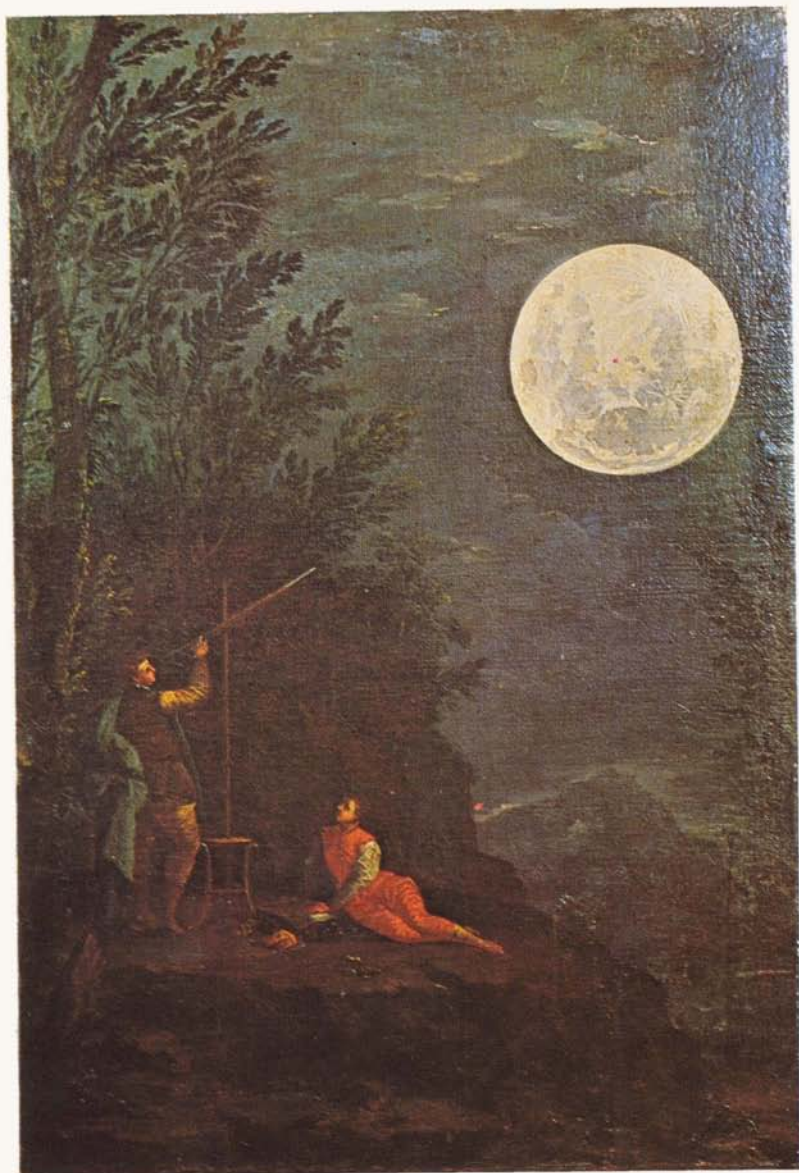

Planetary Science:
A Lunar Perspective

STUART ROSS TAYLOR



The Moon depicted in a painting by Donato Creti. Oil on canvas, 1711. [Bedini, S. A. (1980) PLC 11: xiii.] Courtesy the Vatican Monumenti, Musei e Gallerie Pontificie. This illustrates the state of planetary observation at the beginning of the eighteenth century. Most of the succeeding advances in this field have occurred in the past decade.

Planetary Science: A Lunar Perspective

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Typeset by the Lunar and Planetary Institute, printed by Publishers Production International, and bound by Arnold's Bindery in the United States of America.

Library of Congress Cataloging in Publication Data available from the Library of Congress CIP Division, or from the publisher.

Cover: An artistic perception of a portion of Mare Ingenii (S. Adlis-Vass, artist).

Back cover: An artistic rendition of the view south across Mare Imbrium (S. Adlis-Vass, artist).

