# RETURN TO THE MOON: LUNAR ROBOTIC SCIENCE MISSIONS



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## ABSTRACT

There are two important aspects of the Moon and its materials which must be addressed in preparation for a manned return to the Moon and establishment of a Lunar Base. These involve its geologic science and resource utilization. Knowledge of the Moon forms the basis for interpretations of the planetary science of the terrestrial planets and their satellites; and there are numerous exciting explorations into the geologic science of the Moon to be conducted using orbiter and lander missions. In addition, the rocks and minerals and soils of the Moon will be the basic raw materials for a lunar outpost; and the In-Situ Resource Utilization (ISRU) of lunar materials must be considered in detail before any manned return to the Moon. Both of these fields -- planetary science and resource assessment -- will necessitate the collection of considerable amounts of new data, only obtainable from lunar-orbit remote sensing and robotic landers.

For over fifteen years, there have been a considerable number of workshops, meetings, etc. with their subsequent "white papers" which have detailed plans for a return to the Moon. The Lunar Observer mission, although grandiose, seems to have been too expensive for the austere budgets of the last several years. However, the tens of thousands of man-hours that have gone into "brain-storming" and production of plans and reports have provided the precursor material for today's missions. It has been only since last year (1991) that realistic optimism for lunar orbiters and soft landers has come forth. Plans are for 1995 and 1996 "Early Robotic Missions" to the Moon, with the collection of data necessary for answering several of the major problems in lunar science, as well as for resource and site evaluation, in preparation for soft landers and a manned-presence on the Moon.

The exciting possibility exists of a mission to the Moon in early 1994. The project "Clementine" by SDI and NASA plans for long-life testing of sensor technology in the realistic, stressing, space environment, but will also fly to the Moon and go into polar orbit for two months. Its remote sensors will collect chemical, mineralogical, and physical data about the surface of the Moon. All these studies are part of the basic geoscientific characterization of the Moon as a planet, as well as a means of finding the Moon's best available resources. Such studies will affect our general understanding of the nature and origin of the Moon and of its resources. Most of the homework has been done for a timely return to the Moon. It remains to be done.

## Introduction

On July 20, 1989, on the twentieth anniversary of Neil Armstrong's first small step onto the Moon, President Bush stated the goals of "returning to the Moon, this time to stay" and "the first human mission to Mars." This effectively started the Space Exploration Initiative and set us back on course for manned exploration of these nearby planets. However, studies, strategies, and plans for just such an initiative have been a part of a subset of NASA's agenda since Apollo.

This paper will review some of the important plans for a return to the Moon in the immediate future. However, in order to put these plans into proper perspective, I will present a brief discussion of the science rationale of such a return and a historical review of several workshops and plans and preparations that have not come to fruition, yet have laid the groundwork for the present endeavors. A significant portion of the following has been taken from my files of reports from numerous workshops and committee meetings which have not been formerly published. I gratefully acknowledge use of these sources and thank one an all of the authors. In particular, the recent efforts of the members of the Lunar Exploration Science Working Group (LEXSWG) have provided substantial input to this review endeavor.

## Scientific Importance of the Moon

Before we went to the Moon and returned with samples, some postulated that its composition and consistency was similar to a green-colored dairy product. With the first examination of the rocks and soils brought back by the Apollo 11 mission, these conjectures were dispelled. And then began detailed dissection of these precious samples, which in turn led to theories for the origin and evolution of the Earth's sister planet. It was soon realized that the Moon's thermal budget rapidly decreased such that almost all of the magmatic activity was concluded after 1.5 billion years. What we are seeing today is the "death mask" of the Moon from about 3.0 Ga. Although the Earth and Moon are the same age, the Earth has maintained its thermal budget and has continued to evolve, erasing to a large degree any remnants of its early history. Inasmuch as the Earth and Moon are thought to have undergone approximately the same types of early evolution, it is felt that the Moon provides an invaluable "window into the Earth's past". Indeed, **the Moon plays a key role in planetary science,** a "role model" for the terrestrial planets. The Moon's origin is intertwined with that of Earth: its craters preserve a record of meteoroid fluxes through time, which relates to extinctions of life on Earth; it preserves a detailed record of its early evolution. The Moon is an ideal body on which to study the processes, such as impact, that have shaped the other solid bodies in the solar system.

