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Minor bodies: small actors in Solar System's history

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Abstract. The so-called Minor Bodies are very interesting and important for our understanding of the origin and history of our Solar System. We review here many reasons why the study of these bodies is an essential branch of modern Planetary Science. Due to space constraints, the focus is mostly on the asteroids, the small bodies that orbit the Sun mainly in the region of transition from the inner Solar System to the region of the outer planets. Both theoretical as well as practical considerations concerning the importance of these bodies are presented, to convince the readers that these bodies are not a kind of uninteresting "big pebbles", as often believed by non-specialists, but fascinating subjects for exciting astrophysical investigations.

1. Introduction

During the night of April 26, 1861, Giovanni Schiaparelli discovered a new asteroid, which was later named (69) Hesperia. In his long activity as an observer, this was his only one asteroid discovery. To put things in their historical context, it may be useful to remind what was the state of asteroid science at that epoch.

The first asteroid, (1) Ceres, had been discovered in 1801 by Giuseppe Piazzi. The existence of a "missing planet" orbiting between Mars and Jupiter had long been suspected due to the fact that the sequence of values of of the orbital semi-major axes of the known planets appeared to be described by some kind of simple mathematical relation, long known as Titius-Bode law. In that sequence, a predicted value of about 2.8 Astronomical Units for the orbital semi-major axis of a hypothetical body orbiting between Mars and Jupiter did not correspond to any known planet. For that reason, several observers had undertaken a search for this supposedly "missing planet", and the discovery of Ceres seemed to represent a triumph of this observational effort, at the same time supporting an interpretation of the Titius-Bode relation in terms of an expression of some still unknown, but real physical law. The situation was going to evolve quickly, however. Within a few years, other new moving objects were discovered around the ecliptic. These discoveries had the merit to open a new exciting field of investigation for the mathematicians and astronomers of the time, namely the development of the techniques needed to solve the problem of the computation of the orbit of moving bodies based on their recorded celestial coordinates measured in different epochs. The great mathematician K. F. Gauss developed the mathematical tools and procedures to solve this problem (Gauss 1809), and his method is still known by today students. It was so discovered

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that the newly discovered celestial bodies were actually orbiting in the region between Mars and Jupiter. The body discovered by Piazzi was actually very close in semi-major axis to the value expected by the Titius-Bode relation for the missing planet. However, Ceres turned out to be faint, suggesting that this new object had to be really tiny compared to the known major planets. The same was true for the other new bodies that begun to be discovered since then, at an increasing rate. The brightest of these objects, soon collectively named ”asteroids”, was (4) Vesta, which reaches an apparent magnitude slightly beyond the detection limit for human eye at the epochs of its maximum apparent brightness.

Instead of a missing planet, a new population of minor bodies had therefore been discovered. The discovery rate increased rapidly with the improvement of telescopes and the development of better detectors than the human eye. Today, the number of *numbered* asteroids, namely those having been observed during more than one opposition, and having orbits accurately determined, exceeds $250,000$, but the real number of existing objects is much higher. Asteroids, comets (already well known at the time of Schiaparelli), Trans-Neptunian objects (discovered only starting since the 80s of XX Century), meteoroids, are now collectively known as the minor bodies in our Solar System. They constitute a heterogeneous population of objects with different properties and individual histories. The main differences among them seem to arise mainly from differences in the regions of original birth, comets and TNOs having been accreted at larger heliocentric distances than the asteroids, and on consequent differences in the abundance of volatile elements in their overall compositions. What makes all the minor bodies so interesting for modern investigations in Planetary Sciences is the fact that many of them are thought to be very primitive, their physical properties having been poorly modified since the epoch of their formation. As a consequence, these bodies can provide essential information on the physical environment that characterized different regions of the Solar System at the epoch of planetary formation.

