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The observation of near-Earth objects from the space at thermal IR wavelengths

A. Cellino[1]

INAF – Osservatorio Astronomico di Torino, strada Osservatorio 20, 10025 Pino Torinese (TO)
e-mail: cellino@to.astro.it

Abstract. Near-Earth objects are a population of bodies very important for our understanding of the formation and evolution of planetesimals in our Solar System, as well as from the point of view of the threat they represent for the Earth's biosphere. Two basic issues are currently open and deserve a dedicated effort: (1) the overall physical characterization of the NEO population and (2) the discovery of objects orbiting mostly or entirely inside the Earth's orbit. It seems that the best way to address the above issues is the development of dedicated observing facilities working at mid-IR wavelengths. A dedicated space-based platform would be the ideal solution, but some alternatives can also be taken into account.

Key words. Near-Earth Objects – Thermal emission – Space-based observations

1. Introduction

The innermost region of the Solar System, characterized by the presence of the terrestrial planets from Mercury to Mars, is also populated by a swarm of minor bodies, that are collectively called NEOs (near-Earth objects) due to the fact that they can experience close approaches with our planet. These bodies have sizes ranging from that of interplanetary dust up to some tens of kilometers. NEOs experience chaotic orbital evolutions, and during their orbital wandering they can sooner or later intersect the Earth's orbit. In these circumstances collisions become also possible. The population of modest-size impactors is the source of the meteorites, whereas larger objects, with sizes beyond some meters or tens of meters can produce local or global devastations. It is generally assumed that objects 1 kilometer in diameter are sufficiently large to produce a global catastrophe in the case of an impact, having defined a global catastrophe as an event leading to death of more than 50% of the total human population. According to recent estimates, the number of NEOs larger than 1 km should be of the order of 900–1000 (Bottke et al. 2000), when considering purely NEOs of asteroidal origin. These objects steadily orbit in the inner Solar System, and only a fraction of the order of 40% has been discovered so far. They are conventionally separated into different or-

Send offprint requests to: A. Cellino
Correspondence to: strada Osservatorio 20, 10025 Pino Torinese (TO)

Table 1. Definition of the different classes of near-Earth asteroids

Atens	a$<1AU$,	Q$>0.983AU$
Apollos	a$>1AU$,	q$<1.017AU$
Amors	a$<1.3AU$,	q$>1.017AU$
IEOs	a$<1AU$,	Q$<0.983AU$

bital subclasses, as summarized in Table 1, where a, q and Q are the orbital semi-major axis, perihelion and aphelion distance, respectively; the values of 0.983 and 1.017 AU correspond to the perihelion and aphelion distances of the Earth, respectively, and IEO stands for *Interior to Earth's Orbit*.

It is generally assumed that the cumulative size distribution of near-Earth asteroids, like that of the main-belt population, can be approximated by a power-law, but the value of the exponent is still uncertain. A contribution of comets or extinct comets to the NEO inventory also exists and must be considered in the computation of the actual impact hazard. NEOs have been the subjects in recent years of a considerable attention. Public institutions have payed attention to the existence of the impact hazard, and have recommended the development of dedicated programs of research aimed at discovering in advance the largest possible number of NEOs. It is clear, in fact, that any possibility of developing a credible system of defense against these bodies, is related to the ability of discovering the possible impactors well in advance, in order to have more time to react. In fact, a tiny orbital deflection can be sufficient to avoid an impact if the change of linear momentum is imparted well before the impact, whereas increasingly amounts of energy are needed if an object is discovered shortly before a possible collision. The existence of a real impact hazard is certainly a good reason to study NEOs. However, it should be clear that it is not the only one reason. This can be understood if one considers that NEOs constitute a greatly heterogeneous population of bodies originating from very diverse regions of the Solar System. Several dynamical mechanisms exist and can explain how minor bodies belonging to populations as different as main-belt asteroids, long and short-period comets and Transneptunian objects (TNOs) can be perturbed and eventually reach the region of the terrestrial planets. These mechanisms include perturbations from nearby stars (for bodies orbiting in the Oort cloud), close encounters with the giant planets and collisions, leading to suitable changes of the orbital elements. The existence of many regions of instability in the space of the orbital elements a, e, i (semi-major axis, eccentricity and inclination) ensures that chaotic orbital motion can be achieved, leading generally to significant increase of eccentricity. When the perihelion distance starts to be located in the region around or within the Mars' orbit, close encounters with Mars and the other terrestrial planets can occur, and the objects can be temporarily or definitively trapped into the inner Solar System. This seems to be the most likely history of NEOs originating from the asteroid main belt (Migliorini et al. 1998). The typical lifetimes of NEOs are generally short, since their orbits are highly unstable and evolve over short timescales. The most common end-state seems to be a collision with the Sun itself, or ejection from the Solar System, while also a small but non-zero probability of impact with one of the terrestrial planets exists (Gladman et al. 1997). Numerical integrations indicate that typical NEO lifetimes should not exceed values of the order of 10^7 years, shorter times (by a factor of ten or more) being also typical for objects achieving resonant orbits like the 3/1 or 5/2 mean-motion resonances with Jupiter. All this means that NEOs are fresh samples of all existing populations of minor bodies of the Solar System. Moreover, they are the closest objects that can be observed (apart from our Moon) and this means that they offer a unique possibility to analyze the properties of the smallest objects detectable from Earth. Being subject to fast orbital evolution, they are also among the youngest objects that we can observe. All this is of the highest importance for modern planetary science. A short list of topics that can receive essential input for analyses of the physical properties of NEOs includes the following items:

- Assessment of the differences in composition among bodies accreted at very different heliocentric distances.
- Analysis of the primitive gradient in composition in the Solar protoplanetary disk.
- Origin and evolution of meteorites.
- Role and effectiveness of space-weathering phenomena, progressively modifying the albedo and spectroscopic properties of planetary surfaces.
- Physics of the events of catastrophic collisions among minor bodies.
- Overall inventory and size distributions of asteroids and comets.
- Thermal histories of asteroids and comets.

only to mention some of the most outstanding issues. Due to the above reasons, it is surprising that we know still so little about the physical properties of NEOs. Improving this situation is a task of the highest priority for modern planetary sciences.

2. NEO physical characterization

Most of the NEO-related activities carried out in recent years have been aimed at the *discovery* of as many objects as possible, mostly in the framework of the so-called Spaceguard Survey, first proposed by a NASA working group (led by David Morrison) in January 1992. The Spaceguard goal is to be able to discover 90% of the NEOs larger of 1 km within ten years. However, NASA took a real commitment in pursuing the Spaceguard goal not earlier than 1998. While it seems likely that the Spaceguard goal can hardly be reached within 2008, it is certain that the development of dedicated observing facilities (like LINEAR) has produced a huge increase in the NEO discovery rate. This can be clearly seen in Fig. 1, in which the cumulative number of NEOs discovered during the last thirty years is plotted as a function of time (continuous line). In the same Figure, the points indicate the relative fraction of discovered NEOs for which some reliable estimate of albedo and size is available, again as a function of time. It can be seen that, apart from a period of ten years, when the number of discovered NEOs was very low and albedo and size were known for about one half of them, the situation has dramatically worsened during the last 10 − 12 years, when the discovery rate has started to dramatically increase, whereas little has been done at the same time in the field of albedo and size determinations. These are parameters of primary importance for physical characterization, then by looking at the Figure, it is easy to conclude that physical characterization is “losing the race” against discovery.

This is a very unsatisfactory situation from many points of view. From a purely scientific perspective, NEOs are very interesting for the reasons mentioned in Section 1, then a major effort should be made in order to derive their basic physical properties. These include their sizes, composition, spin state, surface texture and albedo, overall shape, and internal structure (Huebner et al. 2001). All of the above properties are very important and should be determined. But we are still very far from this. Spectroscopic and spectrophotometric observations of NEOs have been performed extensively in recent years, and they have provided spectrophotometric data for about 100 objects. These data have been found to be important for clarifying the possible relation between ordinary chondrites and asteroids belonging to the S taxonomic type (Binzel et al. 2001). At the same time, spectra and colors can

