PLANETARY SCIENCE from Apollo to Io and Beyond

by

Michael B. Duke and Leon T. Silver

July 20, 1979 marks the tenth anniversary of Apollo 11's landing on the Moon; this began a decade of intense scientific studies and moved the Moon from the realm of astronomy into that of the geological sciences. In reviewing the perspectives and theories presented at the recently held 10th Lunar and Planetary Science Conference, the authors highlight the great interdisciplinary range of planetary scientific progress that has characterized both the Conferences and the past decade.

The Apollo landing on the Moon, together with other NASA missions, such as the Viking exploration of Mars, Mariner 10's trip to Venus and Mercury, and the probes of Venus and the Moon by the U.S.S.R., opened up comparative planetology as a vigorous scientific discipline of first rank importance in productivity. The 10th Lunar and Planetary Science Conference, held March 19-23 in Houston, Texas, U.S.A., recapitulated and continued the progress made during the "Appollo decade".

The Conference

Seven broad topics were considered:

1. *Constraints on structure, composition, and history of planetary interiors* (Studies to determine physical, chemi-

cal and thermal models for present states and histories of planetary interiors.)

2. *Characterization and evolution of planetary crusts* (Studies of the nature, origin, fractionation, emplacement mechanisms, and time scales for development of planetary crusts.)
3. *Characteristics and movements of materials on lunar, planetary and asteroidal surfaces* (Studies of composition, chemical reactions, rates of overturn, lateral and vertical mixing, erosion rates, volatile transport at the surfaces of and within regoliths, and other studies of dynamic surface processes.)
4. *Nature and effects of impact processes* (Studies related to the mechanics of impact cratering, characteristics of

Jupiter with its moons (Io, left and Europa, right) as seen from Voyager 1 on February 13, 1979. (All photographs of Jupiter and its moons in this article are courtesy of NASA and the Jet Propulsion Laboratory, Cal Tech, U.S.A.)

impact crater deposits, processes of formation and modification of impact craters and basins, and physical and chemical effects of impact processes on materials.)

5. *Characterization and evolution of volcanic landforms* (Studies of the origin, fractionation, and emplacement history of volcanic rocks; characterization and regional distribution of volcanic deposits and studies of volcanic morphologic features; and determinations of ages of volcanic features).
6. *Extraterrestrial materials as solar/interplanetary/interstellar probes* (Studies of solar and cosmic ray interactions; interactions of cometary and/or meteoritic particles with planetary surfaces; the search for extra-solar system components.)
7. *Earliest history of the solar system* (Studies of the physical state, chemical composition, and homogeneity of the solar nebula; physics, chemistry and chronology of condensation and accretion processes; early history of solid bodies.)

In addition, special symposia were held on (1) The Earth from Space, (2) Future Exploration, (3) The Tenth Anniversary of Apollo, and (4) Reports on Viking-Voyager-Pioneer.

Over 720 scientists from 13 countries attended the Conference, absorbing new data from laboratories and spacecraft, new theories, new perspectives on the Earth and other planets, and a little nostalgia commemorating the Apollo experience. Over 500 abstracts were included in three soft-bound volumes distributed to attendees and nearly 300 presentations were delivered orally.

Visitors at the Lunar and Planetary Institute exhibit, 10th Lunar and Planetary Science Conference.

Lunar Volcanism

Prior to Apollo, a relative chronology had been proposed for the history of lunar surface features on the basis of superposition of mappable units and relative intensity of cratering on surfaces. The early Apollo missions calibrated the crater frequency curve and established a minimum range of age and composition for the basalts that filled the maria, 3.8 - 3.2 billion years ago. Even now, according to Earth-based telescopic data and continuing analysis of Apollo orbital geochemical data, the range of lunar basalts is being extended in age and composition.

