OBJECTIVES AND REQUIREMENTS OF UNMANNED ROVER EXPLORATION OF THE MOON

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Abstract. The scientific value of unmanned rovers for continued lunar exploration is considered in light of Apollo findings which suggest that the Moon's surface is more heterogeneous than expected. A set of major questions and investigations involving composition, internal structure, and thermal history are presented that form a scientific rationale for use of unmanned rovers in the post-Apollo period of lunar exploration. Visual, petrologic, chemical and geophysical measurements that are essential for an unmanned rover traverse over previously unexplored lunar terrain are discussed. Unmanned rovers are well-suited for low-cost, low-risk preliminary reconnaissance where measurement of a few definitive parameters over a wide area is more important than obtaining a wide array of detailed results at a given site.

1. Introduction

Apollo 11 and 12 results, together with recently announced reductions in the manned lunar exploration program, necessitate a re-evaluation of the utility of unmanned Lunar Roving Vehicles for achieving the scientific objectives of lunar exploration. Use of unmanned roving vehicles in lunar exploration has been recommended by several groups of scientists (Adams *et al.*, 1969; Hess, 1967; Nat. Acad. Sci., 1969). The role of unmanned rovers is generally considered to involve reconnaissance traverses and widespread geophysical surveys. Many of the principles for rover utilization discussed here have been discussed in previous reports (e.g., Speed *et al.*, 1965; Jaffe *et al.*, 1970). However, we wish to emphasize the unique and indispensable value of the roving vehicle – a value which is *not* preempted by returned sample studies. This special value of rover exploration derives, in part, from the discovery by Apollo sample studies that the Moon is more chemically evolved and *heterogeneous* than first thought. Examination of gross lunar properties is now required to convert the detailed, but intensive and highly local information obtained from returned sample studies to extensive, or bulk lunar properties. Many parameters that appear to vary randomly over a small area may do so only because of local impact homogenization, and in the large, may exhibit precise systematic variation. To expose such systematic variations, either an impractical number of stationary landers, or a few landers with long traverse capability, must be employed.

The possible use of unmanned rovers should be in accord with a logical overall plan for post-Apollo lunar exploration. The scientific rationale should be based on the following considerations:

(1) Major scientific objectives of post-Apollo exploration.

(2) General types of exploration strategy in which unmanned rover exploration is more useful than other approaches.

(3) Specific measurements or observations, relative to the major science questions, which are within the performance capability of an unmanned roving vehicle.

It is essential first to outline some major scientific objectives for the post-Apollo missions based upon our present knowledge of the Moon gained from the Apollo 11 and 12 missions and from previous unmanned missions.

2. Present Major Scientific Questions

The major goal of lunar scientific exploration remains to determine the origin and history of the Moon and its implications for the origin and history of the Earth and the solar system. At present the major hypotheses of lunar origin are: (1) accretion as an independent body subsequently captured by the Earth, (2) accretion independently within the Earth's gravitation field, or (3) bulk fission or volatilization from the primitive Earth. To distinguish between these, evidence must be obtained on the events and processes affecting lunar material during the primitive stage of planetary accretion and solar system formation.

From Apollo 11 and 12 results, we know the Moon is, in many ways, a more primitive and less modified object than the Earth. We can therefore expect the Moon to provide information on the formation of bodies, particularly the Earth, in the early history of the solar system. Lunar surface material appears to be chronologically old, but highly 'evolved' geochemically and petrologically (i.e., differentiated). In an absolute sense, the Apollo 11 and 12 samples cannot be considered chronologically primitive. Studies of Apollo samples indicate that, although older than Earth rocks, most lunar crystalline rocks (basalts) appear to have crystallized less than 3.7 billion years ago (cf. Lunar Sample Examination Team, 1969, 1970), nearly a billion years after chondritic meteorites crystallized, and after the most eventful portion of lunar history. Also there are indications from geochemical material balance calculations that mare basalt may be chemically representative of 5% or less of the mass of differentiated material on the Moon (e.g., Urey *et al.*, 1971). Obviously, then, a critical step in tracing lunar evolution is to search for indigenous lunar material which is more primitive chronologically and/or chemically than mare basalt. Even if truly unmodified or primordial lunar material is not to be found on the surface, it is important to find and analyze other large, highly evolved lunar rock types that, like the mare basalts, were ultimately derived from the bulk starting material. This information, together with geophysical data on the deep interior, may allow us to resynthesize or hypothetically establish the composition of bulk lunar material from its component derivative parts.

