Planetary exploration: Scientific importance and future prospects

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Study of planetary bodies by direct exploration using robotic and manned spacecrafts is a frontier area of research. Many nations are planning missions to the moon during the next two years and to other planets in the coming decades. These plans include establishing permanent human presence on the moon and Mars sample-return mission by 2015. The Indian Space Research Organization is also formulating a long-term plan of planetary exploration. Chandrayaan-1, an unmanned orbiter mission to the moon is in an advanced stage of implementation, slated to be launched in 2008. The possibility of manned space missions is also being debated. I discuss here the scientific merits of missions to various planetary bodies in the solar system and evaluate the priorities. Missions to moon, Mars, Mercury and Galilean satellites of Jupiter appear scientifically most exciting. A direction for future planetary exploration is outlined.

Keywords: Chandrayaan-1, planetary exploration, solar system, space resources.

THE planets in the solar system can be divided into three major groups, the inner rocky planets, Mercury, Venus, Earth and Mars, the giant gaseous planets, Jupiter and Saturn and the outer icy planets, Uranus and Neptune (Figure 1). Besides the enigmatic Pluto, milliards of small bodies forming the asteroidal and Kuiper belts and the tenuous comets extending to the farthest reaches of the solar system, going out to about 100,000 AU, may represent the earliest and the most primitive objects formed in our solar system. During the past half a century of planetary exploration, all the planets, their important satellites, comets and asteroids have been imaged from a close distance by American, Soviet and European space missions. Samples of the moon and a comet have been brought back for laboratory analysis and meteorites originating in different asteroids and planets have been identified. As a result, a large and accurate database is now available to formulate a meaningful exploration programme. Planetary exploration has reached a stage to address questions about the formation and evolution of our solar system. It is now possible to precisely define the science goals, prioritize them, design appropriate instruments for achieving these goals and carry out systematic study of various bodies, establish outposts for automated or manned exploration, and retrieve samples for laboratory studies. There is a renewed interest in planetary exploration with plans of robotic or manned missions to the moon, Mars and beyond. One advantage in future planetary exploration now is that there are six space agencies (National Aeronautics and Space Administration (NASA), Russian Federal Space Agency, European Space Agency (ESA),

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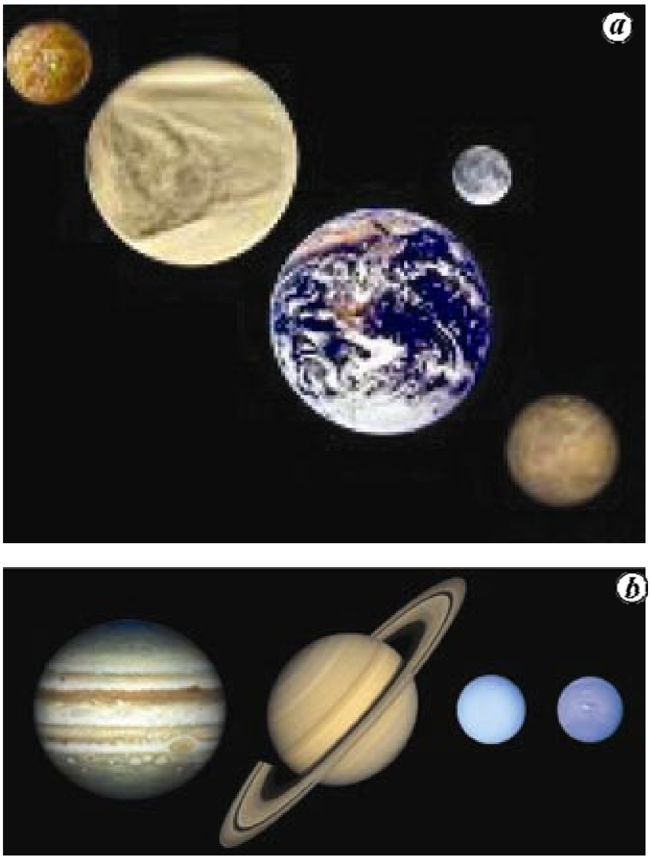

Figure 1. ***a***, The inner rocky planets, Mercury, Venus, Earth (with its moon) and Mars. ***b***, The outer giant planets, Jupiter, Saturn, Uranus and Neptune.

Japanese Aerospace Exploration Agency (JAXA), China National Space Administration (CNSA), and Indian Space Research Organization (ISRO)) interested in planetary exploration over the next several decades. It should be possible to maximize scientific returns by cooperation and coordination of space programmes of various countries. The International Lunar Exploration Working Group (ILEWG) is facilitating such efforts for lunar missions and a similar Working Group (IMEUG) has been operational for Mars.

There are two main goals of planetary exploration: (i) understanding the formation of the planetary system from the solar nebula, various stages of their chemical and geological evolution and timescales, and (ii) assessment and exploitation of planetary resources for human habitation. I make an attempt here to summarize some of the key questions about various planetary bodies that can be resolved by planetary missions.

Current status and future plans

Science missions

Fly-by or orbiter missions during the past half century have explored all the planets and their important satellites in our solar system. Many of these missions were equipped with imaging, magnetic, gravity and other remote-sensing instruments operating in gamma rays, X-rays, ultraviolet, visible, infrared or radio waves giving global and synoptic data. Landing and rover missions have enabled experiments to be carried out on the surfaces of some planets and to gather information about the planetary environment, mineralogical, chemical and geological processes. In addition, the sample-return missions have brought back surface rocks and core samples from several locations on the moon, making it possible to carry out trace element, isotopic and geochronological studies. Capability of sampling far-off small bodies like comets and asteroids has been perfected and we now have samples from comet Wild-2 available for study in the laboratory. Samples of an asteroid have been collected and are on their way to the earth. Based on the vast amount of data now available, I survey some selected planets for important problems in planetary science, and then describe a few current missions and outline the direction for future exploration.