In recent years, evidence has suggested an early crustal formation period, driven by unknown but short-lived energy sources, followed by a hiatus until radioactive decay could remelt mantle rocks to produce the mare basalts. However, the question of pre-mare basaltic volcanism is being vigorously pursued. Did the style of lunar volcanism change abruptly or gradually from the period of early crustal formation to the mare-filling period? The answers are made difficult by the coincidence of the end of intense early

bombardment and the apparent onset of mare basalt volcanism about 3.9 billion years ago.

P. Schultz (Lunar and Planetary Institute, U.S.A.) and others have studied dark-haloed impact craters that penetrate lighter ejecta from the large impact basins such as Orientale and Imbrium. Correlating these dark-haloed craters with Mg/Si ratios from the Apollo orbital X-ray fluorescence experiment, they conclude that basaltic rocks were extruded before the Imbrium event, prior to 3.95 billion years ago.

N. Hubbard (Johnson Space Center, U.S.A.) has interpreted the X-ray fluorescence data to suggest that the Eastern Maria are more aluminous than those of the center of the Earthside lunar disk. A very low titanium basalt was first reported last year from the Soviet Luna 24 samples (J. Papike, SUNY Stony Brook, U.S.A.) and this year an additional chemically distinct Apollo 11 basalt type has been described (D.W. Beatty et al., Cal Tech, U.S.A.) from studies of small fragments from the lunar regolith.

These and other results suggest that our knowledge of the range of lunar basalts is still limited, as might be suspected considering the small number of Apollo and Luna sampling sites. New data continually improve models of the evolution of the Moon's mantle and its crustal-mantle interactions, and as ages can be established, of our understanding of pre-3.95 Ga volcanism.

Ancient Crust

Just as basalts provide insights into the lunar mantle during the period 3.3 - 3.9 billion years ago (and probably not too much has changed in the mantle subsequently), the rocks of the lunar highlands provide clues as to the nature of processes that formed an ancient crust. In prior years, the discovery of lunar highlands rocks with no demonstrable meteorite-related siderophile elements led to the definition of a "pristine" highland rock suite. This has been continued with the discovery of several more examples based on Ir, Au, and other siderophile element analyses of clasts from highlands breccias and soil (P. Warren and J. Wasson, UCLA, U.S.A.).

The origin of these "pristine" rocks is in hot dispute, with A.E. Ringwood (ANU, Canberra, Australia) contending that they are crystallized from impact-produced melt lakes, whereas E. Anders (University of Chicago, U.S.A.) insisting they are not pristine at all. H. Wanke (University of Maine, U.S.A.) believes that they are pristine and that Ni, Co and Mg abundances in the lunar and terrestrial mantles are essentially identical.

Comparing the Moon's crust with the Earth's mantle is still hazardous. Warren and Wasson point out that their "pristine" highlands rocks are strangely missing the anorthositic norites believed to predominate in the Moon's crust. These discussions may lead to a clearer understanding of the compositional relationship of Moon and Earth, which is critical in evaluating the fission and separate accretion hypotheses for the formation of the Moon.

Lunar Differentiation

Current models for the Moon adopt the early formation of a thick, plagioclase crust between about 4.6 and 4.4 Ga ago as the completely molten 200 km or thicker "magma ocean" solidified. F. Oberli, J. Huneke, and G. Wasserburg (Cal Tech, U.S.A.), combining U/Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic data, have narrowed the interval of original crystallization for rock fragments from an Apollo 16 and an Apollo 17 breccia to 4.47 - 4.51 Ga and suggest that this may be an age of major lunar differentiation.

The fact that early planetary differentiation occurred, without the benefit of long-lived radioactive heat sources has also become increasingly clear through the study of differentiated meteorites. D. Mittlefehldt (UCLA, U.S.A.) reported that basalt fragments from howardite (polymict breccia)

achondrites show a variety of rare earth element abundances that suggest temporal, spatial, and thermal inhomogeneities in the parental asteroidal bodies, in which the meteorite basalts formed 4.5 Ga ago. T. Lee, G. Wasserburg, and others (Cal Tech, U.S.A.) reported at a previous conference that chondritic meteorites show magnesium isotope anomalies due to decay of primordial ^{26}Al .

