Solar System Evolution

A New Perspective

This completely rewritten new edition begins with an historical perspective of the place of the solar system in the universe. Evidence from meteorites is used to describe how the planets were formed and the giant planets are considered in the light of the asteroids and why Pluto is not a planet. Explanations on why Earth and Venus turned out so differently, and how Mars and Mercury are the survivors of many similar bodies, are also discussed. The formation of the Moon in a giant impact leads to an assessment of the importance of collisions and impacts in the solar system. It is concluded that our solar system is the end-product of many accidental and chance events. This leads to the philosophical discussion of whether planets like our Earth are likely to be found elsewhere in the universe.

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A New Perspective

SECOND EDITION
An inquiry into the chemical composition, origin and evolution of the solar system

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Preface to the First Edition

The true dimensions of the terrestrial globe were revealed mostly in the fifteenth and sixteenth centuries, principally through the technical development of truly ocean-going vessels and the magnetic compass, which enabled the exploration of the oceans. Even with these advantages, the real extent of the Great Southern Continent or *terra australis incognita* had to await the voyages of Cook in the eighteenth century. This flood of new geographic knowledge replaced the medieval view of the world (although Flat-Earth societies still persist). Such understanding was gained only very slowly. A detailed knowledge of the topography of the ocean floors and our understanding of their composition and origin has been obtained only a little ahead of our radar pictures of the surface of Venus.

Our exploration of the solar system is at a similarly heroic stage. The distant points of light, barely resolvable in telescopes, have been revealed through the use of space vehicles, the latter-day equivalent of the Portuguese caravels, as separate worlds, with an astonishing amount of diversity.

The information has been rapidly and widely disseminated, electronic media having superseded the printing press of the Renaissance. Everyone is informed of the striking new discoveries. Although no Eldorados have emerged, the pictures reveal a plurality of worlds unimagined by the Elizabethans. Every satellite has turned out to differ in some significant feature from its neighbor: ". . . the sense of novelty would probably not have been greater if we had explored a different solar system" [1].

This comment on the jovian system reveals a fundamental truth. Lurking behind the photographs and radar images is a new observation, uncomfortable for *Homo sapiens*. What combination of circumstances could reproduce in some other planetary system the detail observed in our own solar system or lead to the assembly and evolution of a clone of the Earth? Whether one contemplates the battered face of Mercury, the crumpled crust of Venus, our own water-sheathed planet, the vast deserts and gigantic landscapes of Mars, or the profusion of distinct icy satellites of the giant planets, the uniqueness of the individual planets and satellites informs us of a sober fact: The system is unlikely to be duplicated in detail elsewhere.

Other planetary systems doubtless exist. That they would resemble ours in any but the broadest detail is only a remote possibility. Too many chance events have occured to bring our system to its present condition. Jacques Monod [2] remarked on the uniqueness of the evolutionary path for life and of the apparently unsurmountable difficulties of duplicating our version of intelligent life elsewhere. The planets and satellites are rich in diversity and the difficulty of producing clones of our present solar system makes duplication as unlikely as the possibility of finding an elephant on Mars.

Despite the cornucopia of new information about the solar system, it is curious how little effect this has had on the development of theories for its origin. The Apollo and Luna data from the Moon had almost no impact on theories of the origin of the solar system, or indeed of the Moon, until comparatively recently. The reason for this is partly the unusual circumstances of lunar origin and evolution and the very large amount of new data from separate fields that had to be assimilated.

The complexity of the solar system is not in accord with theories that start from some simple initial condition. Such hypotheses do not predict the diversity of the present system. Thus, while it is tempting to look for grand unified theories to explain our solar system, the basic approach is wrong and the trail is false. Too many chance events occur. Among the many singular events that determined the outcome, a few examples may be cited: the size of the fragment of the molecular cloud that became the solar nebula; the formation of the Sun as a single rather than a double or multiple star; the huge size of Jupiter and its controlling influence on the asteroid belt and Mars; the random accretion events that made the Earth larger than Venus; the unique collisions that produced the bone-dry Moon and the high density of Mercury (a red herring for grand theories); the differences among the satellite systems; and the hundred other curious features of the solar system such as Hyperion tumbling chaotically until the end of time. All are the result of events that might readily have taken a different turn.