*To
Noël
Susanna, Judith and Helen*

Preface

The technical triumph of manned landings on the Moon and the return of samples from the lunar surface has provided scientists with a unique opportunity to advance our understanding of the nature, evolution and origin of the solar system. The nine suites of samples recovered by the Apollo and Luna missions have provided so many answers that it is now difficult to recall our state of ignorance before July, 1969. The new knowledge is contained in a massive outpouring of scientific literature, conservatively estimated at 18,000 articles which have appeared in the past decade.

In a previous book, I attempted to survey and comprehend the state of lunar science at the close of the active period of lunar exploration. That work records the state of lunar science as of April, 1974, following the evaluation of the results from the final manned mission, Apollo 17, in November, 1972. In that book, I was concerned with extracting the evolutionary history of the Moon from the great mass of data on the lunar samples. The story as recorded in *Lunar Science: A Post-Apollo View* has survived reasonably well. Many new data have appeared, new models have been proposed, and refinements of existing models have been carried out. No substantial reason exists to attempt the essentially minor changes of a second edition: instead I have adopted the maxim "what I have written, I have written" [1], letting the work stand as a statement of lunar science at that time, and I have essayed a new approach.

In 1974, only early results from other planets were available. Now a considerable advance in our knowledge of the solar system has occurred and I have attempted to extend the knowledge gained from the lunar data to provide some insights into this wider sphere. Accordingly, I have used the lunar story as a basis for understanding the origin and evolution of the solar system. In the early days of the manned missions, the term "Rosetta Stone" was often used. In a sense, the usage is correct. The study of the lunar samples has proven to be a key to understanding, for example, much about meteorites. The Moon remains the only body which we have visited and sampled with a proper understanding about the relation of the samples to the overall evolution of the planet. The Moon, as revealed from those studies, is sufficiently different from the Earth, both to render terrestrial analogies hazardous, and to provide another example of planetary differentiation processes. The tendency to regard the Earth as a norm, and terrestrial geochemical processes as a model for those on other planets, has not survived the encounter with the lunar data. Many details, such as the contrasting behavior of chromium on the two planets, have provided salutary warnings of the hazards of extrapolating from one planet and of the problems of the statistics of small numbers. The same warning applies to the lunar samples. Accordingly, I have tried to utilize the lunar data along with

our long terrestrial experience to provide a synthesis. The subject matter and treatment is heavily biased toward the lunar data, since these have provided the major advance in our understanding of planetology.

Some of the information given in the previous book has changed little since 1974, and it has proven necessary to retrace some familiar ground. For example, the lunar stratigraphic sequence was already well established, and only the subdivision of the Pre-Imbrian into Nectarian and Pre-Nectarian is new. Some of the same figures have been reused. The beautiful earth-based lunar photographs taken by the Lick Observatory have never been surpassed and it seemed pointless to replace them. They are still worthy of study, for our spacecraft photographs of many planets and satellites are at about the same resolution. The reconstructions of the lunar surface in previous ages by Davis and Wilhelms reappear for similar reasons and there are a few other similar instances throughout the book. In some disciplines, such as organic geochemistry, no significant new material has appeared, and the reader is referred to the previous text for enlightenment.

During the writing of *Lunar Science: A Post-Apollo View*, a very large number of questions about the Moon had not been resolved, and were the subject of intense debate. Thus the question of whether water was present on the Moon was under consideration; the nature of the regolith-forming processes awaited proper study of the core tubes. The questions of origin of the Cayley Formation and light plains deposits, and of whether volcanism existed in the highlands continued to persist. The composition and origin of the highland crust was a major problem. Possibly, it had been added to the Moon like a coat of plaster. Although the volcanic versus impact debate over the origin of the craters had been resolved before the landings, the formation of multi-ring basins was in dispute. The origin of mare basalts, whether from primitive or cumulate sources, was under active discussion, together with the question of the origin of the europium anomaly. There were still questions about model age interpretations. No Sm-Nd data were available. These were first reported in March, 1975, at the 6th Lunar Science Conference and immediately disposed of single-stage models for mare basalt genesis. Whether the Moon had been wholly melted, or not melted at all, was also a matter of dispute. The solar nebula was generally held to have been isotopically homogeneous with the data from the oxygen isotopes just beginning to suggest otherwise. Thus the intellectual climate in which the book was written was very different from that of today. It was at the time a fascinating intellectual exercise to judge among the many competing explanations, particularly when they lay outside my own specialty.

