Available online at www.sciencedirect.com
SCIENCE DIRECT®

C. R. Physique 6 (2005) 321–326

COMPTES RENDUS
PHYSIQUE

http://france.elsevier.com/direct/COMREN/

The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs : impacteurs potentiels de la Terre

Internal structure of Near-Earth Objects

Richard P. Binzel [a], Wlodek Kofman [b,*]

[a] *Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b] *Laboratoire de planétologie de Grenoble, BP 53, 38041 Grenoble cedex, France*

Available online 19 February 2005

Presented by Pierre Encrenaz

Abstract

For the purposes of mitigation, the internal structure of near-Earth objects (NEOs) remains one of the most important but least understood parameters. From a science point of view, the internal structure is equally intriguing. Knowledge of the internal structure can reveal the collisional history, and in the case of comets, may also reveal the accretional history. Here we briefly review some of our current understanding of asteroid interiors and focus on the application of radar and radiowave tomography techniques that may be applied to study NEO interiors. ***To cite this article: R.P. Binzel, W. Kofman, C. R. Physique 6 (2005).***
© 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.

Résumé

Pour pouvoir envisager une protection contre les impacts des géocroiseurs (NEO) l'un des paramètres les plus importants est leur structure interne mais celle-ci reste aujourd'hui mal compris. D'un point de vue scientifique, leur structure interne est intrigante. Sa connaissance nous permettra d'appréhender les processus collisionnels et dans le cas des comètes, nous révéler les mécanismes d'accrétion. Dans cet article, nous passons brièvement en revue nos connaissances actuelles concernant les structures internes d'astéroïdes et nous nous concentrons sur l'utilisation des radars et des techniques tomographiques pour les étudier. ***Pour citer cet article : R.P. Binzel, W. Kofman, C. R. Physique 6 (2005).***
© 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.

Keywords: Near-Earth object; Asteroid interior

Mots-clés : Géocroiseur ; Structure interne d'astéroïdes

1. Introduction

While spacecraft rendezvous and flyby missions have greatly increased our knowledge of asteroid and comet nucleus surface characteristics (e.g. Sullivan et al. [1]), our understanding of their interior properties remains minimal. For most objects, the internal structure may be a complicated result of accretional structure, gravitational accumulation, and rock (or ice) mechanics. Currently, the internal structure of small bodies is best described using terminology proposed by Richardson et al. [2] and further elaborated on by Binzel et al. [3].

---

* Corresponding author.
E-mail address: wlodek.kofman@obs.ujf-grenoble.fr (W. Kofman).

1631-0705/$ – see front matter © 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.
doi:10.1016/j.crhy.2005.01.001

We use the word *monolith* to describe an essentially wholly intact unit having a strength that is effectively equal to its tensile strength, i.e. the maximum force per unit area that a body can withstand before fracture or rupture occurs. An *aggregate* is a body having less coherence than a monolith, being comprised by many different structural units with distinct boundaries or interfaces between the units. If the interfaces are the result of the body's primordial formation, rather than by collisional fracturing, we use the term *primitive aggregate.* For the case where the boundaries are sufficient to reduce the tensile strength, we describe the body as being *fractured*. We note that for a fractured body, its original shape remains mostly unaltered – it is primarily the internal structure that has begun to make a substantial transition from being a monolith or an aggregate. As fractures increase, the object becomes a *shattered body*, where the interior structure is even more dominated by an abundance of joints and cracks. In this case, the relative tensile strength (defined as the effective tensile strength divided by the tensile of its constituent material) may approach zero. Again the overall shape of the body may remain nearly unchanged in this case. Changes in overall outward shape and appearance may become apparent for a body that is *shattered with rotated components* whose interior has been thoroughly fractured (by collisions or tidal stresses) such that original interior units have been displaced and reoriented. An object is described as a *rubble pile* when its interior has been completely shattered and reassembled, such that the new structure is likely to be completely disorganized relative to its original state. If the units gain some cohesion after reassembly, the body may be referred to as a *coherent rubble pile* or a *coherent aggregate*. A volatile-rich body may gain cohesion through an increase in temperature and become a *thermally modified primitive aggregate*, or in the case of strong cohesion become a *lithified primitive aggregate*.