Scientists and philosophers have been attempting to find an explanation for the origin of the solar system since the question was first raised by the Greeks, but a universally acceptable scenario has yet to appear. A major reason for this failure to solve one of the oldest scientific questions has lain in the approach adopted. Another planetary system will differ in numbers and sizes of planets and satellites. Thus, the quest for a universally applicable solution to the origin of the system is not fruitful. Attention is better directed to explaining how the various aspects of the system came about.

In this book I have attempted to provide this and to describe our current understanding of the origin and evolution of the solar system. In this respect, I have followed the path of most previous investigators in trying to account for the existence of the planets, satellites, asteroids, and comets. The formation and evolution of the Sun as a quite normal G-type star is well enough understood, so in this account it is mainly an offstage companion to the discussion. The book is biased toward a geochemical point of view because of my field of interest. Cosmochemistry and geochemistry are not, however, without their difficulties, and those readers who wish to find a simple statement of the composition of the Earth will be disappointed to learn that many problems yet remain. I have, nevertheless, been unable to resist treading among other areas, conscious that such a path is fraught with as many perils as those recorded by John Bunyan (1628–1688) in *The Pilgrim's Progress*.

The subject is rendered very difficult by the wide variety of contrary opinions held among investigators and the many alternative explanations offered for the same set of data. Sometimes the data are suspect. It is thus surprising to find that the students of cratering frequently disagree on the numbers of craters involved. One might have hoped that at least the database was agreed on. However, it is a common error to underrate the difficulties of subjects outside one's experience. The diversity of opinion is only exceeded by the strength with which the opposing views are held and defended, supporting the thesis that subjectivity is more common in science than hoped for [3]. This has not made my task easier in trying to reach some conclusions about the status of our understanding of the solar system.

Readers may complain that I have chosen to cover too broad a canvas and that the scope of the book should be restricted to areas of immediate competence. Thus, they may question why topics as disparate as Chiron, comets, crustal development, calcium-aluminum inclusions, chondrules, and Copernican Revolution, and lunar cataclysms are all discussed.

The problem is that detail in one area may provide a crucial constraint in another. If one paints with too broad a brush, error may creep in. Grand theories are useless if they cannot explain the minute details. Thus, the concept of giant gaseous protoplanets condensing from fragments of the nebula was viable until it was demonstrated that Jupiter and Saturn were not of the solar composition required by the theory. The rare-gas isotopic abundances in the terrestrial planets rule out the popular concept of late-accreting veneers of carbonaceous chondrites. Consequently, an apparently minor detail from one topic may negate extensive work from another, just as the presence of the europium depletion in lunar mare basalts removed the model, developed from experimental petrology, that these lavas were derived from a primitive unfractioned lunar interior.

The reverse of this particular coin is that the mere accumulation of the staggering amount of detailed observations in the solar system is of little use unless there is some unifying concept; the discovery of the Periodic Table was needed to make sense out of the bewildering array of properties of the chemical elements.

Although this book treads into far more nebulous territory than, for example, *Lunar Science: A Post-Apollo View* [4], it might be recalled that the state of our understanding of the Moon at that time was also beset with many misconceptions and false trails, a particularly good example being the many ingenious but erroneous explanations advanced to explain the europium anomaly [5].

It therefore behooves workers in this interesting field to consider all the details if they wish to avoid error, unless they want to make all the planets out of CI carbonaceous chondrites, or the Moon from the Earth's mantle. In this context, I had hoped, somewhat naïvely when beginning this task, to conclude with definitive compositions at least for the terrestrial planets. What has emerged in reality is that even the major-element compositions of the inner planets are poorly constrained. A solution will have to wait until the problems of the moments of inertia of Mars and Mercury, the nature of the lower mantle of the Earth, and that of the light element in the core, among many others, are resolved.

