nuclei in near-Earth space. Anchoring a spacecraft on an object that has unknown surface conditions and very low gravity is a prime concern to several spacecraft missions under development. Resource extractions (*e.g.*, metals and building materials from asteroids and water from comet nuclei) are closely related topics.

A ROADMAP TO DETERMINE GEOPHYSICAL PROPERTIES AND GEOLOGICAL STRUCTURES OF NEAR-EARTH OBJECTS

We developed a roadmap for acquisition of geological and geophysical data and for physical characterization. It consists of four parts: the creation of a database, experimental and theoretical simulations, small bodies missions and instrumentation, and physical characterization by remote sensing. We discuss these four parts of the roadmap below.

The Near-Earth Object Database

The NEO database consists of four parts: an observational database, a material properties database, database for missions and instrument development, and a database useful for dissemination of projects and results and for public outreach.

Observational Data–The observational database should contain detailed data for a representative sample of ~30 asteroids and some comets. This number represents approximately the 1σ level of the estimated 1000 NEOs larger than 1 km in diameter. However, it falls far short of the 1σ level of the estimated 25 000 NEOs larger than 200 m that could cause considerable regional damage. Exempting active, dormant, and extinct comets, Main Belt asteroids are considered as typically representative of near-Earth asteroids. Ground-based observations will be the main source of spectra, light curves, and related properties. On the other hand, space-based observations and measurements will be the main source for determining dimensions, shapes, craters, masses, densities, spin states, *etc.* The observational database should gather, connect, and supplement data from various existing databases.

Most of the observational data of importance to NEO collision mitigation can be acquired either by remote sensing from the ground or from spacecraft flybys. For example, some indication of the shape, such as the ratios of the axes, can be obtained from ground-based observations. Radar can determine the shape in much more detail including surface roughness, but the object must come close to Earth. Satellite-based sensors with infrared and visual focal plane arrays could be used not only to detect asteroids with orbits largely interior to the Earth's orbit, but would obtain albedos and effective diameters of most Earth-crossing asteroids (Tedesco *et al.*, 2000). Mass determination requires at a minimum a close and slow spacecraft flyby, but better a rendezvous. The mass of an object is determined from its gravitational interaction with the spacecraft, causing a departure from its trajectory that is measured by ground-based Doppler and range tracking of the spacecraft. In addition, optical navigation images of the NEO against a star background improve the relative position of the spacecraft with respect to the NEO. The inherent difficulty of a mass determination is evident by the measurements made by the *NEAR–Shoemaker* spacecraft at Eros. The gravitational interaction of Eros resulted in a deflection angle of the spacecraft trajectory by 0.06 arcsec and a change in the heliocentric velocity of ~0.15 mm/s (Yeomans *at al.*, 1999). The density is obtained from independent measurements of mass and volume. The volume is derived from the shape of the NEO as determined from laser ranging. Determinations of mass and density become even more difficult for objects smaller than asteroid 433 Eros. Completed, ongoing, and planned missions to asteroids and comets will fill many of the gaps in our knowledge. Such missions include Galileo, Cassini, NEAR–Shoemaker, DS-1, Stardust, CONTOUR, Deep Impact, Muses-C, and Rosetta.

Material Properties Database–We consider two extreme approaches for nudging an object out of its orbit. One extreme is to apply a relatively small force for a long time. This method is preferred and can be implemented if a warning of a potential collision is determined decades in advance. It has the advantage that the incoming object is less likely to fragment under the influence of the collision avoidance measures. Fragmentation could cause a series of smaller, but still catastrophic, collisions with Earth over very wide or possibly global regions.

The other approach is to use a large force for a very short time. The impulse transmitted to the object is the same in both cases. However, the reaction of the object may differ significantly. When a sudden (*e.g.*, explosive) force is applied to an object, a shock wave may be transmitted through the object. This shock wave causes material to spall off on the far side of the object. The spalled material carries momentum with it, therefore reducing the effectiveness of the applied impulse.

Static Data–By static data, we mean data important for applying a gentle push during collision mitigation. In terms of impulse transmitted to an NEO, this means a small force acting over a long time. Static data include mass and its distribution in the object, data for porous ice–dust mixtures including density, porosity, and pore radii, the complex electric permittivity, thermal conductivity, heat capacity, enthalpy, and sound speed.