**The Moon is the only extraterrestrial body from which we have samples from known locations.** The six U.S. Apollo and three Soviet Luna Missions samples nine distinctly different portions of the Moon. Granted, they were all restricted to the nearside equatorial belt. Based upon intense scientific study of these lunar samples, we have been able to reconstruct the birth and adolescent development of this planet. And **the Moon is the most accessible body in the Solar System making its exploration easier to achieve.**

The lack of an effective atmosphere (about $10^{-12\,\mathrm{torr}}$) on the Moon has permitted solar-wind particles to hit the surface of the Moon and to become imbedded in the soil. And as the soil was formed and "gardened" by micrometeorite impacts, layers developed within the upper regolith leading to the soil profiles which were sampled by the numerous corings and brought back to Earth. The various particles from the Sun provide us with detailed information of the evolution of its nuclear past. It has been said that **lunar soil preserves a 4 billion-year record of the Sun's history --** "the Moon is a solar telescope with a tape recorder".

With as much as we have learned about the Moon, there remain many unsolved problems in lunar science. Table 1 lists many of the questions which remain to be answered concerning the Moon. This list is not meant to be "all inclusive", but is meant only to refresh your memory about some of the most important lunar science issues. A perusal of this list amply demonstrates that, although we have come a long way in our understanding of the Moon, we have a ways to go. And many of these questions can only be answered from new data, both remotely sensed and from direct sample investigations.

**TABLE 1. Fundamental Questions in Lumar Science**

- What is the origin of the Moon and its relationship to Earth?
- What is the nature of primordial crust and mantle?
- What is the magmatic history of the Moon and how does lunar evolution set constraints for small planets?
- Was there a mágma ocean, and what was its nature?
- What is the full range of highland rock types and how are they related to each other?
- What is the full range and ages of mare basalt compositions and what are the spatial relationships of various basalt types?
- What is the nature, origin, and regional extent of KREEP?
- What is the nature of impact processes and how is material redistributed on local, regional, and global scales?
- Was there a cataclysmic bombardment 3.9 billion years ago?
- Is there water at the poles?
- What is the nature and evolution of regolith for airless bodies?
- What are the thicknesses and maturities of lunar soils?
- Does the Moon have an iron core?
- What is the origin of lunar paleomagnetism?
- What are the resource potentials of the Moon?

**How did the Moon form?** Actually we have narrowed in on the question rather well with what we refer to as the "Giant Impact Theory", wherein a large body about the size of Mars, 1/6th the mass of Earth, collided with the Earth at an early stage of its development some 4.6 BYA. The chemistry fits for such a theory and the dynamics do as well, particularly since our Moon is really far too large to be considered a true Moon - it is really a coexisting planet. **What is the evolution of the lunar crust and mantle?** This question involves establishing 1) whether the Moon really underwent an early phase of global melting to yield a magma ocean; 2) the thickness of the lunar crust, 3) the depth of early lunar differentiation; and 4) the structure and composition of the mantle. **What is the magmatic history of the Moon?** The question involves establishing 1) the nature and duration of igneous activity in the highlands; 2) the effects of early intense bombardment; and 3) the nature and duration of mare volcanism. **What is the history and nature of impact processes on the Moon?** This question involves 1) determining the depth of impact mixing in the highland crust; 2) establishing the size and shape of complex crater and basin excavation cavities; 3) determining the ratio of locally-derived material to primary ejecta in basin- continuous deposits; and 4) establishing the homogeneity or lack thereof in large basin impact-melt sheets. **Is there an iron-rich core in the Moon?** This question involves establishing 1) the siderophile element abundances in the Moon; and 2) geophysical techniques for direct detection of a core. **What is the thermal history of the Moon?** This question involves establishing 1) the mean surface heat flow; and 2) the present lunar geotherm. **What is the origin of lunar paleomagnetism?** This question involves establishing 1) direct detection of a lunar core; and 2) the orientations of regional surface magnetization as a function of surface age. **What is the nature of the lunar regolith?** This question involves improving our understanding of 1) vertical and lateral mixing in the regolith; and 2) the details of regolith maturation. It is our knowledge of this regolith which is the basis for our proposed exploitation of lunar resources.

