Chapter 10

THE SIGNIFICANCE OF LUNAR AND PLANETARY EXPLORATION

10.1 The Lunar Evidence

Having accomplished a preliminary exploration of the solar system, we now possess a general understanding of the problems of and constraints on planetary origin and evolution. Much of our information has been derived from the study of the Moon. We have been able to establish the following sequence of events from the lunar evidence:

Differentiated planetesimals accreted to form the Moon within 100 million years of the isolation of the solar nebula. The Moon became partially to completely molten and large-scale crystal-liquid differentiation produced a feldspathic crust and a complex mineralogically zoned mantle, from which some 20 differing types of mare basalts were subsequently erupted. Whether the initial melting produced a magma ocean or several smaller-scale melted regions is partly a semantic problem, since the bulk of the Moon went through this process on a timescale of 100–200 million years.

By 4.4 aeons, the interior had crystallized, as shown by the isotopic data, and the feldspathic crust was in place. For the next 500 million years, the crust was subjected to the full fury of bombardment by planetesimals and lesser objects. The resulting chaos in the upper crust explains much of the petrological and chemical complexities of the highland samples. Possibly the crust did not become stable against the raining impacts until 4.2 aeons. The declining stages of the bombardment are preserved in the majestic ringed basins and large craters of the highlands. The basin-forming events were over by 3.8 aeons, with the formation of the Imbrium and Orientale multi-ring basins. A "terminal cataclysm" does not appear to be required.

This date (3.8 aeons) provides a younger limit for heavily cratered surfaces, which are common throughout the solar system, and is perhaps the single most important result from the Apollo mission. The similar age of the oldest terrestrial crust, in Isua, Greenland, has an as yet undetermined relationship to the great bombardment, which must also have struck the Earth.

The slow generation of heat by radioactive decay produced basaltic lavas by partial melting from the deep lunar interior from about 4 to 3 aeons. This stage, involving a secondary differentiation and transport of incompatible elements to the outer regions, is still continuing on Earth and apparently persisted to young periods on Mars. Such basaltic volcanism provides probes of planetary interiors and information about the constitution of the mantles from which they are derived. The surface rocks exposed to cosmic radiation provide not only detailed evidence of their exposure history, but also provide information on the history of the sun.

The bulk composition of the Moon is sufficiently different from that of the mantle of the Earth to provide first-order evidence for accretion of planets from a heterogeneous assemblage of planetesimals. The varying compositions of the planets, satellites and meteorites demand differing proportions of metal and silicates with varying enrichment and depletions of refractory and volatile elements. The simple pre-Apollo scenarios of capture and fission have been replaced by complex models of double-planet formation. The sophisticated understanding we have acquired of the closest, most accessible object in the solar system must serve to remind us that our pre-Apollo thinking about the composition and history of the Moon was effectively unconstrained [1].

The ultimate benefit from lunar exploration is that we can, in effect, stand upon the lunar surface, understand its complexity in detail, and use it as a platform from which to contemplate the other planets and satellites from a superior vantage point.

The knowledge we have gained from the lunar samples has both promoted our understanding and created a new interdisciplinary and integrated scientific community, capable at present of dealing decisively with any solar system observation or material. The development of expertise in this field was not really predictable in advance [2]. The planetary discoveries even impinge on cosmology, for the existence of fossil surfaces 4 aeons in age places stringent limits on the variation of the gravitational constant G with time.

10.2 Future Missions

The political aspects of the space missions cannot be addressed here [3]. The current question of the value of the space program echoes the complaints levelled against most early explorers who failed to return enough gold. The lesson of history is that unexpected but generally beneficial results follow such voyages. What we are looking for is not always what we find. The Beagle expedition was organized by the premier naval power of the age, interested in better navigational charts of the South American coast. It was not forseen that the observations by Darwin would result in a fundamental change in our perception of the relationship between man and nature.

Astronomical research, well funded since the days of the Babylonian and Egyptian observers and the builders of Stonehenge, has concentrated mainly on the search for answers to fundamental questions. Many questions from the present stage of solar system exploration could be answered quickly by a series of unmanned space probes. Landers or orbiters equipped with gamma-ray detectors can readily obtain the surface distribution of the radioactive elements K, U and Th. These elements are often strongly concentrated by differentiation processes into the outer regions of planets. Their abundance and surficial distribution provide first-order geochemical information about both the geochemical evolution and the bulk composition of the planet. This information can be coupled with the relative ages of the planetary surfaces established by photogeological crater counting methods or (in the case of Venus) radar imagery. It is therefore possible to begin to establish the pattern of planetary and crustal evolution for each planet or satellite once we have data on the radioactive elements. These missions first need to be calibrated against the lunar surface by polar orbiter type missions, which would provide the full surface coverage that we still lack for the Moon.

Techniques for establishing relative ages of planetary surfaces become less secure as we depart from the terrestrial neighborhood, and the estimates of past meteorite flux rates become less certain. The precise ages of the surfaces need to be established by radiometric dating techniques. Surface ages for Mars and Mercury would provide the next quantum jump in our understanding of the history of the solar system.

How can this task be accomplished? Is it possible to make sophisticated age determinations in remote automated laboratories? This question is worth pursuing at length. Should we have obtained further remote data from the Moon, in 1969, in preference to a sample return? The Surveyor V and VI analyses confirmed the basaltic nature of the maria, but the Surveyor VII analysis on the ejecta blanket of Tycho did not lead us to the concept of an anorthositic highland crust. This was immediately deduced from the presence of a few feldspathic grains in the Apollo 11 sample return, 50 km from the nearest highlands. By the time of the Apollo 12 sample return, the isotopic analyses revealed much of lunar history. The analyses provided decisive evidence of early 4.4 aeon differentiation of the basaltic source regions, along with the eruption of lava some hundreds of millions of years later.