To determine the overall composition and the accumulation history of the Moon, it is necessary to know not only the chemical and petrographic characteristics of rocks representative of the two presently obvious surface provinces, the maria and highlands, but also the mass fraction of the Moon each represents. This can be estimated based on seismic, deep electro-magnetic sounding, and heat flow results, together with constraints imposed by geochemical material balance calculations.

Representative data are therefore needed on the chemical and petrographic character (including trace element abundances) of the highlands and their structural relationship to the maria. In addition, data indicating the nature of material beneath the maria and highlands must be sought. Eventually, some aspects of the nature of the processes (especially the energy sources) causing chemical differentiation on the Moon can be inferred, as well as some characteristics of the bulk initial material on which these operated to produce the observed surface materials. It must be borne in mind that important or abundant rock types may have originally existed in the mare regions that now have only scanty surface expression, owing to efficient coverage by later mare basalt flows. The search for remnants of these requires great mobility in the exploration system used.

From study of Lunar Orbiter photographs of craters and very large unfilled basins (e.g., Orientale) we have a general idea of the structures developed by large impacts on the Moon, and on the overall geometry of the mare filling. We have, however, no clear indication of the time history of mare filling, or of the nature of 'anomalous' characteristics such as mascons. Evidence of post-basin, pre-mare-fill cratering suggests that the time of basin formation and that of mare filling may be significantly different. The history, extent, and cause of filling bear directly on the early thermal history of the Moon, and on the past and present mechanical state of the interior.

Thus, we need to determine the crystallization ages of rocks from possible indigenous pre-flow material within the maria, and from immediately adjacent highland material. If the proper techniques and sampling procedures are employed, these may date the impact and time of basin formation, which can then be compared with the time of filling based on the chronology of mare basalt.

In theoretical studies, the thermal history of a planet is strongly coupled to the accretion history which determines initial temperature and perhaps compositional profile. The calculations require specification of radioactive abundances, which are obtained from data on terrestrial materials, meteorites, and now from lunar samples. The resulting models must be consistent with: (1) data on the deep interior, including seismic and electromagnetic sounding data, and the figure of the Moon, (2) observed surface heat flow, (3) geochronologic and possibly paleomagnetic data, and (4) surface chemical and petrographic data. Our ability to reconstruct earliest lunar history will be strengthened by seismic determinations of lunar internal structure, determinations of remnant magnetic fields, widespread determinations of heat flow, and absolute and relative age relations of major lunar rock provinces.

From these interrelated problems evolve a set of major questions dealing with lunar history and a set of prerequisite investigations, the results of which will allow that history to be deciphered.

A. MAJOR QUESTIONS:

(1) Initial source of bulk lunar material: (a) where was its location in the circumsolar cloud or in the Earth? (b) what was its preaccumulation chemical evolution?

(2) Mode of accumulation of the Moon; (a) did it accumulate by independent accretion or by derivation from the Earth? (b) what was the time of accumulation, i.e., elapsed time since the effective cessation of nucleosynthesis? and (c) what was the duration of accumulation?

(3) Post-accumulation lunar history: (a) what are the major Moon-wide geological processes and their energy sources: (b) what are their chronologies.

B. PREREQUISITE INVESTIGATIONS:

(1) Distribution of surface chemical and isotopic compositions, including trace elements.

(2) Distribution of major rock types and their mineralogical and petrographic variations.

(3) Correlation between morphology, composition, and chronology of surface material.

(4) Present thermal regime including internal temperature distribution.

(5) Internal structure and petrology, and physical state of the interior.

At the completion of the Apollo missions, it is unlikely that satisfactory answers to any of these questions will have been obtained due to the small number of sites visited. Missions of the unmanned rover type are unlikely to provide complete answers to the major and prerequisite questions, but they may provide a unique means for step-by-step accumulation of essential scientific data that would otherwise be unreasonably expensive or hazardous to obtain.

3. Detailed Investigations

To provide answers to the broad questions just discussed, detailed investigations must first be completed to answer some critical questions regarding the systematics of surface and near-surface properties of the Moon that have been posed by the results of Apollo 11 and 12 missions. The Apollo studies showed that the Moon is heterogeneous and complex in terms of its chemistry, structure and chronology. This complexity is not random or chaotic, but has system or order that can be understood by sufficient sampling in a geologic context.

