Planetary sciences and exploration: An Indian perspective

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Studies of cosmic ray records in meteorites and lunar samples in the nineteen sixties mark the beginning of research in planetary sciences in India. These studies led to very significant results that include discovery of ancient solar flare records in meteorites and constancy of solar and galactic cosmic ray fluxes over long (million year) time scales. Several research groups in India studied fossil records of nuclear track, noble gas, nitrogen, trace element and radioactivity in returned Apollo and Luna samples to understand both the nature of long-term solar wind, solar energetic particle and galactic cosmic ray fluxes as well as chemistry of lunar rocks and soils and their evolution on the lunar surface. The identification of meteorites of martian origin has also led to studies of such meteorites to understand the evolution of martian atmosphere over time. Analysis of diagnostic trace elements in samples of Cretaceous-Tertiary (K/T) boundary and chronology of Deccan volcanism supported asteroid impact as the cause of extinction of life ~65 million years ago. Studies of impact craters records in the Indian shield have also been pursued and led to the identification of new impact structures. The realization that some primitive meteorites host refractory oxides and silicates that are some of the first solids to form in the solar system has opened a new window to study the events and time scales leading to the origin and early evolution of the solar system. Meticulous studies of isotope records in early solar system solids using secondary ion and noble gas mass spectrometry techniques, primarily done at the Physical Research Laboratory, Ahmedabad led to the identification of fossil records of short-lived nuclides of stellar origin in early solar system solids. Studies of these records provided a chronological framework for the origin and early evolution of the solar system, led to the identification of the short-lived nuclide $^{26}$Al as the heat source for early melting of planetesimals and bolstered the proposal for a supernova triggered origin of our solar system.

Studies of planetary astronomy carried out in India have also led to significant results that include the discovery of the rings of Uranus and of new asteroids. Observations of cometary dust and emission of X-rays from planets as well as analytical modelling of martian ionosphere and aerosols and cometary atmosphere have also yielded important results.

A new chapter in planetary science research in India was scripted with the successful launch of Chandrayaan-1 on 22 October, 2008. The data obtained by instruments onboard Chandrayaan-1 has already yielded significant new results and the Chandrayaan-2 mission is being planned with a targeted launch in 2012. Future planetary exploration plans are being formulated with Mars and comets/asteroids as plausible targets. This review provides a brief outline of planetary research activities in India from the very beginning, a broad outline of important contributions made during the last two decades and a future perspective, including those for planetary exploration.

1. Introduction

The solar system consists of a central star, the Sun, surrounded by eight planets, a few minor planets, and a large number of planetary satellites, asteroids and comets populating different regions of the solar system. Our present understanding of the origin of the solar system is based on our

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knowledge of star formation processes coupled with astronomical observations and laboratory as well as remote sensing studies of various solar system objects. The formation of the solar system can be traced back to a natural or triggered gravitational collapse of a dense interstellar molecular cloud fragment, about 4.6 billion years ago. This led to the formation of a massive object at its centre that became self-luminous due to the continuous input of gravitational potential energy of the infalling material and the proto-Sun was born. The residual gas and dust surrounding the proto-Sun, the so-called solar nebula, continued to feed the proto-Sun until the increased gas density and associated pressure towards the center of the nebula brought a halt to the accretion and the nebula material settled down to the central plane under the influence of the gravitational effect of the Sun. Dust grains grew in size during this process of settling through mutual aggregation and the process of growth continued in the denser environment of the disk formed in the mid-plane leading to formation of meter-sized objects. Further growth of objects took place due to local gravitational perturbation in the disk and ten to hundred km-sized objects, the so-called planetesimals, were formed. Analytical studies, assuming certain initial conditions, suggest that this whole process can take place in less than a million years, a very short time scale if we consider the age of the solar system. Collisional aggregation between planetesimals can lead to the formation of sufficiently massive objects that can gravitationally perturb and attract other smaller objects towards it leading to a run-away growth resulting in the formation of planetary-sized objects. The time scale for the growth of planetesimals to planets could be several tens of million years or more.

In recent years, our ability to identify solar system objects that can provide records of events and processes taking place during the very early evolutionary stages of the solar system has considerably improved our understanding of the formation of the solar system. Most of the information in this regard comes from studies of meteorites and, in particular, carbonaceous chondrites that closely resemble composition of the solar photosphere and represent some of the most primitive samples of the solar system. Evolution of the Moon and Mars can also be studied by analyzing lunar samples brought back by the Apollo and Luna missions and studies of lunar and martian meteorites. Extraterrestrial samples, representing different stages of evolution of the solar system, that are currently available for laboratory studies are depicted in figure 1. The various remote sensing missions to planets and their satellites over the last four decades have also provided us with a wealth of information about the planets, satellites, asteroids and comets and the space environment around these objects. In the absence of any previous review covering work done in India on different aspects of this field, we provide a brief overview of the initial stages of research in the field of planetary sciences.
carried out in India and a broad perspective of research conducted during the last two decades and possible future directions.