We have only sampled about 5% of the lunar surface, which consists of a region plus and minus some 10-20° from the equator. The highlands are virtually unexplored. Because of latitude restrictions, the polar regions were not visited. Perhaps there is permanently frozen water there! We have never been to the backside of the Moon which from remote data seems to be distinctly different in lacking large basins and maria. All in all, we have done miraculously well with the few samples we have. Can you imagine parachuting down on a half dozen places on Earth and coming up with all the answers? We have so many major unanswered questions about our own Earth, such as when and where will the next major earthquake occur?

## Lunar Resources

The rocks and minerals of the Moon will be included among the raw materials used to construct a lunar base, largely because of the cost of bringing material from Earth. **The prime resources will be found in the assemblage of rocks and minerals which represent the end products of both internal and external geochemical and physical processes.** In particular, it is the relatively unconsolidated rock and mineral matter, the regolith, on the surface of the Moon which will almost assuredly provide the necessary resources for colonization. The fragmental material of the regolith is composed mostly of disaggregated rocks and minerals, but also includes glassy fragments fused together by meteorite impacts. The finer fraction of the regolith (i.e., $<1$ cm) is formally referred to as soil. The soil is probably the most important portion of the regolith for use at a lunar base. For example, soil can be used as insulation against cosmic rays, for lunar ceramics and abodes, or for growing plants. The soil contains abundant solar-wind implanted elements, as well as various minerals, particularly oxide phases, which are of potential economic importance. For example, these components of the soil are sources of oxygen and hydrogen for rocket fuel, helium for nuclear energy, and metals such as Fe, Al, Si, and Ti.

As the above discussion emphasizes, the soil will be the material base for most of the resource utilization. In order to "prospect" for such resources as solar-wind implanted hydrogen and helium, it necessary to have detailed knowledge of the maturity of the soils. This will necessitate an integration of chemistry and the ferromagnetic resonance measurement for the presence of single-domain native iron $I_s$/FeO, a value which directly relates to soil maturity. But the determination of $I_s$ will involve actual handling of the soil. All is not lost, however. It is possible to approximate the grain-size distribution of a lunar soil by remote sensing, and the grain size is roughly correlated with maturity.

It is interesting to speculate upon the possibility of lunar **ore deposits.** At this stage in the development of lunar base concepts, it is difficult to foresee the exact needs or economics of any such lunar endeavor. It is probable that we will never mine ores on the Moon in order to bring the metals back to Earth. However, there are certain minerals known to be present on the Moon which will undoubtedly be used almost immediately by the early lunar settlements -- e.g., native iron ($Fe^o$) for structural purposes and ilmenite ($FeTiO_3$) for oxygen production. In addition, other oxide minerals such as chromite ($FeCr_2O_4$) and ulvospinel ($Fe_2TiO_4$) may be used for their oxygen or metal contents.

Most of the "ore minerals" on Earth are sulfide and oxide phases. These concentrations of minerals most commonly result from deposition by hydrothermal solutions (i.e., 100-300°C watery solutions).

However, the Moon does not possess appreciable amounts, if any, of water; therefore, the presence of ore minerals deposited by hydrothermal solutions is improbable. However, there are other means of concentrating ore minerals (e.g., chromite, ilmenite) which are based on "fractional crystallization" and "crystal settling".

Crystallizing minerals will settle within a melt if their densities are greater than the melt. On Earth, such accumulations are commonly found in "layered intrusions" and are known as stratiform deposits. In fact, the mineral chromite, $FeCr_2O_4$, which constitutes the world's major source of the strategic metal, chromium, occurs in mafic strata of large igneous complexes. However, only 3 layered intrusives -- the Bushveld of Transvaal; the Great Dyke of Zimbabwe; and the Stillwater Complex of Montana -- are known to contain substantial amounts of chromite.

On Earth, particularly in remote regions, prospecting for ore deposits often entails aerial magnetic surveys. This is an advanced technology. It is possible that this can be adapted to remote sensing from an orbiting satellite such as a lunar orbiter.