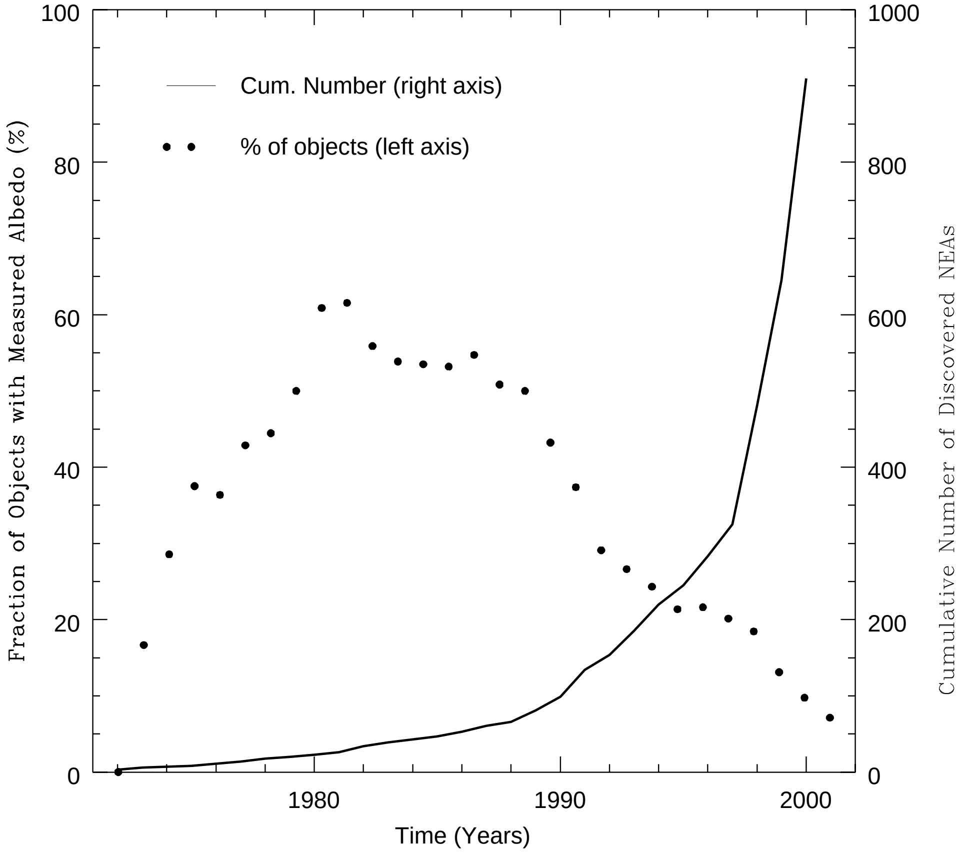

Fig. 1. A comparison between the discovery rate of near-Earth asteroids (line) and the fraction of these objects for which a reliable estimate of diameter and size is available (dots) is shown, as a function of time. From this plot (based on data provided by courtesy of Ed Tedesco) it is evident that physical characterization is clearly "losing the race" against discovery.

be useful to identify objects having properties similar to what is expected for objects of cometary origin. But the situation is not satisfactory in many other respects. In particular, this is true for the sizes of the objects. Knowledge of the size is very important, because it is a basic parameter to interpret the overall properties and histories of these bodies. In particular, the size distribution of NEOs is obviously related to the size frequency of their parent bodies in the asteroid belt and in the outer Solar System, and to the efficiency of the dynamical mechanisms of transfer from their birth places to the inner Solar System. In particular, the dynamical lifetimes of the objects can be affected by size-dependent non-gravitational effects like the so-called Yarkovsky effect. This is a recoil due to the thermal radiation emitted from the surface of the bodies, heated by solar radiation. The importance of this effect has been increasingly emphasized in recent years (Farinella and Vokrouhlický 1999). At the same time, a knowledge of the sizes of NEOs is essential from the point of view of the impact hazard. It is evident, in fact, that knowing that a given object is in a collisional path to the Earth, does not solve the problem of impact mitigation. The consequences of an impact, and the amount of linear momentum that must be delivered to the object in order to modify suitably its orbit, depend on its mass. Masses are usually very hard to obtain, but knowing the size can be sufficient to derive a reasonable estimate of the energy delivered by the impactor. Moreover, the prediction of impact events in the future is critically affected by the capability of computing the dynamical evolution of the objects taking also into account the size-dependent Yarkovsky effect mentioned above. Another important consideration is that the impact hazard depends obviously on the number of potential impactors. Thus, knowing the size distribution of the NEO population is important to assess the impact frequency of objects having sizes in different ranges, corresponding to different consequences in the case of an impact (from local devastations to global catastrophes). According to current knowledge, the probability that each human being has to be killed by an interplanetary body within the next year, is of the order of one over a million. But this estimate is still very uncertain, and only a much better knowledge of the size distribution of the potential impactor population can allow us to derive a more reliable estimate. Even the current value, however, shows that the impact hazard is not negligible, and must be considered as a global planetary emergency. On the basis of the above considerations, it seems that it is very urgent to find the way of improving the current poor situation concerning our knowledge of the sizes of NEOs. This should be considered as a task of the highest priority, but, as we will see below, it is not easy to solve the problem.