Search for bedrock. We have no clear-cut idea of the initial field relations for any of the crystalline rocks obtained by Apollo 11 and 12. The question is, does the regolith represent the underlying bedrock, or is it a quasi-sedimentary deposit of diverse origin? We do not know whether the Apollo rocks are indigenous to the collection sites or; if indigenous, what position in the local stratigraphic column they represent. We cannot tell at present whether these crystalline rocks result from minor local volcanic activity (either intrusive or extrusive) or Moon-wide activity. The cause of the apparent hiatus between the formation of mare basins (at 4.5 billion years?) and filling would be extremely important if it were a Moon-wide event. Thus, important objectives in future lunar surface explorations should be to: (1) search for and sample outcrops of *in situ* lunar bedrock, (2) determine the stratigraphic positions, contact relationships and orientations of specimens obtained from these outcrops.

The local stratigraphic column at any mare (or highland) site is presumably most clearly exposed in fresh crater walls, although where they occur, outcrops may be covered by fall-back debris and slump deposits and distorted by impact. The rim deposits contain material from within the region of the crater bowl, but at present the relevant stratigraphic relations are indeterminate in detail. Undistorted, though perhaps poorly exposed stratigraphic columns and cross-sections could be obtained in rille or graben-like structures. The rearch for near-surface bedrock might well center on such features. Distorted bedrock, perhaps from great depth, might be found at major central peaks.

Determine the physical properties below the regolith. The 6 m thick regolith observed at the Apollo 11 site (Shoemaker *et al.*, 1971) may be merely that produced in the 3.5 billion year history of the mare surfaces by a relatively low flux (compared with the accretion flux) of very high-energy meteoroid bombardment from the asteroidal belt and beyond. This low regolith thickness is compatible with the observed crater density and age relations in the maria and (possibly) the low abundance of meteorite material in the regolith.

Present data suggest a complicated history of discontinuous mare filling, over an extensive period of time, which produced stratigraphic sequences of flows, multiple regoliths and possibly intercalated intrusive layers. Beneath the mare fill and in the highlands we might expect a 'mega-regolith' perhaps kilometers in thickness, created by final stages of the lunar accretion flux. This larger regolith may be compatible with the essentially saturated distribution of 10–100 km craters on the highlands and far-side; mare flows may merely represent islands of consolidated material within this regolith. According to these arguments, the primitive, crater-saturated surface may be hidden by basalt flows both on the maria and locally on the highlands. The mare basins *per se* may belong to the early distribution. One objective, then, is to search for density variations or discontinuities at depth up to several kilometers. Below a few kilometers, phase changes (solid-solid and possibly solid-liquid) and compositional changes may produce both gradual and sharp changes in density and rigidity. Rover may deploy an appropriate sensor array for seismic studies and the detection of such structure.

Correlate the distribution and field relations of surface rock types. It is important to correlate the broad distributions of rock type with features on Lunar Orbiter photographs or with geologic units inferred from the photographs. The objective is to relate, where possible, compositional parameters to terrain province or type, elevation, gravimetric orbiter data (over large areas), and location on the Moon. Such correlations will allow us to extrapolate properties beyond the areas covered by rover. Of special interest are mare-highland boundaries.

Determine the distribution of crystallization ages. Both the absolute (radiometric) and relative (structural and stratigraphic) ages of rock units are required from wide areas on the Moon in order to understand the nature of the maria filling, the chronology of rocks and events below the regolith, and the age relationships between mare and highland deposits.

Determine the distribution of natural radioactivity. The objective is to determine the surface distribution of K, U and Th and its correlation with rock type, geologic age, and location on the Moon. Ultimately this, in conjunction with other data, will allow us to estimate the vertical and lateral extent of the strong K, U and Th surface enrichment (over meteorities). This information is crucial to our understanding of the magmatic and energy history of the Moon as a whole.

Search for gas evolution (ambient atmosphere). Ambient atmospheric pressure and composition should be measured as functions of: (1) proximity to suspected local indigenous sources of volatiles as indicated by transient or periodic phenomena such as surface obscuration, seismic activity or thermal anomalies, (2) proximity to the terminator at sunrise, and (3) times of occurrence of Earth tide maxima or local seismic activity.

Measure temperature and heat flow. Temperature versus depth in different terrain provinces together with thermal conductivity should be measured in order to determine surface heat flux. With estimated dimensions of regions of radioactive enrichment, this can then be related to the contribution of heat from internal radioactivity and other heat sources such as initial heat.

