Chapter 1

Introduction

1.1 Asteroids

Asteroids are a population of “small bodies” orbiting the Sun at distances ranging from inside the orbit of the Earth to beyond Saturn’s. Other objects with orbital semi-major axes beyond the orbit of Neptune have been recently discovered. These are the so-called Kuiper Belt Objects (KBOs) which, although sharing the asteroid nomenclature, are more closely related to comets. Asteroids are thought to be remnants of the building blocks that formed the planets 4.6 G.y. ago. Therefore, they conserve the record of the primordial material and possibly the initial conditions existing in the solar nebula at the time of the planet formation process. The nature, size and orbital distribution, as well as the evolution of asteroids are crucial for the understanding of the formation and evolution of the planets and the entire solar system. The large majority of asteroids orbit the Sun between Mars and Jupiter in the so called Main Belt, but one of the most important legacies of planetary science of the last century is the discovery of a population of small bodies orbiting the Sun in the near Earth space.

Crossing the region of the inner planets is a heterogeneous population of minor bodies coming from almost everywhere in the solar system, the so-called near-Earth objects or NEOs. NEOs include also some nuclei of extinct comets. NEOs of asteroidal origin are called near-Earth asteroids (NEAs). The crater record on the inner planets, on our Moon and on the Earth demonstrates how NEAs (asteroids dominate the population of crater-forming bodies in the inner solar system) have punctuated the history of the terrestrial planets with large scale impacts and that they will continue doing so (Ivanov et al., 2002). The study of asteroids, and in particular of NEAs, is therefore ultimately related to the history and evolution of the Earth’s biosphere and, so to say, to the past and future existence of life on our planet. For instance, over the last two decades, it has been convincingly argued that the impact of a multikilometer asteroid or comet 65 m.y. ago led to a mass extinction event that eliminated the dinosaurs (e.g., Alvarez et al., 1980). In addition, asteroids offer a source of volatiles and an extraordinarily rich supply of minerals that can be potentially exploited for the exploration and colonization of the solar system in the twenty-first century.

The following paragraphs are devoted to a description of the major characteristics of asteroids relevant for this study. An extended and up-to-date overview of asteroids is given by Bottke et al. (2002a). It is of interest to compare the rapid growth of new scientific findings and discoveries in the last 10 years to what we already knew in 1989 (e.g. Binzel et al., 1989).

1.2 Main Belt Asteroids

Nowadays, more than two hundred thousand asteroids are known orbiting the Sun in the Main Belt. The biggest object, 1 Ceres, about 900km in diameter, was the first asteroid to be discovered back in 1801 by Giuseppe Piazzi. 2 Pallas and 4 Vesta are about 500 km large and 10 Hygiea, the fourth bigger asteroid, has a diameter of about 400 km. The number of asteroids rapidly grows as their size decreases. The size-frequency-distribution (SFD) of Main Belt Asteroids (MBAs) can be expressed mathematically as a power law: $N(>D) = K\ D^{-b}$, where b is the cumulative diameter population index. Although there is evidence for a variable index in the size distribution of asteroids, the value of b for relatively small objects (50-10km) lies between 1.95 and 3.0, according to different extrapolations. It is recognized how the size frequency distribution of MBAs is a direct consequence of the collisional evolution (Davis et al., 2002) that asteroids experienced during their history. Dohnanyi (1969) predicted that an asteroid population in collisional equilibrium should eventually evolve to a SFD with a cumulative power law slope index of –2.5. However, it is widely believed that the largest asteroids (although where “largest” begins is a debated question) are primordial objects whose sizes have not been significantly altered by collisions. There are indications that the whole asteroidal population made of objects with diameter smaller than about 400 km is collisionally evolved. However, the slope index of the actual SFD does not follow exactly Dohnanyi’s law. This is due to the fact that effects of collisions are not independent on the size of the bodies as Dohnanyi’s hypothesis assumes.

