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Outstanding problems in planetary science

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Abstract. This paper is a review of possibilities for planetary science in India. Challenges in understanding the solar system are first reviewed. A proposal is made for an institute of global environmental studies, from an astronomical perspective, in order to integrate our knowledge of star and planet formation and of atmospheres and surfaces into the understanding of our environment. Many of the outstanding problems in planetary science concern the analysis of large databases obtained from space missions. The Sun is discussed in addition to the heliosphere, magnetospheres, atmospheres, rings and satellites, surfaces and interiors, and comets, asteroids and their debris. The paper closes with remarks on techniques and operations. Because of my own background, the paper emphasizes small bodies, the role they played in the formation of the solar system and the hazards due to ongoing impacts of comets and asteroids.

Key word : planetary science—solar system

This compilation of outstanding problems was suggested by R. Cowsik, Director of the Indian Institute of Astrophysics, in order to stimulate planetary science in India. I have written this paper through reading abstracts and sections of chapters of the Space Science Series (SSS) of resource books published by the University of Arizona Press, which are listed in the References. Generally there appears need for integration, for a synthesis in planetary science, that could be obtained by reading the Space Science Series books. There are, of course, the chapters in the *Protostars and Planets* books, but the theme of origins returns in practically all of the books in the SSS, particularly those edited by Kerridge & Matthews (1988) and by Atreya *et al.* (1989). The books are a source of ideas for future work on outstanding problems; many of the chapters end with a discussion of future directions.

In this paper one should take into account that I am presenting an overview of the present literature, which is to discuss the present "fads" in science. An imaginative scientist who wants to explore new directions and observe with new types of techniques should try to transcend beyond the present stage in order to find truly rewarding new directions. One of my limitations is that I am an observational astronomer of comets and asteroids and that I will see the opportunities for the future mostly from that angle. It is on the interface of astrophysics and planetary science that new and surprising progress could be made, especially in India with its tradition in theoretical physics, founded by C. V. Raman, M. N. Saha, S. N. Bose, H. J. Bhabha, V. A. Sarabhai and others (Mishra 1976).

The above iteration and synthesis could be done in India perhaps better than elsewhere because of relative isolation and possible concentration. India has a relative quietude compared to the more rushed atmosphere and amount of time that must be devoted to fund-raising in the United States. An enormous database has been obtained in the United States and elsewhere from spectacular spaceflights. The integration of these data may not have been sufficiently completed by their associated experimenters, especially because they have been occupied with building instruments and observing. There are always opportunities to obtain data from space missions, which NASA publicizes through *Announcements of Opportunity*.

1. Origin of the solar system, from an astronomical perspective

There is consensus that stars and planetary systems are formed from the collapse of interstellar clouds of molecular gas and dust. Old theories such as fission of a cloud from the Sun due to the close passage of another star have been abandoned. The strength of the present theories is that one can combine the studies of many stellar systems and their formation with the detailed studies of the origin of the solar system. Such a combination is made in the *Protostars and Planets* books edited by Gehrels (1978), Black and Matthews (1985), and Levy and Lunine (1992) as a subseries within the SSS.

Strom (1985) presents an overview of protostars and planets from an astronomical perspective, in contrast to the planetary perspective by Levy (1985) (Sec. 2 of this paper). Strom mentions the importance of magnetic fields during the pre-stellar collapse phases, and the possibility of astronomical observations of outflows from young stellar objects, also for the discovery of circumstellar disks. It might be a prime example of what could be done in India, namely to look into possibilities of combining magnetohydrodynamics into the study of the origin of solar system. Time and again authors suggest that magnetic fields should be taken into account (e.g. Elmegreen 1992). In addition to the observational aspect of finding more of these disks, and observing, for instance, their polarization (various chapters in the book edited by Gehrels 1974), theoretical work is needed to understand them or even to establish that there is a direct connection between these disks and the formation of planetary systems. Several questions are listed by Strom for the study of the initial mass function, the star-forming history of individual cloud complexes, the role of embedded stellar populations, outflows from young stellar objects, and circumstellar disks. The Levy and Lunine book contains material on outflows, dark clouds, and young stars. I do not suggest, however, that astronomers in India search for circumstellar disks or material since this is an old discipline already pursued at many other observatories.

In addition to optical polarization measurement of integrated light, measurements are being made with radio or submillimeter telescopes of Zeeman splitting due to magnetic fields in interstellar clouds (Heiles *et al.* 1992; McKee *et al.* 1992). Again, considerable work has already been done elsewhere.

T-Tauri phenomena of accretion disks and flows of the pre-main-sequence phase and mass accretion in circumstellar disks are discussed in various chapters in the *Protostars and Planets* subseries. The T-Tauri phenomena are believed to be due to accretion disks (Basri

& Bertout 1992 and other chapters). Researchers of stellar variations in India may find it fruitful and may be able to provide insight into the early stages of solar system formation. In addition to T-Tauri, there are other young variable stars such as FU Orionis discussed in the *Protostars and Planets* books (e.g. Hartmann *et al.* 1992). Furthermore, the statistics of binary formation are still poorly determined.

The chapters by Stevenson *et al.* (1986) and Safronov *et al.* (1986) are particularly of interest for the study of the origin of the solar system as a whole. Safronov *et al.* :

> .Furthermore, dynamical consideration should be more closely connected with chemical studies. Finally, we believe that the theory of circumplanetary protosatellite disks should be a part of a general theory of disk-like structures in astrophysics. The origin and evolution of galaxies, accretional disks in double-star systems, protoplanetary disks around some stars, swarms of bodies and particles around planets (in particular, planetary rings) now attract the steadily growing attention of specialists, both theorists and observers.

The chemistry of interstellar gas and grains is reviewed by Irvine & Knacke (1989). They discussed it in view of studying the atmospheres in the solar system as well as the survival of interstellar molecular material containing the volatile elements in primitive solar system objects, including comets, carbonaceous chondrites and interplanetary dust particles. The origin of the solar system is also treated in the book edited by Atreya *et al.* (1989), as well as in the *Protostars and Planets* books, but their discussions are more refined because of the volatiles that occur in comets and certain asteroids as well as in planetary atmospheres. Generally, the interface of the solar system with the interstellar medium presents outstanding problems, and work can be done on both the stellar and planetary side.

2. Origin of the solar system, from a planetary perspective

Levy (1985) presents an overview of protostars and planets from a planetary perspective. He lists several detailed unsolved problems in planetary science, mostly theoretical, for the study of the stages before and during the beginning of the solar systems.

Levy also emphasizes the importance of the discovery of other planetary systems. From the commonality of processes of star formation follows that planetary systems should be present in large numbers throughout the universe. Even the gross structural features of our planetary system seem largely the result of deterministic processes, rather than the result of chance alone. Levy (1985) therefore concludes that many planetary systems throughout our universe may resemble this one. Searching for planets of other stars has been overviewed by Black (1991; also see McMillan *et al.* 1994). It is my impression that planets of other stars will be discovered in the near future by astronomical facilities in the United States, because of their previous accomplishments in this area with several powerful groups competing.

Planets did not accrete entirely directly from interstellar gas and dust. There is abundant evidence that the accretion happened in part via an intermediate stage of planetesimals, objects of sizes on the order of 1-100 km of which we may still be observing remnants in the form of comets and asteroids. These ideas are presented in the chapter by Melosh *et al.* (1992). The question of when and where planetesimals formed is discussed in detail by Weidenschilling & Cuzzi (1992). To what extent the formation of stars is not directly from the interstellar gas and dust but via the intermediate stage of such planetesimals is an attractive problem.

The importance of collisions has become much more prominent during the past decade. Even the origin of the Moon and the tilt of Uranus are now believed to be due to the largest of collisions.

It has become clear that the large gaseous planets in the outer solar system have sizable cores at their centre that played a role in the accretion of the gaseous envelope. At the beginning of the formation of the solar system its inner part, including most of the asteroid belt, was heated to about 1300 K, which indicates a hot protosolar nebula. 1500 K is suggested by Tscharnuter & Boss (1992), while at a distance of 4 AU the temperatures had already dropped to 150 K.