At present, our ability to describe these possible states far exceeds our ability to measure them – yet this provides the challenge for our future exploration. In this article, we briefly review our current state of knowledge for asteroid and comet interiors, including our limited understanding for near-Earth objects (NEOs). We highlight the application of radar and radiowave tomography techniques which may be the first to be applied for the in situ study of NEOs.

2. Current views

Although our current view of asteroid and comet interiors is limited, some basic and in some cases confusing information is starting to emerge. Most basic is a calculation of an object's bulk porosity, requiring both a mass and volume determination. While mass determinations have classically relied on mutual perturbations between the largest asteroids, the discovery of satellites among main-belt asteroids (Merline et al. [4,5]) and near-Earth objects (Margot et al. [6]) has substantially increased the available results. The astrometric capabilities of the GAIA mission are expected to further provide ∼100 mass estimates for main-belt asteroids.

Insights into the interior are obtained through a comparison between the bulk porosity and the 'grain density', i.e. the average density of the constituent material at a scale of a few cm or smaller. Grain densities are obtained through laboratory measurements of meteorites (Consolmagno and Britt [7,8]), which also provide estimates for the 'microporosity' arising from fractures, pores, and voids on the scale of millimeters to a few microns. Key to application of the grain densities in comparison with bulk densities is the assumption of a particular correlation between a laboratory meteorite material and the asteroid being studied. As these correlations remain 'best estimates' for the present time, we must consider carefully what uncertainties are introduced by these assumptions. Yet even with these uncertainties, distinct groupings in bulk porosities are beginning to emerge. Britt et al. [9] find three basic groupings based on large scale voids or 'macroporosity'. Objects having effectively zero macroporosity include the three largest asteroids Ceres, Vesta, and Pallas. Their sizes, (about 1000 km for Ceres and about 500 km for Vesta and Pallas) provide sufficient self-gravity to minimize macroporosity. Asteroids in the 30–300 km size range may typically have macroporosities ranging from 15–25%. The only asteroid to be orbited to date, Eros (∼30 km in size), has a macroporosity of ∼20% (Wilkison et al. [10]). Results from the Near-Earth Asteroid Rendezvous mission (NEAR) give the inference that Eros is a heavily fractured or shattered body, but has not undergone a history of being disrupted and reaccumulated as a rubble pile. NEAR data suggest that the interior of Eros is highly homogeneous, with an offset of only 30–50 m between the center of mass from the gravity and shape models (Miller et al. [11]; Zuber et al. [12]; Thomas et al. [13]). Even with a heavily fractured interior, structural features (ridges, grooves, etc.) visible on the surface demonstrate that still Eros retains some significant degree of tensile strength (Prockter et al. [14]). The third group of objects, mostly falling in the size range of 50 to 250 km may have macroporosities in excess of 30%. Objects in this size range may be the best candidates for 'rubble piles', i.e. these may be objects that have been substantially disrupted and reaccreted with a very different internal structure from how they originated. A very bizarre case is 16 Pysche having an M-type reflectance spectrum and a strong radar reflectivity that implies a very dense (metallic) composition. Using an iron meteorite grain density and current mass estimates result in an inferred porosity of >70% for Psyche. Such a seemingly unphysical result clearly points to our limited current understanding. More understandable is 253 Mathilde (50 km diameter) which is inferred to have a carbonaceous chondrite-like composition and a macroporosity near 40%.

Our understanding of internal structure down to the smallest sizes represented by the majority of NEOs remains limited, but inferences may be drawn from their rotational properties. Asteroid lightcurve studies (e.g. Pravec and Harris [15]) reveal a transition near 100 m. Objects larger than 100 m typically rotate with periods of ∼2 hours or longer, suggesting they are structurally weak – any faster rotation rate would place their interiors in tension and they would fly apart. Thus self-gravity may be the most important factor in binding objects together all the way from stellar masses to ∼100 m asteroids. Below ∼100 m, most NEOs are found to rotate faster than 2 hours, requiring tensile strength binding their internal structure. Thus it appears that ∼ 100 m may represent the transition size between ‘intact’ monoliths and fractured/shattered bodies held together by gravity.

3. Radar techniques

Ultimately, the improvement in our understanding of the interiors for small bodies will require direct measurement techniques. While orbiting spacecraft can give a global view of the average interior characteristics, direct measurements through techniques such as ground penetrating radars (GPR) can define much more localized subsurface properties. Up to now radars on the space missions (Earth Observation Program, Marsis on Mars Express, Cassini radar) work essentially in the altimeter and SAR mode. Applications of these techniques to perform tomography is the next major step. Here we highlight the principles for applying this technique for small bodies such as NEOs.