Collisions have modified not only the size frequency distribution, but also the orbital distribution of MBAs: it is worth to point out here how a plot of asteroids orbital eccentricities as a function of the semi-major axis reveals a non uniform distribution, as shown in the picture below. The figure has been obtained by plotting the synthetic proper elements[2] of 71291 numbered asteroids calculated by Knezevic and Milani. The database of asteroid proper elements is available on-line from the web page of the AstDys service at: http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo?proper_elements:0;main

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[2] proper elements are quasi-integrals of motion, and thus represent the "average" characteristics of motion over very long time spans. See Z. Knezevic et al. 2002 or visit, for instance, the help page of the AstDys database, manteined on-line at http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo?help:0;menu

One of the major features clearly visible in Fig. 1.1 is the presence of significant clumpings of objects already identified by Hirayama in 1918 as "families" (Hirayama, 1918). There are approximately 25 reliable families and over 60 statistically significant clusters identified in asteroid proper orbital elements (see Zappalà et al., 2002 and Bendjoya and Zappalà, 2002 for detailed discussions of asteroid families). Hirayama used the term "families" because he believed to be the outcome of the catastrophic disruption of a parent body and indeed, confirmation of their likely collisional origin from dedicated spectroscopic campaigns has been a major result. Detailed studies of the physical properties of these "groupings" have been carried out (see Cellino et al. 2002).

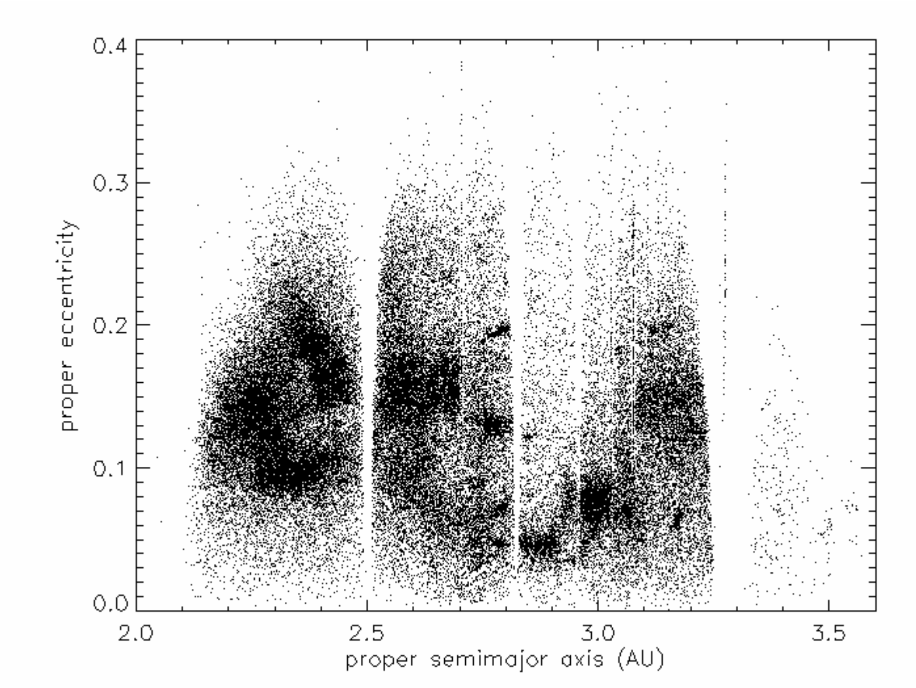

Fig. 1.1 Plot of the semi-major axis versus eccentricity fro main belt asteroids. Note the presence of significant clumpings of objects already identified by Hirayama in 1819 as "families" and the the Kirkwood gaps.

Asteroid shapes are also a direct consequence of their collisional evolution that these objects have experienced during their histories. They range from rather spherical to elongated concave and irregular, indicative of a fragmental origin. The easiest way to infer information about asteroid shapes is from their lightcurve, which is primarily related to the varying illuminated portion of the cross section visible to the observer as the asteroid rotates. Typical rotation period are about 9 hours with extremes ranging from under 3 hours up to several weeks.

