THE ROLE OF SPACE MISSIONS IN THE ASSESSMENT OF THE NEO IMPACT HAZARD

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ABSTRACT

The impacts of Large Near-Earth Objects (NEOs) on Earth could trigger a global catastrophe. Even relatively small objects are capable of causing large local damage, either directly or in combination with other phenomena i.e. the large waves known as tsunamis.

This paper describes the interest of dedicated space missions performing NEO discovery, monitoring and characterisation in order to assess the real magnitude of this hazard. This interest had been established by previous theoretical work; however, until now the full range of NEO space systems had not been explored in the scope of a single activity. In order to have a deeper insight into this matter the European Space Agency (ESA) issued a call for proposals for dedicated NEO payloads or NEO missions. Following selection by a panel of recognised experts six independent teams carried out parallel studies for half a year into preliminary mission analysis and design that were completed in January 2003. The rational behind these missions is discussed here.

INTRODUCTION

NEO impacts could be considered as the most severe of all possible natural disasters, though fortunately they are also rare ones. There is now overwhelming evidence that large impacts (of objects with dimensions in the order of kilometres) have had catastrophic consequences in the past [1], [2]. These impacts have nevertheless been uncommon, but smaller objects are relatively more frequent and can cause significant damage when they hit the Earth at random intervals of hundreds or thousands of years.

ESA has carried out several studies on the subject [1], [4], [5]. The last one finished in January 2003 and performed an assessment of six different space mission concepts, all of them dedicated to gather information on several aspects on the NEO hazard. In this activity two broad types of space missions have been addressed, and are described below with their relative merits and drawbacks.

I. SPACE BASED NEO OBSERVATORIES BENEFITS AND LIMITATIONS

Space missions dedicated to the detection, tracking (i.e. orbit determination) and remote characterisation (e.g. determination of taxonomic type and surface albedo) would be significantly more capable than most ground-based surveys. The objective of this type of missions would be to improve and expand our catalogue of dangerous objects. Though space borne telescopes cannot be made as large and powerful as their terrestrial counterparts, for these tasks and as a consequence of improved viewing geometry (especially as the observing point moves closer to the Sun) and better observation conditions the space option enables an improved access to certain types of objects: these include Inner to Earth Objects (IEOs) and Atens, that due to their proximity to the Sun in the sky are often difficult to observe. These favourable conditions can also result in efficient and extensive surveys in which smaller objects down to a few hundred meters in size may also be detected. Observation strategies can also be devised to ensure that newly discovered objects are re-detected again after they have moved to a new orbital location, thus providing a set of data that can enable the determination of accurate orbits. This in turn allows their future trajectories (and Earth encounters, if any) to be predicted.

Finally, a space observatory can also have an unobstructed access to a broader range of wavelengths (e.g. in the IR) and to achieve a more efficient duty cycle than from below the Earth's atmosphere, as in the case of ground-based telescopes.

Variation of object brightness with solar phase angle

As a result of their orbits being close, or partly interior, to the orbit of the Earth, most NEO can only be observed from ground-based observatories at small solar phase angles for a very limited part of their orbits, when they are close to the opposition point. As a matter of fact this is the reason why many of them are only detected when they are in close proximity to the Earth or after they have passed by close to it ("near miss").

However, the apparent brightness of an asteroid increases rapidly with decreasing heliocentric distance and decreasing solar phase angle, and a NEO survey located in orbit interior to the Earth's could greatly benefit from this effect. According to the simulation of Jedicke et al (2002) [6], a NEO search telescope situated in the orbit of Mercury would discover objects in the phase angle range 16º ± 11º compared to a range of 44º ± 27º for an optimum ground-based survey. As shown in figure 1 this could be translated in a dramatic improvement of the telescope performance.