An electromagnetic signal propagating within the interior of a small body is attenuated due to the object’s complex dielectric and magnetic properties. The properties of materials will depend in general on the composition, and for the case of ice, on the temperature, the nature and concentration of impurities. The complex dielectric constant and the complex permeability are determining factors for the wave propagation. The attenuation, which is a major parameter for radar use depends on the loss tangents within the material medium:

$$\operatorname{tg}\delta_d = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega_o \varepsilon}, \quad \operatorname{tg}\delta_m = \frac{\mu''}{\mu'}, \tag{1}$$

where ε', ε'', μ', μ'' are real and imaginary parts of dielectric constant and magnetic permeability, σ is the conductivity. The attenuation factor is given by:

$$\alpha = k \cdot \frac{c}{c_{\mathrm{med}}} \sqrt{\frac{1 - \operatorname{tg}\delta_d \cdot \operatorname{tg}\delta_m}{2} \left[\left(1 + \operatorname{tg}^2(\delta_d + \delta_m)\right)^{1/2} - 1 \right]}, \quad k = \frac{2\pi}{\lambda}, \tag{2}$$

where c the velocity and λ wavelength in free space. For a non-magnetic medium with very low losses $\operatorname{tg}\delta_d \ll 1$, which is probably the case for asteroids and comets, one has:

$$\alpha = \frac{\pi}{\lambda} \cdot \frac{c \cdot \operatorname{tg}\delta_d}{c_{\mathrm{med}}}. \tag{3}$$

From Eq. (3), one sees that the attenuation coefficient is directly proportional to the frequency. Another way to see these results is that the losses are directly proportional to the conductivity of the medium. This formula can be used to evaluate the penetration depth in the cometary and asteroid materials. Other processes (scattering, multi-path propagation, reflection…) also contribute to the wave attenuation. As we want to use the radar to study interiors using the reflection (diffraction) of signals on the discontinuities, the reflection and transmission coefficients are also factors determining how much of the incoming signal amplitude is reflected and transmitted. These quantities allow the estimation of the power of the incoming radar signal and therefore the radar capabilities.

For materials covering the likely composition of asteroids by taking into account the porosity of the materials, as described above, using the Rayleigh mixing formula (Shivola and Kong [16]), it is possible to calculate the dielectric constant and the attenuation. For porous granite, the attenuation is about 8 to 20 dB/km, while for basalt, it is 10 to 30 dB/km. If the absorption is of the order of 10 to 30 dB/km, the radar will be able to investigate objects that are few kilometers in size or penetrate this depth. However, if the absorption reaches 60 dB/km or more, the penetration will be limited to tens or hundreds of meters, at best. These values are valid for a radar operating at a low frequency (e.g. 10 MHz). For a radar operating at 450 MHz, the losses are much higher and can be in the order of 2000 to 3000 dB/km for granite, for example. It is clear that even for very porous materials, this radar will be unable to operate. Only a mapping of the surface or of a few meters of the sub-surface will then be possible. For cometary materials, the penetration will be much better due to the lower loss tangent. Kofman et al. [17] estimated the loss to be of order 1 to 20 dB/km at 100 MHz. For icy satellites of the giant planets the penetration was evaluated in the feasibility study of Europa Radar Sounder (Blankenship et al. [18]) and the frequency of 50 MHz was fixed for the radar.

The scattering of radio waves by the surface and by internal irregularities is also an important factor which one has take into account to evaluate the useful signal from the interior to surface echoes ratio. This ratio determines the signal detectability. These parameters are essential to the radar performances. The scattering depends strongly on wavelength and roughness surface parameters ratios which of course depends on the studied body. The frequency dependence of attenuation makes the choice of low-frequency radars (5–50 MHz) strongly recommended in order to ensure a good penetration. For the case of ice, the penetration can be of course higher as the attenuation is lower ($\tan\delta = 0.004$–0.01). The choice between different techniques; GPR, sounder or tomography approach, depends on the type of explored object, scientific objectives and mission possibilities. The choice of the low frequency naturally influences the overall instrument characteristics and essentially on the dimension of the antenna. The exact choice of the frequency results from a trade-off between science and technical limitations.

