17. THE MOON (LA LUNE)

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1. Introduction

Members of Commissions 16 and 17 have voted by a substantial margin (102 yes, 4 no, 1 abstention) to merge the two Commissions. The merger will take effect at the 17th General Assembly.

2. Lunar Research: Countries Other Than the U.S.S.R.
(W.M. Kaula)

The principal books on the Moon published during 1976-1978 are listed in references 1-8. A bibliography of lunar and planetary research appears regularly in The Moon and the Planets.

GEOLOGY

Although there has been slight acquisition of new data, the study of the surface features of the Moon has progressed in the directions of: (1) more quantitative description of lunar surface evolution; (2) physical modeling of features, and the relating of model parameters to quantitative descriptions; and (3) comparative studies of the surfaces of the Moon, Mercury, and Mars.

It is now accepted that the principal shapers of the Moon's visible surface were great impacts more than 3.9×10^9 years ago, depositing extensive ejecta blankets as well as creating basins. Little can be inferred about earlier history, but the subsequent interactive evolution of decreasing meteoroid infall, dwindling volcanism, and thermo-tectonic adjustments has been mapped fairly well (13, 17, 18, 22, 24, 47). For the last 3.9×10^9 years, the dominant trend of lunar endogenic activity has been a cooling, and hence the shutting off of magma vents and the development of compressive features, such as wrinkle ridges. The youngest mare lava flows are now estimated to be 2.3×10^9 years old (13).

The main physical modeling effort has been on cratering, attempting to explain such phenomena as formation of multiple rings, extensive melt occurrence, etc. Rigorous computation of hypervelocity impact is possible only for impacts of $\leq 10^{17}$ ergs (38), so that scaling arguments must be used for larger events (8,32). The inferred history of the lunar surface is now the main control on comparative planetary studies. On a more recent and shallower scale, regolith studies have continued to develop by a combination of statistical modeling and isotopic measurements, reflecting mainly local events over the last few 10^8 yr. (27).

CHEMISTRY AND PETROLOGY

Mare basalts, which were extruded less than 3.9×10^9 years ago, are now agreed to be either secondary differentiates from the cumulates complementary to the crust, or primitive differentiates which have interacted strongly with the cumulates (39, 43).

The history of terra rocks is less well understood. The bulk of them range in Al_2O_3 content from 18% to 35%, and appear to be breccias: mixtures of impact

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melted and metamorphosed fragments. Consequently, they represent a random sampling of the crust with a weighting function decreasing with depth, plus a minor but clearly identifiable admixture of meteoritic material. In recent years there has been an emphasis on finding pristine samples, which may be igneous differentiates rather than remelted breccias. Most clearly pristine are some dunite clasts found in Apollo 17 rocks and a few anorthositic samples from Apollo 15 & 16 sites. These rocks appear to be from the lower and upper parts of the early lunar crust. Also strong candidates for pristineness are troctolitic and noritic samples found at Apollo 17. Much more in debate is the history of KREEP rocks: basaltic in major element composition, but highly enriched in incompatible lithophiles and alkalis. While it is agreed that the composition must reflect the last solidification at depth that was excavated at the time of Imbrium impact, it is not clear to what extent there has been subsequent remelting and recombination (22, 33, 34, 42, 53).

Nd-Sm isotopic techniques have now been applied to lunar rocks, complementing the U-Pb, Rb-Sr, and K-Ar dating methods. Some of the pristine clasts have been dated as being as old at 4.6×10^9 years, thus confirming more indirect isotopic inferences that the bulk of the lunar crust was differentiated more than 4.4×10^9 years ago. With some exceptions for which there are plausible explanations, there is now fair agreement in the dating of rocks by different techniques. The number of ages older than 3.95×10^9 years is still rather few, reflecting a general resetting of radioactive rocks by the major impacts at that time (31, 37, 52, 54).

Remote-sensing techniques (Apollo orbiter gamma- and x-ray measurements, terrestrial spectrophotometry) show three dominant patterns. (1) High 'KREEP'-like content is correlated with the western hemisphere maria, Imbrium and Procellarum. (2) The average terra has an intermediate anorthositic gabbro composition ($\sim$24%Al_2O_3), similar to that of the abundant breccias, with aluminum positively correlated with topographic elevation and K, Fe, Mg negatively correlated. (3) There are appreciable variations of TiO_2 content of mare rocks, but they are not as systematically correlated with age as those of returned samples (10, 11, 25, 40, 41).