Evidence has also been found that lightning was included in the violent events of the early system (Morfill *et al.* 1992). Conditions in the solar nebula, and therefore in nebulae for star formation in general are learned from meteoritics; Kerridge & Matthews (1988) have edited a book on that main theme. The book has chapters on evidence of circumstellar and interstellar material found in meteorites, and discussions of the processing of the material during successive stages of evolution. A later review of outstanding problems is by Palme & Boynton (1992). Prinn (1992) lists six outstanding problems in molecular spectroscopy for the stage in circumstellar disks. A new branch of meteoritics is that of organic matter in comets and meteorites, and this study is, of course, connected with that of the origin of life on Earth and the question of the existence of life elsewhere.

3. Environmental studies on an astronomical scale

Astrophysicists and planetary scientists are coming together regularly to work jointly on the *Protostars and Planets* series, but they are mostly authors who write on either the stellar or the solar-system aspect. In this Section I propose the full integration in terms and by the founding of an institute for global environmental studies. Its dedication would entail the cosmological perspective of the origin and evolution of the universe, galaxies and stars, applying this to and interacting with the study of the origin of the solar system and its subsequent evolution, including that of life and how to protect it on Earth. The time seems ripe to promote this type of interaction between scientists with various perspectives over the full range of cosmology to environmental studies on a global scale. The preambles for such a unification of science have been with us already for a long time. For instance, there is the interdisciplinary book *The Galaxy and the Solar System* (Smoluchowski *et al.* 1986) which is not restricted to astrophysics, nor to planetary science. The Preface follows :

> While two broad fields of astronomical research—our galaxy and our solar system—have been progressing rapidly, areas of concern common to both have remained until recently relatively inactive. In the last decade there has been intense interest in a more detailed study of the galactic neighborhood of the Sun, of the outer limits of the solar system and in topics such as the velocity and mass functions of neighboring stars, the location and motion of the Sun in the Galaxy, the penetration of interstellar and interplanetary dust, the distribution of molecular clouds and of galactic radiation and gravitational fields, of galactic cosmic rays, and the role of nearby supernova. The general question of the influence of the galactic neighborhood on the solar system has received particular attention recently because of the expected perturbations of the outer reaches of the solar system by passing stars, by molecular clouds or by gravitational fields and because of the proposal that the Sun may have a companion star. The latter possibility aroused special interest because of its possible relation to the suggested periodic extinctions of species on the Earth.

The debate is evident throughout the book; the Acknowledgments section shows that there was much correspondence and argument. One should perhaps not emphasize this topic for the sake of finding a solar companion or a Tenth Planet, because the chance of finding one is so low, but rather for the exploration of the interface between the solar system and the galaxy. The environmental connection is clear; it is quite specific in the chapter by Clube & Napier (1986) who warn us about impacts of giant comets—new comets that hit the Earth without much warning. A book devoted to the hazards due to impacts by comets and asteroids is being organized (Gehrels 1994a) at the time of writing this paper.

Frisch and York (1986) surmise that the temperature on Earth may be affected severely as the solar system is approaching a region of higher average density than in the recent past. This needs further investigation, with better knowledge of the distribution of nearby interstellar material.

Greenberg (1986) made an early prediction of an extremely low comet albedo of 0.05 in visual light, which was later confirmed from spacecraft observations of Comet Halley. He raises the issue of organic and inorganic cometary contributions to the Earth which is a new topic and of great importance for understanding the origins of the oceans. The most recent overview of the topic is by Chyba *et al.* (1994).

The oceans show evidence of a nearby supernova explosion a few million years ago; this is discussed by Clayton *et al.* (1986; also N. Gehrels & Chen 1993), and they indicate essential work to study the effects more in detail. The event itself would have been quite dramatic, a possibly stressful situation for the emerging human race.

Delsemme (1986) indicates the possibility of a solar companion star :

> A set of 126 cometary orbits that have been least influenced by the planets has been selected : their orbital angular momenta show a large anisotropy in a plane almost perpendicular to the ecliptic. This anisotropy would dissipate by orbital diffusion in 10 to 20 Myr, and therefore it cannot come from primordial or galactic effects; it must be due to a recent impulsive event in the Oort cloud. Gravitational perturbations due to fast-moving stars or molecular clouds (20 to 30 km s^{-1}) are demonstrated not to produce generally any isotrophy; a massive body is needed that is slow enough to be likely bound to the solar system (200 to 300 m s^{-1}). The strip of the sky centered on its presumed orbit reveals large anomalies in the ratio of retrograde to prograde comets, extending across half of the sky, these anomalies suggest the position of the perihelion of an eccentric orbit. Identification with the Nemesis of the geologists is proposed. Other possibilities are mentioned, although none stands out as more likely than the existence of a slow massive body (not necessarily Nemesis) piercing the Oort cloud < 20 Myr ago.

I made a survey of Delsemme's strip on the sky, but it would be beneficial to repeat it more carefully. If nothing else, it would be a search for brown dwarfs that could be extended to other parts of the sky.

Weissman (1986), on the other hand, firmly concludes against the existence of a small unseen solar companion or a Tenth Planet causing periodic comet showers from the inner Oort cloud, as unsupported by dynamical studies or analyses of the terrestrial and lunar cratering record. He generally discusses Oort clouds around other stars.

The outstanding problem of the occurrence of life has already been mentioned. A local problem within the solar system is that of the distance from the Sun at which a habitable planet could have formed. Criticizing previous estimates of 0.95 to 1.01 AU, Kasting & Toon (1989) derived a lower limit at 0.85 AU and the outer limit much farther away, perhaps beyond the orbit of Mars. This is a major parameter in the "Drake equation" which yields the chance of life occurring anywhere in the universe.

The Indian Institute for Astrophysics (IIA) has a program to observe comets and asteroids, for which the funds have been made available by the Government of India, the Smithsonian Institution of the United States, and by IIA itself. Observing with charge-coupled devices (CCD) was discussed by Gehrels (1981). There are four environmental reasons for searching for near-Earth objects (NEOs) : first, they or their parent bodies are left over from the original formation of the solar system. By studying them we look back in time to the formation of the Earth. The studies are intricate in the interconnections of comets, asteroids, meteorites, and meteors. The identification of parent bodies for the meteorites is an ongoing problem. Also the mechanisms for getting the fragments of collisions in the asteroid belt to become near-Earth asteroids that can collide with the Earth, require complex studies involving the theory of chaos. The mechanisms of obtaining comets and transporting them into the Oort cloud, and then the mechanism of transporting them from the Oort cloud to become NEOs are basic to the understanding of the solar system and its origins.

In yet another way NEOs are connected with the origins of human beings, namely through the understanding of their major impacts on the great extinctions in the history of life on Earth. The classical example is at the Cretaceous-Tertiary boundary. The extinction of about 65 million years ago has been known for several decades by biologists and geologists. Through the work of Luis Alvarez and his team at the University of California at Berkeley, it became clear that an extraterrestrial body was involved with that extinction. Our evolution is not gradual, as would follow from Darwin's theory, but rather punctuated by the impacts of asteroids of about 1 kilometer in diameter and larger.

The third reason to be involved with NEOs in an environmental sense is the hazards due to comets and asteroids (see Gehrels 1994a, b). Our knowledge of the statistics of objects that cross the orbit of Mars comes from telescopic searches and counts of craters on the Moon. A precise determination is still lacking. Recent derivations range between 1,200 and 2,200, having diameters of 1 kilometer that could now or in the foreseeable future come close to the Earth. This includes old cometary cores that have passed by the Sun often and close enough to have had their volatiles exhausted so that they now are indistinguishable from the fragments from the asteroid belt. Objects larger than 10 kilometers do not seem to occur close to the Earth; apparently the fragmentation in the asteroid belt is such that the large objects survive the collisions with their orbits nearly unchanged. We are fortunate that the orbits in the asteroid belt are stable, that they do not hit the Earth, for their diameters range up to 1,000 kilometers! Such large objects may have hit the Earth during its formation, but if that had happened in recent times, life would have been obliterated. Even at 10 kilometers there may be only ten that cross the Earth's orbit, and only once in about 100 million years will one of these hit the Earth, according to various astronomers' estimates.