Moreover, a common side effect of asteroid collisions is the production of ejecta and regolith. Polarimetric observations (e.g. Dollfus et al., 1989) have suggested that large asteroids have a thick layer of regolith covering their surfaces. However, regolith has also been observed directly on smaller objects such as 951 Gaspra and the near Earth asteroid 433 Eros. The discovery of a deep layer of regolith on objects with low escape velocities was somehow surprising. Moreover, on the asteroid 253 Mathilde, the existence of large scale craters whose boundaries are adjacent one to another and whose diameters are almost comparable with the radius of the asteroid, made necessary to review our knowledge of the bulk porosity and surface composition of these bodies.

As a matter of fact, although the orbital distribution of asteroids has been known since a long time, a clear picture of the compositional structure and distribution was obtained only at the end of the '80s. On the basis of visible spectroscopy and/or UBVRI color photometry, it was possible to identify two broad classes: neutrally colored asteroids were labeled "C" type and more reddish objects were classified as "S". The letters were chosen for spectral similarities with carbonaceous (C) and stony (S) meteorites. C types appear to be more abundant in the outer part of the belt, while S types are more prominent in the inner. By 1979 two other major classes were added: E (enstatite) and M (metallic). The Eight Colors Asteroid Survey – ECAS – (Zellner et al., 1985) gave a strong boost to the asteroid taxonomic classification and the observations collected by the Infra-Red Astronomical Satellite (IRAS) (Tedesco et al., 1992) allowed the albedo for more than 2000 asteroids to be derived and a cross correlation with taxonomy to be performed. C type asteroids were found do be predominantly dark with an albedo in general no higher than 0.10. S type objects correlate with intermediate albedos ranging from 0.10 to 0.25. Likewise do M type asteroids. Although E types show reflectance spectral or color feature very similar to M types, their albedo is higher: from 0.25 to 0.60.

Another important feature clearly visible in Fig. 1.1 is the presence of gaps (the Kirkwood gaps) in correspondence with orbital resonances with Jupiter. It has been shown that test bodies entering several powerful mean-motion resonances with Jupiter (e.g., 3:1, 4:1, 5:2) can have their eccentricities pumped up to Earth-crossing values, usually over timescales of ~1 million years. In some cases, orbital motion inside these resonances is chaotic enough that test bodies can be pushed directly onto Sun-grazing orbits. Similarly, the υ_6 secular resonance, lying along the inner edge of the main belt, is now seen as one of the primary sources of near-Earth objects (see Morbidelli et al, 2002a, for further details).

Dynamical calculations (see, for instance, Morbidelli et al., 2002a; Bottke et al., 2002a) show that typical orbits for NEOs are chaotic and non stable. Lifetimes for NEOs are of a few million years with these objects finally ending up with a crash into the Sun, being ejected from the solar system, or impacting one of the inner planets. Given such short lifetimes, the present NEO population cannot be made of objects that orbits amongst the inner planets since the beginning of the solar system: NEO population must have some source of resupply.

Years of work in the field of Celestial Mechanics have shown that the near-Earth Objects come mainly from 5 sources :

1. the ν6 resonance region at the inner border of the asteroid main belt,
2. the 3:1 resonance region in the middle of the asteroid main belt,
3. the Intermediate Mars-Crossing (IMC) population,
4. the Outer Belt (OB) population,
5. the population of dormant Jupiter Family Comets (JFC).

Moreover, non-gravitational forces like that produced by the so-called Yarkovsky effect[3] (e.g. Bottke et al., 2002b and references therein) may play an important role in allowing small asteroids and asteroidal material to undergo a drift in orbital semimajor axis and eventually escape the main belt by entering a mean-motion and/or a secular resonance. The general scenario, very much simplified in the scheme which follows, for how asteroids are delivered from the main belt to the inner solar system (and Earth) is the following: an asteroid undergoes a catastrophic disruption or cratering event and ejects numerous fragments; most are not directly injected into a resonance. Fragments with diameter smaller than 20 km start drifting in semimajor axis under the Yarkovsky effect . These bodies jump over or become trapped in chaotic mean-motion or secular resonances that change their eccentricity and/or inclination. These resonances are capable of pushing them onto planet-crossing orbits. From here, they may become directly members of the NEA populations. Alternatively, objects may be trapped on Mars-crossing orbits and, eventually, a close encounter with Mars modifies their orbits such that they become NEAs.