It is not possible to give in the limited space of a short article a satisfactory description of the variety of existing minor bodies. For this reason, in what follows we will focus on the asteroids, and we will try and explain some reasons why these bodies are still so interesting 150 years after the discovery of (69) Hesperia by Schiaparelli. In focusing on asteroids, we should not forget that according to recent studies, the differences between different kinds of minor bodies, in particular between asteroids and comets, might be not very sharp. In particular, the recent discoveries of asteroids exhibiting a cometary activity (Hsieh 2009), and possibly containing water, tends to indicate that some classical ideas about the distinctions between minor bodies will possibly change significantly in the near future.

2. Asteroids as interesting astrophysical bodies

For a long time, asteroids were considered essentially as a “zoo” of small bodies exhibiting interesting dynamical properties, being subject to important gravitational perturbations by the major planets. In particular, the effect of different kinds of possible resonances on the orbital motion, including mean-motion resonances (mainly with Jupiter), and secular resonances can produce spectacular orbital changes, which can be sufficient to transfer objects to different regions of the Solar System. This makes also possible the occurrence of close encounters with some of the major planets, including the Earth, with potentially catastrophic consequences for the biosphere of our planet. Asteroidal bodies with orbits that sweep the region of the terrestrial planets are collectively named near-Earth asteroids (NEA). This fact is at the basis of a well known and popular field of investigation in asteroid science, namely the discovery of potentially hazardous objects (PHO) among the population of existing near-Earth objects (NEO, including both NEA as well as a number of extinct cometary nuclei orbiting in the inner region of the planetary system), and the development of credible hazard mitigation strategies. The governments of several countries are cur-

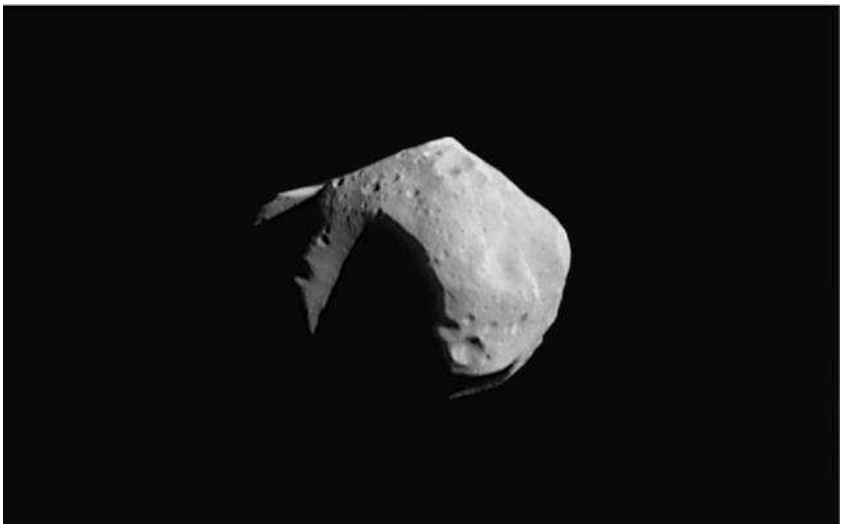

Fig. 1. Image of the asteroid (253) Mathilde obtained during the *rendez-vous* with the Galileo space probe. Mathilde is 60-km in size, and an evident property of this asteroid is the presence of very large craters having sizes of the order of the radius of the object. It was previously believed that no asteroid could sustain impacts producing such a big craters without being completely pulverized by the event.(Courtesy of NASA)

rently investing resources to support NEO research programs, since it has been recognized that the risk is not negligible. In fact, it is now commonly accepted the interpretation of some important events of mass extinctions occurred in the past on the Earth as having been the effects of collisions with km-sized interplanetary bodies.