The probability of impact by one of the asteroids larger than 1 kilometer is very low, but for two reasons it would be wrong to dismiss this hazard and not take any precautions. First, these are just statistical numbers, but the probability of such a disastrous effect happening tomorrow is just as great as a million years from now. Secondly, the energies involved are so great that the Earth's atmosphere would be seriously affected. From a comparison with the studies of nuclear winter conducted by various experts, it follows that a major effect is due to small dust particles being shot into the stratosphere and then spread in longitude and latitude by the jetstreams. Indeed, the modeling shows that the effects are as serious as those of a nuclear winter and that the result of an asteroid larger than about 1 km in diameter would be to cause the demise of human society as we know it today. When the impact occurs in a region of deep layers of limestone, it is particularly the carbon combining with oxygen in the Earth's atmosphere to produce CO_2 and a greenhouse effect. This was apparently the case in the Yucatan Peninsula where a crater, perhaps as large as 300 km in diameter, has been identified as the site of the impact of 65 million years ago. Hundreds of millions of years ago it had been a tropical rainforest. Only a few percent of the Earth's surface has such deep layers of limestone; the Australian Barrier Reef is another example.

An outstanding problem connected with concerns for our lives and environments is the new discipline concerning the question of what action to take when a dangerous asteroid has been identified. Two NASA workshops raised a major discrepancy : a debate between planetary scientists who propose to concentrate on objects larger than 1 km because these cause global disaster of nuclear-winter proportions, and nuclear engineers who see their techniques available to take care of dangerous objects of all sizes down to 20 meters in diameter. Statistics obtained in the Spacewatch program (Sec. 9) indicate that there are as many as 10^8 near-Earth objects down to 20 meters in diameter.

A key parameter in the controversy is that only a few thousand could be found and their orbit determined, even in a span of 20 years with a proposed international network of six telescopes. The probability of identifying an impactor larger than 20 meters heading for a city is about 10^{-8}. A wide-angle optical telescope system could provide several days warning of proximity objects. Radar could then make the trajectory more precisely known, and rockets would have to be ready with warheads larger than currently available (Canavan & Solem 1992). The chance of thus saving a city is about 10^{-4} per year.

The fourth reason to be involved with NEOs lies in the future, namely in the possibilities of sample return, and even mining, for *in situ* study and exploration of asteroidal and cometary materials. The greatest attraction is for extracting water from carbonaceous objects, water needed especially for manned exploration. This topic will be further discussed later in this Section.

There is already great activity at various laboratories and universities discovering near-Earth objects, so the question arises whether or not India could contribute new information. Considering the above four reasons to be involved with NEOs, it is a premise that the NEOs have to be discovered first. It is an astronomical assignment to discover and obtain orbits for them, and IIA with its astronomical background is in a position to participate in this effort. Since IIA is already funded to work on NEOs, it would have a headstart compared to other organizations where the first funding would have to be obtained. It is also true, however, that the competition is rising rapidly. In any case, the involvement with NEOs would put India in the forefront of a new discipline tackling a range of outstanding problems of studying origins, hazards, future sample return, and environmental concerns. The concept of accomplishing this in a frame of an institute or school of environmental studies would be new.

It could be valuable to teach a graduate course in planetary atmospheres as part of the education of meteorologists. According to the book edited by Atreya *et al.* (1989), it seems likely that some of the new ideas regarding the atmospheres of various planets that have been obtained from spacecraft could yield a better understanding of the atmosphere of the Earth. This would be the case not only for obtaining new research ideas, but also for training meteorologists who deal on a daily basis with the prediction of weather and large scale atmospheric phenomena. Not many meteorologists have participated in the missions to the outer planets, nor have many planetary scientists participated in the meteorological space missions in orbit of the Earth. Perhaps new progress could be made by a combination of these data by people trained in meteorology as well as in planetary sciences.

An outstanding problem seems to be that of the temperature of the early Sun and of the early Earth. It is a complex problem on the interface of astrophysics and earth sciences. The early Sun may have had a lower luminosity than at present, but the Earth may have been hotter than at present because of an enhancement in the greenhouse effect due to water vapor and little absorption as yet of CO_2 by the terrestrial rocks compared to the present rate. The problem is reviewed in a chapter by Kasting & Grinspoon (1991). It appears to be a pioneering chapter for a new discipline in environmental sciences rooted in astrophysics and planetary science. In general, this book, edited by Sonett *et al.* (1991), is a pioneering effort in a broader sense on the periphery and interface of various sciences.

The later developments on the Earth such as ice ages and glaciations may be connected to variations in the solar luminosity. This problem is also studied in the book edited by Sonett *et al.* (1991).

Not all of these studies are environmental as there are strong connections with the study of meteoritics and comets and asteroids as part of the astronomical study of the solar system; these topics will be discussed in individual sections below. Physical studies of near-Earth comets and asteroids can be done with astronomical telescopes. A number of scientists are doing this type of work already, but there still seem to be opportunities for more of these physical studies, if not for inventing new techniques, particularly because the number of newly discovered NEOs is increasing rapidly. Of the newly-discovered NEOs more than half do not have follow-up physical studies of their colours in order to determine their composition, of their lightcurves in order to obtain their shape and state of rotation, and of their radar properties, for lack of personnel and telescope time. This topic will be further discussed in Section. 9.

One might argue that the environmental aspects detract from a pure astrophysics dedication. But is it not important to be involved as scientists in the plight of common man, especially in India? Sarabhai (1974) addressed this concern as follows :

> The real social and economic fruits of technology go to those who apply them through understanding. Therefore, a significant number of citizens of every developing country must understand the way of modern science and of the technology that flows from it.. . An ability to question basic assumption in any situation is fostered by probing the frontiers of science, whatever field one may be engaged in, whether it is Biology, Genetics, or Space Research. It is this ability, rather than an empirical hit-and miss approach, which proves most effective in tackling the day-to-day problems of the world. It follows from this that countries have to provide facilities for its nationals to do front-rank research within the resources which are available...Broad understanding of the physical and social environment in which man lives is the most urgent task which faces all humanity...Lack of insight concerning the environment in which man operates has posed a problem at all times...The consequences...are more serious to the security of the world than they were ever before. The task of promoting an understanding of science is of course at the core of the problem of education...Acquisition of technology by itself does not contribute to this understanding.

Physicist Peter Kapitza (1984) is quoted, as follows :

> The future of civilization depends on whether existing governments are able to provide solutions to global problems...problems must be expressed clearly and convincingly and widely discussed. This can be done mainly by scientists, since they can talk with sufficient authority on the possible solution of global problems for the benefit of mankind. Thus, we should not stand aside from the solution of such problems but realize their connection with our scientific work

A major outstanding and continuing problem in solar system studies is the comparison of the other planets with the Earth for the purpose of learning about the Earth. This topic is also an environmental one on a global scale. Such a comparison has not as yet been done systematically. We plan to publish a Space Science Series book on the topic of *Terrestrial Planets* or *The Earth as a Planet* when an editor/organizer can be found.

If India would want to participate in the deep space program, a simple flyby mission of Mercury, imaging the 60% of the surface that has not as yet been examined by Mariner 10, would be something new that, as far as I know, is not being planned elsewhere. Papers are appearing on the geologic history of the craters. There are many outstanding problems on Mercury compared to other bodies in the solar system because only the flyby mission of Mariner 10 has been done so far. An example is the uncertainty whether or not Mercury has a molten core. Russell *et al.* (1988) list 20 unsolved questions regarding the magnetosphere alone, and they see a great need for a planetary orbiter mission for Mercury. Na and K were discovered on Mercury by Potter and Morgan, and He and O by the investigators using the ultraviolet spectrometer on Mariner 10 (Hunten *et al.* 1988). The density of Mercury implies an iron-to-silicate mass ratio about twice that of the other terrestrial planets; the uncompressed density is about 5.3 g cm^{-3} compared to 4.45 g cm^{-3} for the Earth (Cameron *et al.* 1988). We shall discuss Mercury further in Section 7.

The Space Science Series book, *Venus,* edited by Hunten *et al.* (1993) is probably out of date because of the various space missions since that time for which other reports and books are coming into the literature. *Venus II* is being prepared, with a meeting scheduled in 1995.

The book, *Resources of Near-Earth Space,* edited by Lewis *et al.* (1992) describes a discipline with a new set of problems that concern science and engineering, as well as environmental studies and possible future resources for astronauts and cosmonauts in space. For transporting people into space, the greatest benefit would be to locate water in usable and economic form. Carbonaceous asteroids, for instance, are known to have crystalline forms of water. The mining and processing of these materials in order to make them usable in space is now being studied (Nichols 1992). Problems of transportation to the Moon, near-Earth asteroids, and to Mars are also discussed in this book. Nearly all the chapters offer suggestions for future work and research. The United States and Russia are considering to return to the Moon to set up bases. Staehle *et al.* (1992) discuss six specific sites of interest for lunar bases, and it is not too early to start detailed studies of these sites, perhaps even including Earth-based astronomical telescopes. International cooperation is also emerging in the exploration of Mars and its satellites. Small missions to near-Earth asteroids are beginning to be executed.