Thus, short-lived radioactivity could have been a source of heat from which early planetary differentiation occurred. J. Minear and co-workers (Johnson Space Center, U.S.A.) have modeled the heating of asteroidal bodies heated by ^{26}Al and demonstrated a range of possible behaviour, including core formation and partial melting. It appears that even small bodies can have been completely differentiated into the classic core, mantle and crust structure, and that initial crustal formation is likely to have been early.

Models

The crusts of the other terrestrial planets do not seem to have experienced the complexities of plate tectonics observed for Earth. A good deal of effort has been expended on deducing models of the crusts of the planets, to draw general conclusions on the applicability of principals of isostasy, crustal thickening, and petrologic evolution of the crusts.

B. Bills (Jet Propulsion Laboratory, U.S.A.) demonstrated that Moon, Mars and Earth all show some degree of isostatic compensation, but that the classical Airy or Pratt models need to be modified to explain the statistical behaviour of topography and gravity harmonics. S. Solomon (MIT, U.S.A.) and J. Head (Brown University, U.S.A.) have continued to examine the lunar "mascon" mare basins for evidence of their tectonic history. They find that the basin flooding occurred primarily during the first 20-30% of the basin filling episode, and that the growth of the lunar lithosphere can be followed in the succession of extensional and compressional features formed as the basins filled. H. Melosh (Cal Tech, U.S.A.) also has used geological mapping combined with gravity data to

calculate that the lunar lithosphere 3.5 - 3.8 Ga ago was 25-40 km thick, similar to the Earth's current lithosphere. The Moon at that time had a radiogenic heat production similar to that of the Earth today.

Crustal Composition

The lunar crustal composition appears to have been predominantly anorthosite, norite and related materials. The "magma ocean" concept has been devised to explain lunar concentration of feldspar in the crust. Chemical modeling of that concept is underway. J. Longhi and P. Boudreau (University of Oregon, U.S.A.) have contributed a magma mixing model for the development of the anorthositic rocks, which explains the rare earth element abundances as well as the mineralogical evidence - nearly constant feldspar composition with widely variable mafic composition. G. McKay and others (Johnson Space Center, U.S.A.) have presented a model by which the magma ocean could have differentiated toward the enigmatic KREEP basalt composition that seems to have appeared at about 4.4 Ga.

All this raises the question of what was happening on Earth. W. Phinney and colleagues (Johnson Space Center, U.S.A.) are studying anorthositic inclusions in the Beaver Bay and Duluth, Minnesota complexes, which they tentatively believe may be residual from an early terrestrial crust. And, based on terrestrial petrologic observations, J.V. Smith and co-workers (University of Chicago, U.S.A.) suggest that devolatilization associated with charnockite formation stabilizes planetary crusts; they predict relatively large amounts of granulite metamorphism on Venus.

Impact Processes

Impact processes have dominated the surface history of the Moon and Mercury and are present on all the terrestrial planets and satellites, with the apparent exception of one of Jupiter's moons - Io - which is so active volcanically that impact craters do not long survive (Figures 1 and 2).

Figure 1. This is the image in which the first extraterrestrial volcanic eruption (the bright curved volcanic cloud on the limb) was discovered. The dramatic view of Jupiter's satellite Io shows two simultaneously occurring volcanic eruptions. One can be seen on the limb (at lower right) in which ash clouds are rising more than 260 km above the satellite's surface. The second can be seen on the terminator (shadow between day and night) where the volcanic cloud is catching the rays of the rising sun. Seen in Io's night sky, Jupiter looms almost 40 times larger and 200 times brighter than our own full Moon. This photo was taken by Voyager 1 on March 8, 1979, looking back 4.5 million km at Io.

