Lunar Orbiter: Tracking Data Indicate Properties of Moon's Gravitational Field

Abstract. *After only a few days in orbit, the first U.S. satellite of the moon has already produced data which have provided new information about the moon's gravitational field. Results indicate that the spacecraft will probably not impact on the moon before it completes its photographic mission, but that it will probably do so in about 8 months. Preliminary indications are that the moon has a relatively large pear-shaped component and that the gravitational properties will be of considerable scientific interest.*

During the first few days after its injection into lunar orbit, we analyzed the tracking data produced by Lunar Orbiter I, the first U.S. satellite of the moon. We used a series of computer programs especially designed for this analysis. Our immediate purpose was to produce a first estimate of the overall gravitational field of the moon. This estimate was used to predict variations in the orbit of the spacecraft, in order to enable us to make decisions with respect to control of the mission. Our long-term objective is to determine the precise properties of the lunar gravitational field. We can achieve this objective only after considerably more data from Lunar Orbiter I and future lunar satellites have been accumulated.

Preliminary results from our analysis of the early data indicate that there is no danger that the spacecraft will impact on the moon before it completes its photographic mission, which involves approximately 8 days for taking photographs and 3 weeks more for reading out the data and transmitting them back to earth. The results further indicate that variations in the orbit during the photographic period will not significantly degrade the quality of the photographs. In particular, we estimated that the pericenter altitude would decrease by about 8 to 10 km during the first 4 or 5 days of photography and then increase by somewhat less than this amount during the remainder of the 8 days. We considered these results to be sufficiently accurate to permit an orbital transfer maneuver from the initial lunar orbit to a lower final orbit with pericenter altitude very near the optimum value for close-up photography, a maneuver which could not be designed with much degree of confidence prior to this first flight because of lack of knowledge of the higher-order components of the lunar gravitational field.

In our analysis, to provide an overall estimate of the lunar gravitational field for mission control, we solved for some 21 coefficients in the expansion of the gravitational potential function in terms of spherical harmonics through degree and order 4 (*1*). Even though the program is capable of solving for additional coefficients, this number was thought to represent a reasonable sampling of the gravitational components for the intended purpose. A number of the coefficients changed somewhat as the data arc was increased, a situation to be expected in view of the short data arc, which produced high correlations between the various coefficients. However, short-term predictions of orbital variations with complete sets of coefficients gave consistent results. The variety and magnitude of the coefficients obtained in these early solutions indicate that the gravitational field of the moon has some interesting properties. With one possible exception, we do not consider these early solutions sufficiently precise to permit discussion of particular coefficients in any detail.

Preliminary indications are that the moon has a relatively large coefficient for the third zonal harmonic ($C_{3,0} = -J_{3,0}$), with a value of about 1×10^{-4}. This is the gravitational field component which can be visualized as a very slight tendency toward the shape of a pear superimposed on the essentially spherical figure, axially symmetric with respect to the polar axis, and with the stem of the pear at the north pole of the moon. As a basis for comparison, the corresponding value for the earth is about 2.5×10^{-6}, or about 1/40 as large, with the same sign. Assuming that the density within the moon is uniform and equal to the mean density, we find that the pear-shaped component would correspond to a bulge at the lunar north pole of about 0.4 km, a depression at the south pole of the same amount, and an intermediate depression and bulge in the northern and southern hemispheres, respectively, of half this amount. However, we do not suggest that this pear-shaped component constitutes the overall figure of the moon, for all the other coefficients also contribute to the figure. These coefficients must be included when they have been determined with some degree of confidence.

The major effect of the third zonal harmonic on satellite motion is that it causes a periodic variation in the eccentricity of the orbit, and consequently, a periodic variation in pericenter altitude, with a period equal to that of pericenter revolution. With $C_{3,0} = 1 \times 10^{-4}$, and with the present pericenter altitude of Lunar Orbiter I, it is highly probable that the spacecraft will eventually impact on the surface of the moon. Our preliminary estimate is that impact will occur in about 8 months.