2. Solar and galactic cosmic ray records in extra-terrestrial samples

Studies of extra-terrestrial samples was initiated at the Tata Institute of Fundamental Research (TIFR), Bombay, in the mid-sixties to look for fossil records of ancient cosmic ray heavy nuclei tracks preserved in meteorite samples. Low energy heavy nuclei ($Z > 20$) of solar or cosmic origin incident on silicate grains in meteorites or lunar samples can create microscopic solid state damages that can be enlarged by suitable chemical etching and one can use a high magnification optical microscope to look at such linear damage trails along the path of the cosmic ray heavy ions (see figure 2) that are termed as nuclear tracks (Fleischer et al. 1975). The great advantage of using lunar sampleless or meteorites as probes is the fact that they are exposed to cosmic rays in space for millions of years and thus provide tremendous collecting power even if one looks at a small grain less than a millimeter in size. In fact the first records of cosmic ray iron-group very heavy ions were found in meteorites (Fleischer et al. 1967). One of the major discoveries in the field made during this period by the group at TIFR, concurrently with an European group, is the observation of ancient solar flare heavy ion tracks in silicate grains of certain meteorites (Lal and Rajan 1969; Pellas et al. 1969). The low energy (1–100 MeV/n) solar flare heavy ions have a range less than a millimeter in silicate material and as atmospheric ablation removes the surface layers of any meteorite reaching the earth, one does not expect to observe solar flare records in meteorites. The identification of solar flare tracks in grains collected from interior of meteorites is based on a characteristic gradient in track densities as a function of depth within the grain and also high track density compared to the average background density of tracks produced by high energy galactic cosmic rays (see figure 2). It is obvious that such grains were exposed either in space or on the surface of the meteorite parent body, an asteroid, where they received solar flare irradiation before they became a part of the host meteorite. Meteorites containing solar flare irradiated grains were also found earlier to contain records of solar wind ion implantation (Gerling and Leveski 1956; Wänke 1965; Eberherdt et al. 1965), as inferred from studies of noble gas records in them, and were termed as gas-rich meteorites. These observations led to the prediction that rock and soils exposed on the surface of the moon will have abundant records of solar energetic particles (SEP) that would have had unhindered access to the surface of the moon that is devoid of an atmosphere or an intrinsic magnetic field. This was indeed confirmed when the returned lunar samples were analyzed later. Studies of gas-rich meteorites have provided a wealth of data on ancient solar flare records (figure 3) going back to more than 4 billion years (Goswami 1991; Goswami et al. 1980, 1984). Studies of nuclear tracks in lunar samples also led to the first observation of enrichment of very heavy nuclei ($Z \geq 30$) relative to the Fe-group in ancient solar flares (Bhandari et al. 1973a) compared to their normal solar abundance. This observation was confirmed in contemporary solar flares (Shirk 1974) based on data obtained from spacecraft experiment. The first experimental evidence for an active early Sun with flare activity at least thousand times greater.
than at present also came from studies of nuclear track and noble gases in grains from gas-rich meteorites (Caffee et al. 1987; Hohenberg et al. 1990; Caffee et al. 1991) that have received their solar flare irradiation more than 4.2 billion years back. Noble gas data for the grains having solar flare records in gas-rich meteorites show that they have received energetic particle irradiation doses that are orders of magnitude higher than those received by the non-solar flare irradiated grains (figure 4). Since orders of magnitude difference in galactic cosmic ray irradiation for these two groups of grains can be ruled out, the excess seen in solar flare irradiated grains can be attributed to an intense short-term irradiation by solar energetic particles from an active early Sun prior to their compaction into their host meteorite. A much earlier study of nuclear track records of galactic cosmic ray heavy nuclides in lunar samples and meteorites showed that the relative abundances of Fe group and heavy nuclei (\(Z \geq 30\)) group show little variation with time or distance in the solar system (1 to 3 astronomical units) during the last few billions of years (Bhandari and Padia 1974) indicating a remarkable similarity in the elemental composition of sources responsible for these nuclei in the galactic cosmic radiation.

The nuclear track records in the lunar samples also allowed delineation of time scales of mixing and turnover of the loosely consolidated lunar surface, the so-called lunar regolith, due to bombardment of meteoritic objects over a wide size range. The presence of solar flare track records in lunar drill core soil samples, collected at various Apollo sites, suggests that lunar soils currently at different depths were once exposed to solar flare radiation on the lunar surface indicating extensive mixing and turnover of the lunar regolith. Studies of galactic cosmic ray track records in lunar rock samples also allowed delineation of their lunar surface exposure durations that are typically a few million years. The erosion rate due to micrometeorite impacts on exposed rock surfaces on the moon was estimated to be about a millimeter per million years. For an exhaustive review of the work done during the early years of the Apollo and Luna era reference is made to Lal (1972).

Studies of nuclear track records in meteorites were soon followed by studies of radioactivity in meteorites and lunar samples resulting from interactions of solar and galactic cosmic ray proton and alpha particles with target nuclides such as Na, Mg, Al, Si, Ca and Fe in lunar samples and meteorites (Reedy and Arnold 1972; Lal 1972;
last few million years (Bhandari et al. 1981). A close match of expected and observed values suggests constancy in the SEP flux over the above time scale (from Bhandari 1981).

Records of radioactive and stable noble gas nuclides produced by low energy (1–100 MeV/n) contemporary solar energetic particles can be found easily in surficial layers of returned lunar rock samples exposed directly to the Sun, while those produced by high energy galactic cosmic rays can be found in samples of both lunar samples and meteorites. The half-lives of different radionuclides, such as $^{26}$Al (0.72 Ma), $^{53}$Mn (3.7 Ma) allowed estimation of long-term averaged galactic cosmic ray intensities in 1–3 AU space. Studies of galactic cosmic ray produced shorter-lived radionuclides (e.g., $^{24}$Na; half-life = 2.6 y) provide a way to delineate the strength of the solar modulation effect of galactic cosmic rays over the 11 year solar cycle, while records of relatively longer-lived nuclides (e.g., $^{44}$Ti; half-life 63 y) allow extending such study over much longer durations by selecting meteorites that fell at different times during the last two centuries. Results obtained from studies of solar flare produced $^{26}$Al activity in lunar samples exposed at the surface for different durations, shown in figure 5, suggest that the solar flare activity averaged over time scale >100,000 years has remained nearly the same during the last few million years (Bhandari et al. 1975, 1976; Bhandari 1981). The possibility of a variation in the solar activity at smaller time scale cannot be ruled out when one combines data for other shorter-lived nuclides such as $^{81}$Kr (half-life = 0.21 Ma) and $^{14}$C (half-life = 5730 y) (Reedy 1998).

A careful study of $^{44}$Ti produced during the period 1883 to 1992, in suitably selected meteorites that fell on Earth at different epochs of the above period, showed that during one of the prolonged solar quiet times, the so-called Gleissberg minima, the heliospheric magnetic field was much weaker than that estimated from observation of sunspot number (Bonino et al. 1995).

Studies of noble gas records in lunar and meteorite samples were also initiated during the Apollo era using indigenously built noble gas mass spectrometer. Studies of cosmic ray produced stable noble gas nuclides in meteorites or lunar samples provide the integrated exposure ages of these samples to cosmic rays in space or on the lunar/asteroidal surface. Similarly, studies of radiogenic stable noble gases, such as $^4$He and $^{40}$Ar (products of U, Th and K decays, respectively) provide information on the formation ages of the analyzed samples (see, e.g., Ozima and Podosek 2001).