Moon: This is the most mysterious body in the solar system in the sense that its origin is not well understood. How among the four inner planets (Figure 1 *a*) only the earth got to acquire such a large and permanent satellite which was initially very close to the earth (≤20 earth radii), whose isotopic composition is the same as that of the earth and the chemical composition is largely similar to the earth's mantle, still remains a puzzle. In comparison, Mercury and Venus have no satellites and Mars has only two small and transient satellites (Phobos and Deimos), which will not stay in the Martian orbit for long. For this reason, existence of the moon in circum-terrestrial orbit has been debated seriously and several hypotheses have been advanced. The capture hypothesis proposes that the moon was formed somewhere else in the solar system and then got captured by the earth in a close orbital encounter. However, it has been shown that capture of a large body by the earth is improbable and would require a special orbit; it will rather collide with the earth than settle in an orbit around the earth. Moreover, the isotopic ratios of oxygen do not favour the formation of the moon elsewhere, far away from the earth. The binary hypotheses rests on the premise that the moon and earth were formed together, side by side, as a binary system from the same cloud of dust and gas. Formation in one of the Lagrangian points where the gravitational forces of the earth–sun system balance each other is favoured[1]. This hypothesis explains some of the chemical and isotopic similarities between the earth and the moon, but the orbital parameters argue against such a hypothesis. A third possibility, i.e. accumulation of earth ejecta produced by large impacts[2,3] has also been discussed and one of the important goals of lunar exploration is to understand the mechanism of formation of proto-moon and its acquisition by the earth.

Beginning with *Surveyor* landers on the moon by NASA and six *Apollo* (*Apollo 11*, *12*, *14*, *15*, *16* and *17*) and three *Luna* (*Luna 16*, *20* and *24*) sample-return missions, the equatorial front side of the moon has been studied in great detail. During the past decade and a half, *Clementine*, *Lunar Prospector* and *Smart-1* have produced maps in several wavelength bands and added a wealth of information about lunar surface topography, gravity, albedo, chemical and mineral composition[4–7]. Based on these studies, important stages in the early evolution of the lunar crust and its interior have been identified, and a lunar calendar of major geologic events has been constructed. Some of these results have been summarized by Taylor[8] and Bhandari[9]. In spite of this exhaustive study which included experiments conducted in orbit around the moon and on the lunar surface as well as analysis of samples brought back from its different regions and the lunar meteorites found in Antarctica, there are many gaps in our understanding of the origin of the moon.

The most favoured hypothesis now for the origin of the moon is the 'Giant Impact Hypothesis'. This involves a chance collision of a stray body with the infant earth and explains its chemical, isotopic and dynamical characteristics[2,10,11], but the composition of the impactor and formation of ancient mare on the moon remain partly unresolved. Some of the mares were formed during a solar-system-wide ~100 million year collisional epoch around 3.8 b.y. ago when many large bodies, left over from planetary formation process, impacted most of the inner planets of the solar system, including the Moon and the earth. This important event has been termed as 'late heavy bombardment'[12,13].

As revealed by the fossil records in the old sediments, life on earth started immediately following this late heavy bombardment era. Whether the impacting bodies had anything to do with the origin of life on earth is not clear. However, it seems important to understand the early (pre 3 b.y.) event history of the moon, which holds important clues to the formation and early evolution of the earth itself. The large moon orbiting early earth had a sobering effect on the earth's obliquity[14,15], giving more hospitable environment for life to evolve. The close proximity of the moon to the earth in the remote past resulted in stronger tides and, if life on the earth originated in the oceans, the lunar tides had a strong influence on the evolution of life in oceans and from oceans to land. It is for this reason that a concentrated effort on the exploration of the moon is being undertaken by various space agencies, and currently four missions are in progress. These include *Selene* (now renamed *Kaguya*, launched September 2007, Japan), *ChangE'-1* (October 2007, China), *Chandrayaan-1* (2008, India), *Lunar Reconnaissance Orbiter* (*LRO*, 2008, NASA). *Lunar-A* (Japan) and a long-term *Robotics Lunar Exploration Programme* (*RLEP*, NASA) have also been proposed. In addition, Russia is planning *LunaGlob* mission around 2009. While the Indian, Chinese and Japanese missions are primarily science-oriented, a major emphasis of the NASA missions is to identify resources and suitable sites for establishing a lunar base to use the moon as a gateway for further exploration of Mars and the solar system beyond.

Another important aspect of the lunar exploration is understanding the earth–moon interaction. The earliest records of events on the earth have been obliterated because of intense geological activities here (plate tectonics, volcanism, weathering, etc.), whereas the moon has been quiescent over the ages with little change, except cratering by meteoritic, asteroidal and cometary impacts. In such high-velocity impacts, some material escapes, resulting in the exchange of material between the earth and the moon because of their close proximity. Occurrence of several lunar meteorites in the Antarctica bear evidence to the efficacy of such an exchange process. This opens up the possibility of finding records of the earliest terrestrial events on the moon. As we learned from the moon, numerous large impacts occurred during the period of late heavy bombardment (3.9 b.y. ago), when the lunar mare were formed, and a few impacts have been occurring sporadically on the earth subsequently over geologic times. Large impacts result in severe biotic extinctions on the earth as documented at the Cretaceous–Tertiary boundary 65 m.y. ago. Since microorganisms can remain frozen for millions of years at low temperatures, e.g. at lunar poles and can be identified later, several interesting possibilities arise. However, finding terrestrial rocks on the moon is worse than looking for a needle in a haystack and search in Apollo soils resulted in the identification of only a few earth chips on the moon.