It is of interest to compare our preliminary estimate of the value of $C_{3,0}$ with values discussed by other authors prior to the flight of Lunar Orbiter I. On the basis of an argument pertaining to accommodation of equal stress in the moon and in the earth, Kaula (*2*) determined a scaling factor to be applied to values of coefficients of the gravitational field of the earth to arrive at estimates of those for the moon. In this manner he estimated $\pm 0.93 \times 10^{-4}$ as an upper value for $C_{3,0}$ for the moon; the magnitude of his coefficient compares favorably with our estimate. C. L. Goudas has made surface harmonic studies, based on several independent sets of coordinates of points on the lunar surface, from which he has derived estimates of $C_{3,0}$. His work and assumptions are conveniently summarized by Kopal (*3*). From one set of points he determined a value of 0.98×10^{-4} for $C_{3,0}$, but from another set he found about the same magnitude but the opposite sign. We can only say that a value he obtained from one of the sets he investigated compares very favorably with our estimate.

The tracking data used in this analysis were two-way Doppler data, providing a measure of the relative velocity between the spacecraft and the stations of the NASA Deep Space Network in Australia, Spain, and California. The main computer program is based on the procedures of differential corrections and weighted least squares, with a 12th-order numerical integration of Cowell-type equations of motion. All calculations are performed in double precision.

Tracking data will be obtained from Lunar Orbiter I as long as the spacecraft is in operation. The preferred period for obtaining tracking data for gravitational field determination is after the end of the photographic phase of the mission, at which time spacecraft maneuvers will be curtailed in order to minimize extraneous factors.

WILLIAM H. MICHAEL, JR.
ROBERT H. TOLSON
JOHN P. GAPCYNSKI
NASA Langley Research Center, Hampton, Virginia

References

1. W. H. Michael Jr., and R. H. Tolson, "The Lunar Orbiter selenodesy experiment," in proceedings of the 2nd International Symposium on the Use of Artificial Satellites for Geodesy, Athens, Greece, 1965, submitted for publication.
2. W. M. Kaula, in *Advances in Space Science and Technology*, F. I. Ordway, Ed. (Academic Press, New York, 1963), vol. 5, p. 210.
3. Z. Kopal, *Space Sci. Rev.* 4, 737–855 (1965).

25 August 1966

Oxygen Fugacities Directly Measured in Magmatic Gases

Abstract. *An electrochemical device was used to measure the fugacity of oxygen* (f_{O_2}) *in holes drilled through the crust of Makaopuhi lava lake, Kilauea Volcano, Hawaii. Results obtained within 6 months of the lake formation show that log* f_{O_2} *normally varies linearly with the reciprocal of the absolute temperature, and that chemical changes occurring in the cooling tholeiitic basalt are reflected in the* f_{O_2} *values measured in the holes.*

Knowledge of the fugacities of volatile components in magmas at various stages of crystallization is vital to clear understanding of the mechanisms of igneous and associated processes. Particularly emphasized recently is the fugacity of oxygen (f_{O_2}); it is now realized that oxygen fugacity is one of the more important factors in determining the course of differentiation in basaltic magmas (*1, 2*). Most work on this subject to date, however, has concentrated on laboratory studies of simple mineral assemblages under controlled atmospheres; experiments with natural rock samples are few (*3, 4*). Other approaches to the problem depend on thermodynamic extrapolations of equilibrium oxygen fugacities of analyzed volcanic and fumarolic gases (*5, 6*), or of observed mineral assemblages (*7*), to high temperatures.

To obtain data in a more direct way, a project was launched (*8*) to develop a reliable, rugged, and sensitive probe to measure oxygen fugacities of magmatic gases above and within a body of crystallizing basaltic magma. While the laboratory work was still in progress, an eruption occurred on the upper east rift of Kilauea Volcano, Hawaii, 5 March 1965; a circular lava lake of tholeiitic basalt was created, approximately 400 m across and 82 m deep, in the west pit of Makaopuhi Crater. During the eruption, the lava varied little in bulk chemical composition (SiO_2, 50.06 to 50.19 percent; MgO, 8.33 to 8.49 percent by weight), and except for minor settling of crystals of olivine it has not since differentiated appreciably.