An important contribution from studies of noble gas records in lunar and gas-rich meteorite samples carried out in India was the identification of the isotopic composition of neon, emitted during energetic solar flares. It is generally not possible to partition out the solar flare component of noble gases in an extra-terrestrial sample exposed to solar radiation in the presence of the order of magnitude more abundant low energy solar wind component. This problem was circumvented by sequential mild etching of the samples to remove the trapped low energy (keV/n) solar wind component that resides within the top 0.1 μ of the sample so that the deeper sited high energy (MeV/n) solar flare component, that have much longer range than the solar wind particles, can be deciphered easily. The first results on long-term averaged solar flare noble gas isotopic composition (see figure 6) was obtained using this approach (Nautiyal et al. 1986; Padia and Rao 1989); similar result was also reported by other groups (Wieler et al. 1986).

Several martian meteorites have also been investigated, to decipher their cosmic ray exposure duration in space as small objects following their ejection from Mars and hence their probable delivery mechanism to Earth. Nuclear track and noble gas studies of the martian meteorite ALH84001 showed that the Mars–Earth transit time for fragment ejected from Mars could be up to 16 Ma and is consistent with model calculation for the case of a direct ejection from Mars and transfer to Earth (Goswami et al. 1997), rather than two (or multi) stage break up events in space, following ejection from Mars, prior to reaching Earth (Gladman et al. 1996).

Most of the work discussed above was primarily done at TIFR until 1973 and then at the Physical Research Laboratory (PRL), Ahmedabad. During this period studies of extraterrestrial samples were
also initiated at the Indian Institute of Technology (IIT), Kanpur. The focus of research at IIT Kanpur, was the study of cosmic ray produced radioactive nuclides in meteorites. \(^3\)H activities in artificially irradiated silicate targets have been studied to simulate meteoroid irradiation and derive production rates (Trivedi and Goel 1973). Expertise gained in these studies was also applied for neutron activation analysis of trace elements in lunar and meteorite samples. In particular, radiochemical methods developed for the assay of \(^4\)He and \(^{14}\)C have been used for the study of Li and N abundances in moon and meteorite samples through their production by reactor irradiation by the nuclear reactions \(^{6}\)Li(\(n,\alpha\))\(^2\)H and \(^{14}\)N(\(n,p\))\(^{14}\)C, respectively (Shukla et al 1978). Lunar samples from Apollo and Luna missions and all classes of meteorites have been extensively analysed for N and Li (Goel and Kothari 1972; Murty et al 1982, 1983). Both radiochemical and instrumental neutron activation analysis techniques were developed for the study of several trace elements as well as for the isotopic composition of Os and Hg (Goel and Murty 1983; Thakur and Goel 1989).

The return of the Luna 16, 20 and 24 samples by Russia and providing the same to the Indian National Science Academy (INSA) for scientific research led to participation of Bhabha Atomic Research Center, in addition to PRL and IIT, Kanpur, in lunar sample studies. The results from the multi-disciplinary studies conducted by these groups that included analysis of nuclear track, noble gas, nitrogen, major and trace elements, mineralogy and petrography have provided very useful results that appeared in a special publication Further advances in Lunar Research of INSA, in 1974 and also in an INSA proceeding volume in 1979 in addition to other publications in international journals (Bhandari et al 1973b; Goswami 1978; Bhasin and Sunta 1979; Deshpande et al 1979; Goswami et al 1979; Murali et al 1979; Murty et al 1979a, b). During the period from 1965 to 1980 more than a hundred publications resulted from studies of extraterrestrial samples carried out in India.

3. Origin and early evolution of the solar system

In the mid-eighties, the focus of planetary research in India shifted to studies of meteorites to understand the early evolution of the solar system, evolutionary history of meteorites and their parent bodies, the asteroids, and continuing studies of past solar activity. The important results on studies of past solar activity, including that from an active early Sun have already been noted earlier. In the following we provide a brief outline of research activities carried out primarily at PRL in the field of solar system studies.

Astronomical observations of Sun like stars during its initial stages of evolution, the so called T-Tauri stars, suggest an extremely active early phase for our Sun that could have raised the temperature of the solar nebula to more than a thousand degree centigrade. Analytical studies of condensation of solids from a hot gas of solar composition at low pressure (\(\sim 10^{-3}\) Atm) suggest that the first solids to form in the nebula will be oxides and silicates composed of refractory elements Al, Ca, Mg and Ti (Grossman 1980) such as Corundum (Al-oxide), Hibonite (Ca-Al-oxide), Spinel (Mg-Al-oxide), perovskite (Ca-Ti-oxide) and Fe-free silicates (anorthite, fassait, diopside, fosterite). In fact, carbonaceous chondrites, that represent some of the most primitive and pristine solar system objects available for laboratory studies, contain such rare microscopic refractory solids (see figure 1), that are now collectively termed as Ca-Al-rich Inclusions (CAIs) and are considered to be the first solids to form in the solar system (Grossman 1980; Macdougall and Goswami 1981). Advances in experimental techniques allow us to analyze these microscopic solids in great detail and the results obtained from such studies have led to new ideas and concepts about the formation and early evolution of the solar system. Precise estimate of the time of formation of these refractory solids also provide us the age of the solar system and the current best estimate is 4567±1 million years (see, e.g., Russell et al 2006).
The chemical composition and mineralogical make up of the various meteorites suggest that their parent bodies, the asteroids, have undergone very different evolutionary histories. CAIs are mostly present in a group of meteorites called chondrites, and more abundant in the sub-group carbonaceous chondrites, whose chemical composition closely matches that of solar atmosphere, making them some of the most primitive meteorites that have suffered very little or no thermal or shock metamorphic history. The parent bodies of non-carbonaceous or so-called ordinary chondrites have gone through various degrees of thermal evolution (see, e.g., Huss et al 2006). The name chondrite is derived from the fact that these meteorites have abundant sub-mm to mm-sized silicate spherules called ‘chondrules’ that are a product of high temperature transient events in the nebula that lead to melting of nebular solids followed by rapid cooling (see, e.g., Scott and Krot 2005) leading to their spheroidal shape (see figure 1). Chondrules are considered to be the second set of solar system objects to form in the solar nebula following the CAIs. The parent bodies of the so called differentiated meteorites that include achondrites, irons and stony-irons (see figure 1) have undergone melting and differentiation leading to metal-silicate fractionation (see, e.g., McSween 1999). Understanding of the processes leading to formation of the achondrite parent bodies is important for understanding differentiation processes undergone by all the terrestrial planets.

