PLANETARY SCIENCES: physical and dynamical study of minor bodies and natural satellites of the Solar System

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The study of the minor bodies (asteroids, comets,trans-Neptunians, natural satellites etc.) is of particular relevance for understanding the formation process, the early phases and the subsequent dynamical, physical and chemical evolution of the Solar System. The lack of important modifications since their formation can give crucial clues on the status of the early solar nebula, and on the processes occurring some 4.5 billion years ago. Their observed diversity points to the existence of important thermal, dynamical and chemical gradients along the nebula that must also have affected the evolutionary history of the planets, and that requires a diversified approach for an overall vision. In particular, the following aspects that are subject of vast interest in the international community, constitute the scientific background of the present project (see references below of the research group and of other international groups on the subjects):

A - Origin and nature of the Near Earth Asteroids/Objects (NEA/NEO). Their orbits come very close to that of the Earth, in several cases intersecting it and posing some impact threat. Their origin is not well known yet: they could be inactive/dormant comets, with a very pristine composition, but also more geologically processed asteroids. The NEA/NEOs population appears extremely heterogeneous in all their aspects: physical properties, shapes, albedos, surface compositions. A fraction (possibly large) of the total are binary systems; studies of their light curves demonstrate in some cases a complex rotational status, others show a long rotational period not easily explained in the framework of the current dynamical and collisional models. This heterogeneity of properties is reflected also in the different taxonomic types (all types being present), with the associated questions on their origins. Their orbits are chaotic and their life time indeed is shorter than the age of the Solar System. This short time scale is at variance with the almost constant craterization rate during the last 3.8 billion years. One or more sources must then exist capable of maintaining a stationary population.
The main source is represented by Main Belt asteroids: their collisions (or mobility due to Yarkovsky effect) can inject fragments into orbital resonances that bring these bodies on orbits typical of NEAs. Eros (recently visited by NEAR) seems to be a prototype of this evolutionary path. Another source, but less numerous is repesented by extinct or dormant cometary nuclei. An example is comet P/Encke, a small active comet on a NEA type orbit. Another interesting aspect of NEOs is that they likely represent a major source of meteorites, in particular of the ordinary chondrites. If this idea will be confirmed, their

association with the Main Belt will be reinforced. The importance of the study of NEAs/NEOS is internationally and widely recognized. Several space missions (NEAR, DS1) have already encountered a NEO, the Japanese MUSES-C aims to bring back a sample of their material. Therefore, a good wealth of detailed information of physical, geological, dynamical features is or will be available. However, spacecraft will encounter only a severely limited number of them and, as a consequence, ground data will always be needed for the population global view. Long duration surveys are required both for discovery of new objects and for the subsequent follow up to determine their physical properties.
So, the study of NEA/NEO is extremely important not only for the comprehention of the origin and properties of these objects, ma their undoubtly relation with the other asteroids, comets and meteorites is important for the study of the minor bodies of the Solar System.

B - The radial distribution of the asteroids in the main belt shows a compositional variation with a gradual transition at about 2.5 AU where objects richer in silicates are slowly substituted by objects more and more richer in organic materials and hydrated silicates. The latter seem to have retained their original mineralogy, providing therefore information on pristine conditions in this part of the nebula. The existing surveys are particularly active in searching for hydrated materials on asteroids, for organic materials in the outer main belt, for ices on Trojans. Stimulating is also the comparison between asteroids and meteorites. Furthermore, a great deal of efforts is devoted to the understanding of the similarities between asteroids and comets. The same material causing the low albedo in the asteroids of the outer main belt could be indeed a component of the cometary nuclei.

C - Among minor bodies exists a class of asteroids which is in 1:1 mean motion resonance with Jupiter, the so-called **Trojans**. These bodies have semi-major axes approximately equal to that of Jupiter, and are clustered into two stable Lagrangian points (L4 and L5). At the present, about 1500 Trojan are known. Owing to their peculiar orbital configuration, Trojans have a great importance for understanding the solar system dynamics, but still little is known about their origin. According to recent models, they would have formed when Jupiter formed: Trojans could be planetesimal trapped by the sudden increasing of Jupiter gravitational field . From a physical point of view, their composition resembles that of Short-Period Comets (SPC). SPC can also represent a source for Trojans (about 10%). It is likely that other giant planets show the same population of asteroids, infact recently the first Neptune Trojan has been discovered (2003). However, in contrast with Jupiter, the Neptune's Trojan had probably been captured after the Neptune formation. It could be originated from the Kuiper belt. Concerning the terrestrial planets, 6 Mars' Trojans have been detected, so far. Also possible Earth's and Venus Trojan candidates have been detected, but in this case the observations are difficult because of the low solar elongation involved.

