EXPLORATION AND USES OF CELESTIAL BODIES OF THE SOLAR SYSTEM

by Marcello CORADINI
European Space Agency
Paris, France

Introduction

At the end of the fifties the first man-made objects left the gravitational field of the Earth in an attempt to reach the closest celestial body, the Moon. Those attempts, many of them unsuccessful, gave rise to the exploration of the Solar System. Some thirty-five years later, Pluto is the only planet of the Solar System as yet unexplored; men have walked on the Moon, three comets have been flown-by, Mars has received the visit of a good number of orbiting and/or landing vehicles as has Venus, the gaseous giants have been visited by four probes.

The reconnaissance part of the exploration of the Solar System is almost concluded and a new phase needs to be started.

In the past - and up to the present day - there were two main motivations which convinced administrators to invest funds in space exploration: competition between political blocs and science.
For a number of reasons these motivations are losing momentum and the space business is desperately searching for new justifications at a time characterised, on the one hand, by the disappearance of worldwide political confrontations and, on the other, by the curtailing of funds on the objectionable assumption that science is a social luxury.

* Mission Accomplished
@ Mission Under Development or Under Way

MANNED LANDING			*								
SAMPLE RETURN			*								
ROVER			*								
LANDER		*	*	*							
ORBITER		*	*	*		@	@				
FLY-BY	*	*	*	*	*	*	*	*	*		*
TELESCOPE OBS	*	*	*	*	*	*	*	*	*	*	*
SOLAR SYSTEM EXPLORATION 1992	MERCURY	VENUS	MOON	MARS	ASTEROS	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO	COMETS

The new concept of space exploration which is presently developing within the space-faring nations makes use of a mixture of science, technological advancement, socio-psychology, ecology and exploitation in an attempt to justify major investments in this field.
From this standpoint the exploration is obviously identifying space targets which can offer an opportunity to satisfy all of the above motivations. The choice is consequently very limited: sending a probe to a comet is a technological (and industrial) challenge and certainly provides us with fundamental and novel science; however, a comet will indeed never be considered either as a place for the settlement of a manned base (social and psychological aspects of the exploration, i.e. the adventure) or as a potential space ore deposit (exploitation aspect). By the same token a very large manned orbiting facility (technology aspect) will be difficult to realise in the absence of compelling scientific, industrial or even ecological (transfer to space of dangerous productions) motivations.

The only bodies of the Solar System which offer the opportunity of merging together the various motivations and justifications just mentioned are the Moon, Mars and perhaps the asteroids; nevertheless, time scales of future exploration and uses might differ dramatically.

Past Discoveries and Future Exploratory Needs

The Moon

The US Pioneer Program represents the first attempt to target a man-made object to the Moon: results were not exciting but at least these first launches triggered a technological advancement which in a short time would have brought a man to walk on the surface of the Moon. In USSR the Luna Program had a better fate, and already at the second launch the Moon was struck by the little Russian probe. Luna-3, in 1959, was able to take the first photograph of the far-side of the Moon: it was not an exceptional quality picture but it showed, for the first time, some features of the surface which, seven years later, were confirmed by the images transmitted by the US Lunar Orbiter . Another first in the exploration of the Moon was scored by the Russians in 1966 who succeded in making the Luna-9 spacecraft land safely on the surface of our natural satellite. Since then, successful US and Soviet missions to the Moon have indeed been numerous, culminating in the well known manned missions.These missions have contributed to the discovery of many fascinating and unexpected phenomena such as mascons, moonquakes, lunar magnetism, depletion in volatile elements. None of these has been thoroughly explained and the limitations in the amount and quality of the data available at present are partly responsible for this.
The scientific case for further lunar studies can be summarised as follows: understanding of the origin and early evolution of the Solar

System; history of the Earth-Moon system; identification of lunar resources.

Once the science of the Moon is comprehensively assessed it is the use of our natural satellite and the exploitation of its resources which need to be studied and realised.

The Moon has retained, through the absence of significant erosion and deposition, as well as the evident lack of plate motions and the early cessation of the volcanism, a more complete record of primeval events in the Solar System than any other major body in it. Data from this record is of key importance in attempting to answer the question of the origin of the Solar System. Moreover, the theories about the Earth developed by geologists, geophysicists and geochemists require testing on other than Earth data. For this essential scientific procedure the Moon offers a most suitable challenge: while a terrestrial body, it is probably the one that differs the most from Earth.