Some salient features of the astronomical, chemical, mineralogical and geological aspects of the moon have been summarized by Bhandari[9]. A lot of information is available about the moon's surface features such as topography, albedo, distribution of mineral and chemical constituents, gravity anomaly, etc. based on *Clementine*, *Lunar Prospector* and other missions. Still many gaps remain in our understanding of the moon[16]. A major gap is related to the lunar polar regions which were not observed by the *Clementine* mission, because of its orbital inclination. Is there hydrogen or water ice deposited on the permanently shadowed region of the lunar poles which are expected to be at –230 K? The other region requiring a detailed study is the far side of the moon, specially some of the features in the South Pole Aitken basin (Figure 2), which is probably the largest basin in the whole solar system and may have lower crust or upper mantle material exposed on its surface. Basic scientific problems now confronting us are listed in Box 1. Some of these problems

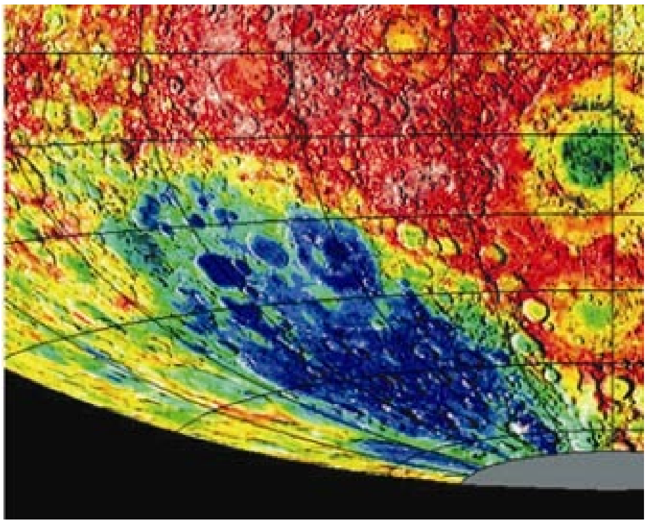

Figure 2. South Pole Aitken basin (about 2500 km in diameter and 12 km deep) on the far side of the moon, where lower crustal material may be exposed (ESA false colour photo).

Box 1. Moon: important scientific problems

- Formation: Giant impact?, formation at Lagrangian points?
- Internal structure: Core and magma ocean formation, chemical and mineral stratigraphy.
- Formation of large mare basins: Late heavy bombardment, its timing and extent in the solar system, role of tellurian moons and interplanetary bodies.
- Role in the origin or evolution of life on earth.
- Polar deposits of organics, hydrogen or water and transport of volatiles on the surface of the moon.

have been discussed elsewhere[16,17]. Based on these considerations, *Chandrayaan-1*, the orbiter mission to the moon proposed by ISRO was designed[18,19] and will be briefly discussed later in this article.

Mars: This is one of the most interesting planets because of its 'geological' history, atmosphere and ancient or possibly even present-day hydrosphere. It has been an object of focused exploration because the environment there is considered to be congenial for supporting life. *Viking-1* and *2* orbiter-lander pairs carried out experiments[20] during 1975–76 to determine any biological activity on the planet. Although observations indicated the absence of any biogenic processes, some of these conclusions may not be unequivocal. These missions were followed by a series of orbiters and lander/rovers by USSR and USA. During the past decade *Mars Global Surveyor* (launched in 1996), *2001 Mars Odyssey* and *Mars Express* of the ESA (launched in 2003) have provided a large number of high-resolution images and a wealth of data on surface features, climate, atmospheric processes and magnetic field, etc. The most successful twin-rovers *Spirit* and *Opportunity*, with on-board instrument for imaging, like Panchromatic Camera and Microscopic Imager, and those for determining mineralogy, texture and structure of rocks, like the Mössbauer spectrometer, alpha-particle X-ray spectrometer, magnets and rock abrasion tools, etc. were launched in 2003 by NASA. For the past three years these rovers have provided evidence for river channels, lakes, sedimentary deposits and nature of the Martian bedrock, some of which is basaltic in nature, reminiscent of volcanic activity.

Presence of water on this planet in the recent past[21] (Figure 3) and the possibility of occasional volcanic activity or impact of a large asteroid or comet bringing out subsurface water and carbon dioxide to create environmental conditions and hydrospheric cycles[22,23] for life to evolve or sustain for reasonably long periods of time (10^3 to 10^4 years), have been debated. Such scenarios for extinct or extant life on this planet have made Mars the most exciting planet for future exploration.

Figure 3. Evidence of river network, sudden floods and sedimentary layered deposits in an area of about 75 × 100 km on Mars (NASA photo).

Much has been learnt about Martian history from meteorites which came to the earth from Mars. These Martian meteorites (e.g. Shergotty meteorite which fell in Bihar, and those collected from Antarctica) have preserved records of ancient atmosphere of Mars, giving us some idea about the evolutionary history of the Martian atmosphere[24]. They have also provided some insight into the geologic processes operating in different regions of Mars.

Three spacecraft (*Odyssey*, *Mars Express* and *Mars Reconnaissance Orbiter*) and two rovers are currently exploring Mars. Additional missions, namely *Phoenix*, *Mars Science Laboratory* and others are being planned. Plans for a sample-return mission by NASA during the next decade are being made. The primary objectives of these missions are to look for palaeowater record, fossil life-forms and composition of Martian samples. There are many aspects of Mars which deserve further study (Box 2). Study of Martian atmosphere, ionosphere, weather/dust-storms, plasma environment, surface magnetic fields and solar–wind interactions would be scientifically rewarding. A low altitude (<100 km) orbiter with atmospheric and plasma probes for studying Martian atmosphere and environment along with complementary remote-sensing instruments for studying Martian surface for mineralogy, chemistry and records of palaeo-water may provide better information than that available now. Anomalous concentration of methane can be biogenic and therefore an orbiter mission dedicated to measurement of methane[25] in the atmosphere and its source on ground can lead to identification of pockets of biological activity. A long sedimentary core at a suitable site will be extremely useful in understanding Martian history and its geologic and climatic evolution.

Mercury: Being the smallest and least altered of all the rocky planets, Mercury holds clues to our understanding of the formation of the solar system. There is a special interest in Mercury because it has the highest density

Box 2. Problems related to Mars

- Stratigraphy of sediment deposits in crater lakes.
- Internal structure.
- Evolution from earth-like thick and warm atmosphere 3.8 b.y. ago to present tenuous and cold atmosphere.
- Palaeo- or subsurface water, transient (hospitable) atmosphere and fossils?