Further analyses of the lunar samples have resolved many of the problems listed above, but a number remain unsolved. Many questions suffer from lack of sufficient resolution in the data, a problem which may be referred to as the "Martian Canal Syndrome."

As in the previous book, the emphasis is on interpretation and synthesis. The Moon appears particularly well suited to this type of approach. It has a comparatively simple history, and responds well to large-scale overviews. The Moon is built on a large scale. The infinite complexity of some lunar samples such as the highland breccias is due to the repeated effects of large impacts, a comparatively simple concept, although the effects are complex.

I have avoided the temptation to include much about the Earth in this book, for various reasons: (a) the amount of information available is huge; (b) adequate treatment would demand so much space that it would be difficult to do justice to the subject and avoid swamping the data from the other planets and satellites; (c) the surficial geology, volcanic landforms, plate tectonic mechanisms and much else, including the atmosphere and hydrosphere, are unique to this planet and cannot be addressed adequately in the space available; and (d) our insights into the composition, structure and evolution of the core, mantle and crust are in many ways at an early stage. Much work remains to be carried out on the significance of the trace element and isotopic evolution of the mantle. In this context, the picture of lunar evolution which has emerged has provided new insights into the early history of the Earth. Occasionally I have been unable to resist commenting on various aspects, such as the development of the continental crust and the bulk composition of the terrestrial mantle (Chapter 8), which form an important constraint on our ideas of planetary evolution, and on the relationship between the Earth and the Moon. Finally, the origin of the Earth is addressed briefly in Chapter 9.

The problems in dealing with the information from the other planets and satellites are large. Those workers who have expected more insights on planets other than the Moon should recall that our knowledge of these bodies is comparable to that of the Moon in the pre-Apollo era. There is excellent photography, some geophysical data and a little chemistry from remote samplers. The analogy with the data base for the Moon in 1968-69 is nearly complete.

Our experience with the lunar samples was salutary and informed us that much of our pre-mission thinking was in error. This is a common situation in science. In a book such as this, concerned with the scientific results of the space program, we must be cautious not to push the data beyond the limits of resolution, and so fall into Martian canals or dust-filled maria.

The quality of the photographs returned from the Pioneer, Mariner, Voyager and Viking missions has provided one of the more aesthetic experiences of the age. Analogies with the heroic period of the early terrestrial navigators are appropriate. Perhaps the beauty and strangeness of the surfaces of the planets and satellites will prompt a new literary or poetic flow-

ering. We must not let those excellent pictures deceive us into believing that we fully understand all that is visible or, by extrapolation, that we comprehend the nature of the planets or satellites. This phase of exploration is a preliminary, rather than a terminal phase. The appropriate analogy is with the pre-Apollo and pre-Surveyor stages of lunar exploration. The Ranger, Orbiter and Russian photographs of the lunar surface resolved only a few questions about the nature of the lunar surface. "Information was limited to the images and once again it was demonstrated that a surface cannot be characterized by its portrait . . . the heightened resolution of the pictures did not resolve the arguments. The moon remained inscrutable at all scales" [2]. "It is evident that pictures of strange material in a strange environment do not lead to unique deductions as to composition" [3]. These cautionary tales are to remind us that our knowledge of the other members of the solar system is similar to our pre-Apollo understanding of the Moon. This is a reason for continued exploration at an enhanced level, including sample return. Accordingly, in this book, which is biased toward cosmochemistry, I have emphasized the lunar data, despite many temptations to extrapolate beyond our present understanding of the other planets and satellites.

Meteorites provide unique and crucial evidence on early conditions in the solar nebula, and the lunar data have shed much light on previously obscure problems. It is, however, not possible in a book of this length to make more than passing reference to them, mainly in Chapters 8 and 9. Theories for the origin and evolution of the solar system must accommodate the new meteoritic evidence, which demands book-length treatment in its own right.