It has been known since the last century that lunar tidal friction is causing the Moon to retreat from the Earth; from the Apollo and Luna samples chemical affinities between the Earth and Moon have been discovered. The interpretation of the meaning of this close early relationship is one of the profound questions of astronomy and a key to the origin of our planet and its natural satellite.

Despite the 382 Kg of samples returned by six Apollo missions and 250 gr brought back by Russian automatic vehicles, we can state that a number of fundamental questions about the Moon are still awaiting an answer.

The sampling was indeed adequate for us to develop a first order understanding of the nature of the lunar surface and its stratigraphy, thanks to the simplicity of the overall lunar geology characterised by a basic two-fold division into the dark maria and the highlands. Before Apollo we knew virtually nothing about the chemical composition of the Moon: even that of the surface rocks and sediments was an open question.
Now we know that, apart from metallic iron and the siderophiles (mainly non-volatile elements which concentrate in metallic phases) and volatile elements, the Moon is similar to Earth in its elemental abundances, and its rocks and minerals are parallelled by the igneous rocks of the Earth's crust. Yet the depletion of siderophiles and volatiles have to be fully explored.
To proceed further in our understanding of the Moon, and especially to provide definitive answers to the above key questions, selenochemical and selonophysical mapping of the entire surface, particularly the far-side and the polar regions, is needed. High resolution spectral reflectivity measurements and multispectral/stereo imaging of the lunar surface in the visible and near infrared have not yet been performed from lunar orbiters simply because the methods were not available. With present day technology unique information on the mineralogical/chemical composition of the lunar surface, its detailed morphology and altimetry could be cheaply obtained.

This basic information on the surface should be complemented by observations of the overall shape of the Moon, as deduced from almost conventional radar altimetric measurements, and the determination of the low degree and other spherical harmonics of the lunar gravitational field would help us to determine the isostatic state of the Moon over various scales.

Prior to Apollo, the Moon was believed to have no magnetism. However the remnant magnetisation of the lunar samples and the discovery of superficial magnetic anomalies have proven the existence of a magnetic history of the satellite. The origin of the primeval field which magnetised the rocks is still somewhat controversial: a complete map of the lunar magnetic field anomalies would go a long way to resolving the question.

These and a number of other scientific questions on the past production and present distribution of the volatiles or the thermal history of the Moon should be answered as a "conditio sine qua non" to a further manned exploration of the satellite.

From this standpoint it is essential, in the course of a second stage of exploration, to ascertain the existence of usable resources for the establishment of manned facilities and perhaps, on a much longer time-scale, for the settlement of a lunar colony.

The first available source of material [for construction and/or protection] on the Moon is the regolith whose mechanical properties (compaction coefficient, hardness, etc) must be evaluated as well as grain-size distribution and geographical distribution and thickness. Once this information is available the regolith can be used as "bulk material" to be excavated, packaged and transported wherever needed.

More "noble" rocks are those which can be used or treated for the production of fundamental materials such as iron, titanium, aluminium and silicon. These minerals are primarily ilmenite and plagioclase as well as olivines and pyroxenes which contain significant quantities of iron.

Ilmenite is concentrated in the Mare regions of the Moon and is supposedly abundant. Its presence on the lunar surface can be identified from orbit by means of gamma-ray and optical/infrared spectroscopy. On the surface, electromagnetic sounding technique followed by rapid X-ray fluorescence analysis can provide us with good information on local concentrations of metallic materials.

Plagioclase is very common in the lunar crust and is considered as one of the major potential sources of aluminum and silicon. Remote sensing techniques to acquire regional distributions and geophysical/geochemical probing to determine local concentrations do not differ from the ones just mentioned.

The existence of metallic deposits cannot be excluded "a priori". Terrestrial type deposits must be excluded due to lack of transport and concentration by fluids. However, magmatic segregations or fractionation related to major impacts can have taken place and attention should therefore be focused on vents, dark material regions and orange glass regions.
Volatiles such as carbon, hydrogen, nitrogen and noble gases are mostly originated by trapping solar wind in the regolith; degassing during meteorite impacts cannot be ruled out. Search for trapped gases should not be neglected, nor the possible existence of water in cold traps in the polar regions. Should a preliminary search at lunar scale be unsuccessful, the strategy of lunar exploration and manned base settlement should immediately be re-focused.

The exploration phases devoted to the identification of the lunar resources, besides its practical aspects, serve beautifully the so-called "Science of the Moon" whose goal is the understanding of the origin and evolution of the Moon and the Earth-Moon system.