4. Time scales of early solar system events

A major breakthrough in our understanding of time scale of events in the early solar system came following the identification of fossil records of the now-extinct short-lived nuclide $^{129}$I (half-life = 15.7 Ma) in a meteorite based on the observed excess of its stable decay product $^{129}$Xe (Reynolds 1960). This observation provided evidence that the freshly synthesized short-lived nuclides of stellar origin were present at the time of formation of the solar system. Since then the presence of close to a dozen such nuclides of different half-lives, ranging from 0.1 Ma ($^{41}$Ca) to 82 Ma ($^{244}$Pu), at the time of formation of the solar system, has been confirmed. In particular, the discovery of the presence of the short-lived nuclide $^{26}$Al (Lee et al 1976) has dramatically changed our view of the time scale of the early solar system processes in this field.

Records of now-extinct short-lived nuclides with short half-life [e.g. $^{41}$Ca (0.1 Ma), $^{26}$Al (0.72 Ma), $^{60}$Fe (1.5 Ma), $^{53}$Mn (3.7 Ma)] in early solar system solids can serve as high precision relative chronometer of events and processes taking place during the early evolution of the solar system (figure 7). However, this is strictly valid only if these nuclides are injected into the protosolar cloud from an external source, plausibly a stellar source, and distributed uniformly in the solar nebula so that they are characterized by canonical solar system initial abundances. In such a case, the abundance of these radio-nuclides in early solar system solids forming at different epochs will be systematically different from their abundances in the first solar system solids (CAIs) and this time difference can be accurately ascertained with precision of $<0.1$ Ma. However, the possibility that some of these nuclides were in fact produced within the solar system itself via interaction of solar energetic particles (SEP) with nebular gas and dust was also proposed (see e.g., Shu et al 1997). If true, this will invalidate the role of these nuclides as a relative chronometer of events in the early solar system. Research done at PRL for more than a decade has provided very significant results in this field. These include identification of fossil records of the radionuclide $^{41}$Ca, having the shortest half-life amongst such radionuclides detected so far, in first solar system solids (figure 8; Srinivasan

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**Figure 7.** A schematic illustration of the time scale of processes taking place, starting from the proto solar cloud collapse to the formation of various solar system objects. The relative time intervals could be precisely determined from a study of the fossil records of the stable decay products of now extinct short lived radionuclides present in the early solar system, as illustrated in the inset.
within the time frame of less than a million years, inferred from the presence of $^{41}$Ca in early solar system objects (Vanhala and Boss 2002). Various stellar sources, such as, low mass stars that end their life as a thermally pulsing asymptotic giant branch (TP-AGB) star, high mass stars that end their life as supernova as well as massive Wolf–Rayet stars that have a very short lifetime (several millions of years) and may also have an explosive end are considered as plausible sources of the short-lived nuclides present in the early solar system. These nuclides are produced during nucleosynthesis processes taking place in these stars towards the end of their life. Model calculations were performed by several groups in USA and Europe to estimate stellar production of the short-lived nuclides and their stable counterparts, mixing of the freshly synthesized stellar material with pre-existing proto-solar cloud devoid of the short-lived nuclides, the time interval between production at the stellar source to the formation of the first solar system solids where fossil records of the short-lived nuclides are found, to infer the most plausible stellar source of the short-lived nuclides present in the early solar system solids (see figure 9; also Goswami and Vanhala 2000; Goswami et al 2005 and references therein). At present there is a general consensus that a high mass star that ended its life as a supernova is the most probable source of the short-lived nuclides present in the early solar system (see e.g., Huss et al 2009).

The detection of fossil records of the short-lived nuclide $^{10}$Be (half-life = 1.5 Ma) in early solar system solids (McKeegan et al 2000), which is not a product of stellar nucleosynthesis, and is produced only by energetic particle interaction with target nuclides such as C, N and O, have again raised questions on the suggested stellar origin of the short-lived nuclides present in the early solar system. A combined study of $^{10}$Be, $^{26}$Al and $^{41}$Ca records in refractory early solar system solids carried out at PRL clearly showed that $^{10}$Be is present in early solar system solids that are devoid of the other short-lived nuclides, such as $^{41}$Ca and $^{26}$Al and thus the source of $^{10}$Be is decoupled from the source of the other two nuclides (Marhas et al 2002). This reaffirmed a stellar origin of the short-lived nuclides. Analytical calculations also suggest that contribution, if any, from energetic particle interactions to the inventory of most of the short-lived now-extinct nuclides present in the early solar system is small, at <10% level (Goswami et al 2001, 2005; Marhas et al 2002).

Our present understanding of the evolution of the early solar system suggests the refractory CAIs to be the first solar system solids to form in the solar nebula. As noted earlier, the next solids to
The early melting of asteroids, representing the parent bodies of the achondrites, requires a viable heat source and several possibilities have been proposed. In particular, energy released during the decay of the short-lived nuclide $^{26}$Al, initially present in these objects, has long been considered as the most plausible source (Urey 1955). The short half-life of this nuclide, coupled with reasonable abundance of Al in solar system objects, make this an ideal candidate for early melting of parent bodies of achondrites. Following the identification of $^{26}$Al records in some of the first solar system solids, several unsuccessful attempts were made to identify fossil records of residual $^{26}$Al in samples of differentiated meteorites (Davis et al 1988; Bernius et al 1991; Hsu and Crozaz 1996). A major contribution of the PRL group in this field is the first identification of $^{26}$Al record in samples of the differentiated meteorite Piplia Kalan, an achondrite, that fell in Rajasthan in 1996. $^{26}$Al-Mg isotope studies of plagioclase and pyroxene in this meteorite using an ion microprobe revealed excess $^{26}$Mg in them resulting from in situ decay of $^{26}$Al (figure 11; Srinivasan et al 1999). This resolved one of the long standing issues in planetary sciences for more than three decades. This finding also suggested that the process of accretion, heating, melting, differentiation and crust formation in asteroids representing parent bodies of achondrites was complete within 3–5 Ma. Later studies of records of $^{26}$Al and another now-extinct short-lived nuclide $^{182}$Hf in achondrites confirmed the results and put a more stringent constraint of <3 Ma for this differentiation process and in some cases this time scale could be even ~1 Ma (see, e.g., Halliday and Kleine 2006; Wadhwa et al 2006).