(5.4 g/cubic cm) among all the planets and a global magnetic field. The interior structure of Mercury is therefore of much scientific interest for understanding its early differentiation history. Mercury is therefore considered to be the test bed for theories of formation of the solar system. Furthermore, earth-based radar observations show the presence of water in its polar regions. In spite of its proximity to the sun, water has survived because some regions in the poles, being under permanent shadow, are very cold. Some interesting scientific problems about the evolution of Mercury[26,27] are listed in Box 3. In spite of much interest, the planet has not been explored in detail, because the gravity-assist mode is the only feasible way to send a spacecraft to Mercury and this requires several years to reach the planet.

NASA's *Mariner 10* mission in the mid-seventies was the only mission to fly-by Mercury a couple of times and has provided us some images and preliminary information. Several ambitious missions are currently being planned. NASA had launched the *Messenger* mission to Mercury in 2004 with planned fly-by the planet during 2008–09 and finally orbiting the planet in 2011. The other mission currently planned is *Bepi-Colombo* by ESA and JAXA, which will have two orbiters – one for remote sensing of the planetary surface and the other for investigation of particle environment. This mission will carry X-ray, gamma-ray and visible–IR spectrometers for studies of surface mineralogy and composition; stereo-imaging and laser altimetry for global topography and gravity field, magnetometer and energetic particle and plasma spectrometer for monitoring the environment of Mercury.

Venus: This planet is physically similar to the earth in size, mass and density, but different in its evolutionary history. The high surface temperature (about 477°C) and high CO_2 atmosphere with pressure about 90 times the earth's atmospheric pressure suggest that its evolutionary history was unique due to run-away greenhouse effect. Radar mapping of the surface of Venus revealed that its surface is covered by mountains, large craters and lava flows, and is indicative of active global volcanic episodes which occurred about 500 M.y. ago. The important question about the evolution of Venus relates to its interior processes that result in volcanic eruption on a global scale and also circulation, composition and interaction of its atmosphere with its surface leading to extremely different rotation rates for near-surface and upper atmospheric layers. USSR made Venus a prime target of study and sent a series of *Venera* missions, including landers and orbiters; and NASA's *Magellan* missions provided important information about atmosphere and surface conditions of Venus. The ESA has recently launched *Venus Express* with an array of instruments and the *Mission PLANET-C* of JAXA is at an advance stage of planning and is to be launched in the next few years. Both these missions, particularly *Venus Express*, will provide new data on this planet by 2010. Exploration of Venus relates specifically to its unique evolutionary history and may not be critical from the point of view of general evolution of the solar system. Therefore, Venus offers a special case study of planetary processes which do not occur elsewhere.

Box 3. Mercury: some scientific problems

- High density (5.46 g/cubic cm): Causes.
- Silicate deficiency: Early differentiation, internal structure.
- Late heavy bombardment: Formation of large basins.
- Polar ice and its origin.

Outer planets: These planets have an entirely different formation and evolutionary history. Arguments for their early as well as late formation relative to other planets have been advanced[28]. The first close glimpse of Jupiter, Saturn, Uranus and Neptune systems was taken by *Pioneer-10* and *11* spacecrafts, followed by *Voyager 1* and *2* fly-by missions during the decades following their launch in the 1970s. The *Hubble telescope*, *Galileo*, *Chandra* and other missions also observed features in the atmospheres and their satellite systems. All these missions have made several important discoveries regarding the dynamics and structure of ring systems, surface properties of the satellites, etc. The discovery of water-ice, sulphur and other volatiles on several of the Galilean satellites of Jupiter make them specially interesting objects for further exploration[29]. Ganymede is not only Jupiter's largest moon, but the largest one in the entire solar system; it is larger in diameter than Mercury but has only about half its mass. *Galileo* orbiter data suggest that Ganymede is differentiated into a three layer structure: a small, partially molten iron or iron/sulphur core surrounded by a rocky silicate mantle with an icy shell on top, with an ice crust floating over a warmer ice mantle that may contain liquid water[29]. Evidence of water ice on Europa is more compelling (Figure 4).

Callisto has the lowest density (1.86 g/cubic cm) among the Galilean satellites. From recent observations made by the Galileo spacecraft, Callisto appears to be composed of a crust about 200 km thick, and beneath the crust possibly a salty ocean more than 10 km thick. Their proximity to Jupiter containing organic molecules, ammonia etc. in its atmosphere, which are necessary constituents of life make the Galilean satellites attractive from the point of view of possibility of biological activity.

Saturn's moons are even more exciting. Images of the tiny moon Enceladus taken by *Cassigni* show geysers erupting from its surface. Obviously there is an internal source of heat which spews such water fountains. The *Cassigni–Huygens* probe studied the atmospheric and surface features of Titan, the enigmatic moon of Saturn[30,31].

Figure 4. Evidence of icy surface on Europa (diameter 3122 km).

Ethane and methane, both liquids under Titan's conditions as also carbon dioxide, cyanogens and benzene were detected there. Thus Titan, having a reducing atmosphere similar to the pristine earth when life originated, mainly containing ammonia, nitrogen, methane, etc, albeit the extremely low temperature, has been considered as a laboratory of pre-biotic processes.

Asteroids and comets: Comets, asteroids and Kuiper Belt Objects (KBO) are of prime interest because some of them contain the most primitive and pristine materials of the solar system, possibly the building blocks of planets[32]. Each group of these objects has diverse compositions reflecting evolution to a different degree under different physico-chemical conditions. Their analysis may allow us to understand the nature of material from which the planetary formation process started in different regions of the solar system and the variety of conditions that existed during this epoch.

Asteroids with size ranging from a few kilometres to a few hundred kilometers, may be considered as protoplanetary bodies. Some of the asteroids were partially molten and internally differentiated very early in the history of the solar system. They are also the parent bodies of different types of meteorites. Asteroid reflectance studies have led to classification and association of different asteroids to different meteorite classes, which are well studied for trace element and isotopic composition in the laboratory. A better understanding of evolution of asteroids will be valuable towards understanding the evolution of planetesimals and their thermal history and early solar system processes which occurred within a few million years of formation of the solar nebula, finally leading to the formation of planets[33].