In this paper, however, we are mostly interested in explaining other reasons why it is so interesting to study asteroids. Compared to Schiaparelli and the astronomers of his time, the planetary scientists of our generation have been lucky enough to live the transition from an epoch in which asteroids were essentially unresolved star-like objects producing tracks in photographic plates, to the present epoch in which we have at disposal a wide variety of information concerning the *physical properties* of these bodies. This allows us to characterize many asteroids as real, tiny ”worlds” exhibiting individual properties. The biggest asteroid, (1) Ceres, with a nearly spherical shape and a diameter around $1,000$ km, is now officially classified as a dwarf planet according to the criteria approved by the International Astronomical Union in 2006. The different pieces of information at our disposal about asteroids have been and are produced by the application of a variety of remote-sensing techniques, including visible and IR photometry, spectroscopy, polarimetry, radar, high-resolution imaging, as well as by *in situ* investigations by means of space probes (see, for instance, Fig. 1). In particular, the wealth of data at our disposal is such that some common beliefs and prejudices spread among both non-specialists and, unfortunately, also among several professional astrophysicists, are now completely wrong, and should be eradicated. In particular, we want to express our point of view here in a synthetic, not orthodox, but hopefully mind-provoking way. Let us then state clearly that, although the asteroids are known to be, in general terms, small rocky bodies, this does *not* mean that they are simply a kind of big, uninteresting pebbles. As a matter of fact, by the way, pebbles are *not* uninteresting, since they are aggregates of minerals, which in turn are solid-state chemical compounds. Rocks have long and fascinating histories, which may date back down to the early epochs of formation of our Solar System. Therefore, asteroids are indeed interesting targets for astrophysical studies. Even if they are so small and close to the Earth.

There is much we want to understand about asteroids. In principle, we would like to know how many they are, what is the distribution of their sizes, what are they made of, what is their internal structure and their density, what are their rotational properties, what is their history, how and when they formed, what kind of evolution they experienced since the epoch of their birth, and, more in general, what kind of information they can provide us concerning the formation of our planetary system. For some of the above questions we have already some satisfactory answers, as we will see in the next Section, whereas problems are still open about questions mainly concerning the internal structure of the bodies, and their densities. The problem of density is a particularly tough one, since we have at disposal only very limited information on the *masses* of the asteroids. This is trivially due to the fact that they are small, and the effect of their masses on the motion of other bodies, including the planet Mars and the asteroids themselves in case of mutual close encounters, is generally extremely small and beyond any measurement capability. In recent times, however, things are starting to change: on one hand, the discovery of binary systems (see Fig. 2) has opened new perspectives, since measurements of the orbital period of the companion can lead to infer the total mass of a system. On the other hand, in a few years a new astrometric space mission of the European Space Agency, Gaia, will be launched and is expected to achieve such great astrometric performances as to being able to measure the tiny orbital deflections experienced by small asteroids experiencing close encounters with some of the biggest objects present in the asteroid Main Belt. According to current expectations, masses for about 100 asteroids should be determined with satisfactory accuracy by Gaia.

3. Origin of the asteroids

In the past, for many decades it was believed that Main Belt asteroids, namely the vast majority of objects orbiting mostly between 2.1 and 3.3 AU from the Sun, were a swarm of fragments produced by the disruption of a single planet originally formed in that region. It is likely that this interpretation could have been considered as plausible and exciting by the astronomers belonging to the generation of Schiaparelli, and to many who came later. The reason was that this interpretation would fit nicely with the belief that the Titius-Bode relation was a real physical law, although difficult to explain based on known physical principles. If a planet had to be there according to Titius-Bode, and what we see instead is a huge number of minor bodies, it would be tempting to conclude that these bodies are the products of the disruption of this missing planet. This conjecture was mentioned and supported in the past in many books.

The above theory on the origin of the asteroids is no longer accepted by the specialists, due to a number of reasons. One reason is that planets do not explode. The only one possible mechanism to disrupt a planet is given by an extremely violent collision with another body having a comparable size, but such an event seems extremely unlikely. Moreover, the requirement of spreading the fragments over such a wide interval of heliocentric distances is also barely impossible to be satisfied based on what we know about the outcomes of catastrophic collisions. According to commonly accepted models, the Earth itself suffered an extremely violent impact with a Mars-sized body very early in its history, but the effect of such an impact was ”only” to create the Moon.