D - **Natural satellites** also belong to minor bodies. Owing to the many space missions devoted to this task, the knowledge of the satellites properties has greatly increased in the last decades. However, many are the problems still open: the possible existence of an ocean underneath the surface of Europa, the origin of Titan's atmosphere, the double face of Iapetus, the anomalous cratering of Triton, just to mention the most important ones. Moreover, the recent discoveries of many small new satellites (leading to a total of 63, 31, 17 and 13 satellites respectively for Jupiter, Saturn, Uranus and Neptune), have risen new questions concerning the origin and evolution of satellite systems.

In particular, the irregular component of satellites has acquired many new members and the possible existence of satellites families (like for the main belt asteroids) is now under discussion. It seems likely that some satellites can have a family, produced by some collisional event. If confirmed, this theory would put forward the idea that collisions suffered by a single satellite can affect the whole satellite system . However, a part of these satellites could have had a different history: they could have been captured (like the well-known case of Triton). In this case, they may be linked with asteroids.

E - **Centaurs and Trans Neptunians**. The discovery of these objects can be considered quite recent: the first Trans Neptunian was observed in 1992, even if the existence of the Kuiper Belt, located beyond Neptune, had been assumed since 1950. The discovery of these objects has undoubtly influenced the theories of the origin and evolution of the Solar System and has explained for example the origin of short period comets. The Kuiper Belt contains objects with some hundreds kilometers diameters and is located beyond Neptune, between about 40 and 500 AU, and is what remains of the outer solar nebula. The Centaurs, located between Jupiter and Neptune and also recently discovered, are very likely objects in transit from the Kuiper Belt to the inner Solar System with caotic orbits which cross the orbits of one or more giant planets. Centaurs and Trans Neptunians can be considered compositionally unaltered being formed in the outer regions of the solar nebula and for this reason they are the most representative of the primordial planetesimals. So their study is fundamental to obtain important clues on the formation of out planetary system. Owing to their faintness (visual mag >20) few data exist on their physical properties. In fact the observation of these objects requires appropriate telescopes like the VLT, NTT, Keck, etc.

In the complex scientific scenario expounded in the previous section, our group carries out theoretical and observational activities. These activities can be divided in several projects devoted to the physical and dynamical study and the search of Near Earth Objects and of other minor bodies of the Solar System including also the natural satellites:

Project 1: Visible and Near Infrared spectrophotometric survey of NEOs.
This program is in progress since several years ago, with data taken during several observational runs allocated to our group at the telescopes of ESO (NTT telescope) and TNG . This important observational campaign has produced until now one of the largest spectrophotometric data base of NEOs for the large spectral range covered (0.40-2.5 micron) and the number of observed objects (about 100 spectra). The results that we have obtained and are obtaining are extremely internationally competitive (see publications). We have already defined the taxonomic class (linked to the superficial mineralogy) of the objects (already known only for few of them) and this is important also for the "mitigation" studies connected to these objects because it gives information on their composition and structure.
We have determined the presence of absorpion bands, found in other very few objects and we have performed the comparison with the meteorites (ordinary chondrites, carbonaceous and achondrite meteorites, a set of about 2000 meteorites); we have identified some NEOs spectroscopically more similar to Vesta than the other V-types already known. We have identified almost all the taxonomic classes present in the Main

Belt and among these also an object probably belonging to the rare R class.
This research has produced until now several papers, a PhD Thesis (Simone Marchi) and at present it is the argument of the PhD of Sara Magrin and of the Laurea degree thesis of Sabina Danese. In Fig.1 we report an example of the spectra obtained so far: the spectra cover a wide spectral range, often uninterrupted from 0.4 to 2.5 micron, with good photometric precision.

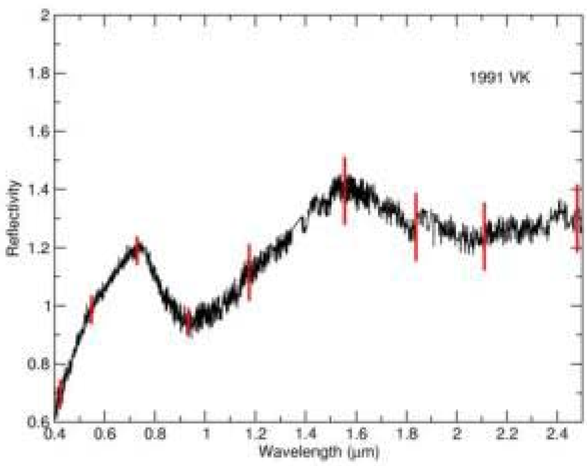

Fig. 1 - Example of a NEO spectrum obtained at ESO-La Silla with error bars.