Dynamic Data–By dynamic data, we mean data relevant to impulsive transmission of an impulse during collision mitigation. This implies a large force acting over a short time, an explosion. Among dynamic properties are the momentum coupling coefficients, strain rates such as Young's modulus, the Poisson ratio, yield flow or fracture stress in compression and in tension, Hugoniots, the Grüneisen parameter, and energy and momentum dissipation rates.

Missions and Instrument Development–We will need several fully instrumented rendezvous missions to gather the internal properties and structures of NEOs. Such mission also may define additional types of measurements that will be needed and explore different techniques for their effectiveness, limitations, spatial resolution, and dynamic ranges to determine and characterize whole-body properties of a variety of NEOs. Lander technology will have to be developed as part of the fully instrumented missions but also as goals for missions of opportunity. After these basic determinations have been made, micro-spacecraft missions may follow to explore detailed and specific properties. In a final phase of NEO exploration, we may investigate flyby measurement techniques using instrumented penetrators and swarms of minipenetrators.

We consider two categories of instrument development: (1) *in situ* surface and remote-sensing instruments and (2) instruments for determining bulk properties. Remote-sensing instruments have been widely used and are well developed. Spectroscopic and thermal infrared measurements for determining emission properties fall into this category. The *in situ* surface instrumentation, such as multi-axial accelerometers, sample coring, and penetrators to determine composition and geology will need further development. Penetrators and landers that can work in swarms on and just below asteroid and comet nucleus surfaces may need to be developed.

In the second category are instruments for determining bulk properties. This group encompasses the most important aspects for primary and secondary goals of geophysical and geological exploration of NEO properties. While drilling and digging on an NEO can provide detail about the composition and structure of an NEO, it does so only locally, at one spot and to a very limited depth of typically one to a few meters. Analysis of waves that penetrate an NEO to a depth of several hundred meters or are transmitted through the entire object give whole-body or global information. Among such waves are electromagnetic (radio) waves and sound (seismic) waves. While general background radiation can be useful, it is easier to analyze artificially induced waves and pulses. Radio tomography and seismology are complementary methods to achieve the goals of geological and geophysical exploration of asteroids and comet nuclei. Electromagnetic radiation is limited to nonconducting materials. Typically, these objects are fluffy and porous such as comet nuclei that are composed of ice and dust and carbonaceous asteroids. Sound waves rapidly dissipate in these objects. On the other hand, sound waves propagate well in dense objects such as stony and metallic asteroids.

To determine sound speeds of three-dimensional compression or shear waves or two-dimensional surface (Rayleigh) waves, timing is important. Timing of waves is easiest for artificially induced waves. Sound speed relates directly to material strength parameters. In addition, the wave shape is useful in the analysis of material properties (see, for example, Huebner *et al*., 2001).

Radio tomography does not provide as much information about material properties as it does about the structure of an object. The analysis is difficult. Depending on the electric permittivity, materials refract, reflect (scatter), and absorb radio waves. Reflections occur at interfaces between materials. They also reveal fractures and other discontinuities in materials. Thus, radio tomography is very useful in revealing the internal structure of an object. This is very important for distinguishing, for example, monolithic objects from rubble pile objects. Tomographic techniques convert measured radio echoes into three-dimensional images of the interior of an NEO. The procedure is similar to ultrasonic imaging in medicine. We distinguish between transmission and reflection tomography. For transmission tomography, a transmitter as well as a separate receiver is needed. For example, the transmitter can be on a rendezvous spacecraft orbiting an NEO while a receiver is on its surface. Reflection tomography on the other hand, can have the transmitter and the receiver on the orbiting spacecraft. It has the added advantage that the timing from the reflected signal reveals the location of a discontinuity on the object. Multifrequency radio tomography permits penetration of the radio signals to different depths. The most powerful radio tomography is a combination of multifrequency transmission and reflection tomography. The complex permittivity of materials determines the speed of the radio signal propagation and its dissipation in the material.

We encourage complete data analysis of past and present missions to exploit all information that may be useful for NEO collision mitigation. We also encourage development of new missions to small solar system bodies. In particular, to accomplish good data analysis we need missions using multi-axial accelerometers, sample coring, and penetrators to determine thermal properties (heat of fusion, heat of vaporization, heat conduction, heat capacity, *etc*.). Analyses of patterns and transmission speeds of waves that penetrate the entire body provide the best whole-body properties. Transmission radio tomography (*i.e.*, the determination of the complex electric permittivity) will work best on comet nuclei and carbonaceous asteroids. Reflection radio tomography can reveal reflecting surfaces (*e.g.*, fractures) within a stony body. Seismology is best suited for consolidated (as opposed to highly fragmented or porous) objects. For example nickel-iron objects absorb radio waves while easily transmitting seismic (sound) waves.