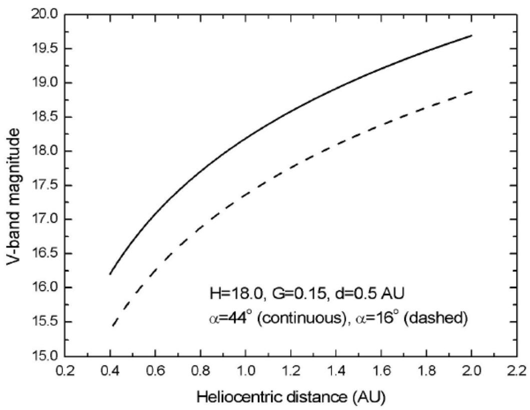

Figure 1. Plots of V-band magnitude versus heliocentric distance for an asteroid with absolute magnitude H = 18 (roughly 1 km in diameter) at 0.5 AU from the observer and at solar phase angles of 44° and 16°. These phase angles are typical of those at which asteroids would be discovered with an optimum ground-based search telescope and a telescope located in the orbit of Mercury, respectively. The plots show the dramatic brightness advantage of a search telescope located in the orbit of Mercury.

Variation of Zodiacal light contribution with heliocentric distance

There is however a drawback in observing at smaller heliocentric distances: the increased brightness of the zodiacal light (i.e. sunlight being scattered by the dust in the ecliptic plane) effectively reduces the limiting magnitude of a telescope and therefore hinders its ability to detect faint objects. For a given exposure time, pupil diameter and object brightness, the signal to noise ration S/N can be expressed in the following way

$$S/N = \frac{F_{NEO}}{F_{NEO} + N\,(F_{ZL} + F_N)}^{1/2} \quad (1)$$

where F_{ZL} is the flux (expressed as number of counts per pixel), contributed by the zodiacal light, F_{NEO} is the number of counts per pixel due to the object and N is the number of pixels that constitute the NEO Point Spread Function (PSF)

Though presently there is a lack of a totally reliable model –partly due to the scarce observational data- it can be reasonably assumed that the zodiacal light brightness in the visible band varies as $1/r^3$. Following this assumption, which is on the conservative side (theoretically the variation depends of the heliocentric distance as $1/r^n$, where $2<n<3$ depends on the radial dust distribution that is chosen) and the numerical value of the variables is estimated, it is shown that that the variation of the limiting magnitude with the heliocentric distance can be expressed as

$$V = 21 - 2.5\,\mathrm{Log}\,(F_{NEO} / 22.1) \quad (2)$$

where

$$F_{NEO} = \frac{9 + \sqrt{81 + 36(22.1/R^3 + 10}}{2}$$

This variation is plotted in Figure 2. The reduction of the limiting magnitude of the telescope is significant, However simulations by Morbidelli et al. in the frame of EUNEOS study (see below) prove that improvement due to the reduced solar phase angles dominates, and makes a survey more and more efficient with decreasing telescope heliocentric distances.

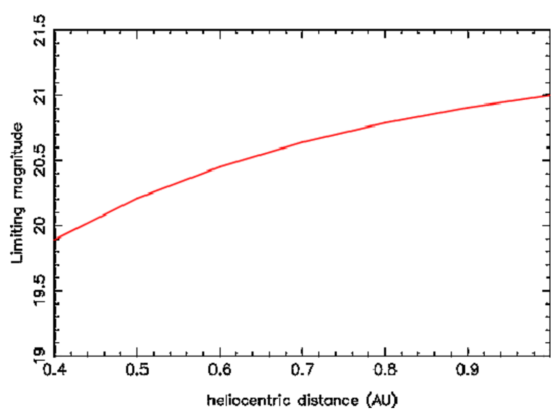

Figure 2.Variation of the limiting magnitude of a telescope as a function of its heliocentric distance. The limiting magnitude drops by 0.8 magnitude when being moved from 1 AU to 0.5 AU, and 1.1 magnitudes when being moved to 0.4 AU.