**Lunar Observer Mission**

It should be apparent from the above discussion that we are in need of a return to the Moon for the sake of science, as well as for preparation for lunar base. Such a plan has been around since the very end of Apollo. In the mid 1970s, plans were made for **LPO,** a lunar Polar Orbiter mission. Each year a "new start" was not forthcoming, and these plans were moved ahead into the future. After some 10 years, the LPO lost any momentum that it had, and plans were made for the **LGO,** a lunar geochemical orbiter, modelled after the Mars Observer project, which was originally scheduled to start in 1984. In September, 1988, the **LEXSWG** (Lunar Exploration Science Working Group) was formed as an NASA advisory committee which set about promoting a **Lunar Observer.** The scope of the measurements to be made by the Lunar Observer were expanded over those of the former LGO flight package, and it had a proposed start date of 1996, using a Mars Observer backup duplicate space craft.

The science objectives of the Lunar Observer Mission were defined (Table 2). With the data gathered by such a mission, it would be possible to make major contributions to solving many of the problems listed in Table 1. The actual definition of the tasks for this mission are listed in Table 3. As can be readily seen, this orbiter was to be a "do it all at once" mission.

**TABLE 2. Science Objectives of the Lunar Observer Mission**

- Estimate the composition and structure of the lunar crust in order to model its origin and evolution;
- Determine the origin, nature, and size of the lunar magnetic field and estimate the size of a lunar core;
- Estimate the refractory element content of the Moon by measuring the mean global heat flow and using the refractory content of the crust as a constraint;
- Determine the nature of impact processes over geologic time and how they have modified the structure of the crust;
- Determine the nature of the lunar atmosphere and the physical basis for its sources and sinks;
- Assess potential lunar resources.

**TABLE 3. Lunar Observer Measurements to Satisfy Science Objectives**

- o Determine globally the chemical and mineralogical composition of the surface;
- o Determine globally the surface topography and gravitational field;
- o Map globally the distribution of surface magnetic anomalies and measure the magnitude of the induced dipole moment;
- o Obtain a global digital image database along with selected coverage in stereo and color;
- o Measure the microwave brightness temperature as a function of wavelength;
- o Measure globally the composition, structure, and temporal variability of the lunar atmosphere.

The Lunar Observer Mission was designed to make major contributions to the Space Exploration Initiative (SEI) of President Bush. Some of the important contributions to SEI are listed in Table 4. The science objectives of the Lunar Observer were obvious and many. This was an ambitious mission. However, it can be seen from Table 4 that the Lunar Observer also was designed to be a "precursor mission" to a manned-return to the Moon, with the establishment of a Lunar Base. In reality, **most of the needs for site evaluation for the establishment of a Lunar Base are met by the science objectives.**

**TABLE 4. Lunar Observer Contributions to SEI**

- o Contribution to Lunar Base/Landing Site(s) selection;
- o Lunar Base sight characterization - photography, topography, regolith properties, etc.;
- o Resource distribution;
- o Necessary for planning human and robotic fieldwork; remote station location;
- o Necessary for other disciplines:

Astronomy: meter-class altimetry for array site selection;
thick regolith for cosmic ray shielding;
low-frequency radio environment;
Space Physics: knowledge of radiation background;
Baseline characteristics of atmosphere before human operations.

The "payload" for the Lunar Observer was impressive (Table 5). It is effectively a "wish-list" of flight instruments, designed to provide major input into the objectives for lunar science, Lunar Base, and resource evaluation. In fact, the almost 20 years of study and planning had seen the addition of new objectives with the need for new measurements and new instruments. It was a mission which was an essential step in providing the wealth of scientific and engineering information which can lead to flexible and enduring human exploration of the Moon base. Because of the billions of dollars to be invested in a Lunar Base venture, site selection will be one of the most critical decisions to be made by scientists, engineers, and policy-makers in the 1990s. Furthermore, it was considered that if the Lunar Observer was launched early enough, the results could affect conceptual studies detailed design and engineering, and implementation and testing phases of the entire Lunar Exploration Program. The development and siting of future lunar bases could have been significantly enhanced by the Lunar Observer Mission. The bottom line to this proposed mission was to proceed in a timely fashion. However, **the Lunar Observer Mission seems to have "died under its own weight"** so to speak, with all the good words by everyone but without achieving a new start in NASA. This mission involved some 12 flight instruments and had become a huge billion dollar program, not feasible for the austere budgets of the early 1990s.