Measure surface gravity profiles. Widespread surface values of gravity should be obtained for comparison with orbital values. Gravity measurements by rover are therefore desired in mare sites and across highland-mare boundaries. Emphasis should be on measurements in those regions where orbital anomalies such as mascons are well determined.

Search for magnetic fields. The objective is to search for permanent or remnant fields and variations with position, since these are related to the present and past thermal state of the interior.

Conduct deep electromagnetic sounding. Deployment of a net of surface magnetometers would allow analysis of the interaction of the time-varying interplanetary magnetic field (as measured by orbiting magnetometers such as on Explorer 35) with the deep interior of the Moon. From such observations, estimates of internal conductivity and temperature may be obtained.

Search for unusual and unpredicted features or phenomena. Because of its high mobility and lifetime, rover has great potential for discovering unexpected or highly atypical features. These may include rock types that (though possibly abundant) are rarely exposed on the surface, surface coatings or morphology, permafrost in permanently shadowed polar areas, local thermal anomalies, features associated with ray deposits, and surfaces that have been unshielded as well as those that have been well shielded from external radiation or particulate bombardment for substantial periods of lunar history.

4. Manned Versus Unmanned Rovers

All of the detailed programs of exploration just cited require observation over wide areas on the Moon. A rover has the required property of mobility. It should be used for: (1) efficient measurement of widespread lateral variation of surface and subsurface parameters, (2) investigation of important lunar sites too dangerous or impractical for manned approach, including those that require great landing accuracy, and (3) for traverses that might otherwise take too much time.

An important but difficult question is the relative value of manned versus unmanned roving vehicles for performing the above tasks.

The effectiveness of the manned rover, especially one involving geologist-astronauts, would seemingly be superior to the unmanned rover because of the versatility, high quality of observations, and real-time tactical judgments an astronaut could provide. On the other hand, the practical advantages of unmanned missions of the rover type are:

(1) No concern for astronaut safety or well-being.

(2) Time limitations on length of traverse or stationary stay time dictated only by rover capability, not human needs. This means that unmanned rovers can be committed to long traverses in otherwise unreachable or dangerous terrain. It also means greater time for real-time sampling decisions, which is crucial for some types of non-visual information (e.g., radioactivity).

(3) Unmanned missions are cheaper to implement than an equivalent manned program.

These logistic considerations underscore the fact that unmanned rovers are well suited for low-cost, low-risk preliminary reconnaissance where measurement of a few definitive parameters over a wide area is more important than obtaining a wide array of detailed results at a given site.

5. Role and Capability of Unmanned Rover

The chief role of roving vehicles is surface geological and geophysical reconnaissance of wide areas of unexplored terrain, especially in regions where there are heterogeneities and discontinuities in surface and subsurface properties as delineated by Apollo studies, Lunar Orbiter and Apollo photographs, and by other remote-sensing techniques. *In situ* imaging, semi-qualitative analyses, and subsurface geophysical sensing are considered essential. Sample return capability, although extremely desirable, would limit, somewhat, the utilization of rover capability, since either (a) the traverse would have to end at a point suitable for rendezvous with an ascent system, or (b) the rover would have to carry its own ascent system, which would limit the science payload and impose restrictions as to where the traverse could terminate for launch. Sample return tasks may be better suited for manned missions where return is mandatory, or for unmanned limited mobility spacecraft devoted solely to that task at sites that have been shown worthwhile to sample by rover precursors or by information derived from remote observations. However, given the impending curtailment of the manned program, the capability for sample return from long rover traverses assumes greater value.

The rover should have the following fundamental operational capabilities:

(1) Mobility adequate enough to allow travel over a wide range of terrain types

and slopes as delineated from Apollo studies and Orbiter photos.

(2) Imaging system with the dual purpose of navigation and scientific observation (see below).

(3) Ability to obtain accurate location and orientation with respect to an appropriate lunar coordinate system or to landmark features recognizable in Orbiter photographs.

(4) Ability to make orientation and inclination measurements on discernible structures or bedding in rock units when viewed with the imaging system.

(5) The ability to excavate suspected outcrops and obtain fresh *in situ* rock surfaces for examination by the imaging system.

(6) An adequate sample acquisition and manipulation mechanism enabling observation of specific mineralogical features or other textures or structures under a variety of seeing conditions and magnifications.