Moreover, the origin of the asteroids cannot be conceived as a separate process, but it must be included in the general scenario of the formation of the whole planetary system. In this respect, commonly accepted models are based on the concept of planetary accretion from early planetesimals formed within a proto-planetary disk of gas and dust. In this scenario, asteroids, too, should have been formed by accretion of small planetesimals, not by fragmentation of a larger body. The reason why planetary accretion was apparently stopped in the region corresponding to the present asteroid Main Belt and did not proceed

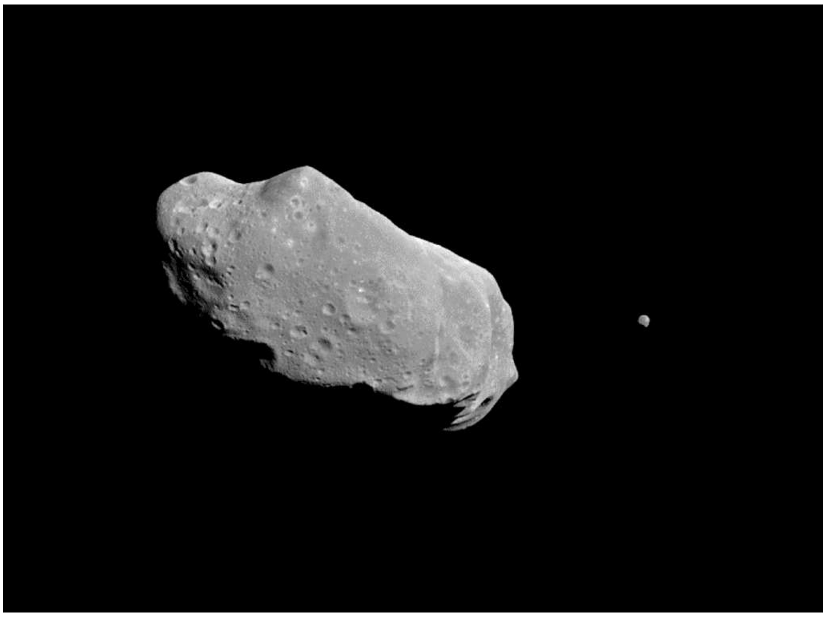

Fig. 2. Image of the asteroid (243) Ida obtained during the *rendez-vous* with the Galileo space probe. On the right, one can see Dactyl, the small binary companion of this asteroid. (Courtesy of NASA)

up to formation of a large planet, has been the debated subject of many models. The main perturbing process has always been thought to be the early growth of the massive Jupiter. Being subject to strong perturbations by Jupiter, the planetesimals in the Main Belt could have started to be ”excited”, with their eccentricities increasing up to values that made mutual collisions disruptive, preventing further growth.

According to more sophisticated models, however, even such a scenario might be too simplistic. Recent numerical simulations indicate that planetary migration played a key role in the early history of the Solar System, with the mutual resonance of the orbital motion of Jupiter and Saturn, and the gravitational interaction of the giant planets with the dust disk remaining at the epoch of disappearance of the gas component, being both major actors in determining the final structure of the planetary system, including the presence of an asteroid belt between Mars and Jupiter (Morbidelli et al. 2009).

In any case, the origin of asteroids is thought to date back to the early phases of the history of our planetary system. Although some physical mechanisms have produced some evolution of these bodies as a function of time, at least some of them are considered to be extremely primitive, being the likely parent bodies of some of the oldest meteorites that we have in our laboratories. These bodies, the so-called carbonaceous chondrites, have ages, derived from analyzes of their isotopic compositions, of about 4.6 billions of years. This is considered to be the age of the Solar System. At least some of the presently existing asteroids, therefore, as well as other bodies originally accreted in different regions of the Solar System, like comets, can still provide essential information to understand the astrophysical environment in different regions of the original proto-planetary disk, and about the mechanisms that led to the formation of the Sun and of the planetary system.