Figure 2. This view of Io was taken by Voyager 1 on March 4, 1979 at a distance of 862 200 km. Circular features are seen that may be meteorite impact craters or features of internal origin. The bright irregular patches appear to be younger deposits masking the surface detail. The high color is believed to consist of mixtures of salts and sulfur, brought to the surface by volcanic activity and other processes.

Understanding of the impact processes continues as a major endeavour of planetary science, with new theoretical work by M. Cintala, M. Parmentier and J. Head (Brown University, U.S.A.) beginning to address the impact of meteoritic materials on icy bodies such as the Jovian satellites (Figures 3 and 4) or Mars polar regions.

S. Kieffer (USGS, Flagstaff, U.S.A.) and C. Simonds (Northrop Services, Inc., Houston, U.S.A.) have considered the creation of impact melt in wet target materials and conclude that much of the Martian dust may be altered impact melt. Coming back down to Earth, D. Gault (Murphy's Science Center, U.S.A.) and R. Strelitz (Lunar and Planetary Institute, U.S.A.) argue about the effect of large impacts in the oceans. These occur with enough frequency (1 per 10^6 years) that the result might be observed in coastline deposits, if large (500 m) tidal waves can be sustained in the open ocean. Strelitz believes that the waves would dissipate in the open ocean.

Also speculating on the impact history of the Earth, P. Weiblen (University of Minnesota, U.S.A.) and J. Warner (Johnson Space Center, U.S.A.) suggest that several late to middle Precambrian intracratonic basins may have been created by meteorite impact. At the Conference, several other workers presented the results of field and theoretical studies of terrestrial impact craters, including H. Melosh (Cal Tech, U.S.A.), M. Dence and R. Grieve (Ottawa, Canada) and D. Roddy (USGS, Flagstaff, U.S.A.).

Radiation Interaction

Lunar rocks and soil and meteorites contain a record of interactions with energetic solar and galactic cosmic radiation, which in principle can be interpreted to provide knowledge about the history of intensity and compositional variations of the radiation on time scales ranging from 10^5 to 10^9 years or more. Current investigations include studies of meteorite cosmic ray exposure ages, composition of solar wind in lunar soils, and general studies of the dynamics of the lunar surface-cosmic radiation interaction.

O.A. Schaeffer (SUNY, Stony Brook, U.S.A.), K. Nagel (Heidelberg, F.R.G.), G. Neukum (Munich, F.R.G.) and H. Fechtig (Heidelberg, F.R.G.) have applied space erosion rates determined on the Moon to meteorites, and conclude that erosion has had a negligible effect on the cosmic ray exposure ages of iron-meteorites. The 50% greater $^{41}\text{K}/^{40}\text{K}$ exposure age than the $^{36}\text{Cl}/^{36}\text{Ar}$ exposure age must be interpreted, therefore, as due to a recent (~ 1 Ma) increase in galactic cosmic rays over the 5×10^8 year average.

In studies of the lunar core which penetrated the famed "orange glass soil" (now believed to be a lunar pyroclastic deposit), O. Eugster et al. (Bern, Switzerland) have demonstrated that the material was irradiated shortly after its formation (3.8 Ga ago) and then rapidly buried and shielded from cosmic rays. Similarly, M. Thimans and R. Clayton (University of Chicago, U.S.A.) have suggested that several Apollo 11 breccias may also contain records of ancient solar wind irradiation, preserved subsequently by shielding.

From other soil studies, R. Wieler et al. (Zurich, Switzerland) have shown that the He, Ne and Ar contents and isotopic composition of the solar wind has been rather invariant over the past 500 Ma. On a shorter time scale, J.E. Evans and L. Rancitelli (Battelle Pacific Northwest Laboratories, U.S.A.) have begun to identify recently discovered Antarctic meteorites with long (~ 1 Ma) terrestrial residence times, which may provide a key to understanding the variation of the cosmic ray flux over the past few million years.