(7) Ability to coordinate multiple-sensor simultaneous observations from several sites, e.g. a rover-deployed seismic or electromagnetic-sounding arrays.

To use the mobility of rover effectively, the instruments carried and tasks performed by a rover must be simple, reliable, and functional in a manner not restricting mobility. Far more will be learned by a few simple, but pertinent, measurements made at many sites than many detailed but superfluous and time-consuming measurements made at only a few sites. Also, a simple payload, hence a simple set of returned data, is more conducive to real-time operational and tactical decisions. These may be crucial in dealing with unexpected situations that could arise on a reconnaissance mission in previously unexplored terrain.

6. Essential Rover Measurements

The optimum scientific measurements for a rover which appear to be within its capability, are those that characterize surface geological units in terms of morphology, texture, and composition, and those of a geophysical nature that permit determination of deeper subsurface structure. Desirable parameters for measurement are those that are apt to vary over a long traverse, and the variation of which can be *correlated* with (1) lithology or morphology as deduced from Apollo and Lunar Orbiter photographs, (2) photometry and spectral reflectance as observed telescopically, and (3) gravimetric and electromagnetic properties as observed from orbit.

Based on the above criteria, a few relatively simple, but fundamental, surface measurements appear essential for unmanned rover traverses over previously unexplored lunar terrain. These measurements are practical and likely to be most feasible within the expected constraints of a rover program.

(1) Continuous high-resolution imaging in the visible, ideally in color and with spatial resolution of at least 0.1 mm in close-up mode. Mono- and steroscopic panoramic views and close views of selected outcrops as well as of individual 'hand specimen' size fragments. Search for bedrock, and delineation of field relations of rock units (e.g., distinction of intrusive and depositional contacts). Determination of

rock texture and fabric are usually done visually, but it seems unlikely that reliable rock identification (to the extent this is valuable) can ever be achieved through the use of imaging systems alone – especially since lunar rocks comprise an unfamiliar array and are often fine grained. Instead, we recommend that this be supplemented with some easily performed compositional measurement requiring no wet chemistry or complicated sample preparation that can, by inference, allow recognition of petrologic boundaries or exotic samples of special interest.

(2) Continuous qualitative compositional characterization of surface material and bedrock outcrops in terms of bulk elemental composition and some easily (no wet chemistry) measured parameters. Gamma-ray and near-infrared-reflectance spectrometry may be suitable tools for this purpose, since radioactive abundances and spectral reflectance characteristics may often be correlated with other chemical and mineralogical parameters. No sample preparation would be required.

(3) Discontinuous but detailed elemental and mineralogical characterization possibly utilizing X-ray diffraction methods of selected specimens or at sites of special interest as delineated by continuous imaging and qualitative compositional determinations. This implies a sample acquisition and preparation system.

(4) Geophysical measurements:

(a) Gravity profiles (discrete measurements with spacing depending on observed variations).

(b) Heat flow measurements (discontinuous) with 'sensitivity' sufficient for detecting fluxes of 10^{-6} cal sec^{-1} cm^{-2}. This is ordinarily an extremely difficult measurement and may not be feasible for an unmanned rover.

(c) Seismic measurements (discontinuous) utilizing deployed surface charges as well as natural (impact or orogenic) events and the 'triggering' effect of Earth-tides.

7. Conclusion

Results obtained by Apollo at widely separated points on the Moon indicate that the physical and compositional properties of the Moon's surface is highly variable from place to place. In order that generalizations according lunar history and origin can be derived despite this complexity, the highly local results of Apollo must be tied together by many additional surface measurements made at intermediate sites. Sufficient sampling of the major provinces on the Moon's surface are best achieved with an exploration system that has high mobility, tactical flexibility and longevity.

Detailed investigations have been outlined which will be essential for achieving the major scientific goals of determining the source of material which formed the Moon, the pre-accretion history of that material, its mode of accumulation, and its post-accumulation history. In continued exploration of the Moon after Apollo, emphasis should be placed on obtaining information which aids in (1) constructing bulk moon compositional models, (2) determinining lunar internal structure, and (3) deciphering the Moon's over-all thermal (energy) history.

These investigations require measurements over wide areas of the Moon's surface. To achieve this coverage and to relate results from Apollo samples to the much less detailed characterization by orbiters of broad geological provinces, mobile landers must be utilized. Unmanned rovers, in principle, have the kind of mobility and life-time that make them uniquely useful for continued low-cost but effective lunar scientific exploration of the post-Apollo period.

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