1.3 Physical characteristics of Near Earth Asteroids and Near Earth Objects

The near-Earth object population includes asteroids, active and extinct comets and the precursor bodies for meteorites. NEOs are defined as those small bodies having perihelion distances $q \leq 1.3$ AU and aphelion distances $Q \geq 0.983$ AU. For objects which clearly do not display any coma or cometary activity or simply presuppose an asteroidal origin, the term near-Earth Asteroid (NEA) is used. Subcategories of the NEA population include the Apollos ($a \geq 1.0$ AU, $q \leq 1.0167$ AU) and Atens ($a < 1.0$ AU, $Q \geq 0.983$ AU), which are on Earth-crossing orbits, and the Amors (1.0167 AU $< q \leq 1.3$ AU), which are on nearly-Earth-crossing orbits. A population inside Earth's orbit ($Q < 0.983$ AU), the so-

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[3] The Yarkovsky effect is a thermal radiation force due to the reactive force of emitted thermal radiation that causes objects to undergo semimajor axis drift and spinup/spindown as a function of their spin, orbit, and material properties.

called IEOs or inner-Earth Object, is also expected to exist (see Morbidelli et al., 2002a; Michael et al, 2000)[4]. These classes are based on osculating orbital elements and it is possible for a NEA to move from a class to another one. It is not possible to compute proper orbital elements for NEAs since dynamical lifetimes for the planet crossing asteroids are short ($<10^7$ yr) compared to the age of the solar system. Gravitational interactions with planets lead to their ejection from the solar system or to planetary impacts or to they fall into the Sun. However, Milani et al. (1989) studying the orbital evolution of a sample of NEAs over a time span of 200 thousand years, proposed six dynamical classes, named after the best-known and most representative object in each class: Geographos, Toro, Alinda, Kozai, Oljato, and Eros.

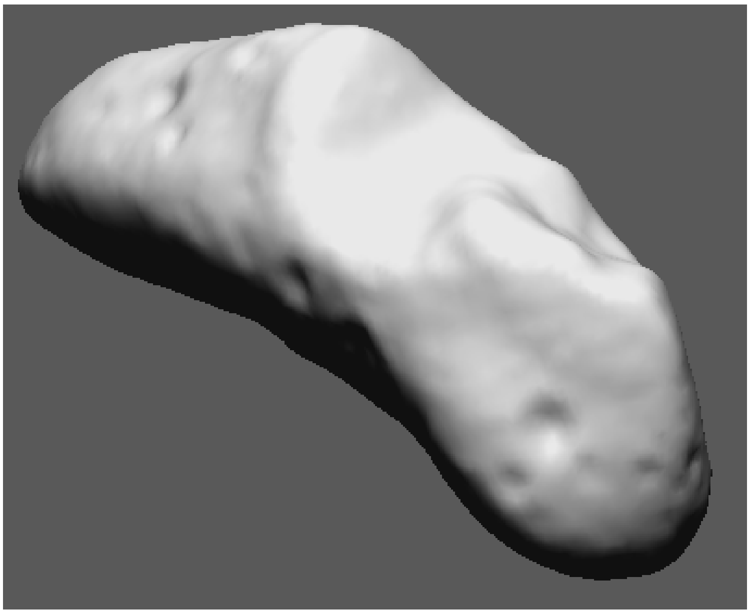

Fig. 1.2 Three-dimensional rendering of the shape model of the near Earth asteroid 433 Eros obtained by the NEAR-Schoemaker mission. This rendering has been calculated using the freely distributed computer program Wings 3-D.

NEAs are small objects: the largest known object is 1036 Ganymed, whose spherical equivalent diameter is about 39 km. For the second biggest NEA, 433 Eros, size and shape have been accurately measured by the NEAR-Schoemaker spacecraft, which orbited the asteroid for almost one year. Its elongated and concave shape measures 13 x 13 x 33 km (Thomas at al., 2002).