Access to small solar elongations

Some types of NEOs, namely the subgroups of Atens and IEOs (Interior to Earth Objects) are extremely difficult to detect and track from ground-based observatories. This is a consequence of their orbits. The Atens group is made up by objects with semi-major axis a<1 AU, but the aphelion distance is larger than the perihelion distance of the Earth, making it possible to see these objects around opposition (0 degrees ecliptic longitude), though not very frequently. In other words the orbits of the Atens are mostly interior to the Earth's orbit, and having short periods below one year they are good candidates to impact on the Earth. On the other hand, the orbits of the IEOs are totally interior to the orbit of the Earth. Thus most of the time the solar elongation of both Atens and IEOs (i.e. their angular distance to the Sun) is very small and the observation conditions are very unfavourable due to the atmospheric scattering of the sunlight and to the increased atmospheric absorption at low elevations over the horizon.

As a matter of fact until this year (2003), in which the first IEO (named 2003 CP20) was detected, and due to these difficulties, the existence of this type of objects was only based on theoretical evidence but none had ever been observed.

Improved sky coverage and duty cycle

As discussed above observations by space observatories do not have to be limited to +/-90° solar elongation band, the night hemisphere on Earth, they can also be carried out "during daytime" as long as pointing directions within a certain minimum solar elongation are avoided to prevent detector damage.

On the other hand, currently there is an unbalance between the number and efficiency of survey programmes on the Earth's Northern and Southern hemisphere. As the most important ones are currently those based in the Northern hemisphere, especially in the US (e.g. LINEAR, NEAT, Catalina Sky Survey, LONEOS, Spacewatch) etc but none of them reach declinations below -30°, more than 25% of the celestial sphere is virtually uncovered. There is no reason why this would apply also to a space based survey, as only the constraints mentioned above i.e. solar disk avoidance would limit its pointing capability in any direction.

As there is no atmospheric scattering, no absorption and no influence of weather conditions the duty cycle of the telescope is greatly enhanced. Observations can be performed non-stop except during specific spacecraft operations (e.g. operation of attitude control thrusters might require taking some precautions), eclipses (depending on the orbital location, and the spacecraft energy storage system) or service outages due to space weather events (e.g. solar coronal mass ejections, etc). Limited visibility of satellite tracking stations on the ground is not expected to have a significant impact due to the low data rates required, provided that only position data are transmitted, and not full images.

Object redetection and orbit calculation

The ultimate goal of the NEO surveys is not simply to detect new objects, but to perform an accurate calculation of their orbits. Only this way can their trajectories be determined in order to ascertain whether they represent a serious threat to the Earth. In order to attain this goal it must be ensured that enough observations of an object are available (at least three), and that their spacing in time is long enough so that the ¨arc length¨ on the sky has a significant angular size. Therefore an observatory must not only be capable of detecting a faint object and identifying it as a NEO, based on its rate of motion against the stars on the sky background. The survey strategy should be such that the same regions of the sky are periodically revisited in order to systematically re-detect, albeit in different positions, the newly discovered -or as it often happens, re-discovered- object.

In space sequential observations cannot be hindered by adverse atmospheric weather conditions. Also, favourable NEO visibility conditions are not only limited to a region of the sky close to the opposition point, especially if the telescope is located within the Earth's orbit. It is therefore much easier to devise a survey strategy that enables successive and repeated observation of sky regions even if the angular separation is important.

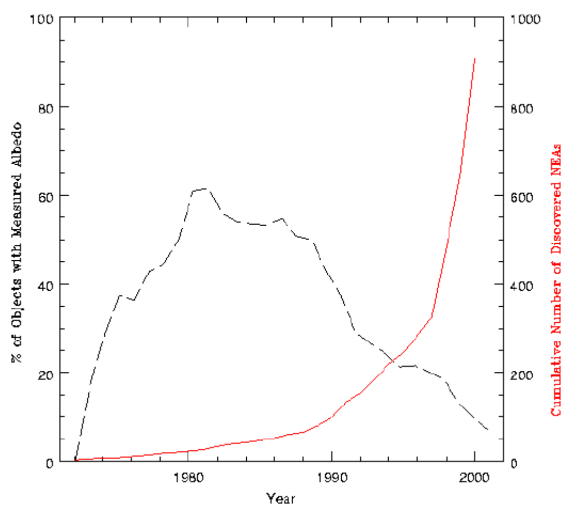

Figure 3. While new objects are discovery at an increasing rate, albedo measurements are available for a decreasing percentage of the total known population, as shown in this plot (from Cellino et al (2002) [7])