4. Reflection tomography approach

In reflection tomography mode, data are collected (received) at the transmitter location. Assuming weak scattering case, the inversion technique is based on the equation:

$$\tilde{E}(\vec{r}) = -\frac{k^2 E^t}{4\pi\varepsilon_o}\,\frac{\exp(jk(r_t + r_o))}{r_t r_o}\int\limits_v \bigl(\varepsilon(r') - \varepsilon_o\bigr)\exp\bigl(-jk(\vec{n} - \vec{n}_o)r'\bigr)\,\mathrm{d}r'.$$

This formula means that the observed scattering field is the spatial Fourier transform of the dielectric constant of the scattering body at the spatial frequency $\vec{q} = k(\vec{n} - \vec{n}_o)$, which depends on the difference between scattered and incident wave vectors. Given our expectation of many fractures within interiors of NEOs, weak internal scattering inside the body is foreseeable. The reflection on the borders of the body has to be treated with other approaches. Probably the geometric optics and Fresnel's formulas will be efficient enough to describe the transition between outside and inside the object (Born and Wolf [19], Kofman and Safeineli [20]). The weak scattering approach may not be valid and in this case, a more general non-linear fitting between the data and some assumed models should be developed. By measuring this for various positions of the transmitter and receiver and for large bandwidth signals, one obtains the set of measurements which can be inverted by the Fourier transform if the sampling in space is dense enough. The radar will measure the scattered signal around the body and using this formula, one can in principle, invert the data and deduce the dielectric properties of the body.

In order to be able to image the interior of the object, radar measurements should be made over a region encircling the object with sufficiently dense sampling to ensure adequate sampling of the spatial spectral domain of the object. The sampling requirement depends on the radar's operation frequency and the object's angular extent as viewed by the radar. Another critical issue is the determination of the radar position with respect to object. This is important since the data processing relies on the coherent combination of radar data. Currently, the radar positioning is a major driver in the design of a coherent tomographic imaging system and it also limits the maximum operation frequency. If the position accuracy required for the coherent processing cannot be met, the imaging will be done by combining the data after ignoring the carrier phase (incoherent imaging scheme). This is not ideal since the resulting image will be low resolution (defined by the signal bandwidth rather than carrier frequency).

Probably a good measurement strategy is to have the spacecraft in a nearly polar orbit. In the case when the orbital period of the spacecraft around the object will be long in comparison with the spin period of the object itself it will be possible to sample a wide range of viewing geometries and to measure backscattered field from a diverse set of viewing angles. The ideal case for data acquisition is to have measurements from all possible views with spacing on the order of the observation wavelength. The obtained data will be stored, sent to Earth, and the data processing will take place on the ground. The required resolution for the final image of the object sets the system requirement for instrument bandwidth and spatial sampling.

5. Example system characteristics

An example system that could be flown on an NEO mission would operate in a low frequency (less than 20 MHz) to penetrate deeply into the asteroid material. A bandwidth of 1 to 5 MHz is necessary to obtain a resolution on the order of tens of meters. The radar should operate in the frequency range from 1–10 MHz, and perhaps higher if one would like to obtain better resolution with less penetration. The bandwidth should be variable generated by the chirp transmission. With such a system, the transmitted pulse illuminates the object and the reflected energy is received at the same location by the same or a different antenna. For a modest or slow rotation of the object and low operation frequency, there is sufficient time to coherently integrate many pulses to increase the signal-to-noise ratio. These data are then stored in the orbiter for transmission to Earth. When the orbiter's position relative to the object has moved sufficiently, this process is repeated until sufficient data has been acquired around the object. The general characteristics of such radar are summarized by the general parameters and requirements in Table 1 (Kofman and Safeineli [20]).