In Fig. 2 we report an example of the comparison with spectra of meteorites.

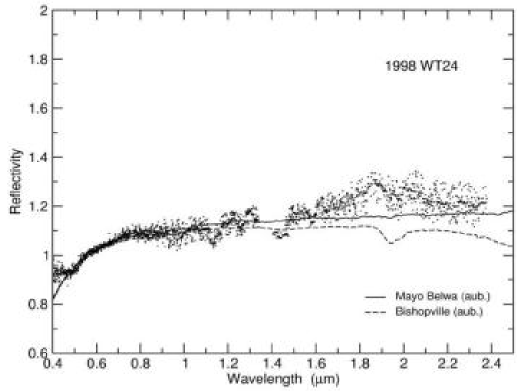

Fig. 2 - Comparison between an observed NEO and some meteorites.

An important effect on NEOs (but present also on other bodies of the Solar System) that we are investigating is the space weathering, that is the alteration of the optical properties of airless bodies surfaces by space environment. Space weathering effects were initially studied on lunar soils. Since '80s space weathering effects were suggested to be present also on other bodies, like asteroids (as well as on planets like Mercury).

This idea was due to a mismatch between laboratory spectra of freshly cut ordinary chondrites (OC) and remote sensing spectra of S-type asteroids (the most populated taxonomic class among NEO), which are thought to represent their parent bodies.

The result of space weathering effect on asteroids is well shown in the reddening of their spectra as reported in Fig.3:

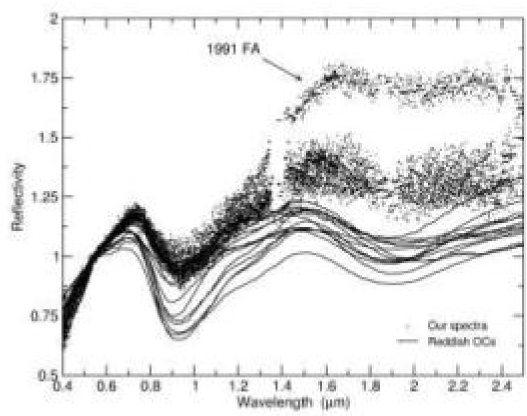

Fig. 3 - Space weathering among the observed NEOs.

Project 2: Mass transfer among satellites of outer planets.
We developed a theoretical study concerning the mass transfer among moons of outer planets. This process has been applied to some pairs of satellites in order to understand superficial features shown by some satellites (see Fig.4). The most important analyzed cases are the Iapetus' Cassini Regio, and the anomalous cratering rate on Triton.
In both cases, our model produces a good match with the observations (see Fig.5).

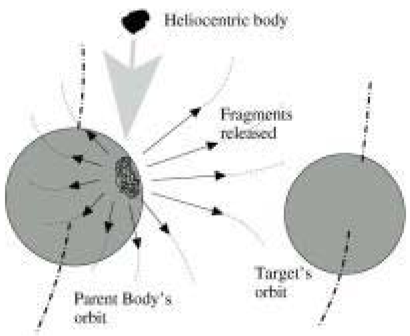

Fig. 4 - The mechanism of mass transfer between bodies on planetocentric orbit.

Concerning Iapetus-Hyperion, our model foreseen that the Cassini Regio (having a maximum estimated depth of 100m) is centered on the Iapetus' leading side, and that it is elongated along the equatorial direction, in agreement with the observations. The penetration in the trailing side is not negligible, but its density of impacts is much less than on the leading side (see Fig.5). The duration of the mass transfer is of the order of 10 My. Moreover, we are still studying if, and in which way, the satellite Phoebe could have contributed to the origin of the Iapetus' dark side

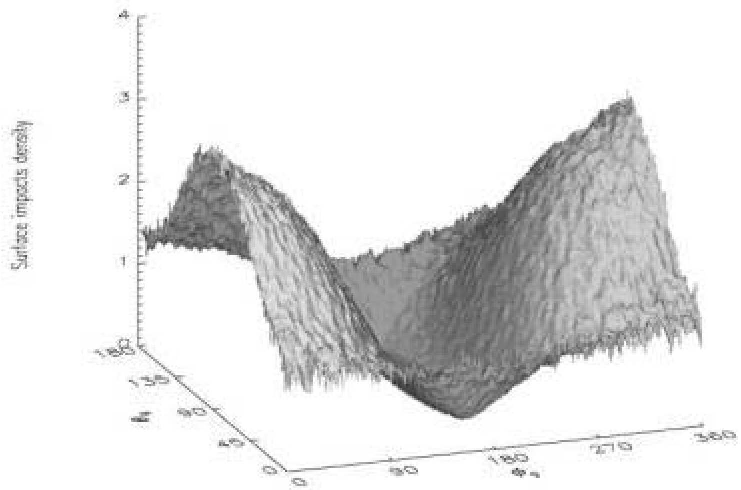

Fig. 5 - Calculated distribution of impacts on Iapetus.