Access to IR wavelengths

Thermal radiometry is based on the measurement of the thermal emission of the objects at mid-IR wavelengths. It appears as the most efficient means of inferring sizes and albedoes for a significant number of NEOs. While the apparent brightness at visible wavelengths depends not only on the size, but also on the albedo, the dependence of the thermal flux upon the albedo is fairly weak. Moreover, NEOs are intrinsically bright at wavelengths around 10 μm (corresponding approximately to the peak of their thermal emission) and can therefore be detected by telescopes with a modest aperture. The process of thermal emission in NEOs is now well understood, and thermal models specifically developed for NEOs like the so-called Near-Earth Thermal Model (NEATM) developed by A.W. Harris of DLR [8], have proved to be very useful to interpret the observations and to extract information on the objects´ physical properties from them [9].

Proposed observatory mission concepts

Three of the concepts put forward during ESA´s *¨NEO Space Mission Preparation¨* six-month assessment explored ways in which dedicated NEO telescopes and payloads could take advantage of the circumstances discussed above.

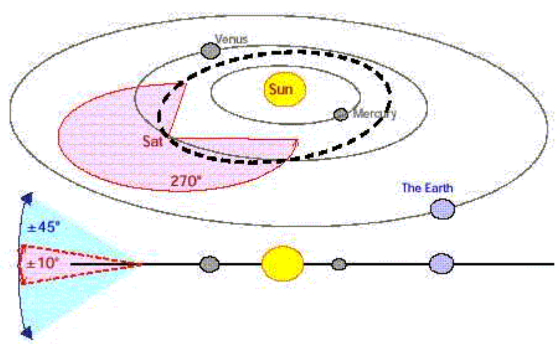

Figure 4. EUNEOS spacecraft orbit and survey strategy.

EUNEOS is a 30 cm aperture and large (3.0° x 3.0°) FOV telescope mounted on dedicated spacecraft located in a 0.5 x 0.7 AU elliptical orbit. Its goal is to achieve at least a 80 % complete survey of the population of Potentially Hazardous Object (PHO) i.e. the subset of the NEO population that carry potential to make threatening close approaches to the Earth, down to a few 100's meters during an operational mission lifetime of 5 years. It would carry out a survey of the entire ecliptic every three days in the +/- 20° ecliptic latitude and +/-130° solar elongation band. The observation strategy would enable a systematic re-detection of the discovered objects, which allows an accurate estimation of the objects' orbits by the spacecraft. This avoids that an object is lost if immediate follow-up from the ground is not feasible, and makes it possible wait till the observation conditions are favorable. Object recovery by ground-based facilities would be possible in 70 % of the cases and would enable to make good orbit estimations. This would require a ground-based telescope capable of pointing at small solar elongations.

Although the implementation of this option was not studied in detail during the *EUNEOS* study, it was also proposed to use visual polarimetry to infer the sizes of the objects being observed, exploiting the correlation between the degree of polarisation of the light reflected by their surfaces and their albedoes.

Another of the concepts that have been studied, is a “hitchhiker” payload mounted on spacecraft in orbit about Mercury or in the vicinity of its orbit, called *Earthguard I*. It consists of a 20-cm Ritchey-Chretien telescope having a 1-degree of freedom gimbal, which enables it to scan in the 77-103° and 257-283° ecliptic longitude arcs with minimal spacecraft operations. During the study it was assumed that it would be accommodated in one of the elements of ESA’s *Bepi-Colombo* Mercury mission, currently under assessment. However the instrument design is flexible enough to cope with alternative scenarios with only minor modifications if this opportunity did not arise.

A third space-based observatory, *SISyPHOS+*, was also assessed. This is a spacecraft carrying both a Visual and IR detecting payloads that would be placed in an orbit about the Earth-Sun system L2 Lagrangian point. Its goal would be to detect new objects (or re-detect objects that had previously become lost due to the lack of observations to compute a reliable orbit) and to use thermal radiometry to perform a systematic determination of albedoes and an estimation of the object’s sizes. Initial assessments early in the study on the possibility of placing the spacecraft in the vicinity of Venus orbit determined that it could improve the mission return - due to some of the reasons outlined above - but also greatly increase its cost and complexity. Thus it was decided that the baseline orbital location would be the Sun-Earth L2 Lagrangian point, which seems to offer advantages in terms of the required FOV and a certain simplification of the scanning strategy, as the areas to be scanned is smaller.