Recently, in response to a European Space Agency Announcement of Opportunity, a project named ISHTAR was proposed. It is a radar tomographer, operating at two frequencies of 10 and 30 MHz, with the design capability to penetrate to depths

Table 1
Suggested radar characteristics

Power: 10 W
Waveform: Coherent
Frequency: <50 MHz (enabling tomography)
Bandwidth: >2 Mhz
Antenna type: Cross-dipole

of over 300 m below the surface of an NEO with spatial resolution of up to 10 m (in length, width and depth). On ISHTAR, the radar tomographer is used in a synthetic-aperture reflection mode, where the signal reflected off the object is measured from a 'virtual' grid of locations around the object, allowing reconstruction of a 3D image of the asteroid interior. The spatial resolution of this 'SAR' radar is determined by the number of points in the grid and the frequency used (Barucci et al. [21]). Within the United States, a mission called 'Deep Interior' has been proposed to the NASA Discovery program (E. Asphaug, personal communication). Deep Interior proposes to perform radio reflection tomographic imaging (Safaeinili et al. [22]) using a 30-m (tip-to-tip) cross-dipole antenna operating at 5- and 15-MHz, with >1 km and a few hundred meters being the respective penetration goals at these frequencies.

6. Concluding remarks

While our knowledge of asteroid surfaces and geology has increased, our understanding of their interiors has remained limited. Future progress is most likely to be made through missions to near-Earth objects as these are the most accessible spacecraft destinations in the solar system. While science is our principal goal for studying these objects, there is also the very important practical benefit of knowing their structures and devising strategies for how an externally applied force could alter their orbital velocities (mm per second or cm per second) in the case that a future collision with Earth is predicted. Radar and reflection tomography represent promising new techniques for detailed interior studies over the types of interiors we expect to encounter. For a low-density and relatively homogeneous objects, a low-frequency radar ($\sim$10 MHz) is required for deep penetration and tomography. The low frequency ($\sim$10 MHz) radar is also required for the high-density homogeneous (solid rock) objects. The radar and radio science can discriminate the type of asteroid and also provide the depth of regolith on the surface.

For inhomogeneous 'rubble pile' types of objects, a radar tomographer can determine the distribution of boulder sizes through radar scattering. The radar requires a wide band of frequencies 10–100 MHz to discriminate between large and small boulders. For a high-density inhomogeneous (fractured or shattered: 100 m to 1000 m blocks separated by deep fractures) a radar is expected to detect large fractures (i.e. voids between same rock type, with same permittivity) of approximately 10% of the wavelength ($\sim$1 m at 30 MHz) or boundaries between different material if their permittivity differs by $>10\%$. The system requires a range of frequencies 10–100 MHz with wide bandwidth. Future missions such as the proposed ISHTAR project or Deep Interior may see the first applications of these techniques to NEOs.

References

[1] R.J. Sullivan, P.C. Thomas, M.S. Murchie, S.L. Robinson, Asteroid Geology from Galileo and NEAR Shoemaker Data, in: W.F. Bottke, A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids III, University of Arizona Press, Tucson, 2002, pp. 331–350.

[2] D.C. Richardson, Z.M. Leinhardt, H.J. Melosh, W.F. Bottke, E. Asphaug, Gravitational aggregates: Evidence and evolution, in: W.F. Bottke, A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids III, University of Arizona Press, Tucson, 2002, pp. 501–516.

[3] R.P. Binzel, M. A'Hearn, M. Asphaug, E. Antonella Barucci, M. Belton, W. Benz, A. Cellino, M.C. Festou, M. Fulchignoni, A.W. Harris, A. Rossi, M.T. Zuber, Interiors of small bodies: foundations and perspectives, Planet. Space Sci. 51 (2003) 443–454.

[4] W.J. Merline, Close L.M., Dumas C., Chapman C.R., Roddler F., Menard F., Slater D.C., Duvert G., Shelton C., Morgan T., Discovery of a moon orbiting the asteroid 45 Eugenia, Nature 401 (1999) 565–568.

[5] W.J. Merline, L.M. Close, N. Siegler, D. Potter, C.R. Chapman, C. Dumas, F. Menard, D.C. Slater, 2001, S/2001 (617) 1, IAU Circular 7741.

[6] J.L. Margot, M.C. Nolan, L.A.M. Benner, S.J. Ostro, R.F. Jurgens, J.D. Giorgini, M.A. Slade, D.B. Campbell, Binary asteroids in the Near-Earth Object Population, Science 296 (2002) 1445–1448.

[7] G.J. Consolmagno, D.T. Britt, The density and porosity of meteorites from the Vatican collection, Meteorit, Planet. Sci. 33 (1998) 1231–1242.

[8] D.T. Britt, G.J. Consolmagno, The porosity of dark meteorites and the structure of low-albedo asteroids, Icarus 146 (2000) 213–219.