Isotopic Anomalies

For the past several years, the recognition and elucidation of isotopic anomalies in meteorites have sparked intense

interest in the early history of the solar system. In particular, new types of anomalies and further systematics in carbonaceous chondrites are being discovered by G. Wasserburg (Cal Tech, U.S.A.) and his co-workers, I. Steele and I. Hutcheon (University of Chicago, U.S.A.), D. Phinney (Johnson Space Center, U.S.A.), and D. Macdougall (Scripps Institute, U.S.A.). The Allende meteorite which fell in 1969, just prior to Apollo 11, has been a prolific source of fragments with strange mineralogical and isotopic properties.

J. Allen, L. Grossman, T. Lee (University of Chicago, U.S.A.) and the Wasserburg group have exposed in detail the strange inclusion "HAL" (Hibonite Allende), a complex assemblage that appears to represent one of the earliest, highest temperature condensates from the solar nebula, but which is isotopically anomalous with respect to other Allende inclusions.

The existing data have stimulated a range of opinions as to the source of anomalous material. S. Margolis (Princeton University, U.S.A.), S. Faik (University of Texas, Austin, U.S.A.) and D.N. Schramm (University of Chicago, U.S.A.) have pursued the notion that a nearby supernova triggered the collapse of the pre-solar nebula, and that some of the isotopic anomalies are due to the incorporation of material from the supernova. In opposition, G. Consolmagno and A. Cameron (Harvard-Smithsonian Center for Astrophysics, U.S.A.) call on complex physical mixtures of various nucleosynthetic assemblages formed in different portions of the solar nebula. An important point is that the meteorites appear to be drawing astrophysics toward a merger with geochemistry and geophysics at an increasingly rapid rate.

Current Exploration

New exploration has always been the driving force behind lunar and planetary science. The Voyager imagery of Jupiter (see box) and its satellites was well-timed for stimulating the scientists gathered at Houston. Io was perhaps most spectacular in that its surface is currently intensively active volcanically (Figures 1 and 2). In a stimulating report, S. Peale (UCSB, U.S.A.), P. Cassen, and R. Reynolds (NASA, Ames Research Center, U.S.A.) predicted intense activity on

THE VOYAGER PROJECT

Two unmanned spacecraft, Voyagers 1 and 2, are now on their way to study our giant outer planets, Jupiter and Saturn, and 11 of their major satellites, several of which are larger than our own Moon.

The Voyager Project was assigned to the Jet Propulsion Laboratory as part of the National Aeronautics and Space Administration (NASA) program of planetary exploration. JPL communicates with the spacecraft through a worldwide network of deep space tracking stations located in California, Australia, and Spain.

Voyager 2 was launched from Florida on August 20, 1977; Voyager 1, which flies a faster trajectory to reach the planets first, was launched on September 5, 1977.

At Jupiter, Voyager 1 made its closest approach on March 5, 1979. Voyager 2, whose more cautious trajectory will avoid much of Jupiter's intense radiation, will make its closest approach on July 9, 1979. Satellites being studied are Amalthea, Io, Europa, Ganymede, and Callisto. Jupiter's Great Red Spot will be photographed and studied intensively by both spacecraft.

Scheduled Encounter Dates

Voyager 2	Jupiter	July 9, 1979
Voyager 1	Saturn	November 12, 1980
Voyager 2	Saturn	August 27, 1981

the basis of a model of runaway tidal heating of Io by Jupiter, in response to eccentricities of Io's orbit forced by perturbations of the other Jovian satellites.

Other results on the atmospheric structure and dynamics of Jupiter were equally spectacular, presented by the Voyager project scientist E. Stone (Jet Propulsion Laboratory, U.S.A.). Results of the Pioneer-Venus mission which recently probed that planet were also presented by D. Hunten (University of Arizona, U.S.A.); they showed an intriguing ^{36}Ar enrichment that is difficult to explain on the basis of current thinking on nebular condensation and planetary accretion models.