However, it is easy to become fascinated with the curious landscapes of Miranda and Triton, the large crater on Mimas, the enormous layered deposits in Valles Marineris, the crumpled terrain of Venus, the rare gas abundances in the atmospheres of the terrestrial planets, the Kirkwood Gaps in the asteroid belt, the relationship of Pluto and Charon, the composition of Comet Halley, or that of interplanetary dust. While contemplating all these marvels, it is not difficult to become lost among the trees, forgetting that the principal purpose of this book it to understand the origin of the system, and to integrate all these wonders into a coherent explanation.

Thus, it is not my intention to provide a detailed travelogue or Cook's Tour of the solar system, tempting though that option may be, since there is already a multitude of good technical books and papers covering both the detail and overviews of the solar system [6]. I assume that most readers are familiar with the spectacular images and I have not attempted to reproduce many of these or provide much mathematical treatment. This is available in the material referenced and it seems pointless to fill up pages with equations of use only to a few specialists.

Rather, I have attempted a commentary on the problems of its origin and evolution. I had orginally planned to start the book with a description of the present solar system, and proceed from there into more nebulous regions, moving backwards in time into the unknown. I was wisely persuaded to begin instead with the solar nebula, and to bring the story forward in chronological order, a decision which has proven robust. However, as one of the editors of *Meteorites and the Early Solar System* remarked, ". . . good reasons could be found for placing every chapter before every other chapter" [7].

In general, I have attempted to reference the most recent reviews and texts; the subject is moving so rapidly that older material quickly becomes of historical interest. In many areas, the subject has come clearly into focus only in the past two or three years as the avalanche of data from the past two decades has been assimilated. Accordingly, much of the older literature is now of historical, rather than scientific, interest [8]. Literature coverage extends to April 1990, with a few later additions.

The deluge of new information and the emergence of some agreement on the general scenario of solar system origin and evolution has turned the subject in a few years from one having the status of a hobby, ". . . pursued by eccentric, elderly gentlemen who fight with one another's theories of the origin of the solar system" [9] to one in which quite detailed scientific questions can be posed. In this context, I have been selective in giving more attention to those studies that fall within the general theme of the planetesimal hypothesis, rather than to give an overview of all competing ideas. Here I have attempted to produce a broad survey pointing to the many questions of interest that can be addressed and the regions in which our understanding is inadequate. Even in those areas such as the surface geology of Mars, where we have much basic knowledge and understanding, many significant questions (for example, the relative importance of sedimentary vs. igneous processes, or the early climate and role of ice) remain obscure. Only a sample return, followed by a manned mission, will supply the answers to these particular questions.

The wealth of new detail leads to the complaint, common to many scientific disciplines, that there is now too much information for any individual to comprehend. In this view, it was simpler in past ages when the corporate body of knowledge was so much smaller.

However, it is doubtful that this is true; scientists in the Renaissance had to deal with a staggering burden of topics such as astrology, alchemy or numerology, on which Newton wasted so much of his time. In any subject where there are no unifying principles, as in chemistry before the Periodic Table revealed an essential simplicity or biology before evolution cast its revealing light, it is impossible for an individual to be an expert in every nook and cranny. Nevertheless, given some general principles of physics and chemistry as a guide, it is possible to discern the forest, even through the thickest underbrush, just as the architectural unity and splendour of a great building may be glimpsed from a distant prospect.

Among the other intellectual baggage that has been discarded, the differences between the relative ages of the universe and the solar system have clearly distinguished their origins; we no longer have to account for them together. The age of the solar system, obtained from meteorites as 4560 m.y., is only about one-quarter of the age of the visible universe. This fact – a relatively recent discovery – separates the origin of the Earth and solar system from that of the universe. This knowledge has become so ingrained in thinking that it is surprising to recall that as recently as 1950, the age of the Earth, established by isotopic dating of rocks, approached and sometimes exceeded the astronomical estimates for the age of the universe.