We must develop probes to measure electric conductivity locally. Measurements of spectroscopic and thermal emission properties such as the intensity as a function of wavelength, particle sizes, particle density, particle temperature, *etc*. are important. Gamma, alpha, neutron, and x-ray probes are useful to measure the composition and structure of objects.

Dissemination and Public Outreach–The origin and evolution of the planetary system and resources exploitation in near-Earth space are topics of great interest. They are directly related to the geological and geophysical properties of asteroids, comets, and comet nuclei. Asteroids and comet nuclei are the building blocks of the planets.

It is also important to inform the public about potential methods of NEO collision mitigation. The first steps in this direction have been taken by establishing the Torino NEO impact hazard scale (Binzel, 2000). However, even broader procedures should be established to inform relevant government agencies and the public in general about impact hazards. An integrated approach of scientific, technologic, and public policy aspects is appropriate. This could be done in semipopular but instructive presentations. Possible projects for public outreach on impact hazards, properties of NEOs, and collision avoidance measures include public forums, high school projects, semipopular articles and forums, museum exhibits, and multimedia websites.

Experimental and Theoretical Simulations

Theoretical Models–Development of thermal models is important for the analysis of asteroid data in the mid infrared. Interpretation of comet nucleus data depends on coupled thermal and gas diffusion models. While temperature profiles determine sound speeds, gas diffusion reveals information on porosity.

Models to investigate the source regions of NEOs will aid in understanding the evolution of the planetary system. These models will answer the question: what are the parent bodies of near-Earth asteroids and how steady is their population? The collision history of asteroids will clarify their injection rates into NEO orbits. The dynamical mechanisms deserve further investigations.

Computer Simulations–Very important are simulations of artificially activated seismic events. What is the best placement of a seismic activator on an asteroid? Since asteroids have no atmosphere and negligible gravity, how does one achieve consistently good coupling of the activator to the body with a minimum of mass and expenditure? What signals do we expect for various objects? What is the best placement of seismometers relative to activators?

Similar questions arise for radio tomography. How complex is the analysis of refracted, multiply reflected, scattered, and attenuated radiation? Simulations of transmission and reflection tomographic experiments will be most useful to answer these questions.

Numerical integration of orbits of observed NEOs is important to understand their history and predict future encounters. Closely related to this are models for asteroid–asteroid collisions. In the case of comets, a further complication arises from the non-gravitational forces (the recoil from the outgassing) on the motion of their nuclei.

Laboratory Simulations–Laboratory simulations are useful to investigate artificially activated seismic experiments. Proportional scaling of objects and wavelengths makes it easy to simulate radio tomography in the laboratory. These types of experiments, when performed in conjunction with theoretical simulations, will be useful tools for mission planning and for analysis of mission data.

Landing and anchoring experiments are a challenge for bodies with little gravity to hold down an instrument package. We have learned much from the successful landing (actually a controlled crash at a very low speed of a few meter per second) of the *NEAR–Shoemaker* spacecraft on Eros, even though it was not part of the mission plan. Landing and anchoring is part of the Rosetta mission to comet Wirtanen. Penetrator technology will play an important role in future missions to NEOs. This technology is in its infancy of development. We must be innovative and expand these techniques to develop experiments with swarms of minipenetrators that can make measurements from flyby missions. Impacting at speeds of ~2 km/s, the minipenetrators will self-destruct. However, if properly instrumented, the rate of self-destruction can be measured to yield valuable local data of material strengths.

Missions to Small Solar System Bodies

Whole-body (global) data acquisition depends primarily on analyses of wave speeds and wave shapes. Artificially initiated seismology, using impacts and explosives, is most useful for measuring the sound speeds for compression, shear, and surface waves. Multifrequency transmission, reflection, and combined transmission and reflection radio tomography are exciting new techniques under development. For example, radio tomography will be used for the Rosetta mission to comet 46P/Wirtanen.