For Proteus-Triton the efficiency of mass transfer depends strongly upon the orbital configuration, and can vary from 0% to 80%.
The duration of the transfer is always less then 3000 y. The shape of

the distribution of impacts is slightly affected by the orbital configuration, and is alway elongated in the north-south direction. The cumulative distribution of craters obtained fits very well the observed one (for craters greater then 5 km). However, the big craters seem due to heliocentric impactors. In order to seek for observational evidence of our model, we also started an observational campaign. We got time in October 2002 to observe Triton with NTT and VLT. We obtained the first face-resolved, 0.4-2.5 micron, spectra of Triton
(we observed the leading side and the trailing one in two different nights). In such way, we were able to analyze differences between the two hemispheres (see Fig.6). We found differences between the trailing and leading side, possibly related with their different cratering history.
Some of them, are likely due to rocky compounds and hence we cannot exclude a possible 'asteroidal' contribution to the observed asymmetry.

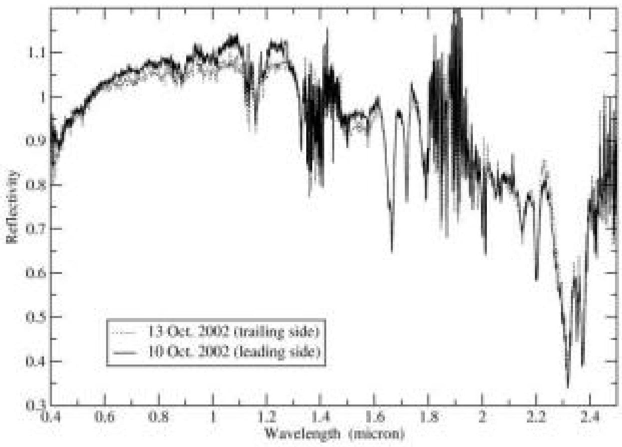

Fig. 6 - Spectra of the leading and trailing sides of Triton.

We started also a dynamical study concerning the origin of the small satellites of Saturn, possibly related with the mass transfer.
The small satellites could be originated from a collisional event suffered by another satellite (like for the mass transfer). After the collision the fragments could have acquired Saturn-centric orbits without colliding with other satellites. However, a part of these satellites may have been captured and hence they could originate from asteroids.

Project 3: Spectrophotometric investigation of Centaurs and Trans Neptunians objects. The study of Centaurs and Trans Neptunians represents one of the most important issues among planetary studies. In fact they are unexplored objects from which fundamental information will be obtained on the origin and evolution of the Solar System.
The existence of the Kuiper Belt was assumed since 1950 to explain the origin of short period comets, whose number and dynamical properties (especially the low inclinations of the orbits), were difficult to be explained with long period comets (P>200 years) coming from the Oort Cloud with random orbital inclinations. So, the Kuiper Belt, with objects with diameters of some hundreds kilometers would be located beyond Neptune, between about 40 and 500 AU, and would be the remnant of the outer solar nebula.
Our group has made observatoons at TNG of these objects and partecipated to a large european observational campaign, a Large program, between 2001 and 2003. This program has been accepted by ESO and performed with the telescopes NTT and VLT at ESO . We have made spectroscopic

observations in the visible and Near Infrared of objects with V mag down to 21 and photometric observations for fainter objects. The results so far obtained represent a unic data base having identified also ices on these bodies. The main property of Centaurs and Trans Neptunians so far identified is the etereogenity of their superficial composition.

Project 4: **Search of Near Earth Asteroids with the Asiago Telescope (ADAS)**.

Since some years ago it is in progress the use of the new CCD camera (covering a field of about one square degree) implemented at the Schmidt telescope of Cima Ekar in Asiago principally devoted to the discovery and dynamical follow up of Near Earth Asteroids with visual magnitudes that can reach about 21. The Asiago Schmidt has been used also for the research of main-belt asteroids and of trojans of Jupiter. We have obtained so far more than 300 denominations and 12 objects so discovered have been definitively numbered.