The very large body of literature has called for much selection and evaluation. I have attempted to provide a synthesis, rather than a catalogue, believing the former approach to be of greater service to the reader. Accordingly, I have had to make various choices among competing models such as on the questions of the existence of lunar cores, terminal cataclysms, magma oceans, KREEP volcanism, hot or cold nebulae, planetesimals or gaseous protoplanets, and many other fascinating but hazardous exercises. I have been fortified in these endeavors by discussions with the superb body of lunar scientists [4] who form an imposing tribute to the rational methods of scientific inquiry.

I have tried generally to reference the latest comprehensive statements on particular topics. I have also attempted to list references to all sources of fact, information, opinion and interpretation other than my own. It is essential in a book of this kind both that a proper perspective be presented and that appropriate formal referencing be attempted. Unsupported statements amount to expressions of dogma, acceptable in works on science fiction, astrology, religion, paranormal phenonoma, extra-sensory perception

and the occult, but not, since the Renaissance, in scientific literature. Books which are commonly not subject to peer review processes may occasionally fall into such a credibility trap [5]. Accordingly, I have attempted both extensive referencing and a measure of peer review [4].

The number of references cited has led, as in the previous book, to the use of an abbreviated style of referencing. It is not practical in a work of this size to cite the fully expanded reference for each paper. Since many of the references are to the *Proceedings of the Lunar and Planetary Science Conferences*, an enormous amount of repetition would occur. One of the aims of this book is to serve as an introduction to the lunar literature, so that the interested reader can pursue any topic in depth and consult the original references. The numbered references at the end of each chapter contain (1) authors names (where there are more than two, the initial author followed by et al., is used); (2) year; (3) abbreviated journal or book title; (4) volume number; (5) initial page number or page number quoted. This provides enough information to enable the reference to be quickly located. Full referencing details including the journal titles are given in Appendix I. In Appendix II, a list of primary data sources is given. I have tried to avoid references to unrefereed papers, internal reports and other "grey" literature, but sometimes this has been unavoidable.

In a book of this size, it is difficult to include an extensive data base. As an example, the recent treatise on *Basaltic Volcanism on the Terrestrial Planets* runs to over 1300 pages on a topic which I have treated in one chapter. Some of the material which I prepared for use in that book has been incorporated in this text with minor amendments.

I have attempted not to dwell excessively on facts which are well known and widely accepted, but have devoted more space to the controversial aspects of the subject. This carries the risk of producing some imbalance in the book, but I have judged it more profitable to adopt this approach rather than to inflict tedious descriptions of well-known material which is readily available in other sources.

The literature coverage extends to November, 1981, including references to the *Multi-ring Basin Conference*, the *Apollo 16 Workshop*, the *Proceedings of Lunar and Planetary Science Conference*, 12B, and to *Basaltic Volcanism on the Terrestrial Planets*. All radiometric age dates have been recalculated in terms of the new decay constants [6].

Stuart Ross Taylor
Houston and Canberra
November, 1981

References and Notes

1. Pontius Pilate (The Gospel according to St. John, 19:22, King James Version).
2. Scott, R. F. (1977) *Earth Sci. Rev.* 13: 379.
3. Urey, H. C. (1966) *Science*. 153: 1420.
4. See Acknowledgments.
5. See for example Smith, J. V. (1980) *J. Geol.* 88: 250.
6. See Chapter 6, reference [105].

The Author

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Acknowledgments

This book was written over a period of fourteen months (October 1980–November 1981), principally at the Lunar and Planetary Institute, Houston. I am grateful to Dr. Roger Phillips, Institute Director, for enabling me to work for extended periods in Houston, providing access both to the library and data facilities and the Johnson Space Center, and to a wide spectrum of lunar scientists.