[9] D.T. Britt, D. Yeomans, K. Housen, G. Consolmagno, Asteroid density, porosity, and structure, in: W.F. Bottke, A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids III, University of Arizona Press, Tucson, 2002, pp. 485–500.

[10] S.L. Wilkison, M.S. Robinson, P.C. Thomas, J. Veverka, T.J. McCoy, S.L. Murchie, L.M. Prockter, D.K. Yeomans, An estimate of Eros's porosity and implications for internal structure, Icarus 155 (2002) 94–103.

[11] J.K. Miller, A.S. Konopliv, P.G. Antreasian, J.J. Bordi, S. Chesley, C.E. Helfrich, W.M. Owen, T.C. Wang, B.G. Williams, D.K. Yeomans, D.J. Scheeres, Determination of shape, gravity, and rotational state of asteroid 433 Eros, Icarus 155 (2002) 3–17.

[12] M.T. Zuber, D.E. Smith, A.F. Cheng, J.B. Garvin, O. Aharonson, T.D. Cole, P.J. Dunn, Y. Guo, F.G. Lemoine, G.A. Neumann, D.D. Rowlands, M.H. Torrence, The shape of 433 Eros from the NEAR-Shoemaker laser rangefinder, Science 289 (2000) 2097–2101.

[13] P.C. Thomas, J. Joseph, B. Carcich, J. Veverka, B.E. Clark, J.F. Bell, A.W. Byrd, R. Chomko, M. Robinson, S. Murchie, L. Prockter, A. Cheng, N. Izenberg, M. Malin, C. Chapman, L.A. McFadden, R. Kirk, M. Gaffey, P.G. Lucey, Eros: shape, topography, and slope processes, Icarus 155 (2002) 18–37.

[14] L. Prockter, P. Thomas, M. Robinson, J. Joseph, A. Milne, B. Bussey, J. Veverka, A. Cheng, Surface expressions of structural features on Eros, Icarus 155 (2002) 75–93.

[15] P. Pravec, A.W. Harris, Fast and slow rotation of asteroids, Icarus 148 (2000) 12–20.

[16] A.H. Shivola, J.A. Kong, Effective permittivity of dielectric mixtures, IEEE T. Geosci. Remote Sensing 26 (4) (1988) 420–429.

[17] Y. Kofman, W. Barbin, J. Klinger, A.-C. Levasseur-Regourd, J.-P. Barriot, A. Herique, E. Hagfors, T. Nielsen, P. Edenhofer, E. Grun, G. Picardi, R. Seu, J. van Zyl, C. Elachi, P. Weissman, L.H. Svedhem, S. Hamran, I.P. Williams, Comet Nucleus Sounding Experiment by Radiowave Transmission, Adv. Space Res. 21 (1998) 1589–1598.

[18] B.C. Blankenship, D.D. Edwards, Y. Kim, P.M. Geissler, D. Gurnett, W.T.K. Johnson, W. Kofman, J.C. Moore, D.L. Morse, R.T. Pappalardo, G. Picardi, R.K. Raney, E.R. Rodriguez, J. Shao, X.-M. Weertman, J. Zebker, H.A. van Zyl, Feasibility study and design concept for an orbiting ice-penetrating radar sounder to characterize in three-dimensions the European ice mantle down to any ice/ocean interface. Prepared by the Europa Radar Sounder Instrument Definition Team, Technical Report 184, University of Texas, Institute for Geophysics "Minimized inversion of incomplete acoustic scattering data, J. Acoust. Soc. Am. 97 (1) (1999) 414–424.

[19] M. Born, E. Wolf, Principles of Optics, Pergamon Press, 1970, p. 808.

[20] A. Kofman, W. Safeineli, Mitigation of Hazardous Comets and Asteroids, Cambridge University Press, 2004.

[21] M.A. Barucci, P. D'Arrigo, P. Ball, A. Doressoundiram, E. Dotto, W. Kofman, R. Orosei, M. Patzold, E. Prozzi, The ISHTAR mission: probing the internal structure of NEOs, in: O. Engvold (Ed.), Highlights of Astronomy, vol. 13, International Astronomical Union, 2003.

[22] A. Safaeinili, Gulkis S., Hofstadter M.D., Jordan R.L., Probing the interior of asteroids and comets using radio reflection tomography, Meteoritics Planet. Sci. 37 (2002) 1953–1963.