3. How to determine the sizes of NEOs

NEOs are simply too small for having their sizes measured directly. They are usually well beyond the resolving power of telescopes of the 6 m class, working with Adaptive Optics. It is not conceivable that very large instruments can produce but a negligible number of direct size determinations in the next years. We are then forced to rely upon indirect techniques. Also in this case, the possible choice of techniques is very limited. It should be taken into account that NEO sizes cannot be simply derived from the measurement of their apparent magnitude during discovery and follow-up observations. The reason is that their apparent magnitudes depend not only on their sizes, but also on the albedos. Since NEO albedos are known to vary by more than one order of magnitude (between less than 0.04 to about 0.5) there is not *a priori* any possibility of discriminating between brighter, smaller bodies and darker, larger ones. Since NEOs are generally small, the uncertainties are such that any given object might belong to very different regions of the size distribution (see Fig. 2). Spectrophotometric data can be useful, since different taxonomic classes (defined on the basis of the spectral distribution of the scattered sunlight at visible wavelengths) are known to be characterized by different albedos, on the average. The colour-albedo relation, however, is not very strict in several cases, and there are taxonomic classes (E,M,P) that are not separable on the basis of spectrophotometry at visible wavelengths, but are characterized by widely different albedos (from very dark to very bright objects). These classes include about 20% of the asteroid population. Moreover, there are recent preliminary indications that NEOs could exhibit in many cases albedos not very usual (higher than average) for their taxonomic classes. This fact deserves further observational tests, but is another reason preventing us from deriving sizes from apparent magnitudes and colors in a straightforward way.

Polarimetry is much more reliable to derive asteroid albedos. The reason is a well known relationship between the surface albedo and some parameters describing the change in degree of linear polarization of the scattered sunlight as the objects are seen at different phase angles (the phase being the Sun - Asteroid - Earth angle). Observations spanning over large intervals of phase are needed, however, and moreover polarimeters necessarily split the incoming beam into components of different polarization. This means that fairly large telescopes are needed to measure the polarization of objects as faint as typical NEOs, and moreover each object must be observed several times. Moreover, the theoretical understanding of the polarimetric properties is still unsufficient and mostly based on empirical relations found in laboratory experiments. Summarizing, polarimetry cannot be considered an efficient tool for obtaining in short times a satisfactory sample of NEO sizes, although it is certainly a very useful technique for calibration purposes. The same is probably true for radar observations. Although there has been a huge improvement in the performances of radar experiments during the last years, times are still premature for developing a fast, systematic NEO radar survey, due to the limited number of existing radar facilities and to the r^{-4} dependence of the radar echoes (r being the distance of the object), implying that large antennas (like the one in Arecibo) are needed. The most efficient technique for NEO size determination seems to be radiometry. This is based on the simultaneous measurement of the scattered sunlight at visible wavelengths, and the thermal emission from the bodies. Both the scattered and thermal fluxes depend on size and surface albedo, then a solution for these parameters can be obtained when both fluxes are simultaneously measured. Technical problems are related to the fact that the thermal emission depends on the temperature distribution on the body's surface, and this in turn depends on several parameters describing the overall thermal inertia of the surface materials and also on the the spin rate. However, these problems are not untractable, and several thermal models have been developed for predicting the distribution of temperature on the surfaces of asteroids of different types (Harris and Davis 1999). The most important problem in NEO (and generally in asteroid) radiometry is that the thermal flux from these objects peaks between 8 and 10 μm. This is a region of the electromagnetic spectrum that is not easily observable from the ground. In the past most asteroid radiometric data have been collected from orbiting platforms, like the IRAS, ISO and MSX satellites. The advantages of carrying out radiometric observations from space are evident, if one thinks that a proper satellite design can allow sensitivity to be limited by sky background only. Moreover, NEOs are relatively bright objects at thermal IR wavelengths. The IR flux from a 1-km NEO is generally comparable to that received from stars having V magnitudes around 10. As a comparison, 1-km NEOs have generally V magnitudes of the order of 20 or fainter. As a consequence, star background is not a big problem in mid-IR, even when observing at small galactic latitudes, as convincingly shown by MSX observations (Tedesco et al. 2000). It should also been mentioned that thermal IR fluxes are much less dependent on the albedo of the objects, with respect to the apparent V luminosities. This removes the problem of the bias against the discovery of intrinsically dark objects, which severely affects the surveys at visible wavelengths. Taking also into account that one single observation is sufficient in principle to derive a reliable size and albedo determination, it is evident that radiometry, possibly from space, would be the ideal tool to improve the current poor situation in NEO physical characterization. Moreover, another big ad-