Studies of short-lived now extinct nuclides have provided a time scale of events leading to the formation of the solar system objects, starting with the first solar system solids, the CAIs, followed by chondrules, chondrites, achondrites and other differentiated meteorites, the stony-irons and irons. This is shown schematically in figure 12. A significant change in the evolutionary time scales

**Figure 9.** A schematic illustration of the solar-stellar connection inferred from the presence of now-extinct short-lived nuclides of stellar origin in CAIs. The stellar source may be identified by modelling production of the nuclides in different stellar sources, their injection and mixing with nuclides present in the protosolar cloud and elapsed time scale between injection and incorporation of the nuclides into CAIs and matching the same with data obtained from laboratory studies of CAIs (from Goswami and Vanhala 2000).
of the early solar system has come about in recent years, primarily due to the revision in the time of formation of differentiated achondrites based on high precision studies of the fossil records of the now extinct short-lived nuclide $^{182}$Hf that decays to $^{182}$W with a half life of 9 Ma. However, there are still gaps in our knowledge and we are not yet close to the final answer of the earliest stage of evolution of the solar system.

5. Nitrogen and noble gas studies of extra-terrestrial objects

In contrast to the records of short-lived nuclides in early solar system objects that may be used to infer time scale of various early solar system events, the records of variations in stable isotope abundances, such as those of volatile elements N and noble gases (He, Ne, Ar, Kr and Xe) are very useful in understanding the evolutionary processes.

Studies of noble gas and nitrogen isotope composition of solar system objects using static mass spectrometry is a highly specialized field. Such a facility has been established at PRL in the late eighties for investigating early solar system processes and formation and evolution of planetary bodies. A brief outline of some of the important results obtained from studies carried out at PRL is presented here.

A class of differentiated meteorites called ureilites contain about 2 wt.% elemental carbon, mostly in the form of micro-diamonds. The origin of the diamonds has been enigmatic. Through a simultaneous study of N and noble gases in bulk ureilites and the separated C phases (diamond,
graphite and amorphous carbon) it has been established that while diamond and amorphous C contain noble gases, graphite is devoid of them. Further, all three carbon phases host N, but with different isotopic composition and N isotope composition in diamonds is independent of their respective host ureilites. These results (figure 13; Rai et al. 2003a, b) rule out the earlier proposal that diamonds in ureilites are product of in situ conversion of graphite or amorphous carbon. These data suggest that ureilite diamonds are nebular products which were later incorporated into the parent body of ureilites.

The textural and petrological characteristics of chondrules suggest their formation by transient heating and melting of chondrule precursor solids followed by rapid cooling (see, e.g., Scott and Krot 2005). However, the exact formation mechanism of chondrules is still not completely understood. Studies of trapped and cosmogenic noble gases and nitrogen components have the potential to resolve this issue. A laser microprobe, capable of analyzing very small amounts of gases from sub-milligram samples has been set up at PRL to analyze individual chondrules to address these issues (Mahajan and Murty 2003). The results show that nitrogen isotope composition of chondrules is different from their respective host ureilites, and it also varies for chondrules from ordinary and enstatite chondrites. These results suggest that chondrule precursor solids are not the same as their host chondrites (Das and Murty 2009), a constraint that has to be accounted for by any chondrule forming mechanism.

The accretion and formation of planets and their subsequent evolution depends on their internal heat content. The volatiles present in the accreting materials will be degassed and get redistributed in the interior of the planet and also get accumulated in the atmosphere (if the body is large enough to retain an atmosphere) or lost to space. Study of noble gases and nitrogen in the atmosphere and interior reservoirs of a planet allows one to model the formation and evolution of a planet.

The presence of martian meteorites in our meteorite collection is confirmed by matching the trapped noble gas compositions in such meteorites with that of contemporary Mars atmosphere obtained by spacecraft that landed on Mars. Ancient martian atmospheric composition inferred from the study of the oldest martian meteorite ALH84001, with a formation age >4 Ga, provided an important input to model the evolution of Mars atmosphere with time (Murty and Mohapatra 1997), in addition to indicating the presence of an interior (Mars mantle) N component, as well as aqueous alteration effects in Mars. Studies of another set of martian meteorites Y000593 and MIL03346 suggest the presence of more than one interior N and noble gas components. Presence of multiple volatile components that are pristine, suggests that Mars mantle remained frozen since very early in its history. This interpretation is consistent with the very low value of $^{40}$Ar/$^{36}$Ar ratio of 42 for Mars mantle, reported so far and suggests a very low degree of degassing for planet Mars, as compared to Earth, a consequence of very early heat loss in the case of Mars.

Earlier studies, based on chemical composition or single element (oxygen) isotopic systematics have suggested carbonaceous chondrites as the dominant building blocks of Mars. However, the bulk Mars Fe/Si ratio and the moment of inertia factor, inferred assuming such precursor composition, are not consistent with the recent and more accurate values obtained by Pathfinder space mission. Based on the two isotopic systems, N and O, it is proposed that Mars is made of E and H chondrites in the proportion of 74 : 26. Such a model (figure 14) not only reproduces the expected bulk Fe/Si ratio and the moment of inertia factor of Mars, but also consistent with Cr isotope systematics (Mohapatra and Murty 2003).

6. Impact crater, volcanism and mass extinction

Impact cratering is a very dominant force in shaping the face of all the inner planets, the planetary satellites and asteroids. Lonar Crater in
Maharashtra (figure 15) is a well-known impact crater. Studies were conducted at IIT Kharagpur, to infer the nature of the impact event and the composition of impacting body based on major and trace element compositions of Lonar samples that are products of the impact event (Mishra et al 2009). Based on textural and mineralogical studies and shock features present in samples of the ‘Dhala structure’ within the Bundelkhand craton, carried out at the Allahabad University, a meteorite impact origin of this structure is now confirmed (Pati et al 2008). The ‘Ramgarh structure’ in Rajasthan, has also been proposed to be of impact origin based on similar studies carried out at the JNV University (Sisodia et al 2006).