Several NEAs have been extensively studied by radar (Ostro et al., 2002). Radar observations showed the large variety of shapes within the NEA population. Spheroids and highly elongated shapes, contact-

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[4] We recall that Q=0.983 and q=1.017 are the values for the Earth.

binary shapes, and binary systems have been revealed down to a size of few hundreds meters (Ostro et al., 2002; Zaitsev et al., 2002). By measuring the total echo power in the two opposite circular polarization, radar is also able to estimate the roughness of the surface at centimeter scale. A large range of polarization ratios have been measured. Their values vary from nearly one, which is an indication of extreme roughness, down to almost zero, which, on the other hand, is an indication of a perfectly smooth surface. Not only radar can provide such an amount of information: it has been recently shown how information about the shape of an airless body can be successfully derived if disk integrated visible photometry is available for a large variety of illumination and viewing geometries (Kaasalainen et al., 2002). NEAs are in this respect the ideal case: they are often observed under a large range (from zero up to more than hundred degrees) of solar phase angles due to their proximity to the Earth and the power of the lightcurve inversion methods can be fully exploited. Furthermore, lightcurve inversion methods allow the direction of the asteroid rotation axis to be determined along with the shape.

Accurate shape models and pole directions for small NEOs open the door to a wide variety of theoretical investigations that are crucial to our understanding of the nature, origin, and evolution of these objects (e.g. Ostro et al., 2002; Kaasalainen et al., 2002). Moreover, the availability of three-dimensional shapes for a number of well studied NEOs is of crucial importance for the investigation of asteroid surface thermal properties and for the calibration of the models of asteroid thermal emission.

NEOs display a wide diversity not only in shapes and sizes, but their physical properties show a broader range of values comparable to what is seen across the entire main belt, consistent with their being supplied from more than one source region. This larger diversity with respect MBAs is also due to the fact that those objects are fifty times the sizes and five orders of magnitude more massive than a typical 1km NEO. Besides meteoritic and dust material, NEOs are amongst the smaller objects in the solar system that we can study. Almost all taxonomic classes of main-belt asteroids are represented among classified NEOs, including the P- and D-types most commonly found in the outer asteroid belt, among the Hilda and Trojan asteroids, or possibly among comet nuclei.

Fig. 1.3 shows that the large majority of NEAs known to-date belongs to the S type taxonomic class, which indicates the inner part of the Main Belt is the major supply region where NEOs come from. However, Binzel et al. (2002), Lupishko and Di Martino (1998), Luu and Jewitt (1989) describe how a bias factor in favor of the discovery of S type NEOs might play a major role in defining the taxonomic type distribution of this population. Given their higher albedo, in limited magnitude surveys, S type asteroids are more likely to be discovered. Moreover, the fall off of the apparent brightness of the darker C types as a function of the solar phase angle is stronger than for S types. Therefore, since NEOs are often discovered at large phase angles the coupling of the two effects might explain the lack of dark objects within the population known so far. Benedix et al. (1992), Lupishko and Di Martino (1998), and Whiteley (2001) all find that after applying bias-correction factors to the observed NEO population, at any given size there are relatively equal proportions of C- and S-type objects within near-Earth space[5].