II. IN-SITU CHARACTERISATION NEO MISSIONS

Until the advent of the space era, photometric, spectrophotometric, infrared observations all made with optical telescopes, and radar observations formed the entire basis for our understanding of the sizes, shapes, rotation states and mineral composition of the NEOs.

Currently it is clear that space borne instruments are the best way - and often the only one - to obtain data on most physical properties of NEOs that are essential for the assessment of the consequences of an impact and the countermeasures that can be adopted to prevent it. There are very different views on the relative importance of the parameters that need to be determined. Table 1 shows a possible ranking of measurement priorities. Nevertheless, there is common agreement about the ones that come first on the list from the point of view of impact hazard assessment Seeking precise velocity, mass, volume, and internal structure determination is mandatory.

Determination of the object mass, size and bulk density

At least the top three parameters can be determined directly by a NEO rendezvous mission among other physical properties, simply by tracking a spacecraft in orbit around the object. All the instrumentation required on the spacecraft would be a communication payload enabling a good estimation of the position of the spacecraft from Earth (which is one of the standard subsystems of any spacecraft anyway, and not part of the payload as such) and a camera in the visible range for size determination and navigation purposes. The mass can be obtained directly analysing the influence of the gravity field created by the asteroid on the spacecraft dynamics, and this way a certain –limited- amount of information could be inferred on the asteroid internal structure. Note however that if the object is very small (e.g. below about 200 m in diameter) the gravitational interaction can be very weak and it will not possible to attain a stable orbit about the object.

Determination of the object internal structure

Most of the parameters in Table 1with priorities 1 and 2 could be determined directly even by a very simple rendezvous mission, carrying a small payload similar to that of ESA´s SMART-1 lunar orbiter. The exception is, however, an important one. Though some important clues can be inferred by analysing the density, gravity field and rotation state of the asteroid, its internal structure can only be studied in detail by active techniques, such as Ground Penetrating Radar (GPR) or active seismology. The aggregation state of the asteroid is important to predict what would happen if it entered the Earth´s atmosphere, and to assess whether a part or most of the object would burn up or it would reach the ground almost intact. Also, it is important to develop appropriate countermeasures to destroy or deflect it while it is still in space. For instance, some of the proposed mitigation techniques to cope with a threatening object include sub-surface or stand-off nuclear explosions. However, the energy released in an explosion or high-velocity impact could be absorbed by the object to a very different degree depending on its structure and macro- and micro-porosity. It could even result in a large number of smaller objects virtually on same trajectory as the original one, and would therefore very likely create a different type of threat and not necessarily provide a solution. Another possibility that is under consideration, using a propulsion system coupled to the asteroid's surface, could be effective in case the object was a monolithic one, but could prove very challenging if the object turned out to be a loose aggregate of boulders kept together only by the weak force of gravity. Therefore the appropriate mitigation technique to utilise in a given situation is highly dependent on the structure of the incoming NEO.

Proposed NEO rendezvous mission concepts

Three rendezvous mission concepts have been studied, all of them based on the premise that a better mission return can be achieved not by selecting a sophisticated payload but by following an inventive strategy.

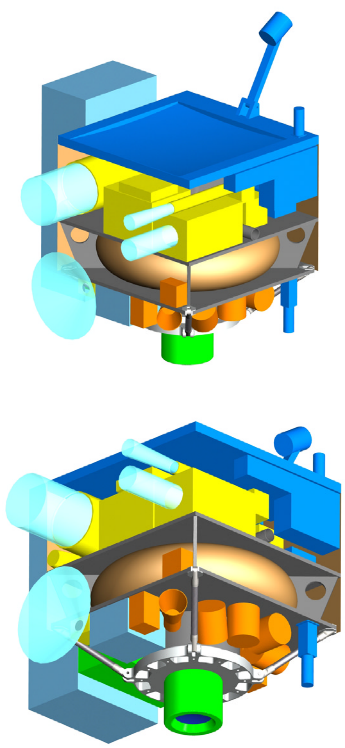

Figure 5. One of SIMONE micro-satellites, overhead and underside X/-Y views.