Asteroid impact has been also linked to large-scale mass-extinction on earth. The presence of iridium enhancement in the clay layer present at the Cretaceous-Tertiary (K-T) boundary dated at ~65 million years ago, led to the suggestion that the large scale extinction of life at the K-T boundary was fuelled by the impact of an asteroid ~10 km in size. However, there is a counter view that this extinction could be due to the eruption of the Deccan volcanism at nearly the same time. Detailed studies carried out at PRL on iridium and other trace element abundances in the K-T boundary layer (figure 16), coupled with extensive geochronological studies to constrain the duration of the Deccan volcanism, using Ar-Ar dating technique, showed that the peak of Deccan volcanism is separated by a couple of million years from the time of K-T extinction giving credence to the asteroid impact hypothesis as the cause of this extinction (Bhandari et al 1996; Venkatesan et al 1993; Shukla et al 2001; Pande 2002).

7. Analytical modeling of martian and cometary atmosphere

Spacecraft exploration of the Mars has provided a large data base on contemporary martian atmosphere including the electron and ion densities in both day- and night-side ionosphere. Several research groups in India from PRL, NPL (National Physical Laboratory, Delhi), BHU (Benares Hindu University) and SPL (Space Science Laboratory, Trivandrum) have carried out analytical studies to understand the martian atmospheric processes in conjunction with the spacecraft data, particularly from Mars 4 & 5, Viking 1 & 2, Mars Global Surveyer (MGS) and Mars Express. Analyses of a large number of electron density profiles obtained by MGS from regions free from crustal magnetic field effects revealed several features that are at
Figure 16. Ar-Ar dating of samples from various strata of Deccan volcanic layers suggest episodic eruption over an extended period of more than six million years with major eruptions predating the K/T boundary event at 65 million years as indicated by the occurrence of the Ir-enriched layer. These results suggest an asteroid impact rather than Deccan volcanism as the most plausible cause for both the iridium anomaly and widespread extinction at the K/T boundary (from Shukla et al. 2001).

variance with theoretical expectations (Mahajan et al. 2007). Neutral densities of seven different species, such as CO$_2$, N$_2$, O$_2$, have been derived from the MGS data to model expected ion and electron densities in the 115 to 220 km zone and are compared with electron density data from the radio occultation experiment in the same spacecraft to validate the model calculations. Analytical modeling of the day time and night time ionospheres of Mars, to cover the height interval up to $\sim$200 km, and taking into account all the relevant atmospheric species, chemical reactions amongst them and considering solar EUV, X-rays and galactic cosmic rays as the ionizing sources, have yielded the height of electron density peaks and electron density that are in reasonable agreement with spacecraft observations. These estimates also allowed the calculation of the approximate heights of the various layers (D, E, F) in martian ionosphere (Haider et al. 2006, 2009; Seth et al. 2006).

The role of aerosols in the martian climate system and its impact on electrical conductivity in the lower atmosphere as well in the day and night-time atmosphere in Mars have been modeled by a group in IIT Kanpur, by considering charging of aerosols via attachment of ions in the martian atmosphere that reduces the atmospheric conductivity. Galactic cosmic rays are the primary ionizing agent in the lower atmosphere and produce molecular ions. Solar photons can also serve as ionizing agents during day time. The ions and ion clusters produced by cosmic rays and solar photons get attached to aerosols during the night time, a feature that gets enhanced during dust storm due to increased dust opacity and resultant increase in the aerosol-ion attachment process. Analytical modeling suggests that a majority of the ions and most of the electrons get attached to aerosols. The conductivity can decrease by a factor of five in the lower atmosphere due to ion attachment processes and could be down by two orders of magnitude during dust storms with opacity of $\sim$5 (Michael et al. 2007, 2008).

Effort has also been made to model the abundances of the C, H, N, O, and S compounds detected in coma of comets using a coupled-chemistry model and considering solar EUV photons, photoelectrons and solar wind electrons as the ionizing sources. Comparison of the analytical data with those observed for comet Halley by Giotto spacecraft provided reasonable agreement and the model could also reproduce the major peaks in the observed spacecraft spectra in the mass region 10–40 amu (Haider and Bharadwaj 2005).

8. Planetary astronomy

Astronomical observations of solar system objects have been also pursued sporadically in the country, primarily at the Indian Institute of Astrophysics (IIA), Bangalore and at PRL. One of the very significant results obtained from these studies is the discovery of Saturn-like ring system of Uranus based on near-infrared observation during a near-grazing occultation of a stellar source by Uranus (Bhattacharya and Bappu 1977). The observations taken from the Kavalur observatory revealed dimming of light, in addition to those expected from occultation by the known satellite system, suggesting the presence of an occulting body (ies) much closer to the planet. IIA has also initiated another project, ‘Kalki’ to survey the sky with a Schmidt telescope to observe comets, asteroids and planets and discover new asteroids/comets. Several dozens of asteroids have been detected during this study including six new asteroids (Rajamohan et al. 1988), the first one of which has since been named ‘Ramanujan’. Inferring the precise size of asteroids using lunar occultation technique has been pursued at PRL from the Mt. Abu observatory and sizes of close to half a dozen asteroids have been estimated with this approach (Chandrasekhar 2007). Studies of optical polarimetry of comets from this observatory have also been conducted to infer the characteristics of cometary dusts. Observations of cometary coma at different locations in
the direction of the comet tail suggest that both comet NEAT C/2001 Q4 and 17P/Holmes have a mix of grains of silicates and organic composition and enhanced abundance of smaller grains as one moves outward in the coma (Ganesh et al. 2009; Joshi et al. 2009).

The Sun emits ultraviolet and X-ray photons from the high temperature coronal regions and it also emits both X-rays and energetic particles during solar flares. These energetic photons and particles can interact with relatively cool planetary bodies and produce X-rays through a wide variety of processes. Space-based observations have detected planetary X-rays from Venus, Earth, Moon, Mars, Jupiter, Saturn, and also from Io and Europa (see, e.g., Bhardwaj and Gladstone 2000; Bhardwaj and Lisse 2007). High spatial and spectral resolution observations of planetary X-rays are important for understanding the processes responsible for production of X-rays on planetary bodies. The space-based X-ray observatories, Chandra and XMM-Newton, are providing excellent data on planetary X-rays and an active programme in this area is being pursued at Space Physics Laboratory, Trivandrum.