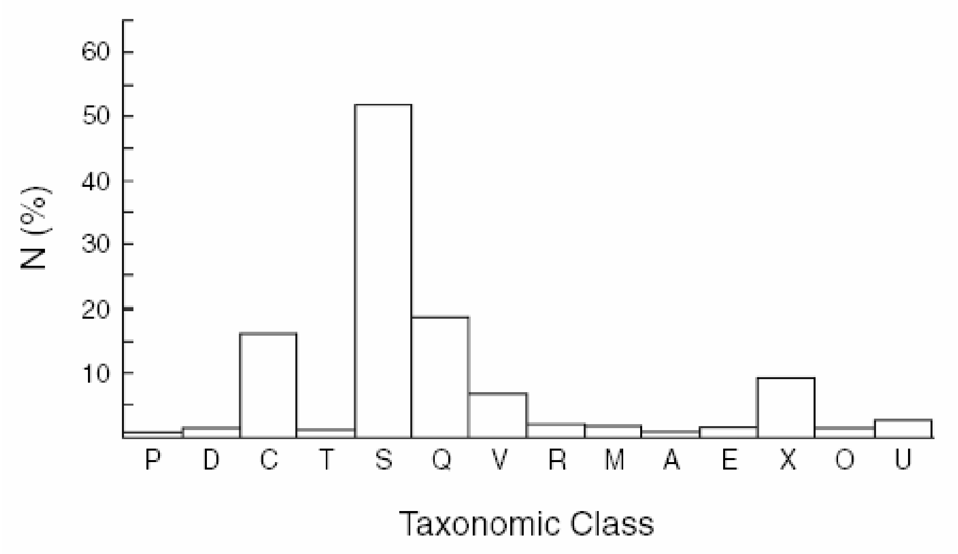

Fig. 1.3 Histogram of the relative proportions of measured taxonomic properties for more than 300 NEOs listed in Table 1, Binzel et al. 2002.

The study of NEO taxonomy and reflectance spectroscopy has always been of great interest in the search for the precursor bodies of the most common types of meteorites: the ordinary chondrites. A long debate over whether the most common (in near-Earth space) S-type asteroids are related to the most common meteorites is outlined by Clark et al. (2002) and by Binzel et al. (2002). This debate has been raised by the fact that over the last 30 years several studies have compared reflectance spectra of asteroids to measurements of meteoritic samples performed in the laboratory. Although links between some asteroidal taxonomic class and some meteoritic population have been found (e.g. V-type asteroids and EHD meteorites), statistically asteroids and meteorites show consistent offsets in spectral parameters such as the depth of some absorption bands as shown in Fig. 1.4. A space weathering effect, i.e. the aging of the asteroid surface due to its exposure to the space environment, has been invoked to explain these spectral alterations.

Chapman (1996) describes the discovery of terrains with different spectral properties on asteroids 951 Gaspra and especially 243 Ida from data obtained by the Galileo spacecraft. This is the

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[5] A bias-correction analysis of the main belt performed by Zellner (1979) suggests that C-types dominate among all main-belt asteroids by as much as 5:1.

demonstration of a "space weathering" process operating on their surfaces, which modifies the reflectance spectra of fresh material to be redder, straighter, and have shallower absorption bands. It operates in the sense that would tend to convert spectra of ordinary chondrites to have the spectral signature of S-type asteroids. These results appear to resolve the major obstacles of the long standing "S-type conundrum" about the provenance of ordinary chondrite meteorites.