One of the proposed mission concepts, dubbed SIMONE, would consist of a fleet of five low-cost and identical micro-satellites. As the spacecraft operate independently they would be able to rendezvous and sample a representative enough subgroup of the population, including different types of asteroids. Their objective would be to determine their masses, bulk densities, gravity field, surface albedoes and mineralogical and elemental surface compositions. The velocity of the spacecraft could be determined with an accuracy of up to ~ 0.03 mms-1 while a spatial resolution better ≤1m during close approaches to within 10 km would enable the determination of the size with an accuracy of up to 1%.

ISHTAR, another of the proposed concepts, is an asteroid orbiter that would use Radar Tomography (i.e. the imaging of the interior of a solid body using Ground Penetrating Radar) to study the object’s internal structure. A reduced renge of frequencies (~10-30 MHz) that can be accommodated on a single antenna would suffice to attain the required penetration depth and spatial resolution. The remaining payload will determine the mass, mass distribution, density and surface properties. Acknowledging the great diversity of the near-Earth asteroid population and though its nominal mission would be completed by studying a single object during some months, the mission has been designed so that it could be extended, and a visit to a second pre-selected object was feasible.

Finally the last proposed mission, called Don Quijote, would carry out an investigation of the asteroid internal structure by using a different method i.e. active seismological experiments. As an additional benefit it would test many of the technologies required for performing an efficient deflection. It would consist of two spacecraft, Sancho and Hidalgo, launched by the same booster but injected into separate interplanetary trajectories. Hidalgo would ultimately impact the target asteroid at a very high speed (>10 km/s) while the other one, Sancho, would have been previously inserted orbit about it. Before the impact the orbiter would deploy a network of seismometers and a set of seismic emitters. The objectives of the mission would be to determine the asteroid internal structure, to constraint its mechanical properties, to determine the feasibility of coupling devices onto its surface and measure the orbital deflection and any changes triggered by the impact of the Hidalgo spacecraft at a very high relative speed.

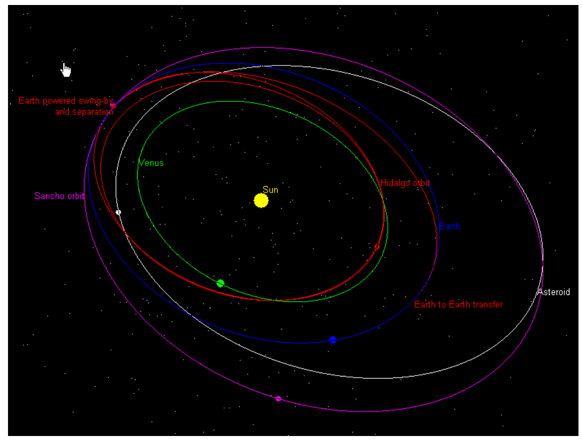

Figure 6. A sample trajectory plot for the Don Quijote mission showing Sancho and Hidalgo separate trajectories.

Priori ty	Paramenter	Risk assessment information derived	Determined from Earth?	Determined by S/C rendezvous?
1	a) Mass, Size, Bulk density, Shape, Gravity field b) Detailed internal structure	a) Kinetic energy (with velocity, from orbit). Inferences for internal structure (macroporosity). Of value to constrain masses, likelihood of fragmentation (atmospheric or tidal) and impact dynamics b) Likelihood of fragmentation and impact dynamics, clues for the development of countermeasures	Mass, density, estimation of internal structure cannot determined unless observable binary; Size estimated by IR / Optical, radar; Shape by radar if not far, model dependant	a) Derived or determined directly b) Can be determined by s/c carrying GPR or seismology package
2	Surface topography / morphology; Mineralogical , elemental composition; Rotation state	Clues to internal structure and properties Hints for the development of certain countermeasures (e.g. engines or other devices operating on the asteroid surface, etc)	Few properties inferred from radar or optical phase functions, spectra. Rotation state by radar if object not far	Could be determined directly at high spatial resolution or good S/N (where applicable)
3	Thermal emission, Magnetic field, Binary detection	Constraints on dynamics (Yarkovsky effect), possible inferences on internal structure (magnetic-?), mass (in binaries)	Not possible for magnetic field, crude estimations of thermal emission possible, binaries can be observed	Could be determined, though sets specific constraints on s/c design