One of the sections in the *Resources* book is entitled "Environmental Concerns", but this is regarding Mars, for consideration of photovoltaic performance depending on temperature, wind, dust accumulation and abrasion. There is fresh impetus and need to study in detail the surfaces of the Moon and Mars, of the Martian satellites, as well as of the near-Earth comets and asteroids.

Some of the studies in planetary engineering may be directly applicable to environmental engineering of Earth. Pollack & Sagan (1992) discuss some of the possibilities of modifying the atmosphere of Mars, but they sound a warning regarding the Earth, as follows :

> Global warming on Earth has already led to calls for mitigation by planetary engineering—e.g., emplacement and replenishment of reflective or anti-greenhouse layers at high altitudes, or sunshields in space. But here especially we must be concerned about precision, stability, and inadvertent side-effects. The safest and most cost-effective means of countering global warming of the Earth—beyond, e.g., improved energy efficiency, CFC bans and alternative energy sources—is the continuing reforestation of about 2.5×10^7 km^2 of the Earth's surface. This can be accomplished with present technology.

4. The solar perspective

Solar astronomy has traditionally stood alone with little interrelation with stellar work, even though solar astronomy is the study of a star in the greatest detail. Nor do the solar astronomers seem to have had much contact with the planetary scientists who study the solar system. The book *The Sun in Time* edited by Sonett *et al.* (1991) will be helpful to put solar physics into the maelstrom of astrophysics and planetary science. The book also overviews the interstellar medium with that of the solar system and particularly the effect the Sun and the solar wind have had and are having on other parts of the solar system.

The flux of high-energy neutrinos measured on Earth does not agree with that predicted by the standard solar model. The present state of this classical problem is reviewed in the chapter by Wolsberg & Kocharov (1991). Much work has been done on this problem and the reviewers express the expectation that the problem may be solved by the mid-1990s.

The question of whether global warming is due to changes in the greenhouse effect or in solar heating is discussed in the chapter by Damon & Sonett (1991). The variations of the solar flux in time are discussed in several chapters in this book.

Stauffer & Soderblom (1991) discuss future work on the problem of angular momentum in solar-mass stars and the possible connection between disks, planet formation and rotation. Saar (1991) suggests future work on the problem of the time evolution of magnetic fields on solar-like stars. Lal & Lingenfelter (1991) suggest the same for the history of energetic particles emitted by the Sun. Luminosity and radius variations are also among the outstanding problems. The comparison of our Sun with other stars is discussed in the books edited by Cox *et al.* (1991) and Sonett *et al.* (1991).

The dynamics that produce the observed solar rotation profile remain a mystery; Libbrecht & Morrow (1991) have already designed the following problem for a graduate course in fluid dynamics in the year 2020 :

> Using the fractal theory of turbulent convection discussed in class, formulate a model of the rotation of a self-gravitating, convecting plasma sphere, the Sun, on your personal supercomputer. For extra credit, derive the period of the solar magnetic dynamo in terms of fundamental quantities.

Dziembowski & Goode (1991) are more optimistic about a resolution of these problems in the near future because of greatly improved oscillation data from groundbased network and satellites.

Regarding the solar dynamo, DeLuca & Gilman (1991) list eight problem areas, indicating that in the majority of them some work has already been done, but there are no definitive treatments. Solar and stellar observations appear to be fruitful for future work; the topic is discussed in various chapters of the book edited by Cox *et al.* (1991). Pulsation of stars seems a topic of increasing importance because more stars are being studied for radial velocity measurements in connection with the search for planets, and such observations tend to bring discoveries of stellar pulsations. Cox *et al.* (1991) not only mention outstanding problems, but also current disagreements regarding solar oscillations. von der Lühe (1991) discusses adaptive optics for the case of solar observations; references are cited from the early 1980s.

The status and future of empirical models of the solar activity cycle are reviewed in the chapter by Rabin *et al.* (1991). They pose the question : Is the Babcock picture today a viable empirical model of the solar activity cycle, and, if not, is there a better model to replace it? Our short answers are "no" and "no."

Kurucz (1991) shows solar spectra from the ultraviolet to the infrared and provides information on how one can obtain copies for particular applications be it in atomic or molecular spectroscopy, or in solar, atmospheric, planetary, cometary or stellar physics.

5. Heliosphere, magnetospheres, and atmospheres

An outstanding problem for all planets is their interaction with the heliosphere. The topic will be treated in a future SSS book *The Heliosphere* edited by J. R. Jokipii, M. S. Giampapa and C. P. Sonett (1994). There are chapters on these topics in the book edited by Hunten *et al.* (1983), and there must be a stream of new data from various space missions in recent years.

Concerning the heliosphere, there is, of course, the well-established discipline of the interaction of cometary plasmas with the solar wind, which will be discussed in Section 8.

The differences between the outer planets Uranus and Neptune, and Jupiter and Saturn still are a puzzle. The Voyager missions obtained essential information, and detailed reports have been written by the scientists involved with these missions. However, new progress in the understanding of the outer planets could still be made. The book edited by Atreya *et al.* (1989) covers these giant atmospheres. A more recent overview has been made by Podolak *et al.* (1992).

The last SSS book on *Jupiter* edited by Gehrels (1976) is mostly out of date, especially because the results of the *Voyager* missions by Jupiter were not available at the time of writing that book. There are, however, chapters on the magnetosphere and atmosphere that may still be of use; one must also consult the papers based on the Voyager flybys published in the *Journal of Geophysical Research* and elsewhere. The same applies to the interior structure of Jupiter.

The magnetospheres and plasma environment of Uranus are discussed in detailed chapters in the book *Uranus* edited by Bergstrahl *et al.* (1991); there must be an array of unsolved problems particularly in the intercomparison of the magnetic fields of the various planets. Unresolved issues are discussed particularly at the end of the chapters by Cheng *et al.* (1991) and Desh *et al.* (1991). Kilometric radiation apparently has not been detected for Uranus by Earth-based receivers. Earth-based radio observations still appear to be productive in the study of planetary magnetospheres.

Prinn *et al.* (1984) and Tomasko *et al.* (1984) discuss outstanding problems in the details of composition, chemistry and transport in the atmosphere of Saturn. The information in the *Saturn* book, edited by Gehrels & Matthews (1984), will be in effect until the next Cassini mission, presently scheduled to arrive in the year 2004, which will also emphasize the study of Titan. The book edited by Atreya *et al.* (1989) was written at a later date. The reddishness of the Great Red Spot has apparently not yet been explained.

The possibility of finding organic and primordial conditions is stimulating future research (see the chapter by Sagan *et al.* 1984). The chapter by Hunten *et al.* (1984) ends with questions or the future regarding Titan. The topic is further discussed in the *Planetary Satellites* book edited by Burns & Matthews (1977).

The chapter by Fegley *et al.* (1991) reviews solar system primordial helium abundances, showing that

> .. the He abundance (by mass) observed for Uranus is 0.262 ± 0.048 which, within the uncertainties, is the same as the value derived for standard evolutionary models of the Sun This agreement indicates that the He/H_2 ratio observed on Uranus is probably representative of that in the primitive solar nebula.

Bergstralh and Miner (1991) ask the following questions for the future :

> What processes enriched heavier elements (atomic number ≥ 3) in the Uranian atmosphere without apparently affecting the primitive He/H ratio? What accounts for the seemingly anomalous D/H, N/H and (possibly) S/H ratios? Do these tell us about initial conditions in the solar nebula? Or do they reflect later evolutionary processes?
>
> The heating rate in Uranus' exosphere is orders of magnitude greater than solar extreme-ultraviolet radiation can supply. Do precipitating electrons power the heating and the observed dayglow, at least partially? What would be the source of these electrons?
>
> The energy to drive Uranus' atmospheric circulation is dominated by solar radiation, which has been incident primarily on the planet's southern hemisphere for 20 yr. Nonetheless, the circulation is organized

around the planet's rotation axis, not around the sub-solar point. Retrograde winds are inferred near the equator and prograde winds are measured at higher latitudes, suggesting that large-scale convective cells dominate the circulation. How can Uranus have such an Earth-like circulation pattern, despite the gross hemispheric asymmetry of energy input to its atmosphere?