The following phases of exploration might deal with the "Science from the Moon", i.e. astronomy and astrophysics in the broadest sense, due to the very favourable observing conditions created by the lack of atmosphere and by the high stability of the crust; and "Science on the Moon" i.e. exporting life on the Moon.
This last aspect has obvious relevance for the setting of boundary conditions for human adaptation to the new environment, safety, health and working efficiency. The establishment of an autonomous ecosystem is another aspect of the life science on the Moon and represents a challenging project but not a huge risk given the proximity of mother Earth.

Mars

The space exploration of Mars started in 1962 with the launch of the Russian Mars 1 probe which was supposed to fly by the planet and send back photographs of the surface. Since then 20 spacecraft have been sent to the red planet; these missions have revealed a planet characterised by many similarities to our planet but also with some striking differences.
Mars is a highly evolved planet with a large variety of superficial morphologies and a complex geologic history. Its internal evolution and the exogenic processing of its surface, which have extended over billions of years, are reflected in the large diversity of surface features morphologically different from similar structures on Earth.

The red planet surface is very asymmetric: most of the southern highlands are densely cratered while the northern hemisphere is sparsely cratered and has many large volcanoes. The boundary between the two hemispheres is roughly a great circle inclined 35 degrees to the equator. The most apparent structures of the martian surface are the huge shield volcanoes in the northern hemisphere and the tectonic canyon "Valles Marineris" over 2000 Km long and 100 Km wide.Other significant features include the polar caps and layered deposits, dune fields and several compressive ridges of planet-wide distribution.

Despite the extensive exploration effort of Mars during the last three decades a large number of questions on its evolutive history, its bulk composition and structure, the mineralogy of its surface etc still need to be answered. This is due to both the complexity of the planet evolution and the lack of geophysical and geochemical data. Furthermore, unlike that of the Moon, the surface of the red planet presents traces of various endogenic processes which have contributed to the "gardening" of the primeval surface in the course of hundreds of millions of years, as in the case of the Earth.

We may ask ourselves: Why Mars?

There are a large number of justifications, principally scientific, as to why Mars has been and will be considered a possible, and logical, goal of the exploration of the Solar System.

We know that Mars, despite the present differences, has gone through an evolutive history which might not be dramatically different from that of our planet. Traces of erosion of the martian surface by flowing of fluids, perhaps water, have been detected; temperatures compatible with the existence of human life have been measured at least in the equatorial regions in summertime. Water is present on the surface, either in the form of ices or trapped in the regolith, and it is easily accessible. There are adequate sources of oxygen in the (water and carbon dioxide) ices and in the gaseous carbon dioxide in the atmosphere to support human presence on Mars.
Radiation is often considered as a possible impediment to the manned exploration of Mars. This is based on our relatively small experience in the field which makes us adopt a conservative attitude. Though the effects of radiation cannot be eliminated, they can be reduced to an acceptable level by means of appropriate protective equipment and early warning devices.

The future exploration of Mars has to provide basic insights into the processes by which the planet accreted from the condensing solar nebula, including the effects of initial temperatures, pressures and compositions on the subsequent evolution of the planet. The internal structure of the red planet and the composition and masses of the core, mantle and crust as well as the present seismicity must become the object of extensive studies. By understanding the internal processes of Mars perhaps the origin of the hemispheric dichotomy will be understood as well as the chronology of the events which contributed to model its surface. Another fundamental piece of information on the evolution of the red planet can be obtained by studying the composition of surface rocks and soil on Mars. The composition of the surface materials of a planet is indeed related to the composition of the interior. The analysis of the surface materials will provide us with information on the history of rocks through volcanic, metamorphic, sedimentary, impact and weathering processes.

Other important questions to be answered are those on the origin and evolution of volatiles on Mars. Part of the present volatiles are not easily accessible being trapped in polar deposits, in permafrost, bound in the superficial regolith. Another part constitutes the atmosphere which is indeed easily accessible and measurable. Compared with that of the Earth, the martian atmosphere represents only a minor portion of the volatiles that have probably been outgassed from the planet and which at some time resided in the atmosphere. An adequate understanding of the evolution of Mars requires that the atmosphere's evolution and its present state be understood in detail. Better knowledge of the earlier existence of periods of more moderate climatic conditions on Mars, maybe characterised by flowing water, higher and constant temperatures and a denser atmospheres, should be acquired.

It goes without saying that the scientific exploration of a celestial body cannot be separated from the precursor missions needed to prepare the way to manned exploration. In the particular case of Mars, the profound knowledge of its geology and atmosphere are "conditio sine qua non" to prepare the way for the establishment of any human settlement, even a temporary one.