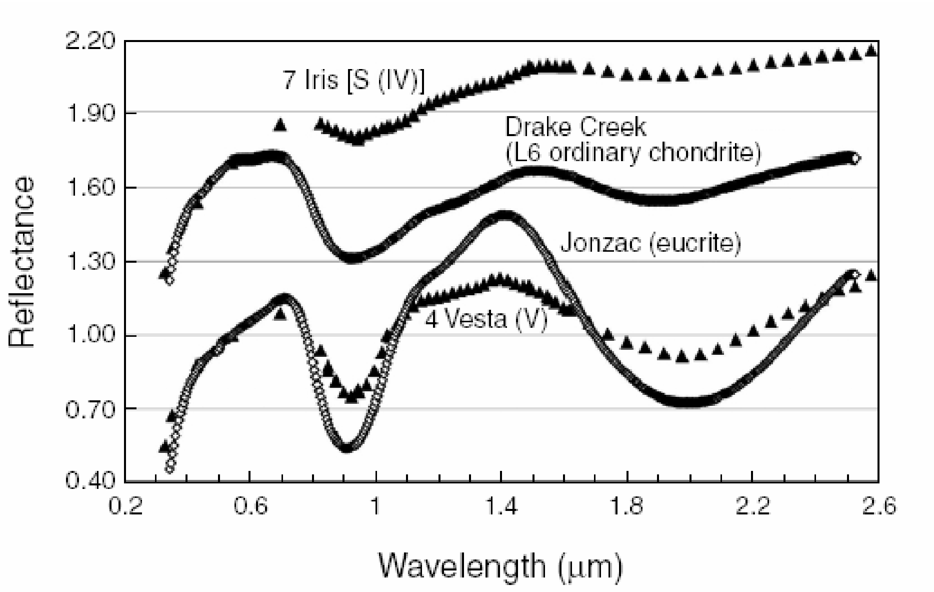

Fig. 1.4 Two examples of reflectance spectra of asteroids along with their meteorites analogs. One explanation for the spectral mismatches is that space weathering processes affect the surfaces of the asteroids, altering them from their original spectral properties. Figure obtained from Clark et al., 2002.

The physical investigation of NEAs, in this respect, opened the door to the possibility of measuring reflectance spectra of small objects not observable in the Main Belt. Within the NEA population, a continuous distribution of spectral properties ranging from the spectral signature common for S type asteroids to the spectrum of ordinary chondrites has been observed. This result is consistent with a size dependent trend indicating that smaller NEAs have younger and fresher surfaces therefore less weathered which most likely display spectral signature resembling that of the ordinary chondrites. For a detailed discussion of space weathering on asteroid surfaces see Clark et al. (2002).

Despite the above-mentioned important improvements that have been made in recent years in understanding the origin and nature of NEOs, many answers are not yet conclusive, and a number of critical problems are still open and deserve further investigations. Although much effort has been devoted in our understanding of the origins of NEOs from a dynamical point of view and in modeling the dynamical transport mechanisms from the main asteroid belt to the region of the terrestrial planets, one of the major problems remains the currently insufficient effort devoted to physical characterization (see Cellino et al., 2002b). A short list of the most fundamental open issues in this respect includes:

1. An assessment of the real inventory and size distribution of NEOs down to small sizes, well below 1 km. An accurate size distribution is the key to integrating the total NEO population for hazard assessment and optimizing survey strategies.
2. A reliable albedo distribution of the NEO population, which can yield to a precise assessment of the contribution of comets, extinct comets and dark objects to the overall NEO inventory.
3. A real understanding of the internal structures of these objects: i.e. are they monolithic, or loose aggregates of chunks of rock held together by gravity? This issue is of crucial importance for the development of effective techniques of orbital deflection and impact mitigation.
4. A better assessment of the real distribution of different taxonomic classes in the NEO population and a clear picture of the way these taxonomic classes correlate with albedos.

1.4 The need of physical characterization of NEOs: statement of the problem

The albedo – the percentage of incoming solar light that the surface of the object reflects – is a fundamental physical parameter for an asteroid. The albedo is the missing link in determining the nature of the NEO population. The distribution of albedos and its correlation with the taxonomic types and the orbital elements of NEOs is the key to understanding their nature, their origin and to obtaining a reliable size distribution for this population of objects (i.e. knowledge of the albedo distribution allows converting the NEO absolute magnitude distribution, which is now well constrained, into a size distribution which, at present, is not). This information is crucial for developing and improving reliable and truly debiased NEO population models (Bottke et al., 2000; 2002a; Morbidelli et al., 2002b). Such models are crucial for the assessment of the impact hazard that NEOs pose to civilization on our planet. The NEO albedo distribution is also crucial to addressing asteroid-comet relationship: could a significant fraction of NEOs be the nuclei of extinct short-period comets? The likely contribution of comets to the NEO population is still an open question.

Unfortunately, upon discovery the only physical information for a NEO is its absolute visual magnitude, H. For albedos in the range 0.05-0.3 (typical of main belt asteroids), an object having an absolute magnitude equal to 18 has an uncertainty in the diameter ranging from 0.6 and 1.5 km. Clearly, this error, larger than a factor of two, makes any reliable assessment of the size distribution of the NEO population very uncertain. Moreover, the typical accuracy of H values for a NEO is of the order of 0.5 magnitudes due to (1) the low signal to noise ratio of the measurements performed by automated discovery surveys, (2) the ambiguity introduced by light curve effects and (3) the often rough data reduction procedure which does not use filters and standard stars from photometric catalogues. Taking into account this large uncertainty on the H value the error on the diameter is thus even larger.