Until recently, most of the missions to asteroids were fly-by type. Asteroid 9969 Braille was the first to be observed by *Deep Space* probe of NASA. This was followed by the *Near Earth Asteroid Rendezvous* (*NEAR*) mission to 433 EROS, which made a detailed study with several remote-sensing instrument[34]. *NEAR* also imaged Comet Hyakutake in 1996 and made the first fly-by of asteroid 253 Mathilde in 1997. Asteroids 951 Gaspra and 243 Ida were also imaged by *Galileo* at its closest approach. The *Hayabusa* mission of JAXA had grabbed the first sample from the asteroid Itakawa in November 2005 and is expected to return the same to earth in 2010. NASA has plans to launch the *Dawn* mission to explore the two largest asteroids, 1 Ceres and 4 Vesta, that have different characteristics and distinct early evolutionary history. This mission is expected to orbit Vesta around 2011 and Ceres by 2015, after completing a 5 billion km trip. Vesta is of special interest because some eucritic meteorites are believed to have originated in this asteroid and also because it has evolved to its present state very early, within 4 or 5 m.y. of the origin of the solar system[35].

Comets are mysterious objects, constituting not only the pristine material out of which the planets have formed, but also interstellar matter which they accrete. Comet Halley has been studied by the Soviet missions *Vega 1* and *2* as well as by US and Japanese missions. Other comets which have been studied so far are Giacobini–Zinner (by *International Comet Explorer* (*ICE*)) and Grigg–Skjellerup by *Giotto*. Recent successful missions to comets are *Deep Impact* which targetted comet Tempel-1 and *Stardust* which explored comet Wild-2 and collected more than 10,000 dust particles from this comet and returned to earth in January 2006. ESA had launched the *Rosetta* spacecraft in 2004 to study comet 67P/Churyumov–Gerasimenko. *Rosetta* consists of an orbiter and a lander with several scientific instruments in the orbiter and on the lander for a comprehensive study.

Rosetta will first orbit the comet and then move towards its nucleus. The orbiter's cameras will map the nucleus in detail, which will help select a suitable landing site. *Rosetta* will then dispatch its lander *Philae* to the comet's surface. Approaching the nucleus at walking speed, *Philae* will fire two harpoons to anchor itself down and study the comet nucleus. The successful completion of this mission, expected to reach its target in 2014, will be an important landmark in planetary exploration. Many missions are being planned now for studies of comets and the KBO[36]. Some of the interesting problems related to comets are listed in Box 4.

In all these efforts towards planetary exploration, search for water has been a common theme. Water is important because it is essential for biological activity and is therefore used as a proxy for life. Hydrogen and oxygen are the two most common elements in the universe and they are easy to combine. Therefore, it is not surprising that water has been found in many planetary bodies. Evidence of ancient water or present icy deposits has been found in Mercury, moon, Mars, Europa, and several other satellites of the outer planets, comets, several asteroids and carbonaceous and H-type meteorites. Yet there is some controversy about the presence of water on the moon. It is therefore necessary to first ascertain and then to quantitatively determine the distribution of water and the form in which it exists in different planetary bodies. This can be a common objective of various planetary missions. Whether conditions at present or in the past in other planetary bodies have been congenial for supporting some sort of life, remains an important question for future exploration. The other proxy for biological activity is methane, although it occurs in abundance in some planetary bodies (e.g. outer planets) due to organic reactions. If such interferences can be excluded, methane can be used as a proxy for biological activity. If the source region of methane in Mars can be identified, it can possibly lead us to sites of biological activity.

There is yet another aspect, i.e. the impact of asteroids and comets on the earth[37], which makes it desirable to study orbits, chemical and mineral composition, and size and strength of asteroids and comet nuclei. Evidence of collisions of asteroids and comets in the past has been found in sedimentary records of the earth[38]. The energy release in these collisions is large, and through a series of processes in the atmosphere and oceans, may occasionally be catastrophic enough to wipe out all the living creatures, including the entire human civilization, in one stroke. Geological, physical, chemical, mineral and isotopic evidence for biological extinction on earth preserved in sedimentary records has been reviewed by Shukla and Bhandari[38]. Study of their composition and orbits, particularly of Near-Earth Asteroids which are more likely to have a close encounter with the earth, is therefore important for predicting and mitigating the effect of their collisions[39].

Box 4. Some exciting problems related to comets

- Most pristine relics of the solar system: Their mineral, chemical and isotopic composition.
- Organic molecules and their role in the origin of life.
- Interstellar matter: Its nature and change through time.
- Formation chronology relative to planets.
- Consequence of their impact on earth.

I have described some important scientific questions about various planetary bodies of the solar system and missions that are in progress now. This discussion is selective and to a large extent subjective, rather than exhaustive and it is desirable to further debate these points, modify and prioritize the scientific aspects so that meaningful programmes of planetary exploration can be planned and carried out effectively. Before discussing the strategy and priorities for future exploration, which has to be drawn within this framework, I describe the other important aspect of planetary exploration, i.e. planetary resources.

Planetary resources

Justification for planetary missions on economic criteria is occasionally made in view of the resources that exist on planets and possibility of their utilization. Although all the inner planets, including asteroids, are made of material largely similar to those of the earth, with little commercial implications, comets and outer planets contain large amount of organic matter and volatiles. Moon, the closest celestial body, is relatively easier to access and its resources have been discussed by Schrunk *et al.*[40]. Assessment and harnessing of resources are also required if human outposts or bases are to be established as is being planned on the moon and Mars. We discuss two aspects which are futuristic but may be of foremost interest. One is helium-3, considered to be an ideal fuel for fusion[41] available in lunar soil but extremely rare on earth, and the other is organics which may be abundant in comets and outer planets.