From this standpoint the strategy developed in the sixties for the exploration of the Moon represents a reproducible example provided that a more scientific slant is given to the inevitable preparatory missions in order to minimise their number and maximise the output.

Asteroids

The first asteroid was discovered by the Italian astronomer Piazzi in 1801. This celestial body was named Ceres and was initially believed to be the famous "missing" planet. Somewhat later, astronomers realised that Ceres was only one of a very large population of about 20.000 individuals characterised by a great diversity of sizes, shapes, mineralogies and dynamical conditions.

About 5000 asteroids are to-day known to orbit the Sun in a particular belt situated between the orbit of Mars and that of Jupiter the so-called "main belt". Few asteroids have orbits that reach the orbits of the Earth, Venus and Mercury: they are the so-called Apollo-Amor asteroids. Other members of the asteroidal population, the Trojans, are found at about 5 astronomical units (A.U.) from the Sun in two particular dynamical points, named after the Italian scientist Lagrange, of the Jovian gravitational field. Those grouped in a belt at about 4 A.U. constitute the Hildas family.

Asteroids continue to be discovered due to the progress of the ground-based observational techniques but also, sometimes, by accident. The more recent availability of Earth orbiting telescopes (IUE,IRAS,HST, and ISO in the near future) has allowed improved study of the known asteroids and will doubtless lead to the discovery of many more in the future.

951 Gaspra is the first asteroid ever to be the object of a spacecraft fly-by. In October 19991 the NASA Galileo spacecraft has approached this asteroid of the S-type at a distance of about 1600 Km, obtaining the first space-borne high resolution image of a representative of the largest family of objects in the Solar System. The Galileo spacecraft, on its way to Jupiter will encounter another asteroid, 243 Ida.

Space borne observations of asteroids are extremely valuable because they offer the possibility to calibrate theoretical models needed to interpret the ground-based observations basically limited to photometry, spectral reflectance, polarimetry and radiometry. Nevertheless, those data will represent a very limited increase of information on the whole asteroidal population, while the interest is particularly focused on the asteroids' multiplicity. Indeed, both the variety of asteroidal families, as well as the similarity of a certain number of parameters, allow us to study the dynamical and morphological evolution of groups of objects which are, together with the comets, the almost uncontaminated "left-overs" of the materials used to build the Solar System.

Knowledge of the asteroids' superficial composition is fundamental to the understanding of the primordial processes of formation of the Solar System. The determination of the spectral and photometric characteristics of the surface of a body is the only possible way to develop clues on the mineralogical differentiation of asteroids. On this basis compositional classes can be determined and evolutionary paths can be inferred. For instance, when the chemical composition of a class of objects is characterised by limited quantities of volatile elements (hydrated silicates) it can be inferred that they formed at very high temperature . On the other hand, asteroids which apparently retain a large quantity of volatiles (carbon/organic-rich silicates) can be classified as more primitive . The interpretation in evolutionary terms of the taxonomic classes produces a fairly detailed description of the processes that gave origin to the asteroidal population. The original composition of the larger asteroids can be modified by an endogenic process such as the magmatic differentiation or by exogenic processes such as impacts, which results in more complex mineralogic aggregates.

Is there any need to explore the asteroids, apart from the obvious scientific desire of knowledge?

In the event of total exhaustion of terrestrial resources, the asteroids could represent a source of raw material for space-borne and ground-based processing. This may indeed sound somewhat futuristic; we should bear in mind,however, that objects such as the Apollo-Amor asteroids can get very close to our planet and, given their small mass, their orbits can be sufficiently easy perturbed in a controlled manner so as to place them either on an Earth orbit or to cause them to fall on the surface of the Moon.

Obviously before embarking upon such an ambitious project we need to know much more about the asteroidal population in order to identify potential targets. This can only be done by means of ad hoc missions designed to acquire detailed information on mass, size, surface morphology and mineralogy. These data can be combined to infer the bulk composition of the body under investigation; determination of of the shape of the gravitational potential surface provides means of establishing the internal mass distribution and homogeneity.
Surface mechanical strength can be measured either in situ or in the laboratory by analysing returned samples. The interior strength can be measured in situ by means of seismic soundings.

Conclusions

Both unmanned and manned exploration and exploitation missions to the Moon, Mars and the Earth-crossing asteroids have fundamental scientific relevance and constitute the new space frontier for humanity.

The technological, political, financial and programmatic efforts which will be required to make these missions a reality within the next 20-30 years are formidable but not impossible. The support of many different communities is needed as well as an effort to internationalise at the highest level the projects which have been described above.

Should these conditions be satisfied humanity will enter a new exciting and challenging space era.

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