Uranus' tropospheric temperature gradient indicates that the ortho-para H_2 ratio is not in thermodynamic equilibrium, but spectroscopic observations suggest that it is. Does layered convection, stabilized by condensation and precipitation of CH_4, account for this anomaly?

6. Satellites and rings

Lunine & Tittemore (1992) discuss outstanding issues for the satellites in the outer solar system in connection with their origins, their formation from proto-satellite disks, while relating back to the composition of molecular interstellar clouds. These topics may be of interest to astronomers who have studied interstellar clouds without having taken into account until now that additional and detailed information may be obtained from planetary science.

Satellites are classified as *regular satellites, irregular satellites,* or *collisional debris;* the Moon, Triton and Charon do not fit this classification scheme (Burns 1986). The disciplines of studying satellites and rings is still mostly in the hands of the experimenters connected with the space missions, and that is likely to remain so through the flux of information from the upcoming Galileo and Cassini missions. Nevertheless, it might be possible for a scientist elsewhere to overview the data and make new progress in synthesis. Special thought might be given to the use of the data of the satellites in connection with solar system origin and star formation.

There is an interface to consider impacting comets and asteroids discussed in Sections 2, 3, 5, and 6 on which only a few people are working. Additional scientists might make progress on outstanding problems connected with collisions and cratering (Chapman & McKinnon 1986).

The interior of the Moon is not well known; several outstanding problems are reviewed in the chapter by Kaula *et al*. (1986). A similar situation occurs for Io and the other Galilean satellites with several questions remaining.

The surge in information regarding the rings of Saturn is still quite recent, and there appear to be unsolved problems. The sputtering effects due to photons and charged particles and micrometeoroid bombardment might be an appropriate area to study prior to and in preparation for the Cassini mission to Saturn. The chapter by Cheng *et al.* (1986) reviews this subject. According to R. Greenberg (personal communication, 1992), there are major problems such as how the rings of Saturn are confined and regarding their lifetime.

Besides the rings long known and recently discovered another set of circumplanetary structure around Saturn has been reported (Vasundhara *et al.* 1985). This was spotted during a pair of occultation events in March 1984 when remarkable symmetry in the extinction curves on two consecutive nights at Kavalur and simultaneous observations from another observatory (Nainital) separated by 1500 km was noticed. Part of the features were confirmed by later occultation events, while some could not be detected at the predicted moments. The group feels that the structure is in the form of a circumplanetary set of rings, whose shapes are distorted from a perfect circular symmetry by effects of planetary magnetic fields on dusty plasma (Bhattacharyya & Vasundhara 1985).

It may now be appropriate to publish the second SSS book on *Planetary Rings.* The topic seems to be firmly in the hands of an experienced group of scientists. The outstanding problems that appear in the 1984 volume have probably now been resolved and this must also be the case for 1985 review by Lissauer & Cuzzi (1985).

In addition to the book edited by Greenberg & Brahic (1984), it is useful to consult the chapters on Saturn's rings in the *Saturn* book produced at the same time. The basic outstanding questions at that time are listed at the end of the chapter by Esposito *et al.* (1984) as follows:

> Are the rings young or old? Almost everyone believes the rings to be as old as the rest of the solar system, but then why are the rings so compact, and why have the inner Saturn satellites not moved out, conserving the angular momentum drawn from density waves?
>
> Are the rings thick or thin? Perhaps they are a little of each; still, this is a basic input to every model of the rings
>
> What are the sources and sinks for ring particles, random kinetic energy, and angular momentum? Not only theorists but spacecraft observers should search their minds and data for the answers.

The electrodynamic processes in the ring system of Saturn (reviewed in the chapter by Mendis *et al.* 1984) pertain to this new field, because the visual phenomena of spokes in the Saturn rings were totally unexpected observations. Mendis *et al.* note :

> The combination of electromagnetic and gravitational forces may be responsible for a number of observational phenomena associated with the fine dust immersed in the Saturnian magnetosphere. However, our present understanding of this area is far from secure. This is partly due to the uncertainties associated with the immediate environment of the grains and the nature of the grains themselves. Even more it is due to the fact that the state of theoretical development of this new subject is as yet immature Clearly more work is needed in the future particularly in relation to collective dusty plasma.

The satellites and rings of Uranus are discussed in detail in various chapters in the book *Uranus* edited by Bergstralh *et al.* (1991), and those of Neptune will be treated in the book *Neptune* edited by Cruikshank (1995). Various investigators and their students are working out the further details of the Voyager data and making intercomparison of the various ring systems of the outer planets.

Outstanding problems for satellites are discussed in the chapter by McKinnon *et al.*(1991) in great detail, but the investigators themselves will probably pursue these topics. Miranda, however, was evaluated in the chapter by Greenberg *et al.* (1991) by only one group of investigators, a rare situation in the SSS which is famous for its "shotgun wedding" of authors from various groups and schools of thought, and it may be productive to have a fresh look by outsiders at this enigmatic satellite.

The Satellites of Jupiter edited by Morrison (1982) discusses the Galilean satellites including the results from the Voyager missions. There are, of course, newer studies which one can find in *Icarus* and in the *Journal of Geophysical Research.* The understanding of the origin and evolution of the Galilean satellites is still in a state of flux as is mentioned at the end of the chapter by Greenberg (1982).

It would seem that a group of geologists taking a fresh look at all the data of the Galilean satellites could make new progress in the understanding of these four different objects. They are so large that if they were alone in space they would be called planets. Yet, they are strongly influenced by the presence of massive Jupiter. The phenomena seem to be so complex and intertwined that surely there must be not only outstanding problems but also new interpretations from the combination of the presently available observations. Such a group would also be prepared for the interpretations of the many data that are forthcoming from the Galileo flybys of the satellites of Jupiter.

The origin of the Moon is seen as an outstanding problem in several chapters of the SSS books, and then there occurred a sudden development in that discipline, namely the theory of the origin of the Moon from a chance collision of a major object with the Earth. The book edited by Hartmann *et al.* (1986) concludes with the discussion of four sets of theories and processes, namely :

> Lunar formation involving capture or fission.
>
> Considerations involving large bodies in the environment of primordial Earth, and chances for close approaches or impacts.
>
> Lunar formation triggered by large impact.
>
> Models emphasizing co-accretion or evolution of a circumterrestrial swarm, of whatever origin.

The prevailing model now seems to have a glancing impact on the Earth by a large object. The book contains detailed discussion of future work.

7. Surfaces and interiors

The interior structure of Saturn is discussed in the chapter by Hubbard & Stevenson (1984). The interiors of the four major outer planets may be studied simultaneously, taking their differences into account; there are chapters in *Uranus* edited by Bergstralh *et al.* (1991), as there will be in the upcoming book *Neptune* edited by Cruikshank (1995). The chapter of Schubert *et al.* (1986) reviews the interiors of Jovian satellites.

A basic paper for the understanding of various surfaces may be the chapter by Veverka *et al.* (1986) whose abstract follows :

> Both exogenic and endogenic effects have been proposed to explain the major observed characteristics of satellite surfaces. The current view is that the basic properties of most surfaces result from the intrinsic composition of a body and its geologic history. Exogenic effects have, however, played a role in modifying the appearance of nearly all surfaces The most important exogenic effect is impact cratering, one manifestation of which is the production of micrometeoroid gardened regoliths on airless bodies. On large, silicate bodies the micrometeoroid bombardment can produce an optically mature, dark agglutinate-rich soil; the nature of regoliths on predominantly ice satellites remains uncertain. Direct accumulation of infalling material does not appear to play a major role in modifying most surfaces. Solar wind radiation effects have not altered greatly the optical properties of solar system objects; magnetospheric charged particles may have modified the optical properties of some outer-planet satellites (e.g. sulfur ion bombardment in the case of some of the satellites of Jupiter). Other effects, such as aeolian and liquid/solid chemical weathering, may be important on satellites with atmospheres like Titan and Triton.

The study of surfaces of solid bodies in the solar system would probably not be a fruitful area for a newcomer; it is well under control by a large group of people who have been working on the identification of various surfaces with the best equipment. For instance, Asteroid 5145 Pholus (1992 AD) has an exceptional red colour, which may have an important connection with its origin possibly in the outer regions of the solar system where it may have been covered with organic materials. This problem may be solved soon.