Helium-3: This is made in the sun by thermonuclear reactions, when hydrogen is converted into helium. Importance of helium-3 lies in the fact that it is possible to produce unpolluting (or radioactively clean) energy by ^{3}He–D or ^{3}He–^{3}He fusion.

$$^3\text{He} + \text{D} = \text{P} + {}^4\text{He} + 18.4\ \text{MeV},$$

$$^3\text{He} + {}^3\text{He} = 2\text{P} + {}^4\text{He} + 12.9\ \text{MeV}.$$

The large amount of energy release in these reactions makes ^{3}He fusion an attractive proposition, since a few kilograms of ^{3}He can meet the annual energy requirement of the whole earth. Helium-3 produced in the sun and carried by the solar wind, impinges on the soil lying on the planetary surfaces, e.g. of Mercury, moon, etc. which have no atmosphere. The turnover of the soil cover (regolith) exposes grains in the top few metres to ^{3}He, which eventually gets saturated to a level of few parts per billion. ^{3}He is difficult to retain in grains since it easily escapes into space. However, it has been found that in the moon, there is an equilibrium amount of a few parts per billion (~5 to 10) in some minerals. The oxide of iron and titanium, ilmenite ($FeTiO_3$) has relatively high retentivity for helium-3. Mapping of iron and titanium on the lunar surface can thus indicate the distribution of ^{3}He.

There are two problems associated with using ^{3}He: (i) Its extraction on the moon for recovering reasonable amounts of ^{3}He involves heating billions of tons of soil to 600–800°C, and (ii) development of suitable fusion reactors on the earth. In principle it appears promising, but would require the development of viable technology for extraction of ^{3}He from the soil on the moon and working fusion reactors on the earth. The ambitious International Thermonuclear Experimental Reactor project, based on the principle of magnetic confinement used in Tokamak, is expected to demonstrate an experimental fusion reactor in about 15 years from now. Power production using D,T, etc. may take another 25 years or so, but if this becomes feasible, ^{3}He can also be used for fusion. Thus, this is an attractive but futuristic proposition.

Organics in comets: Comets are dirty ice balls, mostly made of water-ice and methane. CH, NH and OH radicals, coming from the dissociation of methane, ammonia, water and some complex organic molecules have been found in the comets. The comets are thus a store-house of organic molecules, some of which if harnessed, can have commercial implications. Some molecules are highly evolved and may even serve as building blocks of life. Recently, *Startdust* mission found methylamine and ethylamine in the aerogel which sampled particles of Wild 2 and brought back to earth. When comets encounter planetary bodies such as the moon, this material may get deposited at some suitable sites, like the poles and be retained for a long time because of the prevailing low temperatures there. The lunar missions planned for 2008, such as *Chandrayaan-1* and *LRO*, may be able to characterize and map the polar deposits and confirm if sizeable amounts of organic compounds are present there.

Planetary exploration programme of ISRO

ISRO, since its inception about half a century ago, had well thought out priorities of development and applications of space technology. Vikram Sarabhai, who defined the vision of ISRO, wanted to use space technology for the benefit of the society and national development. This resulted in two sets of satellites: *IRS* series, for remote sensing of natural resources and *INSAT* series devoted to communication, etc. In addition, the past decades have witnessed thematic satellites such as *Cartosat* (*1* and *2*), *Metsat* (*Kalpana-1*), *Edusat*, *Resourcesat*, *Hamsat*, etc. devoted to cartography, meteorology, education, telemedicine, e-governance and disaster management, etc. designed to meet various national requirements, besides a few missions devoted to astronomy and atmospheric studies. Two types of rockets, the Polar Satellite Launch Vehicle (PSLV) and the Geostationary Satellite Launch Vehicle (GSLV) have been developed by ISRO for meeting these requirements. With the successful launch of PSLV in 1994–95, a fly-by or orbiter mission to the moon and some inner planets appeared feasible, but in view of various national priorities at that time, the planetary exploration programme was initiated only towards the end of the last century. A mission to the moon, christened as *Chandrayaan-1* was approved in 2003 as a first step. Follow-up long-term plans for a second mission to the moon and other planetary missions are now being formulated. I first briefly describe the *Chandrayaan-1* mission and then, within the framework of scientific problems in planetary sciences discussed above, propose priorities and strategies for future planetary exploration.

Chandrayaan-1

Chandrayaan-1 is a lunar polar orbiter for remote sensing of the moon from a nominal altitude of about 100 km. The primary objective of this mission is to carry out topographic, chemical and mineral mapping of the moon with a high spatial resolution. It will collect data for a period of two years (2008–10) during which the whole moon will be mapped in visible, near IR and X-rays, making a detailed study of the lunar poles, which will be observed during every orbit. The scientific goals and launch profile have been described elsewhere[18,19,42,43]. It is expected that the chemical, mineral and radioactivity distribution on the moon will be useful in determining the stratigraphic relationship of various litho-units, which should provide crucial information on early evolution of the moon, and transport and deposition of volatiles, organics and water-ice on the lunar poles. These studies should also enable better appreciation of resources available on the moon. Some prime targets on the moon for detailed study have also been identified[19]. *Chandrayaan-1* mission and its scientific challenges have also been discussed in detail elsewhere[18,19] and therefore, we only briefly describe its salient features.

Chandrayaan-1 has eleven payloads and an impactor. Some of the instruments on-board *Chandrayaan-1* and the imaging strategy have likewise also been discussed elsewhere[43]. Four payloads on this mission, i.e. Terrain Mapping Camera (TMC), Laser Ranging Instrument (LLRI), Hyper-Spectral Imager (HySI), and a High Energy X-ray spectrometer (HEX) are the Indian payloads. Besides, there is also a significant international participation in *Chandrayaan-1*. The X-ray fluorescence spectrometer and Sub Atomic Reflecting Analyser (SARA) are joint payloads between Indian and foreign groups. Four international payloads are: a Miniature Imaging Radar Instrument (mini-SAR) and Moon Mineral Mapper (M^3) both from USA, an infrared camera (SIR-2) from Germany (ESA) and a Radiation Monitor (RADOM) from Bulgaria. Figure 5 shows a table model of *Chandrayaan-1* with various payloads and the impactor. The impactor has some imaging and other analytical instrument (e.g. mass spectrometer) and will make observations during its descent before crash-landing on the moon.