4. Physical and dynamical evolution, physical properties

4.1. Sizes, colours, rotations

The determination of the sizes of the asteroids is not an easy task, due to their small apparent angular sizes, which prevent any possibility of direct measurement in the vast majority of cases. The apparent magnitude of an asteroid depends, at a given epoch, by its distance from both the Sun and the observer, by its size, and by its reflective power, or albedo. The dependence on the distances is trivial and can be easily accounted for, but in principle the problem remains of distinguishing between smaller, brighter objects and larger, darker ones. One solution of this problem has been found to measure not only the asteroid brightness at visible wavelengths, where the emission consists only of scattered sunlight, but also at thermal IR wavelengths. The idea is that both the amount of scattered sunlight from an asteroid surface, as well as the thermal emission corresponding to its temperature, depend both on the size and albedo of the object. This technique, called *thermal radiometry*, allows observers to solve for both size and albedo having at disposal some reliable model of the distribution of the temperature on the surface.

Another, independent technique is based on measuring the degree of linear polarization of the visible light of an asteroid observed in different illumination conditions, since the variation of linear polarization that is observed is known to be a function of the albedo (Cellino et al. 2005). Once the albedo is derived in this way, the size can be also derived. The above-mentioned techniques were not certainly known at the epoch of Schiaparelli, when Astrophysics was still in its early infancy.

The visible light we receive from asteroids is scattered sunlight. However, this does not mean that in spectroscopic terms all asteroids are identical. Due to differences in surface composition and surface regolith properties, the reflectance spectra of asteroids are heterogeneous. Since a long time, many researchers have tried to improve our capability to interpret asteroid reflectance spectra in terms of mineralogical composition, taking also profit of the availability of samples of extraterrestrial matter in our laboratories, namely different classes of meteorites characterized by different compositions and different inferred thermal histories.

Apart from the purpose of determining reliably the composition of single objects, a task which is usually quite complicated due to problems of non-uniqueness of the proposed solutions, asteroids can be subdivided in a number of taxonomic classes based on the general properties of their reflectance spectra. A number of taxonomic classes have been introduced by different authors, and there is a general agreement on the taxonomic classification of most asteroids. Some of the proposed classes are believed to have direct counterparts among corresponding classes of meteorites, and there is currently a general consensus about the fact that asteroids belonging to the so-called *S* class include the asteroidal parent bodies of Ordinary Chondrites. The *C* class is thought to include primitive objects likely including the asteroidal parent bodies of extremely old carbonaceous chondrites. Moreover, asteroids belonging to the fairly unusual *V* class should have originated from a collision that excavated a large and deep crater on the surface of the big asteroid (4) Vesta. The fact that Main Belt asteroids are the most important source of meteorites is strengthened by the fact that in all cases in which the orbits of some bright meteorite-delivering bolides could be computed based on simultaneous recording by different observers, the aphelion was found to be located in the asteroid Main Belt. Moreover, different dynamical mechanisms have been discovered, which can move an object from the Main Belt to the region of the terrestrial planets.

Finally, asteroids rotate, and having generally non-spherical, irregular shapes, they present to the observer variable projected cross-sections in different instants. As a consequence, the apparent magnitudes of the objects vary as a function of time. The brightness variation recorded over a time span equal to the rotation period of an object is called its *lightcurve*. From a single lightcurve, it is then possible to derive the value of the rotation period, and some information about the overall shape of the object. Having at disposal lightcurves obtained at different epochs, corresponding to different geometric configurations of the Sun - observer - target system, leads to determine the orientation of the spin axis, and a more precise determination of the three-dimensional shape of the object. Recently, methods to derive this information having at disposal not full lightcurves, but only a set of sparse photometric data obtained at different epochs, have been developed by different authors (Cellino et al. 2009). The importance of the study of rotational properties will be emphasized in Section 4.3.