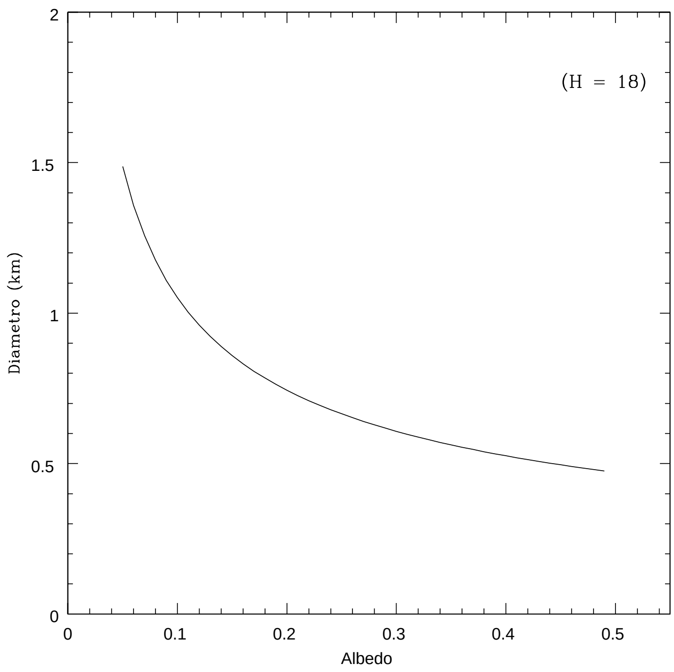

Fig. 2. This plot shows, for the case of an asteroid having an absolute magnitude $H = 18$ (the absolute magnitude being the apparent V magnitude an object would exhibit when seen at a distance of 1AU from both the Sun and the Earth, and at zero phase angle), the corresponding diameter as a function of surface albedo (reflectivity). Since most asteroids have albedos between 0.05 and 0.25, it is clear that the relative uncertainty in the size in the absence of an albedo determination, is very high.

vantage is inherent when dealing with NEO observations from space. This is the possibility of being able to survey the region of the sky located at small angular distance from the Sun. This is the region where Atens and IEOs can be preferentially (or exclusively, in the case of IEOs) detected. The reason is that these objects spend most (Atens) or all (IEOs) of the time at small solar eleongations, and are thus very difficult to discover from the ground. For this reason, we have not yet currently discovered any IEO object, in spite of the fact that orbital integrations of known near-Earth asteroids show that IEOs must necessarily exist, and their number is not negligible (Michel et al. 2000). The capability of being able to fulfil two difficult tasks like physical characterization of a large fraction of the NEO population in short times, and the discovery and physical characterization of new Atens and IEOs, seems a sufficient rationale for proposing a dedicated IR satellite for NEO observations. According to preliminary evaluations, the cost of such a mission seems reasonably low (Cellino et al. 2000). The "trick" here is that for NEO observations it is not necessary to observe in the far-IR, and the resulting temperature constraints for the optics and baffle of an orbiting satellite can be met by purely passive cooling, without the need of heavy tanks of liquid H or He. Only the IR array would need cooling in this mission concept, and this may be achieved by means of a simple active cooler. Following preliminary estimates, a dedicated satellite carrying aboard a modest-sized telescope (70 cm) and very simple focal plane assembly (one CCD for visible wavelengths, and one IR array for thermal IR) would be able to discover 75% of the existing Atens and 50% of the existing IEOs larger than 500 m, in two years of operation. Though being dedicated to NEO observations, this instrument would also certainly produce wonderful data for other fields of modern astrophysics, at least during the fraction of time dedicated to the Aten and IEO survey.

4. Conclusions

Mid-IR observations will be essential in the near future in order to improve our knowledge of the physical properties of NEOs. There are both purely scientific and safety reasons (mitigation of the impact hazard) to pursue this objective. A space-based instrument appears to be *a priori* the best possible solution in order to have at disposal an instrument capable of deriving NEO sizes and albedos, and at the same time discovering large numbers of Atens and IEOs. On the other hand, it is clear that a dedicated satellite does not exist in practice, and is not planned for the near future. While it is worth while to continue the necessary studies and to make new proposals to the most important Space Agencies in the next years, some back-up solution must also be identified. Some possibilities can come from future approved space missions like the ESA cornerstones BepiColombo and GAIA. Both the above missions will be able to detect many NEOs, including Atens and IEOs, and GAIA should also be able to make some spectral characterization of them. But neither GAIA nor BepiColombo will be able to derive accurate size estimates in most cases, since they will not carry aboard the necessary mid-IR arrays for accomplishing this. Speaking about ground-based facilities, some opportunities might be offered by the development of IR observing stations in Antarctica. It is clear that these latitudes are not ideal from the point of view of the possibility of scanning regions of the sky where many NEOs are preferentially located (at small ecliptic latitudes, then mostly low above the horizon from Antarctica). However, the extremely good quality of the environment for IR observations might partly compensate for the above draw-back. For this reason, the planetary community will keep being very interested and will possibly contribute in the developments of IR activities from Antarctica.

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