The terrestrial X-ray aurora is generated by energetic electron bremsstrahlung, while that in Jupiter the dominant mode is charge exchange with ionized heavy ions and solar wind ions with some contribution from electron bremsstrahlung. Observations by Chandra observatory led to the discovery of X-rays from the rings of Saturn (figure 17), revealing that very cold objects in our solar system can also be an X-ray source (Bhardwaj et al. 2005). The energy of the X-rays suggest oxygen in water-icy cold rings is the source of the fluorescent X-rays. The X-ray emission from low-latitude (non-auroral) disk of the planets Earth, Jupiter and Saturn are mostly produced by scattering of solar X-rays by atmospheric species. X-ray emission from non-auroral disk of Saturn could be directly related to a flare from an active sunspot region that was clearly visible from both Saturn and Earth. Thus, planetary X-rays from the giant outer planets suggest their direct link to active processes occurring on the Sun.

Synchrotron radio emissions from Jupiter have been observed using the Giant Metrewave Radio Telescope (GMRT) at Poona (Bhardwaj et al. 2009). These observations provided the first evidence of a large (20%) day-to-day variability at 610 MHz (figure 18) – a finding that could have important consequences for our understanding of the dynamics of Jovian radiation belts as it is generally believed that Jupiter’s synchrotron emissions are quite stable.

9. Planetary exploration

The solar system can be divided into an inner and an outer region. The inner solar system consists of the planets Mercury, Venus, Earth and Mars representing (silicate + metal) objects, while the outer solar system, consisting of the planets Jupiter, Saturn, Uranus and Neptune represents primarily gaseous planets with a small rocky core. The asteroids, left over material of inner solar system objects, populate the region between Mars and Jupiter. All the planetary satellites, both in the inner and outer solar systems are primarily silicate + metal dominated objects with
some of the outer solar system satellites having icy crust/mantle. The four terrestrial planets have several distinct characteristics that are an outcome of their formation and evolutionary differences.

It is generally believed that the planets, as we see today, have formed close to their present location via accretion of planetesimals. The accreted planets evolve due to their internal energy content that is made up of both accretional energy and energy from radioactive decay that will depend on the total mass of the planet and the chemical composition (of radioactive elements), respectively. Smaller planets (like Mercury) may quickly exhaust their heat content either by melting or by loss due to conduction/radiation and their evolution become static. During any large-scale melting, the volatile that are exhaled by the interior of the planet will form the surface reservoirs (atmosphere and/or hydrosphere). If the gravity of the planet is feeble these surface reservoirs are quickly lost and the planet does not have an atmosphere. While for planets of the size of Earth and Venus the heat loss is slow and they continue to evolve and hold the surface reservoirs up to the present, the case of Mars is intermediate. Mars might have ceased to evolve a few hundred million years ago and is also holding a thin atmosphere. Essentially, the size and chemical differences of the terrestrial planets have resulted in their different modes of thermal evolution. A closer look at the surface features to glean the physical, chemical and mineralogical aspects will reveal imprints of the evolutionary records of the planet. At present we have sample return mission only from moon and there are reasons to believe that some of the meteorites are of martian origin. It is therefore essential to have planetary exploration missions to various solar system bodies to improve our understanding of their formation and evolutionary history.

The current decade has seen a revival in the field of lunar exploration, with several new initiatives by various space agencies. These efforts began in 2003 with the Smart-1 mission of European Space Agency that was followed by the Changé-1 mission of China and the Japanese mission Kaguya (SELENE), both in late 2007. These were followed by the Indian Chandrayaan-1 mission in late 2008 and the US mission LRO (Lunar Reconnaissance Orbiter) launched in mid-2009.

The launch of Chandrayaan-1 remote sensing mission (figure 19) to the moon ushered a new era in planetary science research in the Indian context. The initial discussion on the possibility of having such a mission with indigenous capabilities started in 1997 during the annual session of the Indian Academy of Sciences. This was followed by a series of discussions in different forums during the next few years leading finally to the formation of a task team by Indian Space Research Organization (ISRO) early this decade. The task team produced a comprehensive report on all the technical and scientific aspects of the mission, including science objectives and potential science payloads. This report was discussed extensively and finally submitted to the Govt. of India in early 2003 and the same was approved later that year. ISRO fixed a target launch date of early 2008 and the launch of Chandrayaan-1 took place on 22 October, 2008.

Even though the Apollo and Luna missions and the returned lunar samples have provided a large volume of data and plausible evolutionary scenarios for the Moon have been proposed, these missions primarily explored the equatorial regions of the moon. Mapping of the whole moon was accomplished only in the nineties by two US missions, Clementine and Lunar Prospector. The data obtained by these missions have furthered our understanding of the moon and also raised new questions regarding the origin and evolution of the moon (Bhandari 2002, 2004). The need for lunar data at high spectral and spatial resolution for a better understanding of its origin and evolution was clear and the Chandrayaan-1 mission primarily aimed at achieving this objective. The possibility for the presence of resources such
as water in the permanently shadowed lunar polar sites, suggested by data from Clementine and Lunar Prospector missions, and the presence of trapped $^3$He in lunar ilmenite, a potential fusion fuel for the future also enhanced the possibility of using the moon as a potential base for future planetary exploration. The science objectives of the Chandrayaan-1 mission and details of various payloads are described in a series of papers in Current Science (25 February, 2009 issue). This mission has already yielded some important results (presentations in 40th Lunar and Planetary Science Conference, March, 2009, Abstracts: Lunar and Planetary Institute, Houston).

10. Indian missions to Moon, Mars, Asteroids/Comets

Any long-term plan for planetary exploration has to be made in the global context and indigenous technical capabilities. The Chandrayaan-1 mission led to the establishment of a 32 m deep-space network antenna and coupled with the development and induction of new generation geostationary satellite launch vehicle soon, ISRO possesses the capability to send planetary exploration missions to all the inner solar system objects. The currently proposed ISRO plan for planetary exploration within the coming decade has Moon, Mars and Comet/Asteroid as the targets. Chandrayaan-2, officially approved with a targeted launch in 2012, will include a lander and a rover, in addition to the orbiter, for an in depth study of a lunar site of high scientific interest.