4.2. Inventory and size distribution

How many asteroids exist? This is not an easy question. First of all, one should decide what we mean when we speak about asteroids. In particular, at which size can we decide that an object can be still named "asteroid" rather than being considered to be something else, like a small aggregate of dust grains ? And can we call asteroids small objects orbiting in different regions of the Solar System? Conventionally, we use the word asteroids to indicate not only the bodies present in the Main Belt, but also the objects orbiting in the inner Solar System (NEA), and also the Trojans of Jupiter. To assess reliably how many objects of these categories exist is not a trivial affair. The available inventory is forcibly limited to the objects that are brighter than some limiting apparent magnitude. In turn, apparent magnitudes translate into different intrinsic sizes depending on the distance of the objects, and on their albedo (reflectivity). Currently, it is widely believed that the number of existing NEAs larger than 1 km, is of the order of $1,000$, and great efforts are made to discover all of them as soon as possible, since the available inventory of these objects is still incomplete.

A size of 1 km is generally assumed to mark the limit between a global catastrophe and a local devastation, in the case of a collision with the Earth. This does not mean, however, that smaller objects are not intrinsically dangerous. Since the size distribution of NEAs follows generally a power-law distribution, smaller objects are increasingly more numerous, so that the probability of impact with a small NEA is much greater than the corresponding probability for an object above 1 km. The problem is that objects with sizes of the order of some tens of meters can still produce very dramatic effects in the case of a collision with the Earth, including the onset of huge tsunamis, that can potentially devastate the coasts of whole oceans, leading to immense damage and casualties. At the time Schiaparelli discovered (69) Hesperia, he could not probably imagine that asteroids would become in the future such an important source of recognized hazard for the terrestrial biosphere and for human civilization.

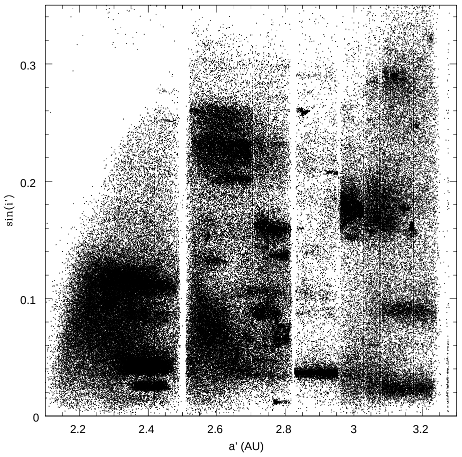

Fig. 3. Plot of the distribution of proper semi-major axis and (sinus of) proper inclinations of the orbits of Main Belt asteroids. Proper orbital elements are a kind of averaging of the osculating orbits over long time scales. It is evident that some values of semi-major axis, corresponding to mean motion resonances with the orbit of Jupiter, are forbidden. Moreover, some evident clusterings of orbits can be easily seen. They correspond to some dynamical families, thought to be of collisional origin (see text). Asteroid proper element data taken from the AstDys web site (http://hamilton.dm.unipi.it/astdys/).

As for the Main Belt, again, the inventory of the asteroidal population is not definitively assessed for objects smaller than a few kilometers. Apart from the fact that it is generally assumed that the cumulative size distribution of the objects is described by a power-law (Cellino et al. 1991), some discrepancies exist between estimates made by different authors of the actual number of existing objects at sizes below the completeness limit, using different kinds of observational evidence. Among the most frequently quoted estimates, the one by Bottke et al. (2005) predicts the existence of 1.2 Millions of Main Belt asteroids larger than 1 km. This is just in the middle between two more extreme estimates of 700, 000 (Ivezić et al. 2002) and 1.7 Millions (Tedesco, Cellino & Zappalà 2005) of objects. Extrapolations to sizes smaller than one km are even more uncertain and model-dependent.

It is very interesting to analyze how asteroid orbits are distributed in the Main Belt. In Fig. 3 the sinus of proper orbital inclination is plotted as a function of proper semi-major axis for Main Belt asteroids. It is easy to see that evident clusterings of orbits are visible in the plot, some of them being relatively small, whereas some other include literally thousands of objects, and tend to mutually overlap. A similar plot can be obtained when plotting proper eccentricity as a function of proper semi-major axis. The existence of clusterings in the proper elements space indicates that objects belonging to a given cluster have very similar orbits, once the fluctuations due to perturbations are filtered out. The interpretation of these clusters, called *dynamical families*, is that they are formed by swarms of fragments produced by the disruption of a number of original parent bodies. The physical mechanisms responsible of the disruption of the parent bodies is thought to be that of *collisions*.