Selene, *Chandrayaan*, *Chang'E* and *LRO* may have overlapping periods of observation during 2008–10. Their time line is shown in Figure 6. Therefore, apart from this international collaboration on instrumentation on *Chandrayaan-1* mentioned above, data sharing and further cooperation and collaboration between some of these missions are also planned, so that one mission may benefit from the data of the previous mission and suitably modify its activity, if possible. Also, there are several possibilities for in-orbit collaboration. For example: (i) impact of a lunar craft of one mission may be observed by other missions to learn about the lunar surface characteristics and near-surface deposits, and (ii) bistatic radar observations of regions of interest, such as south polar regions using Mini-SAR on *Chandrayaan-1* and similar instruments on *LRO* can be carried out. This experiment will be similar to the one carried out on *Clementine*[44], but would involve two lunar satellites instead of *Clementine* and a ground based receiver. It would therefore be an effective experiment to resolve the debate about the origin of the observed anomalous polarization, whether it is due to water-ice or soil roughness properties[45].

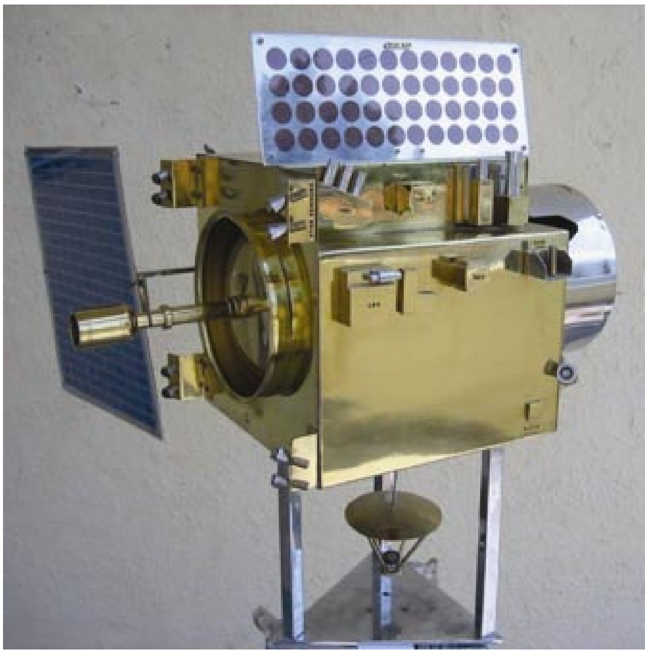

Figure 5. Table model of *Chandrayaan-1* (1/5th size) showing ensemble of payloads. The actual lunar craft is a cube of 1.5 m.

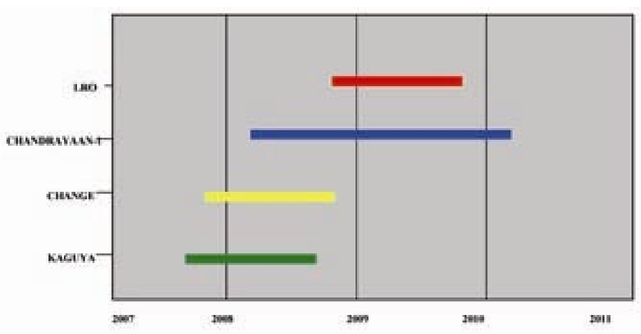

Figure 6. Time line of various moon missions proposed to orbit the moon during 2007–10, showing overlapping periods of observation, offering excellent opportunities in pre-launch and in orbit coordination and cooperation in data analysis.

Strategy for future planetary exploration

As described above, during the past few years there has been a resurgence in planetary exploration programmes with a large number of space missions announced by USA, Europe, Japan, China and Russia for the exploration of several planetary bodies of the solar system. Apart from understanding the evolution of the solar system objects, a major thrust is for finding evidence of life, fossil or living, in extra-terrestrial environments. The most promising bodies for this purpose are Mars or the icy satellites of the major planets in the outer solar system.

In the recent past, there has been a growing interest in using the moon as a test-bed for equipment and operations required for other planetary missions and a gateway for exploration of other solar system bodies. USA has already outlined long-term plans of having permanent human presence on the moon and a moon–Mars route for exploration of Mars and other planets. This will require exploration and utilization of resources available on the moon, necessary for establishing a lunar base in the foreseeable future. Europe, China and Japan also have ambitious programmes of lunar exploration in the coming decades. Considering international interest and participation, the ILEWG has proposed a road map with a base on the moon by 2014.

Under this scenario of a large number of missions in progress, a judicious strategy for future planetary exploration has to be evolved to optimize scientific returns, avoid repetition and enhance complementarity. Many questions need to be debated while embarking on a new long-term programme of planetary exploration. The foremost question is whether the planetary exploration should be driven by science objectives or assessment of resources in space and their utilization. The motivation of recent or planned missions to the moon by China, Japan and Russia is scientific enquiry, as in the case of *Chandrayaan-1* by India. The recent European mission, *SMART-1* was designed primarily for technology development, mainly to demonstrate ion-propulsion system to go to the moon[46], although it had some science component. USA is focusing on resource assessment and utilization in establishing a base. Here I confine to science-based missions, aiming at understanding the origin and evolution of the planetary system. This approach is briefly as follows. If we know the nature of the material (chemical composition, mineralogy, size distribution, etc.) with which planet formation started in the solar nebula (mainly based on study of primitive meteorites and the sun), and we also know the present chemical and mineral constituents and internal structure of various bodies, with the help of models of chemical differentiation processes and some idea about the physico-chemical processes that were operative and the physical conditions that prevailed, we can work out the various stages in the formation and evolution of planets. Such a study should eventually lead to a theory of planet formation and their size-dependent evolution. Furthermore, if formation ages of different materials are obtained by dating various samples, the evolutionary chronology of planets can be constructed and integrated with the theory of planet formation. Isotopic composition is crucial in this reconstruction, because every material can be uniquely identified by its isotopic composition of various elements. The pristine material with which the planetary formation started is expected to be present in comets, some asteroids and KBO, rings of Saturn and interplanetary debris (dust, meteor streams, etc.). Different meteorites have provided isotopic and trace-element signatures of various types of material in the asteroidal belt. Although much can be learnt by exploring every planetary body, be it planets, satellites or small bodies of the solar system, there is merit in being selective to optimize the science outcome. From the arguments presented here, it seems that Mercury holds clues to the formation of the solar system and early differentiation processes, and the moon on the early evolutionary history of the earth, and life on earth and Mars may possibly have fossil or primitive life-forms. Thus the moon, Mars, Mercury, comets and satellites of Jupiter offer the best choice to understand some of the basic questions. Apart from selecting appropriate objects for exploration, there are options related to: (i) manned vs unmanned missions or both, (ii) remote sensing orbiter missions vs landers for conducting experiments on the planets vs sample-return missions, although all the three are complementary. In this debate, it appears that there is scope for robotic orbital remote sensing and sample return missions in preference to lander/rover missions. The main arguments in favour of these preferences is the global synoptic mapping with high resolution made possible with newly available sensors on orbiters and some of the information which can be obtained only by laboratory analysis of materials, such as formation ages, isotopic and trace-element characterization, etc. It seems that lander/rover missions to the moon, for example, would not give the best scientific returns as the twin rovers have given for Mars, because of their different evolutionary history and the moon's large scale monotonous surface geology; rovers are most useful in supporting outposts and bases on the moon. Possibility of manned space programme, specifically for lunar exploration has also been debated by ISRO. It is well known that manned missions are exorbitantly expensive compared to robotic exploration and therefore need serious debate. Robotic missions have greater reach in the solar system, beyond the moon and Mars, and with modern sensors can provide the best route to exploration of the solar system.