The presence of water on Mars during past epochs has made exploration of Mars high in agenda of most of the space agencies involved in planetary exploration. Although most of the recent missions to Mars are concentrating on exploring surface for signature of water, comprehensive studies of the martian atmosphere, ionosphere and aerosol/dust and atmospheric dynamics are still lacking. The proposed Indian Mars obiter mission will focus on the study of Mars upper atmosphere, its interaction with radiation and energetic particles from the Sun, and with galactic cosmic rays, atmospheric dynamics and martian weather. Remote sensing studies of chemical, mineralogical and morphological features of the martian surface as well as magnetic anomalies on the surface (their origin and consequences), will be conducted and focused studies to assess and understand the water-rock interactions on Mars surface and their role on the possible existence of life on Mars will be important science objectives of this mission. It is also proposed to study Phobos, the captured satellite of Mars during this mission.

It is now well accepted that asteroids are the parent bodies of most of the meteorites, except for a small number of meteorites that are of lunar and martian origin. Comparison of the reflectance spectra of asteroids with those of meteorites has established a tentative connection between meteorite classes and possible parent asteroids, not withstanding the effects of space weathering and the consequent alteration of the asteroidal reflectance. The case of comets is more elusive. They are like deep freezers, faithfully preserving the records since the birth of solar system and may contain a greater proportion of interstellar grains in their pristine form. They may also hold clues for the origin of life forming bio-molecules. Although comets are expected to be pristine solar system material, we do not have a bulk sample of comets in our collection. Some of the microscopic extraterrestrial dust particles collected at stratospheric level by high flying aircraft appeared to be of cometary origin. Our present idea about cometary composition is based on remote sensing missions like Giotto to comet Halley and earth based observation of comets. The recent Stardust mission to comet Wild-2 has successfully brought back several thousand particles of microscopic cometary dust. Laboratory analysis of these samples revealed very interesting results including the unexpected presence of a microscopic high temperature refractory object. ESA has launched ‘Rosetta’ mission to conduct both remote sensing and in situ studies of a cometary surface using a combination of an orbiter and a lander. A focussed study of asteroids and comets through space missions is very important, as these bodies have preserved the records of early solar system processes intact. The principle objectives of an asteroid mission are to establish the meteorite-asteroid connection on a firm footing, and understanding the size, composition and differentiation of asteroids in the context of their thermal evolution. There had been several flyby missions to asteroids and only the NEAR orbiter mission of NASA studied in detail the asteroid Eros. The Japanese sample return mission Hayabusa to asteroid Itokawa in 2003, is on its way back with a small fragment of the asteroid and the NASA’s Dawn mission was launched in 2007 for studying two of the large asteroids, Ceres and Vesta. Keeping in view the global scenario, ISRO is proposing a mission to explore comets (flyby) and asteroid (orbiter) during the later part of next decade. The target asteroid will be one of those that are considered probable parent bodies of the primitive/differentiated meteorites and will be selected as per the launch schedule and the possibility of having flyby opportunity of comets and other asteroids. ISRO will have all the infrastructural facilities...
needed for launch, command, control, communication and data transfer in place for the proposed missions.

11. Future perspective

Two of the primary objectives of research in the field of planetary sciences are to understand the origin of the solar system and its evolution to the present state and the origin of life on earth and its possible existence elsewhere. Recent discoveries of planetary systems around sun-like stars tell us that planet formation is not unique to our Sun. However, most of these extra-solar planets are more massive and at greater proximity to the central star, though a couple of cases of ‘earth-size’ planets, with some having atmosphere, have also been detected (Santos et al 2005). Even though observational and laboratory studies as well as modelling efforts led to a broad understanding of the formation of planets, processes that could explain the exo-planets in general and the solar system planets (both terrestrial and Jovian), in particular are not yet well understood. Search for exo-planets will intensify with the recent launch of KEPLER mission by NASA. Efforts are being made at PRL to develop high precision instrument to carry out planet search using the Mt. Abu observatory.

Laboratory studies of microscopic early solar system objects, including the recently returned samples of comet Wild-2, and expected return of Hayabusa spacecraft bringing back asteroid sample will provide further insight into the earliest phases of evolution of the solar system. The presence of presolar grains in primitive meteorites and of now-extinct short lived nuclides in the nascent solar system serve as excellent probes to improve our understanding of solar-stellar relations and the evolution of matter in our galaxy. Recent technical developments have provided us with tools that are capable of probing microscopic samples at a spatial resolution of hundred nanometers and destructive analysis of micro-gram samples for precision elemental and isotopic compositions. Some of these instruments are currently installed in a few research laboratories, universities and IITs in the country and encouraging results have been obtained from them.

Exploration of Mars, the icy satellites of Jovian planets, the satellites of Saturn, Titan, with a massive atmosphere like that of Earth, is expected to provide clues about the possibilities of life forms being present in these environs and will possibly broaden our outlook on the definition of life. Intensive exploration of asteroids and comets will help us understand the evolution of rocky objects in the solar system and may provide definitive answers to the question if comets have seeded life on earth and elsewhere.

The recent foray into planetary exploration by India brought to focus the need to enlarge the scientific strength in this area that was pursued in very few places in the country. The PLANetary Science and EXploration (PLANEX) program, initiated by ISRO with PRL as the nodal center, is putting sustained effort in this direction that has led to some visible results. More than twenty research groups at various research institutes, universities and IITs are working with PLANEX support in areas that are within the broad framework of planetary sciences. Some of the scientific results presented in this review on studies of impact craters and martian ionosphere and aerosols are based on work done under the PLANEX programme. The programme also provides access to state-of-the-art analytical facilities at PRL to all the participating groups and a forum for discussion on various aspects of planetary sciences and exploration. A planetary science data repository along with data analysis tools and expertise will soon be provided under this programme, starting with data from the Chandrayaan-1 mission. We can look forward to a very productive and modern phase of earth and planetary research in the country.

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