I owe, as do all workers in planetary research, an initial debt to Harold Urey and Ralph Baldwin for their early and perceptive insights, which set the intellectual stage for planetary exploration. A further tribute is due to the scientists of the lunar and planetary community on whose work this book is based. During the past decade, I have had fruitful discussions with innumerable individual scientists, and have formed many lasting friendships, so that it is difficult to single out those who have made a special contribution. I am grateful to them for the encouragement to write this book. This body of scientists, interdisciplinary and international, can deal competently with any current scientific observation in the solar system and is perhaps the greatest benefit to have come from the space program.

Books have long been considered as an authoritative source of information, but unless subject to peer review, may commonly reflect the prejudices of the author. Some bias is inevitable, but I have attempted to avoid this trap by prevailing upon several scientists to read chapters dealing with their own specialties. Dr. Don E. Wilhelms has read Chapter 2 on geology and Chapter 3 on cratering. Dr. Fred Hörz also read Chapter 3 and Chapter 4 on planetary surfaces. Professor Larry Taylor has read Chapter 5 on planetary crusts and Dr. David Walker, Chapter 6 on basaltic volcanism. Chapter 7, which deals with many geophysical aspects, has been read by Dr. Roger Phillips, Dr. Len Srnka and Dr. Michael McElhinny. Professor J. V. Smith read both Chapter 8 on planetary compositions and Chapter 9 on the origin and evolution of the solar system.

I am exceedingly grateful to these workers for their time and patience in toiling through rough draft material. Their comments have substantially improved the text, and saved me from various grievous errors. The responsibility for interpretations, shortcomings and errors remains my own.

The production of this book on a short time scale would not have been possible without the aid and help of the staff of the Lunar and Planetary Institute. Rosanna Ridings, Managing Editor, contributed greatly to the efficient editing and production of this book. She was ably assisted by Dory Brandt, Kelly Christianson, Renée Edwards, Lanet Gaddy and Donna Theiss. The preparation of the figures was carried out with artistic skill by Donna Jalufka-Chady, Sharon Adlis-Vass, and David Powell, with S. Adlis-Vass acting as lead designer. Carl Grossman, assisted by Gayle Croft, was responsible for the typesetting of the book. Production of final pages was coordinated by Pamela Thompson. Ron Weber was responsible for supplying much of the photographic material. Jack Sevier read over the entire text. Fran Waranius placed the excellent and essential facilities of the library freely at my disposal. In Canberra, Gail Stewart typed many preliminary drafts with speed and precision.

Many colleagues have supplied illustrative material. The length of the list and the diversity of scientific disciplines represented is a tribute to the interdisciplinary nature of the subject. I am grateful for the help of the following individuals:

I. Adler	J. B. Murray
E. Anders	L. E. Nyquist
C. G. Andre	M. Norman
R. N. Clayton	J. J. Papike
J. W. Delano	R. J. Phillips
R. A. F. Grieve	C. M. Pieters
W. K. Hartmann	J. B. Pike
J. W. Head	S. Pullan
B. R. Hawke	L. Raedeke
F. Hörz	D. J. Roddy
R. M. Housley	C. T. Russell
J. S. Huebner	G. Ryder
R. L. Kovach	M. Sato
J. Longhi	R. S. Saunders
G. W. Lugmair	J. V. Smith
I. S. McCallum	S. C. Solomon
J. F. McCauley	D. Stöffler
D. S. McKay	R. G. Strom
G. A. McKay	L. A. Taylor
A. L. Metzger	G. J. Wasserburg
J. W. Morgan	

A particular acknowledgment is due to Dr. Robin Brett, who ensured my initial participation in lunar studies.

Acknowledgment is made to the following for permission to use copyrighted material:

Anglo-Australian Observatory (Fig. 9.1)

Cerro Tololo Inter-American Observatory (Fig. 9.2)

Lick Observatory (Figs. 2.1, 2.2, 2.4, 2.7, 6.9a)

Scientific American (Fig. 9.3)

The National Aeronautics and Space Administration (NASA) provided the initial sample material, collected with care and expertise, which has made possible the writing of this book. Additional support for the writing of this book was provided through NASA Contract No. NASW 3389, made possible by the kind efforts of Dr. William L. Quaide of NASA.

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