4.3. The importance of collisions

In the early 90s, an analysis of the sample of asteroid lightcurves available at that time led to the discovery that some relatively large objects were characterized by large lightcurve amplitudes and short rotation periods. These asteroids were named LASPA (standing for Large Amplitude Short Period Asteroids). Farinella et al. (1981, 1982) noted that the photometric behaviour of these asteroids corresponded to what one should expect for fluid bodies having large angular momenta and equilibrium shapes, according to the theory developed by Chandrasekhar (1969). In particular, the theory of equilibrium shapes of fluid bodies predicts that, as the angular momentum of the body increases, there is a transition from a spherical shape, to a MacLaurin spheroid, up to a Jacobi triaxial ellipsoid. In the case of asteroids, the presence of objects characterized by rapid rotation and elongated shape, as inferred by their large lightcurve amplitudes, suggested that these bodies could have triaxial ellipsoid shape and behaved as high-angular momentum fluid systems. However, asteroids are certainly not fluid, so how to accept the idea that these bodies could have equilibrium shapes? The answer to this question given by Farinella et al. (1982) took into account the fact that LASPAs are found among relatively large asteroids, above 100 km in diameter. According to these authors, LASPAs were originating from catastrophic collisions. The idea is that it can happen that a large parent body can be totally disrupted by a collision. However, if the object is sufficiently large and massive, the fragments will not reach the escape velocity of the system, and will fall back. In this way, the set of fragments will reconstitute a system having granular properties, a so-called *pile of rubble*, which will tend to reconfigure itself in such a way as to mimic the behaviour of a fluid body.

This discovery was extremely important for the subsequent development of asteroid science. Together with the discovery of the existence of dynamical families, also interpreted as the outcomes of energetic collisions with ejection velocities of the fragments sufficiently high as to avoid re-accumulation, the observations were thus suggesting that collisions have been a very important mechanism of evolution of the asteroid population. Models of the overall process of collisional evolution indicated that most asteroids smaller than 100 km, or even larger, are collisional fragments issued by the fragmentation of larger parent bodies.

Only the biggest asteroids are considered to be sufficiently massive as to have avoided collisional disruption since the epoch of their formations. In this respect, the properties of the large (about 500 km) asteroid (4) Vesta, exhibiting an unusual reflectance spectrum suggesting a basaltic composition, is considered very important. The idea is that Vesta underwent a complete melting and differentiation soon after its birth, with likely formation of a metal core, while lighter mineral floated to the surface, eventually producing a basaltic surface layer. The presence of this crust put some constraints on the rate of collisional evolution of the Main Belt population, since if the collision rate was more intense, the basaltic crust of Vesta would have been progressively destroyed. At the same time, the presence of periodic changes in the degree of linear polarization of Vesta's visible light, with a period corresponding to the rotation, and the discovery of a dynamical family associated to Vesta, suggests that during its history, Vesta had suffered an energetic impact, not sufficient to destroy it, but capable of excavating a very big crater on its surface, with a swarm of fragments escaping and producing the associated family. The discovery of the fact that the members of the Vesta family share the same basalt-like spectrum of their parent body, was considered as a very nice confirmation of the techniques of identification of asteroid families, developed in the early 90s (Zappalà et al. 1990; Binzel & Xu 1991).

Collisions have been the major physical mechanism responsible of a progressive evolution of the asteroid population. This fact must be taken into account when asteroid properties are analyzed to extract from observational evidence hints about the astrophysical environment that characterized the planetary system at the very early phases of its history.