One is comforted on this journey by the steady convergence of scientific ideas toward some kind of consensus, as new facts are acquired. Science is in this way distinct from most other human activities, which display the opposite tendency of divergence with time, a process most clearly revealed by the multitude of religious and philosophical systems.

Stuart Ross Taylor
Houston, Texas
December 1990

Notes and references

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2. Monod J. (1974) *Chance and Necessity*, Collins, 187 pp.
3. Mitroff I. (1974) *The Subjective Side of Science: A Philosophical Enquiry into the Psychology of the Apollo Moon Scientists*, Elsevier, New York, 329 pp.
4. Taylor S. R. (1975) *Lunar Science: A Post-Apollo View*, Pergamon, New York, 372 pp.
5. Ibid., pp. 154–159.
6. There are so many good texts that it would be invidious to choose among them. A good beginning is Morrison D. and Owen T. (1987) *The Planetary System*, Addison-Wesley, Reading, Massachusetts, 600 pp.
7. Kerridge J. F. (1988) in *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), Univ. of Arizona, Tucson, p. xv.
8. The fate of most scientific work is to be forgotten. The typical scientific paper has a half-life of five years, forming a curious contrast to the dominant egos of most workers in the field. The correct is incorporated into the general body of knowledge; the erroneous is mostly ignored.
9. Wetherill G. W. (1988) in *LPI Tech. Rpt. 88–04*, p. 81.

Preface to the Second Edition

My purpose in writing this book is to enquire into the solar system and how it came to be. So much progress has been made in the past decade that this book has been completely rewritten from the first edition. The seven large chapters in that edition have been restructured into fifteen smaller ones that deal more readily with the increased flood of information.

As in the first edition, I have tried to place the solar system in the broader context of the universe. My excuse for venturing into fields such as cosmology is to reinforce the point that the solar system is a relative newcomer in the universe and came about through a fortunate sequence of chance events. A secondary purpose is to try to overcome the narrow and potentially hazardous specialization that is endemic in science and that I talk about in the *Prologue*. I have attempted to educate myself in fields remote from my own through discussions with many colleagues, listed in the *Acknowledgments*.

The book does not follow the usual descriptive arrangement of starting with Mercury and marching stolidly out through the giant planets to Pluto. Instead, the unconventional arrangement I have adopted here has arisen naturally as I have tried to explain how the system arose from the solar nebula and why the various bodies happen to be where they are. The result is that there are many associations that may at first sight seem surprising.

I begin with a brief historical outline that traces the development of thinking about the solar system. This is followed by comments about the place of the solar system in the universe, the formation of stars and of the solar nebula. The important and unique information provided by meteorites on the early evolution of the nebula next sets the stage for considering the formation of the planets themselves. Although long considered as an inevitable process that would produce the solar system as a result of some general law, this view of the formation of "clockwork" planetary systems has been superseded by a recognition that random events have predominated. This accumulation of planets from short-lived disks around stars separates the planetary scientist from the astronomer, who deals with the simpler processes that produce the stars from the collapse of gas clouds. Early violent solar activity swept away the gas and volatile elements from the inner nebula, out to the vicinity of Jupiter. This local increase in density so far from the Sun enabled that planet to form a large core quickly enough to capture the fleeing gas by gravitational attraction. Disks around young stars are short-lived, so that giant Jupiter was the earliest planet to form, followed by Saturn and a little later by the ice giants, Uranus and Neptune, who formed just too late to collect gas. The giant planets are here lumped together rather than separating the gas giants from the ice giants as is customary. These massive bodies probably formed much closer together than where they now find themselves and their present masses are the result of chance rather than the consequence of some pre-ordained plan. At this point, the problems of forming the giant extrasolar planets are considered. A multitude of satellites of the giants formed close upon their parents.