Wright observed that minerals began to crystallize at the following temperatures: olivine, about 1200°C; augite clinopyroxene, 1180° ± 10°C; plagioclase, 1160° ± 5°C; and opaque minerals (ilmenite followed by magnetite), 1070° ± 10°C. The solidus with 3 to 5 percent residual glass was estimated at 990° ± 10°C.

After the lava solidified to a depth of a meter or two, a number of holes were drilled through the crust and an oxygen probe (later described) was inserted. The results of the first series of measurements, between 3 and 6 months after the eruption, revealed interesting and previously unknown features of oxygen fugacities over a crystallizing basalt magma.

The oxygen probe is an electrochemical oxygen-concentration cell arranged

Ni–NiO mixture, Pt | reference f_{O_2}
$(ZrO_2)_{0.85}(CaO)_{0.15}$ | solid electrolyte for O^{2-} ion
Pt, gas phase unknown f_{O_2}

which operates reversibly at temperatures above approximately 600°C and at oxygen fugacities above 10^{-22} atm (*9*). The zirconia-lime solid solution is a chemically unreactive and highly refractory material that becomes a good oxide-ion conductor at elevated temperatures because of oxygen vacancies in its fluorite-type structure (*10*). It is very useful, therefore, as the electrolyte in a high-temperature oxygen-concentration cell (*11*) and is commercially available for fuel-cell application. The electrode reactions at the boundaries of the electrolyte correspond to the reaction

$$O_2 + 4e \rightleftarrows 2O^{--} \quad (1)$$

and the emf of the above cell is therefore given by the relation:

$$E = (RT/4F)\ln [f_{O_2}\,(\text{unknown})/f_{O_2}\,(\text{reference})] \quad (2)$$

where R is the gas constant, T the absolute temperature, and F the Faraday constant. An equation describing the equilibrium oxygen fugacity of the mixture Ni–NiO was given by Eugster and Wones (*12*); by substitution of it for the reference oxygen fugacity and by use of proper numerical values for the constants, Eq. 2 reduces to

$$\log f_{O_2}\,(\text{unknown}) = \{[(2.02\,E - 2.47) \times 10^4]/T\} + 8.94 \quad (3)$$

from which the oxygen fugacity of the gas phase is determined by substituting the measured values of the emf and the temperature.

In construction the oxygen probe resembles a design suggested by Schmalzreid (*9*). A powdered mixture of nickel and green nickel oxide (2:1 mole) is packed in the lower one-third of a flat-bottomed, impervious tube of the zirconia-lime solid solution, which is 3.8 cm long and 8.5 mm in outer diameter. The mixture is electrically connected to a platinum wire by way of a column of nickel powder. The tube is sealed with mullite cement and a fired pyrophyllite plug having a small hole in the center for the platinum wire. Another platinum wire is wound around the lower exterior wall of the tube for several turns and insulated from the rest of the tube by sheathing with a small alumina tube.

For insertion into drill holes the probe is fitted into the lower end of a 61-cm-long alumina tube in which slits are cut for better exposure to the magmatic gases. The alumina tube is attached in turn to stainless-steel tubing; inside the tube, the platinum wires of the probe are connected to a pair of long platinum leads sheathed with mullite beads and mullite spaghetti.

The probe is tested and calibrated in the laboratory before use in drill holes. The probe lasts for several hours in air at approximately 1000°C if the seal is tight and thermal shocks are avoided; it fails to operate properly when the column of nickel powder, oxidized by oxygen leaking through the pyrophyllite plug, can no longer protect the reference mixture from the atmosphere. It also fails when the zirconia tube is cracked by thermal shock or by increase in volume of the nickel column by oxidation. Its lifespan is greatly extended in the reducing atmosphere of an uncontaminated magmatic gas.

When the emf is measured with a vacuum-tube voltmeter of a high input impedance, the probe responds almost instantaneously and reproducibly to