While global (whole-body) data acquisition is preferred, some locally obtained data is also desirable. Local data will usually be limited to a depth of one to a few meters. Drilling and digging is the most likely process of obtaining local data. The Rosetta mission to 46P/Wirtanen will acquire local properties from a lander on the comet nucleus and Muses-C will acquire some local surface properties during its sample return at asteroid 25143 (1998 SF36).

Some critically needed data from NEOs include the object's mass and mass distribution, the spin axis orientation and the spin rate, the moments of inertia of the body, material strengths, the state of fracture of the body, and its composition and porosity.

Comprehensive data analyses of past missions should be carried out in an effort to identify properties most important to successful mitigation. We also endorse new missions to small solar system bodies and their comprehensive data analyses. We must develop models and instrumentation for geophysical experiments.

Physical Characterization

Ground-based physical characterization does not keep pace with the discovery rate of NEOs (Tedesco *et al.*, 2000). The reason for this is the rapidly increasing rate of discovery of NEOs, while the rate of physically characterizing them stays about constant. An increase of remote-sensing characterization is most desirable. A most crucial datum needed for assessing the NEO collision hazard is the mass of each object. We do not know the masses or even the sizes of most NEOs. While mass cannot be determined by ground-based physical characterization, determining the size of an object is a first indication of its mass. What is usually measured is the brightness of the object, which is a combination of its cross section and its albedo. Simultaneous visual and infrared observations permit separate determination of these two quantities.

Ground-based characterization deserves to receive the highest priority after discovery and orbit determination. This requires (1) access to a system that can acquire simultaneously thermal infrared and visible measurements of the largest possible fraction of the NEO population on short notice, and (2) observations of a sample of NEOs over large wavelength and phase angle ranges and with sufficient resolution to resolve spin variations and to provide input for detailed thermophysical modeling.

The detailed requirements should include (1) a primary physical characterization of the general population in order to:

- Obtain a statistically significant database of fundamental NEO properties, namely effective diameter and albedo.
- Measure a number of objects of each taxonomic type.
- Develop a more accurate assessment of the hazard posed by objects in different size and mass ranges.
- Assess selection effects in survey discovery statistics.

(2) Detailed observations of a sample of NEOs over a range of:

- NEO sizes, rotation states, taxonomic types.
- Phase angle (> 90° highly desired).
- Wavelengths, taken simultaneously in the optical, the thermal- to far-infrared, and the submillimeter to radio regions of the spectrum.
- Time to determine light curve amplitudes and shapes.

Observational basis for thermophysical models of representative NEOs requires new observing strategies for which routine rapid access to ground-based or space-based observing facilities for NEO characterization is essential. In addition, consideration should be given to a space-based NEO observing program. It has a number of technical advantages: (1) the detection efficiency is better than ground-based facilities can offer, (2) it has a high duty cycle, (3) observations near the Sun are possible, and (4) it permits mid- and far-infrared observations.

SUMMARY

We have identified many types of data for which measurements from NEOs are needed, but the four most important quantities to be measured from space missions are: the mass, the mass distribution, the material strengths, and the internal structure. Velocities relative to Earth can be determined quite accurately, but we need to know the mass to determine the energy of impact as well as the energy and momentum needed to deflect the object from its collision orbit. We need to know the mass distribution to determine the center of mass of the object. The direction of the applied force should go through the center of mass of the NEO to ensure effective application of the energy and momentum transfer into translational motion and not into spinning the object. Material strengths and material structure determine the response of the object to the applied forces. Global material strengths and structure are best determined from artificially activated seismology experiments and from multifrequency radio tomography. Other important properties of NEOs include the shape and the spin state. These can usually be measured by more conventional means, such as radar and light curves.

CONCLUSIONS

Mass, not size is the important quantity determining the destructive energy of an impactor and the energy needed to deflect it. However, the size together with taxonomic classification is an important indicator of mass. *We must increase remote sensing for physical characterization to determine the sizes of NEOs.*

Digging and drilling give local information only. Global geophysical properties (material strengths and internal structure) can be determined from wave analyses. Seismology for consolidated matter complements radio tomography for loose, nonconducting matter. *We need several dedicated NEO missions for geological and geophysical measurements using seismology and radio tomography.*

It is prudent to *develop the technology to make geological and geophysical measurements now.* We will have to prove the technology and learn how to apply it efficiently. Instrument and mission developments take time.

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