The outstanding questions for the planet Mercury have been listed by Stern & Vilas (1988) :

> What does the still unimaged hemisphere of Mercury look like and what are the inferred geomorphological and tectonic processes?
>
> What is the chemical and mineralogical composition of the surface? What are the textural properties of the surface? How do these vary among geologic units?
>
> What is the full chemical composition of the atmosphere? How do the composition and pressure vary with location on Mercury and orbital phases?
>
> By what process is the Mercurian atmosphere generated?
>
> By what process is the Mercurian magnetosphere generated and how does this magnetosphere interact with the time-dependent atmosphere and variable solar wind?
>
> Does Mercury have a present-day liquid core and attendant dynamo? If so, how much of the core is molten?
>
> What are the global geophysical properties of Mercury (gravity field, heat flow, and seismicity)?
>
> What is the chronology of internal and external processes that have modified Mercury over time? Are there clues about how the planet formed?

Stern and Vilas remark further :

> Beyond these questions, Mercury observations also offer promise toward the general understanding of planetary magnetospheric, cratering and exospheric processes. Further still, Mercury provides a unique location for tests pertaining to general relativity and for the study of solar physics.

Stern and Vilas then continue with a detailed discussion about how these problems can be solved with Earth-based studies, but it seems that little of this is presently being done. The book edited by Vilas *et al.* (1988) provides a detailed guide on how to proceed with the studies of this rather neglected planet. An exception is the follow up by A. Potter of his discovery of the outgassing of the surface of Mercury using some of the best equipment at major observatories.

Bergstralh & Miner (1991) mention as the major outstanding problem regarding the interior of Uranus whether measurement of higher order gravitational moments help arrive at the unique model of the distribution of ice, gas and rock within the interior of Uranus. What will this reveal about the origin of the planet? They mention outstanding problems as follows :

> What accounts for the rich variety of dynamic phenomena exhibited by the Uranian rings? Are these features explained by gravitational interactions with yet-undiscovered satellites?
>
> Is the dark stuff on the rings and satellites carbon-bearing material that has been blackened by radiation? What does this imply about the bulk compositions of the rings and satellites, and, by extension, what might it imply about their origins?
>
> Was Uranus' high obliquity caused by impact of a late-arriving giant planetesimal? If so, does the regularity of the satellite system tell us anything about the origin of the satellites?
>
> Does the geologic activity seen on Uranus' principal satellites (especially Miranda) imply anything about the bulk composition of these bodies, and, by extension, about their origins?
>
> What accounts for the bizarre magnetic field geometry of Uranus? What does this tell us about the interior structure and composition of the planet?

Podolak *et al.* (1991) :

> The low value of Uranus' internal heat source relative to that of the other outer planets is still not well understood. One possible explanation is that part of Uranus' interior is stably stratified due to a compositional gradient In such a case, convection would be inhibited and the heat of accretion would not easily escape, and in this case, the outer half of the planet (by radius) would contribute to cooling by homogeneous convection. This region is probably the place where the magnetic field is generated. Measurements of "synthetic Uranus" imply that this region is sufficiently conducting. It is also consistent with the strength and general complexity of the field A full explanation of the magnetic field is still not available, however. As usual further work is necessary.

Most of the chapters in the book edited by Bergstralh *et al.* (1991) mention detailed questions that are outstanding, usually indicating a desire to conduct another mission to Uranus with an orbiting spacecraft and atmospheric entry probe. A return mission to Uranus is discussed in detail at the end of the chapter by Kurth *et al.* (1991). Uranus' high obliquity is discussed by Kochhar (1989).

8. Comets, Asteroids and their debris

In studying the origin of the solar system, authors of chapters in the Space Science Series books indicate the importance of knowing the population immediately outside of Neptune. Backman & Paresce (1992) discuss the search in the distant regions of our solar system for evidence of planetesimal-sized parent bodies and collision fragments. That is a search from the inside out, complementing high-resolution telescopic observations with evidence of such nebulae from the outside as was done in the case of circumstellar material around Beta Pictoris. To begin with, it seems unlikely that the density profile of the original solar nebula dropped off so steeply that right outside of the massive planet Neptune there would be no other object that would have formed there other than Pluto. A direct-CCD imaging search at Mauna Kea has already yielded several 23rd magnitude objects near the distance of Neptune.

Some searching for objects in the outer parts of the solar system has been done by Kowal (1979) and others, without success other than the discovery of Chiron. The fact that Chiron was a chance discovery indicates distance limitations of surveys for the outer parts of the solar system. The interval between the two plates on which Chiron was discovered was so large, 24 hours—set for much more distant and therefore slower objects—that the motion was exceptional and other objects such as Chiron might well have been missed.

It is an outstanding problem to look specifically for objects far beyond Neptune. Direct observational detection of reflected sunlight of comets in the far-outer solar system is out of the question by orders of magnitude. How to obtain an indirect observational proof of the existence of comets in the Oort cloud and, closer to the plane of the ecliptic, at smaller distances but still outside of the orbit of Neptune is the question.

The theoretical need to know the population in the outer reaches of the solar system is described in the chapter by Duncan & Quinn (1992). The chapter has a discussion of chaos in the case of the structure of the asteroid belt and in the outer planetary regions. They announce the dawn of a new era—that of the numerical exploration of the solar system.

Spacewatch discovered 1992 AD, mentioned in Section 7, a Chiron-like object but with its orbit ranging wider, from near-Saturn to near-Neptune distances from the Sun. Computing the orbit forward and backward in time, Bailey *et al.* (1992) found that it is strongly chaotic.

An overview of progress and of outstanding problems in research on comets was made by Mumma *et al.* (1992). The nature of the grains in coma and tails still has not been established. Adequate photometry on comets and their tails has been done and interpreted using the Mie theory with apparent success. Various astronomers have spent time on polarimetry that then also could be explained using the Mie theory with apparent success (Gehrels 1974). There are, however, cases when photometry and polarimetry, over a range of wavelengths, have been combined, but then the interpretation using the Mie theory became less secure. Additional observational parameters need to be solved for size, refractive index, phase, and their variations and dependence on wavelength. In any case, the Mie theory is useless and its application misleading because it is for spherical particles, and the particles that have been collected by high-altitude balloons and aircraft are not spherical. Probably the only case in the universe where spherical particles are found is in the atmosphere of Venus. A problem that is somewhat less severe is the solution of the interstellar grains where the fits with the van de Hulst theory of infinite cylinders has been somewhat successful, but even here one wonders about the reality of such fits : infinite cylinders? The solution in the form of microwave-analog observations to interstellar grains has been shown by Greenberg and more recently by Giese *et al.* (1986). The parameters seem to scale well, with the same ratio of the wavelengths applied to the sizes of the particles. One can build particles similar to those observed by high-altitude aircraft and rockets and balloons, in clusters of various shapes and compositions. Here again there can be a combination of interests in the applications in the solar system as well as in those of interstellar grains. The latter are seen in forward transmitted light and at various scattering angles, in reflection nebulae. Even though Giese and others have made progress in studying the interstellar grains, the microwave-analog technique has not as yet been applied to cometary problems. The equipment needed is simple, but a large laboratory space is needed because the observations must be done over a range of scattering angles. Even though the principles are simple, the execution has to be done with care, and it may be time-consuming, but not expensive other than in manpower. The problem of deriving the optical properties of cometary dust has been reviewed by Lien (1991).

An overview of planetary dust particles and their connection with interstellar grains is given by Bradely *et al.* (1988). I suggested it might be possible to compare interstellar and interplanetary grains, observed in the interstellar medium and in various places in the solar system such as in the upper atmospheres of planets and on the surface of the Moon (Gehrels *et al.* 1964). This problem and the possibility of learning at the same time about the interstellar grains and about the grains in the solar system, perhaps through the microwave-analog method, now seems more amenable because of the large amount and variety of data available.

Ott (1992) reviews the question of what properties and substances have survived from the interstellar phase. There also is the question whether Hoyle and Wickramasinghe are correct in their persistent arguments that bacteria are still coming to us from interstellar space.

We are aware of a basic limitation to understanding asteroidal compositions from studies in visible light, namely that we are observing only the outer layer, and it could be a layer of dust covering material deeper down that may have a different composition. For microwave observations the radiation comes from deeper layers, but very little seems to have been done with microwave observations on asteroids until recently. Webster & Johnston (1989) report observations on only eight asteroids, and the results are quite interesting. They found physical properties different at deeper layers than at the surface. Disk-resolved observations show a uniform distribution of the microwave properties of the material. Perhaps the new radio equipment in India could be used for these pioneering studies that seem to lie fallow elsewhere.