In view of the above discussion, at the present state of exploration, it seems that unmanned robotic missions involving orbiters with highly sensitive sensors and sample-return missions may be more rewarding compared to fly-by, landing, rover and manned missions. Scientifically, the most valuable sample seems to be long cores at specific locations deep through the planetary surfaces, if they can be brought back for study in laboratories on the earth.

Lunar exploration beyond Chandrayan-1

The moon will continue to remain an object of study because the process by which it was formed in orbit around the earth is not fully understood and there is an element of chance involved in the various hypotheses proposed so far. In view of its importance in understanding the early evolution of the earth, life on earth and its ancient interplanetary environment, *Chandrayaan-1* should be followed by a series of unmanned orbiters and later on, when the technology permits, by sample-return missions. There are many options in defining future missions, but an orbiter–lander pair, with remote sensing payloads such as ultraviolet imagers, and neutron flux monitors which are complementary to *Chandrayaan-1* with an objective of focused study on specific areas of interest, determined by the *Chandrayaan-1* data appears to be a good choice. The prime samples of scientific interest are long cores through the regolith and bed rock, which will provide a wealth of information about the earliest events on the moon. Arrhenius *et al.*[47] have shown that such cores represent sequential deposits over time and may contain record of the moon's evolution from the very beginning. Site selection for cores and any surface experiments have to be done carefully. Some of the potentially interesting sites where the lower crust or upper mantle may be exposed, such as in South Pole Aitken region (Figure 2) have been discussed[48]. Automatic coring and sample-return was demonstrated by the Soviet *Luna* missions in the 1970s. These cores were about a metre long but the same technology can be modified to retrieve longer cores. This is a technically challenging proposition but could be scientifically most rewarding. The sample-return *Moon rise* mission proposed by Duke and colleagues in USA will be a big step in our understanding of the moon.

Exploration of planets and other bodies

As pointed out in preceding sections, two planets appear to be most interesting from the point of view of scientific returns: Mercury and Mars. Since orbiter to Mercury has to follow a complicated route, this mission may be undertaken after new information from *Messenger* and *Bepi Colombo* become available by 2015. It can possibly have high-resolution remote-sensing payloads, similar to *Chandrayaan-1*. Therefore, the 2015–20 time frame will be ideal for undertaking missions to Mercury.

Orbiter mission to Mars will require significant development of technology and automation, and the best course would be to first develop new sensitive sensors for robotic missions. There also exist good possibilities of international collaboration. Mars sample-return mission is being planned by NASA for next decade. The strategy should be to build upon the information made available from current and future missions in progress now, before designing new missions. Search for sources of biogenic methane may be an important objective.

In addition to exploration of the moon and the two planets, Mars and Mercury, low-altitude orbiter missions to Jovian satellites, Europa and Ganymede during the coming decades could be rewarding. If capability for mission to outer planets can be developed, then studying Saturn's ring particles seems exciting. Other objects of scientific importance which may have priority in long-term exploration plans are meteor streams, particularly those which are fresh, and KBO, since they may also contain the material from which the planetary system was formed.

Future planetary missions will require simultaneous development of several technologies, which include launching, navigation and control, communication, automation, robotics, instrumentation and sampling. The Planetary Science and Exploration programme at the Physical Research Laboratory, Ahmedabad was initiated for planning and coordinating these activities. The Indian launch vehicles, including PSLV and GSLV, and its modified version GSLV MKIII are capable of fly-by and orbiter missions to various planetary bodies. However, significant developments such as an additional stage, both for PSLV and GSLV are required for missions to Mars and Venus, whereas Jupiter fly-by is possible with GSLV MKIII. Fly-by mission for both near-earth and main belt asteroids as well as comets is feasible with these launchers. On the other hand, orbiter mission to main-belt asteroids may be difficult due to high impulse requirement, while orbiter missions to near-earth asteroids appear feasible. In all future missions robotics has an increasing role to play. A well-developed automated laboratory which can determine chemical and mineralogical composition and trace element and isotopic constituents will go a long way in providing new information. This has to be accompanied with development of coring and sampling technology.

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MEETINGS/SYMPOSIA/SEMINARS

National Seminar on Science Communication through Creative Genres

Date: 20–23 February 2008
Place: Dehradun

Technical sessions/Sub themes: Fiction as a form of science communication; Poetic expressions as a form of science communication; Creative genres and performing arts; Creative writing for audio-visual-digital media; Creative genres and issues of literacy and medium.

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Workshop on Electron Microscopy and its Application in Material Science and Biological Science

Date: 26–28 March 2008
Place: Kolkata

Topics include: Instrumentation of SEM, TEM, SPM and Specimen Preparation Techniques for SEM, TEM, SPM, Applications of SEM, TEM, SPM in Material Science and Biological Science. SEM, TEM, AFM and CPD Laboratory Demonstration.

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