GEOPHYSICS AND STRUCTURE

The mean crustal thickness of the Moon is inferred to be about 70 km, from a combination of seismology, gravimetry, and altimetry. The interior of the Moon has three distinct zones. (1) The upper mantle $\sim$60-400 km deep has high seismic velocities, extremely low seismic dissipation and low electrical conductivity: evidently a very cool and dry region. (2) The lower mantle $\sim$400-1000 km deep has moderately lower seismic velocities, and higher seismic dissipation and electrical conductivity. (3) The asthenosphere, $\gtrsim$1000 km deep, is too dissipatory to transmit shear waves, and appears to be the warmest zone of the Moon. Despite diligent examination of gravitational, seismological, and electromagnetic data, the existence of an iron core is still unconfirmed: all data types allow, but do not require, a core up to $\sim$400 km radius (16, 21, 35, 55).

The seismic wave velocities of the lunar mantle are consistent with plausible olivine or pyroxene compositions. The principal seismic anomaly is the lower crust primary velocity, 6.8 km/sec, too low for either a gabbro or an anorthosite (29).

Thermal evolution models of the Moon allowing for upward differentiation of lithophilic heat sources and convective heat transfer obtain a general picture of cooling of the outer shell of the Moon and heating up of the central sphere. A significant constraint on these models is the apparent absence of net expansion or contraction of the outer surface (30, 49, 51).

Analysis of lateral variations in gravity and topography has continued, reaffirming the earlier inference that the Moon currently sustains lower stresses than Earth or Mars (12). Lateral variations in the lunar magnetic field measured by orbiters, ±0.3γ in magnitude, have also been analysed for correlations, without any marked indicator being found (46). The greatest anomaly outstanding is probably the unusually high remanent magnetism of some rock samples, indicating an impressing field of ∿1 gauss intensity (15). This problem has lead to speculation about shock effects (50) or a hydromagnetic dynamo in a core $\lesssim 10^{-3}$ the Earth's in mass (45).

ORIGIN OF THE MOON

It is inescapable that the bulk composition of the Moon is depleted in both volatiles (i.e., elements condensing at ≤1200 K) and siderophiles (because of its low density). It is probable that the Moon is enriched in refractory lithophiles, most prominently aluminum. These data lead to a general concurrence that the Moon is constructed of material which has undergone an earlier stage of differentiation. The debate is over the locus of this differentiation, the principal alternatives being the Earth or some now virtually extinct population of smaller bodies, differentiated during accretion from the solar nebula. The principal arguments in favor of an origin of the Moon by 'splash off' from the Earth are siderophile abundances in mare basalts from deep sources, said to differ from expectations for low pressure equilibria, and the difficulty of otherwise satisfying thermal history and crustal petrologic requirements for a heating maximum very near the surface by other hypotheses. The principal arguments in favor of constructing the Moon out of much smaller bodies are the existence of differentiated meteorites and dynamical probabilities (9, 14, 19, 26, 44).

The peculiar composition and large mass in proportion to the primary of the Moon remain as the outstanding problems of the origin of the terrestrial planets.

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3. Lunar Research: U.S.S.R.

(V.V. Shevchenko)

The Astronomical Council of the Academy of Sciences of the U.S.S.R. Two statistical models of regolith dynamics were investigated in cooperation with the Institute of Geochemistry. The dependence of material distribution upon depth and time and the dependence of crater distribution upon radius and shape of craters were studied. The theoretical hypsographic curve was drawn for the relief stipulated by cratering. The evolution time of the layer was shown to be the product of two factors, the first one depending only on the initial depth of deposit of the layer and on the size distribution of craters, and the second one corresponding to the extent of processing of the layer, depending on the size distribution and shape of craters (G.A. Leikin et al., Astron. Vestnik, [2], 1978).

The Sternberg State Astronomical Institute. The preparation of complete maps of the Moon on the scales of 1:5000000 (3rd edition) and 1:10000000 was completed (Ju.N. Lipskij et al., Communications of the State Astronomical Institute, [204], 1977). Statistical data on the distribution of craters with diameters over 10 km on Mars, Mercury, and the Moon were obtained in cooperation with the Institute of Geology of the Academy of Sciences of the U.S.S.R. Comparison of the data was carried out (Yu.N. Lipskiy et al., "Catalogue of the craters of Mars, and the statistics of craters of Mars, the Moon and Mercury", Moscow, 1977; Yu.N. Lipskiy et al., "Catalogue of craters of Mercury and the Moon", Moscow, 1977). Gigantic crater chains on the far side of the Moon, near Mare Orientale, were investigated. The geological structure and age of the region of Mare Orientale and the inter-relations between craters in the chains were considered. (Yu.N. Lipskiy et al., Communications of the State Astromonical Institute, [196], 1978.