4.4. Non-gravitational effects

The interplay of collisions and planetary perturbations was long believed to represent the major if not the only one mechanism to produce a dynamical evolution of Main Belt asteroids, through direct injection of collisional fragments into unstable resonant orbits. Starting from the last decade, however, it was discovered that the situation is more complicated, since new mechanisms exist that must be taken into account, at least for objects having modest sizes.

In general terms, these recently discovered mechanisms are *radiative* effects. The so-called diurnal Yarkovsky effect is due to the fact that an asteroid does not irradiates away instantly the energy absorbed from the Sun. Any real surface is characterized by some thermal inertia, and irradiates the absorbed heat with some delay. During this time delay, however, the object rotates a little around its axis, so that the irradiated heat produces a mechanical momentum, which can either accelerate or decelerate the orbital speed of the body. The net consequence of the diurnal Yarkovsky effect is a drift in semi-major axis. Such a drift is a function of several parameters, including the rotation rate and the direction of the spin axis, the thermal inertia of the surface, the heliocentric distance. It is inversely proportional to the object's size, and for this reason the effect is mainly important for increasingly small asteroids. The Yarkovsky effect has been directly measured in the case of a small NEA, and has been shown to have important consequences for the evolution of the apparent structures of dynamical families, and for the continuous supply of new NEAs.

Another similar radiative effect, called YORP effect, has also been found to be important in producing an evolution of the rotation rate and spin axis direction of small asteroids. It is today believed that the distribution of rotational properties of the asteroid population down to small sizes, and the formation of binary systems from rotational fission, cannot be understood without taking into account the role of the YORP effect. An excellent review of the YArkovsky and YORP effects is given by Bottke et al. (2006).

5. The big problem: What there is inside?

Our knowledge of the physical properties of the asteroids, as we have seen in previous

Sections, is today impressive, but this does not mean that we have already understood everything about these small bodies. As opposite, we have still very much to learn, mainly for what concerns their internal structures. According to present data coming from *in situ* explorations by space missions, the situation is far from being clear. The very limited information that we have about the average densities of the objects visited by space probes indicates a large degree of heterogeneity. Among asteroids larger than 50 km, we have two estimates concerning asteroid (253) Mathilde, characterized by a small average density of 1.3 g/cm^3, and asteroid (21) Lutetia, very recently visited by the Rosetta probe, which turns out to have a density of 3.7 g/cm^3. Such values are diagnostic of huge differences in the internal porosities of these bodies, corresponding to differences between a finely granular structure and a nearly-monolithic one. Also among much smaller objects, including (433) Eros, (944) Gaspra, (243) Ida (the first discovered binary asteroid), (25143) Itokawa, we have evidence of great heterogeneity.

We will not be able to claim to have really understood asteroids until we will not have a satisfactory understanding of their internal structures, which are the final outcomes of the actual history and evolution of these bodies. Moreover, it will be very difficult to set up credible strategies of defense against potentially hazardous objects without a satisfactory understanding of their internal structures, since this is a critical piece of knowledge to predict how a given body will react to an attempt of orbital deflection using different possible techniques, ranging from linear momentum delivery by an impactor, up to attempts of complete pulverization by means of nuclear devices, in case of desperately urgent need.

6. Conclusions

After 150 years after Schiaparelli's discovery of (69) Hesperia, our knowledge of the asteroids has increased up to a level that would have been unimaginable in the nineteenth Century. We should be proud of that, but without forgetting that every new generation of scientists starts as the classical dwarf over the shoulders of the giants who came before.

What is important for our generation, is the awareness that a lot has still to be done and new challenges await us in the future, with so many key problems still open. At the same time, our generation of Planetary Scientists has also the duty to communicate to non-specialists the wealth of beautiful results already obtained, and the role of asteroids as important astrophysical bodies that deserve investigation, both *per se* and as pieces of the complex scenario of stellar formation, and evolution of planetary systems. Just as an example, the collisional evolution of an asteroid belt can produce important amounts of interplanetary dust, that can be detectable also by observers outside the system. This fact appears very important in the new exciting era of discovery and analysis of extra-solar planetary systems.

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