Left over after these major events that shaped the system were the icy bodies in the outer parts of the nebula, where the amount of material was too small to produce more planets. Pluto and the comets are the famous examples, while Uranus and Neptune, migrating outwards, swallowed up much of the material so that the solar system seems to terminate abruptly at the orbit of Neptune. Meanwhile Jupiter, on the sunward side, swept up so much material that only a depleted zone of rubble, now the asteroid belt, was too scattered by the giant to form a planet. For the next 50 or 100 million years, the rocky rubble left over in the inner solar system collected itself into larger bodies, of which Mars and Mercury are survivors. Earth and Venus were more fortunate, the Earth in particular acquiring the Moon from a chance collision with something bigger than Mars. Collisions dominated the growth of all the planets as their variable tilts and rotation rates testify. So the formation of the Earth, that turned out wildly different from its twin, Venus, demonstrates the importance of chance events in making planets and emphasises the difficulties of forming a duplicate of our planet elsewhere, a message reinforced by the startling diversity among the extrasolar planets.

I have attempted to summarise the literature through to the end of 1999 with some outliers into the 21st century. Readers will observe that there is a bimodal distribution in the dates of the papers, a common feature in second editions, that first peak toward 1990 and then toward 1999. As in the first edition, I have tried to refer to the more recent works for two reasons. Firstly, reference to them will in turn enable the reader to refer back to the previous literature on the topic. A more serious reason is that the subject is moving so rapidly that published papers on topics such as the extrasolar planets, the source of water on the Earth or the origin of Uranus and Neptune in our own system rapidly become dated as new information appears. Thus in many areas, papers more than a couple of years old have already entered the realm of past history, interesting only in reflecting the thinking of the period.

However, the purpose of references in a book such as this is also to refer to primary sources, so that I have included a number of the citations from the first edition for this reason. I have excluded all references to conference abstracts and other grey literature except in a very few unavoidable cases where the information is not available elsewhere. I have followed the convention adopted in the first edition of listing references by number in order of appearance in each chapter, rather than breakup the continuity of the text with names and dates. I list first authors only, followed by *et al*., except for two-author papers, as it is pointless in a work such as this to provide lists that on occasion extend to 30 names. With over 1300 references, often to fields remote from my speciality, it is inevitable that I have missed some relevant sources. My apologies for any such oversights.

I have continued to include tables of relevant data, but two developments have altered the more pressing need that I perceived for presenting such material in the first edition. One is the appearance of *The Planetary Scientist's Companion* (Oxford University Press, 1998) that contains much relevant information. The second is the vast amount of up-to-date data available on the Internet that include, for example, lists of extrasolar planets, centaurs and transneptunian objects. Both these developments have made data tabulations less crucial, particularly as a gap of a year or so exists between compiling data and its appearance in book form. In many cases, as with the basic petrological data on meteorites, little has changed in the decade since the previous edition. In others, ranging from updated information on the Galilean satellites to the appearance of the extrasolar planets, the data are new.

This great increase in the availability of comprehensive data-sets thus frees the author to concentrate on understanding rather than merely cataloguing the material. The task of the author, however, differs from that of the compiler. He has a responsibility to the reader to present his own, perhaps biased, interpretation rather than merely to tabulate previous efforts. As one of my colleagues memorably remarked, I prefer to make my own mistakes than to repeat the errors of others. Thus there is still a need for critical evaluation of the mass of available data. This applies particularly to geochemistry where the problem of sampling planetary bodies remains formidable. With this excuse, I have given here my own assessment of such debatable issues as the composition of the terrestrial mantle and crust, the Moon and that of the primitive solar nebula.

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Prologue

A principal task in writing in the first edition of this book was to examine the series of events that led to the formation of the solar system. The conclusion, so greatly illuminated by the previous three decades of planetary exploration by spacecraft, was that random events had predominated in the construction of the great variety of planets and satellites. Thus it was unlikely that duplicates might be found elsewhere. This was in contrast to earlier views that the solar system was as orderly as a clock and that, given sufficient computer power, one might simulate the construction of such a clockwork system from first principles according to the laws of physics and chemistry.