It is noted in the chapter by Webster and Johnston that astrometric precisions need to be improved drastically in order to make radio observation possible. In India, CCDs are available and, with abundant astrometric standards from the Hubble Guide Star Catalog, astrometry can be precise to a fraction of an arc second. Such astrometry is at present not being done except at the 1.5-m telescope at the Agassiz Station of the Smithsonian Astrophysical Observatory in conjunction with the work of its Minor Planet Center. That telescope is overbooked, and to provide immediate help would make any observatory known internationally in this field and would provide essential information, particularly if it would be geared to a program of radio observations of asteroids.

Some of the asteroids must have been heated and differentiated in order to produce metallic asteroids and meteorites. The heating mechanism may not be known for sure, although some have been proposed (Wood & Pellas 1991).

An outstanding, unresolved problem is how to distinguish the near-Earth objects that are debris from the asteroid belt from the extinct cometary cores. No test in physical observations has as yet been devised, and no one seems to know how to distinguish these two very different types of objects. When the inclination of the orbital plane is high, we think it is a comet, but this is likely only in a statistical sense. This problem is discussed in the chapter by Weissman *et al.* (1989).

There are outstanding problems in the spectroscopy of asteroids, as noted by Binzel (1989), who then proceeded to solve them. The same applies to theoretical work in understanding the origin and evolution of the asteroids. There are many outstanding problems concerning asteroids and comets, but it is not clear that in India one could compete with what is now a mature discipline of physical observations and theoretical studies in which several colleagues are participating.

A leading overview of the outstanding problems involving comets is in the book edited by Newburn *et al.* (1991). Jewitt (1991) lists basic cometary problems which await solution by photometry :

What are the physical properties of cometary nuclei?
Which, if any, of the nucleus properties are primordial?
What factors control the rates of growth of mantles on cometary nuclei? Can the mantle fraction be used as an indicator of "exposure age"?
Can mantle coverage reach 100%, and if so, do nuclei choke themselves to death, leaving inert asteroid-like remnant bodies?
What are the physical properties of comets at large heliocentric distances?
What are the grain-coma expansion velocities?
Can water "ice-grain halos" be detected?
Are fading grains ubiquitous among comets?
How do the properties of the nucleus influence the properties of the comas?

Here again lies an interstellar connection—the continuing improvement in our understanding of the comets from the solar nebula, and thereby from the interstellar medium. On the other side of this situation there is a continuing problem of studying the interrelations of comets and interplanetary and interstellar dust, of comets and meteorites, and the distinction between cometary cores from fragments from the asteroid belt. An overview of the various disciplines of studying comets has been made by Whipple (1991).

Fernández & Ip (1991) list significant new contributions to our understanding of comet dynamics as well as unsolved problems. They include the question of periodicity in the terrestrial cratering record and the possibilities of the volatile contribution to the Earth from colliding comets to have been sufficient to supply a few ocean masses of water during the late heavy bombardment that ended about 3.8 Gyr ago (Chyba *et al.* 1994).

The sizes of cometary cores are unknown, largely because the activity of the coma usually prevents observations of the nucleus by itself. Comet Chiron, at about 200 km in diameter, is the largest comet known. Yet we know that its orbit is chaotic so that it may well come much closer to the Sun that it is presently, and, if so, there is the question of whether it will spilt into smaller pieces.

An outstanding problem is still the interpretation of the observed dust-coma morphology and other signatures of the physical processes of activation and extinction of discrete emission of cometary nuclei, which provide basic clues to the understanding of the nucleus-surface evolution. Sekanina (1991) describes developments in the evolution of an active region and he also points out various kinds of comets for which these physical studies should be made. It therefore seems to be a large topic in which new talent might be productive.

Huebner *et al.* (1991) conclude their paper with a section on outstanding problems and directions for future laboratory work on the gas-phase chemistry and the volatility of large organic molecules and related topics.

Meteoritics is a well-established science. Chladni inferred, as early as 1794, an extraterrestrial origin of meteorites. Is there then a new role available for scientists? In India there are already leaders in various studies of meteorites. There are detailed problems such as the identification of the parent bodies of the meteorites. A leading discussion of these problems is in the chapter by Anders & Kerridge (1988); an excerpt from the abstract :

The study of meteorites has already provided us with important constraints on several key aspects of the origin and early evolution of the solar system. These include : the thermal evolution of the solar nebula; the chronology of cloud collapse, nebula formation, grain nucleation and growth, planetesimal accretion, and formation and development of asteroids; the nature and properties of grains in the solar nebula, and the extent to which the chemistry of nebular phases can be modeled within an equilibrium framework. None of these issues are rigorously resolved at this time, however, and much work remains to be done... The study of meteorites and the early solar system represents a source of extraordinary intellectual excitement. We hope that younger readers, in particular, will see a challenge to which they simply must respond.

9. New techniques and operation

The opportunities to study outstanding problems in planetary science depend, of course, on available resources. There always is a strong interaction between available equipment and problems investigated. India has invested heavily in radio astronomy, and therefore has opportunities in the planetary sciences. The possibilities of combining observations in visible or infrared light with astronomical optical telescopes and the radio telescopes at much larger wavelengths might be explored.

There is a photopolarimeter in India which was intended to be generally available to astronomers of various institutions. Minipol had been previously and similarly cloned by the Vatican Observatory (Coyne 1974). Our shop drawings had been provided at considerable expense of the National Aeronautics and Space Administration, and this was done with the explicit intent that the instrument would be generally available to Indian astronomers.

Table 1 illustrates what I am most familiar with, namely scanning with a 2048 × 2048 Tektronix "thin" CCD of 24-micron pixel size, having 70% quantum efficiency. The data in the table are based on the known performance of such a CCD on the 0.9-m Spacewatch Telescope (Gehrels 1991; Rabinowitz 1991). The latter reference gives the corrections for sky background; these corrections depend on pixel size, in our applications coming in at about the 20th magnitude, becoming dominant near the 23rd magnitude.

Table 1. CCD scanning with two telescopes

Characteristics	0.9 meter	1.8 meter
f/ratio	5.0	2.7
pixel size (arcsecs)	1 07	1.01
distance of 50-km object	12 AU	16 AU

The last column is for a 1.8-m Scannerscope which is being built; a high-quality quartz mirror is available. We adopted an alt-az, stimulated by the pioneering work by Chevillard *et al.* (1977), for the mounting. The spacewatch program is overviewed in Gehrels (1994).

CCDs with pixels as large as 27 microns are no longer made. We now have a Tektronix CCD of 24-micron pixel size. This CCD did not appear quite flat, but we found no deteriorating effect in the focal plane. We also feared a problem with full-well capacity such that bright stars may be saturated more than was the case with the thick CCD, and, again, there was no problem. The old pixel size of 1.15 arcsecs was not ideal as we hope to set up the 1.8-m Scannerscope at a site with seeing that occasionally may be as good as 0.5 arcsecs. There are reports of 4096 × 4096 pixels' CCDs becoming available with pixel sizes on the order of 12 microns. Such a CCD would improve the limiting magnitude on the 1.8-m reflector because of reduced effect of sky background.

The last line of table 1 shows the disappointing performance of Earth-based telescopes in the search for small objects in the outer solar system because the brightness decreases with the fourth power of the distance. The numbers are derived with the expression

$$\log d = 3.74 - 0.2V + \log r\Delta \qquad \ldots (1)$$

of Gehrels (1986), for a geometric albedo of 0.06, at zero phase angle; the diameter d is in km, V is the apparent magnitude on the UBV system, r and Δ are the distances in AU of the object from the Sun and the Earth, respectively. The geometric albedo will be much higher for a snowy object and possibly much lower for a comet, as was found for P/Halley.

The distance at which an object of 50-km diameter would be observed is only 12 AU for the 0.9-m; it increases to 16 AU for the 1.8-m telescope. A 50-km object is small compared to the five objects we know in this region of the solar system : Pluto/Charon (2300/1200 km diameter), Chiron (180 km), 1992 AD (>140 km), and 1993 HA2 (~60 km). Large Pluto-type objects could be found much farther. For instance, at 40 AU the diameter of objects that could be found is about 340 km. The chance of finding objects as large as Pluto in the outer parts of the solar system seems small, however, in view of the rather extensive surveying that has been done by Kowal and others who used the Palomar 1.22-m Schmidt, surveying a strip of about ten degrees on each side of the ecliptic.