The Earth as a planet received not only the attention of comparative planetologists, but was the subject of close scrutiny from space. A special evening session attracted an audience of 400, most of whom had spent their entire day in technical sessions, to hear contributions on state-of-the-art applications of remote sensing. A thoughtful introduction by A.W. England, scientist-astronaut, led into oceanography (R. Stewart, La Jolla, U.S.A.), atmospheres and climatology (S.I. Rasool, NASA, and J. Imbrie, Brown University, U.S.A.), global tectonics (K. Burke, SUNY, Albany, U.S.A.) and exploration for resources (F. Sabins, Chevron Oil Co., U.S.A.).

Figure 3. *Ganymede, Jupiter's largest satellite, at a range of 246 000 km from Voyager 1 on March 5, 1979. The height of the satellite frame represents a distance of about 1000 km on the surface. The surface displays numerous impact craters many of which have extensive bright ray systems. The craters lacking ray systems are probably older than those showing rays. Bright bands traverse the surface in various directions. These contain an intricate system of alternating linear bright and dark lines which may represent deformation of a crusted ice layer. The lineations are particularly evident near the top of the picture. A bright band trending in a north-south direction in the lower left-hand portion of the picture is offset along a bright line. The offset is probably due to faulting.*

A clear view of the increasing emphasis on Earth Applications in the NASA priorities emerged. The planetary science community confirmed its strong interest in applying the skills and technology developed in NASA's space flight and basic research programs to the special problems of our sector of the solar system.

In his closing, retrospective remarks on the Apollo program Dr. Noel Hinners, retiring NASA Associate Administrator for Space Science, emphasized the potential for future science in this area, particularly when coupled with the successful development of the Space Shuttle.* In Apollo, the demonstration of technological capability achieved by Apollo 11, was followed by five increasingly important science-productive lunar missions. Now, in the era of the Space Shuttle development, Hinners called on the world science community to prepare for the significant new experiments which can follow the demonstration of launch and orbital capabilities of the Shuttle vehicle. The Shuttle orbital platform should provide a remarkable vantage point for international studies of the Earth and the terrestrial planets.

Dr. James Head of Brown University, U.S.A. (left) receives NASA Certificate of Appreciation for scientific contributions to the Apollo Program from Dr. Noel Hinners, who recently retired as NASA's Associate Administrator for Space Science.

*This transportation system will eventually permit a fleet of five Shuttles, each capable of carrying payloads of over 65,000 lbs to be put into orbit and remain there for weeks before returning to earth. In this way, satellites may be carried up and released in orbit, satellites or other space exploration equipment may be assembled in orbit, and various medical problems may be studied more closely. The first orbit flight for the Shuttle is now tentatively set for March 1980 and should last three days.

ABOUT THE AUTHORS:

As Chief of the Planetary and Earth Science Division, Johnson Space Center, NASA, **Michael B. Duke** is responsible for the administration of a research program in planetary science, operation of laboratory and sample curatorial facilities and advising NASA on scientific aspects of planetary exploration. From 1970 to 1977, Dr. Duke served as Lunar Sample Curator at the Johnson Space Center.

Figure 4. The picture of Callisto was taken at a range of 350 000 km by Voyager 1 on March 6, during Voyager's approach to Jupiter's outer large satellite. Callisto is a little smaller than Ganymede (about the size of the planet Mercury) and is apparently composed of a mixture of ice and rock. The darker colour of Callisto (about half as reflective as Ganymede but still twice as bright as the Moon) suggests that the upper surface is "dirty ice" or water-rich rock frozen on Callisto's cold surface (approximately 120 K or -243° F at the equator). Far more craters appear on the surface of Callisto than on the surface of Ganymede, leading scientists to believe that Callisto is the oldest of the Galilean satellites. Callisto possibly dates back to final accretional stages of planet formation 4.0 to 4.5 Ga ago. The prominent bullseye feature at the top of this picture is believed to be a large impact basin, similar to Mare Oriental on the Moon and Caloris Basin on Mercury. The brighter area is about 600 km across. The outer ring is about 2600 km across.

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