Our experience with the Viking data has been enlightening. The analytical data, analogous to data from the lunar Surveyor landers, tells us of the basaltic nature of the surface, confirming photogeological interpretations, but does not tell us the ages, the composition, or the history of the source regions. The vital isotopic and trace element data are missing. The major element values, subject to much instrumental and geological uncertainty, were only obtained for wind-blown material, not rocks. Thus the quality of scientific information available from remote landers may often be compromised or degraded by factors remote from the scientific objectives.

The expense of sample return missions requires that the scientific information obtained in this manner must be vastly superior to the alternative. A number of factors are relevant to this argument:

(a) The instrumental techniques available in terrestrial laboratories will always be more advanced than those available in remote automated laboratories.
(b) The experiments are difficult to plan in advance. Our whole experience with the Moon illustrates the difficulties of projection in science. If the experimental parameters cannot be altered, one either gets the expected result, or an ambiguous and possibly uninterpretable result.
(c) Returned samples enable experiments not conceived at the time of the mission to answer scientific questions. Many workers can be involved and many experiments can be performed, rather than the few possible in a remote laboratory.
(d) The acquiring of reliable age information, for example, is not only a matter of sophisticated instrumental measurements but is also critically dependent on selection of the appropriate mineral or rock sample. This complex process, familiar to terrestrial workers, is exceedingly difficult to carry out under clean room conditions on Earth. The scientific skills and abilities needed require workers of the highest quality to address these problems, so that human factors are involved as well as instrumental sophistication.

Accordingly, although remote-sensing measurements are very valuable, they can never replace the information that can be obtained from the return of planetary samples to terrestrial laboratories. The latter is judged to be more cost-effective when the time and expertise involved in designing remote laboratories is weighed against the scientific return. Who would trade one mare basalt isochron for 50 Surveyor analyses?

10.3 Man's Responsibility in the Universe

The possibility of the existence of Earth-like planets elsewhere in the universe is frequently addressed. Although the uncertainties are extreme, possibly between 10^{-5} and 10^{-7} of the stars may possess satellites suitable for the origin and evolution of life [4, 5]. This number would provide between one and 100 such planets within 1000 light years of Earth.

The question of the emergence of life is reinforced by the large variety of organic molecules available in interstellar space. There is, accordingly, a good scientific rationale for continuing a search for extraterrestrial intelligence [5, 6]. The message from biochemical studies is more sobering. The course of evolution is not predictable [7]. Even on this planet, where life arose and hominid evolution began more than 4 aeons after accretion, the chances of the appearance of Homo sapiens seem remarkably small. Pollard [4] has noted that continental drift on the Earth provided three separate regions where evolution could proceed independently. When life first invaded the land in the Devonian Period, the continental crust formed a single unit (Pangaea). Subsequently, the Southern Continent (Gondwana) separated, followed by the breaking away of Antarctica and Australia and of South America from Africa. Mammalian evolution then proceeded independently in South America, Australia and Africa. The marsupials evolved in Austrialia. Although primates appeared both in South America and Africa, the New World monkeys never left the trees. "Thus continental drift has produced for us three Earth-like 'planets'. Only on one of them . . . did evolution lead to man" [4, p. 659]. This sobering conclusion reinforces the evidence that we may be unique, alone in a universe that is older than 15 or perhaps 20 aeons, and which contains at least 10^{11} galaxies, each having 10^{11} stars. If this is our position, then we alone, comprised of atoms synthesized in stellar interiors and supernovae, and the product of 4 aeons of organic evolution on this planet, have developed the skills and ability to comprehend the universe and understand its history. If this scenario is correct, we have an awesome responsibility to ensure that our species survives and explores not only the solar system, but, in due time, ventures further afield [8, 9].

References and Notes

1. The range of uncontrolled speculation available in the pre-Apollo literature is a fertile field for the historians of science.
2. A comparison of the pre-Apollo selection of Principal Investigators for the lunar program with the community, which subsequently evolved under the stress of the lunar investigations, reveals a high casualty rate. Less than 15% of the groups remain active and perhaps less than one third contributed significantly to our understanding of lunar science. This illustrates the twin difficulties of identifying both objectives and competent individuals in advance, since unexpected problems arise. The analogy with the history of warfare is close.
3. See, for example, Hallion, R. P., and Crouch, T. D., eds. (1979) *Apollo: Ten Years since Tranquillity Base*, Smithsonian Institution Press, Washington, D.C.
4. Pollard, W. G. (1979) The prevalence of Earth-like planets. *Amer. Sci.* 67: 654.
5. Owen, T., and Goldsmith, D. (1979) *The Search for Life in the Universe*, Benjamin-Cummings.
6. Morrison, P., et al. (1977) *The Search for Extraterrestrial Intelligence: SETI*, NASA SP 419.
7. Monod, J. (1974) *Chance and Necessity*, Collins.
8. Arnold, J. R. (1980) The frontier in space. *Amer. Sci.* 68: 299. A marked feature of hominids is a tendency to travel widely. Arnold comments (p. 299) that "we seem to be

descended from the migrants and innovators. So far as we know, the chimpanzees and gorillas have not left home."

9. See also Tipler, F. J. (1981) *Quart. J. Roy. Astr. Soc.* 22: 133, 279 for a discussion of the history of the search for extraterrestrial intelligence; and Rood, R. T., and Trefil, J. S. (1981) *The Possibility of Extraterrestrial Civilizations*, C. Scribner.