The Astronomical Observatory of Kazanskij State University and Astronomical Observatory Engelgardta. The motion of natural satellites around the centre of mass along an elliptical orbit was investigated. The flat rotation along an elliptical orbit for three cases of the relation between mechanical compression of the satellite and orbital eccentricity was considered (Sh.T. Habibullin). Selenodetic coordinates of 100 craters were established from photographs of the Moon against the stellar background. These coordinates were related to the centre of mass, in order to compile a fundamental catalogue of reference points on the Moon. Absolute altitudes and maps of the limb areas of the Moon were obtained by 8600 observations of occultations of stars by the Moon.

Main Astronomical Observatory of the Academy of Sciences of the Ukrainian S.S.R. A hypsometric map has been compiled of the megarelief on the visible side of the Moon, on a scale of 1:10000000 (I.V. Gavrilov, V.S. Kislyuk, L.A. Karaseva). Rectangular coordinates of 4900 points on the lunar suface are given in a common selenodetic system whose origin coincides with the Moon's centre of gravity and whose axes coincide with its principal axes of inertia (I.V. Gavrilov, V.S. Kislyuk, A.S. Duma, "Consolidated system of the selenodetic coordinates of 4900 points on the lunar surface", Kiev, Naukova Dumka, 1977). A booklet, "Selenodetic investigations in the U.S.S.R." was prepared, Kiev, Naukova Dumka, 1978 (I.V. Gavrilov, I.S. Dovgalevskaja).

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Institute of Earth Physics of the Academy of Sciences of the U.S.S.R. Analysis of the unequilibrium figure of the Moon allowed to determine a bench-mark point on the evolution curve of the lunar orbit: $c \sim 22{,}5R_3$ by $t \sim (3.8-4) \times 10^9$ years ago, where c - the distance between centres of the Moon and the Earth, and R_3 - the radius of the Earth (V.N. Zharkov, A.P. Trubitsyn, Izv. AN SSSR, Fiz. Zemli, [18], 1976).

Institute of Geology of the Academy of Sciences of the U.S.S.R. On the basis of high-resolution photographs of the Moon, geologic maps on a scale of 1:1000000 were prepared for the regions of circular maria, including Mare Orientale, and for continental regions. Ejecta blankets from the marginal maria were found to be of great significance for the structure of the continents (M.S. Markov et al., "Geotectonika", in press).

Abastumani Astrophysical Observatory of the Academy of Sciences of the Georgian S.S.R. An atlas comprising 21 polarimetric maps of the Moon was compiled. Each map shows the distribution of the polarisation degree over the visible lunar disk during a given phase. The measurements were made using the polarovisor-discriminator (V.P. Dzhapiashvili et al., "Polarimetric Atlas of the Moon",

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Kharkov State University. Indicatometric measurements of lunar soil samples from the "Luna 24" mission were completed. Maps of the normal albedo of the visible hemisphere of the Moon were compared (V.I. Ezerskiy, et al., "Physics of the Moon and planets. Problems of astrometry". Vestn. Kharkov. Univer., [137], pp. 8-13, 1976). The problems of mapping the optical characteristics of the Moon were considered (N.N. Evsyukov et al., "Mapping of optical characteristics of the lunar surface", Kharkov. Univ., 1977).

The Institute of Geochemistry and Analytical Chemistry of the Academy of Sciences of the U.S.S.R. The first stage of the investigation of the lunar soil sample delivered by "Luna 24" on August 1976 from the south-eastern part of Mare Crisium was completed. A new type of mare basalt - very low-titanium, high-aluminium ferrobasalt - was discovered (Geochemistry, [10], 1977, pp. 1449-1515; PLSC 8, pp. 3257-3351). A ~100Å film of elemental Fe, Si, Ti, Al was found on the surface of lunar soil particles from "Luna 16" and "Luna 24" (Geochemistry, [10], 1977, pp. 1516-1533). Studies were continued of the relationship between crater morphology and size, the sequence of craters in space and geologic time (Florensky et al., The Moon, 16, 1976, pp. 59-70; Basilevsky, PLSC 7, pp. 1005-1020, 1977) and the data collected by "Lunokhod 1" and "Lunokhod 2" (Mobile lunar laboratory, "Lunokhod 1", v.2, Nauka, 1978; Basilevsky et al., The Moon, 17, 1977, pp. 19-28; Florensky et al., LPS 9, pp. 332-334, 1978).