Table 1. Summary of measurement priorities and benefits considering a simple rendezvous mission

CONCLUSIONS

The European Space Agency (ESA) has performed a number of activities to date to support the characterisation and monitoring of the NEOs. These activities have been organised with the consideration that a phased approach is necessary so as to assess the threat, make a catalogue of the potentially dangerous objects and credible forecasting of impacts and its consequences.

For this type of investigation, space missions offer significant advantages over ground-based facilities. The results of several studies commissioned by ESA provide a very strong support for this view. Space missions could complement and enhance ground-based programmes, extend the surveys, complete the catalogues and provide "ground truth" and fundamental physical data that cannot be obtained any other way.

The studies discussed here represent some of the building blocks towards the development a framework of cooperation, including ESA and its international partners, dealing with the NEO hazard assessment. The implementation of a coordinated approach would enhance the debate, facilitate putting into practice specific projects and prevent the duplication of efforts.

Currently there are no NEO Disaster Management Plans similar to those elaborated to deal with other natural disasters. In case of an advanced impact warning or after an asteroid strike most governments would have little, if any, directions on to handle the situation. Such guidelines could be required even in the case of relatively small (and therefore not so uncommon) events, and would have to be, to some extent, specific to this type of natural hazard and its peculiarities. Having accurate data on these objects is therefore important.

We are not in a position to assure that a NEO impact will not take place. As a matter of fact there is no doubt that unfortunately a catastrophic impact will eventually occur, though presently we do not know how far in the future this will come about. The consequences can be very different depending on where the asteroid strikes, and different nations suffer different risks. An assessment of the impact hazards is therefore recommended at all levels: local, national and international. Ground and space based assets could complement one another in providing the required data for timely and reliable decision-making.

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REFERENCES

[1] Alvarez, L, W. Alvarez, F. Asaro, & H.V. Michel, *Extraterrestrial cause for the Cretaceous-Tertiary extinction*, Science, 208:1095-1108 (1980)

[2] Chapman, C.R. and D. Morrison: *Impacts on the Earth by asteroids and comets: Assessing the hazard*, Nature 367:33-39 (1994)

[3] *Spaceguard Integrated System for Potentially Hazardous Objects* Survey, (SISyPHOS), ESA contract 13265/98/D/IM (1999)

[4] *Study on the distribution of NEO's.* ESA contract 14018/00/F/TB, (2001) http://www.obs-nice.fr/michel/Debiased_NEO.pdf

[5] *NEO hazard mitigation publication survey*. ESA contract RFQ/14472/00/D-HK (2001)

[6] Jedicke, R., Morbidelli, A., Spahr, t., Petit, J-M., and Bottke, W. F.2002. *Earth and space-based NEO survey simulations: prospects for achieving the Spaceguard Goal*, Icarus, 161,17-33, (2002)

[7] Cellino, A., Zappala V., Tedesco E. F.: *Near-Earth objects: Origins and need of physical characterization.* Meteoritics & Planetary Science, 37, 1965-1974 (2002)

[8] Harris, A.W., *A thermal model for near-Earth asteroids*, Icarus, 131, 291-301 (1998)

[9] Delbo, M., Harris, A.W., *Physical Properties of Near-Earth Asteroids from Thermal-Infrared Observations and Thermal Modeling*, Meteoritics & Planetary Science, 37 (2002)

(*) Further details on the studies discussed in this paper can be found at:
http://www.esa.int/gsp/completed/neo/