In the 1992 edition, I commented that "the . . . common occurrence of disks around young . . . stars strengthens the case for the existence of other planetary systems. If so, would they resemble our own? Would we see something like the Galilean satellite system of a few equal-sized planets, systems with one giant planet, or a single brown dwarf companion?" After contemplating the satellite systems around our giant planets, I concluded that "no simple sequence of reproducible events has occurred in our solar system. Other planetary systems . . . will be different in detail to our own. What their satellites might look like is only for bold spirits to predict" (p. 251).

This concept was reinforced in dramatic fashion in 1995 by the unequivocal discovery of extrasolar planets. Now that the question of the existence of other worlds, that has been around for 24 centuries since Democritus, has been answered, I wish to take a different tack in this edition. Nature is able to make a variety of planets in surprising orbits so that the problem posed by Lucretius and most dangerously by Giordano Bruno has moved on to the matter of their habitability. Is there life out there and what are the chances both of finding it and communicating with the "little green men" that are so desperately hoped for by many of the human inhabitants of this planet?

Here I have tried to enquire into this question by studying the detail in our planetary system and making some comparisons with the new ones that are being discovered daily. What emerges once again is the random and stochastic nature of events leading to the formation of planetary systems and the immense difficulties in constructing a duplicate of the Earth. Added to this problem of forming habitable planets are the biological problems, both of the origin of life and its evolution. It thus becomes exceedingly difficult to be optimistic about the possibilities of finding duplicates of the Earth or any extraterrestrial life that remotely resembles *Homo sapiens*.

In a work of this scope, it is impossible to be expert in the many diverse fields that I cannot resist straying into. My excuse for wandering into regions as remote from my speciality as cosmology, where a mere student of rocks has little business, is that science has become dangerously fragmented. This is understandable. The difficulties of becoming expert even in some tiny corner of science are well enough known. We all tend to get into our own particular foxholes, secure in our understanding of alkenes, atomic particles, ants, andesites or asteroids.

This leaves the way open for salesmen of simplistic solutions that purport to explain everything in terms that a young child could follow. Of these, creationism in its various incarnations represents the most serious threat. The whole endeavor of science and ultimately the very survival of our civilized society that has arisen from the study of the natural world in the past four centuries is at risk. One writer has commented that *"though science is stronger today than when Galileo knelt before the Inquisition, it remains a minority habit of mind and its future is very much in doubt. Blind belief rules the millennial universe, dark . . . as space itself"* [1].

One is reminded of what has been called "the failure of nerve" of the ancient world. Following the scientific advances of ancient Greece and the major progress at the Museum and Library (Mouseion) at Alexandria, there followed a retreat into the comfort of myths. Much of the great library at Alexandria, that had found shelter in the Temple of Serapis from civil wars in the 3rd century AD, was destroyed by a Christian mob in 391 AD. The remaining books were burnt in 646 AD by the Arab conquerors of the city [2]. Book burning seems to be a popular and widespread habit, judging from more recent examples that have included both Nazi Germany and the Red Guards of China.

There followed a retreat from objective truth into medieval modes of thought as the Dark Ages began. The stage was set by Saint Augustine (354–430 AD) who ordained that as God had created everything, "it is not necessary to probe into the nature of things" as the Greeks had done. This attitude still survives.

Will faith once again smash science, as happened in the ancient world? This seductive pathway is not without its difficulties. As Harvey Brooks (1971) has remarked *"if the modern era has created social and cultural conditions in which the enterprise of science is no longer viable, it has sown the seeds of its own disintegration and decay, to be followed by the disappearance of a large fraction of the world's present population and a decline in the material conditions of human life. It is a mere detail whether this will come about first through some ecological disaster, through the decay and demoralisation of the technological structure, or through a military holocaust"* [3].

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