Even though more than 2400 NEOs have been discovered to-date, a reliable albedo is known for less than 40-50 objects only. The size distribution of the total population is therefore very uncertain and, at present, it relies on assumed average values of the albedo (usually derived by extending taxonomic schemes valid for the main belt, to the NEO population) to convert the absolute magnitude distribution into the size distribution. Werner et al. (2002) considered size-dependent values of the visual geometric albedo, namely $p_V = 0.11$ and $p_V = 0.25$, for objects with diameters above and below about 1 km. Stuart (2001) used $p_V=0.11$, while Bottke et al. (2000) assumed $p_V \approx 0.15$.

Color information obtained with visible wavelength measurements (UBVRI-photometry or spectroscopy) can be used to classify asteroids into broad compositional types (taxonomy), restricting the albedo uncertainty to within the ranges of 0.05-0.15 for C-type objects and 0.10-0.30 for S-type asteroids. Those albedo ranges which are too broad for any reliable diameter determination are based on measurements obtained for main-belt asteroids, which sizes are in general larger than 50 km of diameter. It is worth to point out here that those objects are fifty times the sizes and five orders of magnitude more massive than a typical 1km NEO.

At present, no reliable information for the albedo range of C-type and S-type NEOs exists. There is evidence that NEOs and small asteroids in general might have a different albedo distribution than larger main-belt asteroids. Studies of the albedos derived by IRAS had shown how the albedo distribution of main-belt asteroids smaller than 50 km has different properties than the one of larger bodies (i.e. the mean albedo increases with decreasing diameter and the clear separation between C-type and S-type asteroids vanishes at the smaller sizes: see Tedesco et al., 1993, for instance). It is not clear whether this is a real effect or it is due to the low signal to noise ratio of IRAS measurements for asteroids of that size. Cellino et al. (1999, 2003) are currently carrying out a campaign of polarimetric observations of small (D<50 km) asteroids observed by the IRAS satellite in order to obtain independent albedo estimates of these objects. Although some indication that IRAS-derived albedos tend to be on the average slightly higher than polarimetric albedos, further data are necessary to draw definitive conclusions.

Moreover, it is not clear whether the present asteroid taxonomic scheme, which is based on the visible spectra and albedos of main-belt asteroids, may be directly applicable in the case of NEOs. For example, in the case of two NEOs with optical reflection spectra typical of C-type asteroids it was derived a radiometric albedo much higher than the value inferred from the taxonomic classification (e.g., Harris et al., 1998; Harris and Davies, 1999). There appears to be several examples of high-albedo C types asteroids in the main belt as well (Harris, 2001).

Assumed values for the albedo on the basis of taxonomy are therefore not only very uncertain, but they might be even affected by large systematic errors.

1.5 Scope of this work

This work aims to significantly increase the sample of NEOs for which size and albedo are available thereby contributing to the first physically based NEO population size distribution.

Albedos and sizes of NEOs are derived by means of the so called radiometric method. This technique makes use of measurements of the thermal infrared radiation that the object emits at mid-IR wavelengths (5–20 μm) and of its visible reflected light, combined with a suitable model of the surface thermal emission (thermal model).

Albedo measurements have been obtained for a sample of carefully selected objects of the NEO population for which reliable reflection spectra and taxonomic information are at disposal. This is to study the correlation of albedos with spectral types and possibly constrain the albedo range for the various compositional classes found within the NEO population.

Gathering data for objects which sizes and/or albedos have been measured with independent techniques (such as radar or polarimetry) is crucial to explore the limitations of the thermal models used in the analysis. A major aspect of the research is the improvement of the models of the thermal infrared emission of asteroids to facilitate the determination of sizes, albedos and other physical parameters of NEOs.