It is seen that a workable schedule for the detection of objects in the outer solar system may be consecutive scans of two hours each, detecting objects out to 40 AU; during long winter nights scans may be three hours. Such operation would be quite efficient as each scan could be two or three hours long if the computer can handle such long scans. Little time would be wasted in the resetting and the ramping up for the first frames of each scan.

Radar is a powerful tool in the study of surfaces to various depths below the surface. This work seems to be done only by Steven J. Ostro of the Jet Propulsion Laboratory. The array of objects and studies is increasing—for instance the increasing discovery rate of near-Earth objects—while the amount of radar-telescope time available in the U.S. is not increasing.

An outstanding problem still is to calibrate the diameter measurements of asteroids, which are determined indirectly from photometry and radiometry, with observations of asteroids that cause stellar occultations. There is a continuing need for occultation observations of asteroids, planets and satellites, and it is well known how nicely distributed the presently existing telescopes in India are in order to obtain cords across the disks. The idea to supplement this network with movable telescopes, on the order of 0.3 m in aperture, has been suggested by J. C. Bhattacharyya (personal communication, 1988). Additional attraction to this idea is that some of these telescopes could be operated by colleges who would thereby come more directly in contact with astronomy than at present. A network of telescopes could be established along the north-south direction of India, equipped with simple photometers. With the general dryness of the climate from northern India to Bangalore in the south, the chances of accomplishing these observations would be greater than in the U.S. The American experience is described by Millis & Dunham (1989). Predictions of the events are regularly published by the Lowell Observatory (e.g. Wasserman *et al.* 1992). An Indian astronomer would be needed to coordinate the program and to compute the predictions of where and when the occultation could be observed.

There is previous experience with occultation observing in India, and it therefore seems likely that the observatories would participate in the rare events. The colleges could also use the small telescopes for observations of stellar brightness variations and light variations of asteroids. For the latter, there still is a great need (see chapters by Magnusson *et al.* 1989 and Binzel *et al.* 1989).

There is an intriguing method of "photometric astrometry," to determine the orientation of the spin axis in space, but it seems to lie fallow; it is an ideal problem for research at the colleges. The method was largely developed, and several papers were written, by high-school teachers in Arizona. The need for more observers is discussed by Millis and Dunham; India with its southern latitudes compared to those of the United States should be a suitable place for observing a set of asteroids entirely its own. Yet another possibility with the small telescopes is the discovery of mainbelt asteroids, but this would be more of a challenge. India's colleges would benefit from the contact with research and astronomers, and the activity on the campuses might help attract budding scientists.

After centuries of experience with building hundreds of telescopes, there still is the outstanding problem of how to improve the steadiness of the image—how to improve the "seeing." The following notes are based on discussion of and experiences with about 40 telescopes built in the last thirty years in Arizona and elsewhere.

A good way to select a site is to fly in an airplane " above" the site, looking from the direction of the prevailing wind to determine what would happen to the moving air before and during the time it arrives at the telescope. The micro conditions around the telescope are very important. The difference in temperature between day and night should be equalized as carefully as possible, with fans and/or open doors, opening about 1.5 hours before the start of operations. People and their abodes, offices and workshops should be kept away from the telescope. The dome should be ventilated during the night, but not too hard, in order to cause laminar flow of air through the slit as much as possible.

The experience at the multi-mirror telescope (MMT) is of importance. The six mirrors were initially figured to have about 90% of the light within an image of 1-arcsec diameter, because the seeing in southern Arizona was believed to be not much better than that. However, on Mount Hopkins it was found that the seeing is as good as 0.3 arcsec during an appreciable fraction of the observing time. It then became rather clear that the reason was not so much that Mount Hopkins is an exceptional site—other telescopes in domes are or had been operating near Mount Hopkins—but that the improvement was due to the fact that there was little in the way of a dome or building. The MMT has a huge opening which is made by sliding doors such that it is practically free in the wind. Further refinements have also been made, for instance by wrapping the telescope struts in aluminum foil.

Some of the MMT lessons were not new to astronomers such as Lyot, Fehrenbach, Dollfus, and Kuiper. At the Pamir Observatory, in the far southeastern regions of what used to be the Soviet Union, telescopes, although still in domes, are on stilts.

Finally, a problem that will always be outstanding is how to best educate young scientists. I was in a tradition of Oort, Chandrasekhar and Kuiper, who worked some 80 hours per week, 4,000 hours per year, and expected the same of their students. At the beginning of our undergraduate career, we were not encouraged to become astronomers and were kept away from the attractive activities such as looking through telescopes and participating in advanced research with a senior professor. The real astronomer would survive! The trend at the University of Arizona presently is totally different : there is a much-advertised and well-funded "Arizona

Space Grant Consortium" for Undergraduate Research Interns who are assigned to senior faculty and are expected to participate and become joint authors in advanced research with that advisor. Furthermore, the required standards for training of university students, now reflected in the scores of the Graduate Record Examination (GRE), are much higher than they were when my generation entered astronomy. The average workweek today is more nearly 40 hours and the number of hours worked per year usually does not exceed 2,000 hours. This may, however, well be the norm for the future, and perhaps it is appropriate because of the increasing number of scientists who can therefore afford to work fewer hours, particularly if they are bright and better trained than the previous generation. The following two paragraphs are taken from Gehrels (1988, p. 305) :

> We should never underrate the younger generation Chandrasekhar made a strong argument for that on the day after he received his Nobel prize in 1983. An experienced Swedish reporter set up a television interview and invited a young Ph.D. candidate in physics to join the laureates. He then confronted the older people with the young one. Did they believe that the new generation works as well as they did when they were young? There was a rather united reaction : the present generation works much less than did theirs. They described laboratories that nowadays seem to be dark and deserted on evenings, weekends, and holidays. All but Chandra. He said nothing, and I knew from Yerkes days that he probably would go against everyone else—if for no other reason than to stimulate the discussion—and that he would do it eloquently Sure enough, the interviewer noticed something amiss after a while and asked Chandra for his opinion, at which he held forth that the present generation, any generation, will be as good and productive as the one that went before I could not help but write him a letter then, needling him a little by saying that his students always were the better ones—like me, you know—and that we were scared enough of him that we did not dare stay away on evenings, weekends, and holidays. He wrote the following reply.
>
> I am, however, very suspicious of an older generation finding the younger generation inadequate. A striking illustration is provided by Lord Kelvin's despondent remark after attending the funeral of Stokes in 1907 : "Stokes is now dead; Maxwell is no longer living; and Lord Rayleigh is not at the Cavendish any more. I shall never come back to Cambridge again." But the Cambridge which Kelvin mourned was soon replaced by the generation of Rutherford and Thomson, to be replaced once again by the generation of Hardy, Littlewood, Eddington, Dirac, Chadwick, Blackett, and a host of others. Similarly, when after Rutherford died and Bragg succeeded him, the generation of young Fellows of Trinity including Freeman Dyson, deplored the passing of a great period; and they become even more critical when Bragg brought in "clowns like Crick and gadgeteers like Ryle." Might I add that in time Crick and Ryle set the pattern for the Cambridge that followed. I think it is always unsafe to be adverse with respect to the future in terms of one's past experience.

I am not clear on how this applies to India. For comparison, we operate the 0.9 Spacewatch Telescope with six people who keep the telescope and dome in full-time operation [for two programs—search for planets of other stars during the bright third of the month (McMillan *et al.* 1994), and CCD-scanning for moving objects the remainder of the month]. Only major tasks such as painting the outside of the dome is provided by others, plus some janitorial service. This small number of people is dictated by shortages in funding, while there also is a certain amount of pride in doing it this way and having a dedicated facility. However, it does require an investment greater than 40 hours per week; occasionally during the winter, it may become an effort of 100 hours over the six nights assigned to each observer per month. Such efforts may never be needed in India where the financial and labour-class structure is totally different. And yet, Chandrasekhar and others believe that a certain hardening seems needed in the education of scientists. They should grow up by doing simple menial tasks first, supervised by student assistants and technicians. If they last, they are of the right mettle. If not, they are weeded out, saving later frustrations. Furthermore, a budding scientist should be engrained with respect for and familiarity with the work and talent of the technicians. This lies at the roots of our management.

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