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4. Working Group 1: Figure and Motion of the Moon

(J.D. Mulholland and M. Moutsoulas)

ORBITAL MOTION

The analytical theory of the lunar orbital motion continues to be the most important uncompleted problem in classical celestial mechanics. The "main problem", defined as the Earth-Sun-Moon triple system, is in reasonably good condition, and further progress is unlikely until the theory of the Earth's orbit is improved. For over a decade, the most urgent need has been for a new solution of the planetary perturbations, and this is still lacking, despite much discussion (1-4). Relativistic corrections are derived for the orbit elements (5), but their use awaits an adequate solution to the Newtonian problem. High-precision observational studies use, by necessity, purely numerical ephemerides generated by numerical integration, in which all planetary effects, as well as the non-sphericity of Earth and Moon, are incorporated in a relativistic formulation of the equations of motion (e.g. 6-8). Some of these ephemerides integrate the orbit and rotation simultaneously, since the two motions affect one another (9,10). Even some of the cross-coupling terms are no longer negligible (11).

The unmodelled secular acceleration in longitude is primarily of geophysical origin, but it may also have a cosmological component. Recent results tend to confirm that Spencer-Jones' value is not so erroneous as was thought a few years ago. Most of them fall within the range $d^2L/dt^2 = -26 \pm 5''/cy^2$, with overlapping error bars.

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Laser range data are still too time-limited to determine the cosmological component, but the upper limit established by the uncertainties, $|\dot{G}/G|<3\times10^{-11}$/yr, is at least compatible with bounds given by other methods (8, 12-14).

The equivalence principle for massive bodies has been tested by examining the "Nordvedt effect" in the lunar motion. Analyses of laser range data give a ratio of gravitational to inertial mass of unity $\pm 1.5\times10^{-11}$, which implies that the Brans-Dicke coupling parameter $\omega>29$ for a scalar-tensor cosmology (15,16).

ROTATIONAL MOTION

The "main problem" in the theory of physical librations has been extended to the few-centimeter level in translational motion at the lunar surface. The analytical and semi-analytical theories apparently still lack a completely consistent solution to the planetary perturbations (17,18). Numerical ephemerides currently attain a much higher internal coherence, but are of finite extent and limited availability (7, 9). One is thus sometimes led to use combinations of different theories in high-precision applications (e.g. 19).

Analysis of the effects of internal dissipation on the observed physical libration indicates a Love number $k_2 = 0.015$, which has been interpreted to give a value of 10 for the lunar dissipation parameter Q. This is difficult to understand physically, and other interpretations are possible, such as viscous interaction between the mantle and a significantly large fluid core (10). Such a low Q is also incompatible with the amplitudes of the free librations determined from the same laser range data; the free libration in longitude seems well-determined at 1"8 amplitude (20,21). Impact stimulation theory (22) suggests that such an amplitude requires a large Q, compatible with seismic results (∿5000), unless there has been a very recent large impact. A theoretical study of the elastic behavior of the Moon concludes that the rotation cannot be correctly computed from Euler's equations, but it is not clear how this affects any of the observational studies (23).

GRAVITATIONAL FIGURE

There is no method by which all of the lunar gravity field parameters can be determined from a single type of observation. Various subsets of these parameters have been obtained using spacecraft tracking, VLBI, laser range, and other data, and most results are in at least general agreement (6,7,20,24,25). Recent joint solutions using Lunar Orbiter 4 tracking and laser range observations have permitted a determination of the gravity field through degree 5 (26). Aside from their influence on the physical librations, these parameters provide an observational determination of the principal moment of inertia parameter C/MR^2, a measure of the internal structure of the Moon; while earlier results produced a value of 0.392, this combined study gives 0.3905 ± 0.0023.

GEOMETRIC FIGURE

Comparison of the geometric figure with the gravitational figure samples the past history of physical processes in the lunar interior. Apollo laser altimeter data show that the ringed mare basins conform to a single reference surface, whose geometric center is significantly displaced from the lunar mass center, suggesting a much different plastic behavior of the interior at some time in the past (27).

Mapping continues, with the publication of a new 1:1000000 scale series to replace the ACIC Lunar Astronautical Charts. The completion of the Apollo Control System (28) provides a basis for larger-scale (1:50000-250000) mapping of particular regions. Current work with improved spacecraft ephemerides should provide greater accuracy in the control net than is now available.

A new Earth-based selenographic system is being derived by using as primary benchmarks about 200 features that co-exist in the Apollo system. The position of the classical primary reference point for ground-based systems, the crater Mösting A, has been redetermined independently (29). Comparison of the Watts and Weimer charts for the shape of the visible limb has led to corrections to the Weimer system, reducing the residual dispersion by about 20% (30). A densification of the Weimer system is now underway.

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