This project is the result of an international collaboration between the Padova Astronomy Dept. and the Padova Astronomical Observatoty with the DLR of Berlin. This project has also given the opportunity to renovate a telescope which was not in function any more. We have obtained useful data from 21 december 2000 to 15 march 2002. After a pause in which the telescope has been improved, the survey (n. 209 in the MPC designation) has been restarted to observe in January 2003. The results so far obtained can be sumarized as follows:

Number of designations found = 315
This site has discovered 6 numbered objects
1 of the numbered objects has been named
9 of the discoveries are identified with numbered minor planets
86 of the discoveries are involved in multiple-apparition orbits
60 of the discoveries are principal designations
47 of the one-opposition objects have >= 30-day arc orbits
66 of the one-opposition objects have < 0-day arc orbits
107 of the one-opposition objects have no orbit

Project 5: Search of trojans of outer planets.

In the light of some recent results concerning the dynamics of the outer planets, we started a survey dedicated to the discovery of trojans of Saturn, Uranus and Neptune (program accepted in 2002 by the Astrovirtel project) which has received the number I03 by MPC. In the Astrovirtel archive we selected all the WFI MPI/2.2m ESO images which fell in a box of 30°x30° around the L4 and L5 lagrangian points of the outer planets. We retrieved about 3500 images for a total of 560 Gb of data.

Several original software tools have already been developed to handle mosaic images (WFI has 8 chips) and discover moving objects on triplets of frames covering the same field.

In particular, fitsblink is a software tool written by a group of researchers from Ljubljana who collaborate in this difficult search. Besides detecting possible candidates, it also gives the possibility to recognize in real time the already known asteroids by using a database containing all of them (this database is continuously updated via the MPC). Another novel tool is Amigo, a fortran code which produces a distribution of asteroid's velocities as projected on the sky (namely velocity in RA and Dec) for any given direction of the line of sight at any date.

Therefore, by using this code for each image, we are able to quickly identify different regions in the RA-DEC velocity plane corresponding to different groups of asteroids, like Main Belt, Jupiter's Trojans, Saturn's Trojans and so on. As a result we have already submitted to the MPC 100 reports, containing approximately 1000 positions of distinct asteroids. The faintest objects identified are around R = 23.7; there are also several fairly bright but not numbered objects (e.g. R = 15.9). Some objects were detected in U-band filters. The MPC has already awarded about 60 designations. We plan to finish the analysis and discussion of the material within this program. In January 2003, the first Neptune Trojan was discovered by an american group. The Neptune Trojan is librating around L4, it has a low eccentricity and a libration amplitude lower than 40 deg. Its inclination is around 1°.3, and its diameter is about 230 km. This discovery lends further weight to our idea for this search.

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Research Products:
2000:
Refereed papers: 2
Proceedings, oral presentations at meetings, posters: 1
2001:
Refereed papers: 4
Proceedings, oral presentations at meetings, posters: 6
2002:
Refereed papers: 4
Proceedings, oral presentations at meetings, posters: 7
2003:
Refereed papers: 6
Proceedings, oral presentations at meetings, posters: 4
2004:
Refereed papers: 7
Proceedings, oral presentations at meetings, posters: 5

List of 5 most representative publications:

Lazzarin, M.; Marchi, S.; Barucci, M. A.; di Martino, M.; Barbieri, C., 2004, **Visible and near-infrared spectroscopic investigation of near-Earth objects at ESO: first results**, Icarus, 169, 373.

Marchi, S.; Barbieri, C.; Lazzarin, M.; Owen, T. C.; Corsini, E. M., 2004, **A 0.4-2.5 µm spectroscopic investigation of Triton's two faces,** Icarus 168, 367.

Lazzarin, M.; Barucci, M. A.; Boehnhardt, H.; Tozzi, G. P.; de Bergh, C.; Dotto, E., 2003, **ESO Large Programme on Physical Studies of Trans-Neptunian Objects and Centaurs: Visible Spectroscopy,** Astronomical Journal 125, 1554.

Marchi, S.; Lazzarin, M.; Magrin, S.; Barbieri, C., 2003, **Visible spectroscopy of the two largest known trans-Neptunian objects: Ixion and Quaoar**, Astronomy and Astrophysics 408, 17.

Barucci, M. A.; Cruikshank, D. P.; Mottola, S.; Lazzarin, M., 2002, **Physical Properties of Trojan and Centaur Asteroids, in Asteroids III**, W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel (eds), University of Arizona Press, Tucson, p.273-287.