**TABLE 5. Strawman Payload for the Lunar Observer**

| Instrument | Application |
|---|---|
| Imaging | Geology, Lunar Base Sites |
| Gamma-Ray/X-Ray Spectrometer | Surface Composition |
| Visual/IR Spectrometer | Surface Composition |
| Thermal Emission Spectrometer | Surface Composition |
| Laser Altimeter | Topography |
| Magnetic/Electron Reflectometer | Surface Fields, Induced Moment |
| Microwave Radiometer | Heat Flow, Regolith Properties |
| UV Spectrometer | Atmospheric Science, Environment |
| Neutral Mass Spectrometer | Atmospheric Science, Environment |
| Ion Mass Spectrometer | Atmospheric Science, Environment |
| Radio Sci. Nearside Grav. Field | O.D. and Farside Gravity Field |
| Radio Astronomy | MHz Survey, Experiment Design |

**A Return to the Moon in Retrospect**

Some of the highlights in the timetable of efforts to establish programs for the return to the Moon are listed in Table 6. An interesting thing to be recognized is that the "delta" in time between the time of a start or meeting date and the proposed launch date seems to always be 4-6 years. One of the few things that seems to have stayed close to schedule is the Mars Observer, with a planned launch date of August/September 1992.

Plans were to make two Mars Observer launch vehicles and to use the second as the Lunar Observer. But this was not done exactly. The competition within the NASA community has always been between a return to Mars versus a return to the Moon. The rationale for the Mars community has been, "Why go back to the Moon? We have already been there." They want a soft landing on Mars, with possible sample return, in preparation for a manned return. Against this rationale and the conviction of NASA administration, it was not feasible to consider much of a return to the Moon, especially if it was going to be as costly a venture as The Lunar Observer.

The President's speech on July 20, 1989, sorted out the priorities that everyone had been arguing over. The birth of SEI gave renewed hope for a return to the Moon in the near future. And the excitement of the moment was seized upon by Johnson Space Center, led to a large extend by Mike Duke. Several organization meetings and workshops were convened, including the Lunar Base Site Selection Workshop. The results of this study were to establish the site selection criteria in order to encompass the three factors of 1) Resource, 2) Science, and 3) Placement/Safety/Rescue Logistics. It became obvious from these meetings that we could not select the best possible site on the lunar near-side without knowing considerably more about the Moon. And the importance of a Lunar Observer became paramount once again.

**TABLE 6. Selected Dates in the Proposed Return to the Moon Timetable**

| Event | Calendar Time | Launch Date |
|---|---|---|
| GSFC LPO | March, 1975 | April, 1980 |
| JPL LPO Demise | December, 1976 | October, 1980 |
| SSEC Report | January, 1983 | November, 1989 |
| Mars Observer Start | October, 1984 | December, 1991 |
| LGO Workshop Report | March, 1986 | December, 1992 |
| LExSWG Formed | September, 1988 | January, 1996 |
| LExSWG 2nd Meeting | January, 1989 | January, 1997 |
| **Bush Speech** | **July, 1989** | **October, 1995** |
| LExSWG 3rd Meeting | May, 1990 | Oct., 1996-Mar., 1997 |
| Lunar Base Site Workshop | June/August, 1990 | 1998 - 1999 |
| **"Clementine" Mission** | **January, 1992** | **Jan.-April, 1994** |
| **Early Robotic Missions** | **February, 1992** | **1995, 1996, 1997** |

**Recent Developments**

The efforts of the numerous persons at Johnson Space Center have been responsible for several developments which have had major impact on the possibility of returning to the Moon in the near future. In July, 1991, a workshop was convened at JSC entitled, "Artemis, the Common Lunar Lander. The theme of this workshop was the consideration of a series of return-to-the-Moon flights with low-budget soft landers each with total payloads of <200kg. These landers were to include rovers with various scientific instruments. And these were to be controlled robotically from Earth.

In 1991, Mike Griffin became a new Associate Administrator (AA) in charge of Exploration for NASA. His vigorous leadership has really brought flames to several smoldering programs. Griffin's endeavors are premised on the idea that, in order to return to the Moon in these times of fiscal stringency, it will be necessary to gain the attention and support of the Congress and the American people. His plan consists of three strategic horizons: 1) return to the Moon immediately with low-budget orbiter missions, 2) in five years, to send people once more to the Moon; the last half of the 1990s should also see more robotic exploration of Mars; and 3) beyond 2000, focus on sending people to Mars. This is very optimistic, yet possible with the proper support from Congress and particularly from NASA.

In February, 1992, a workshop entitled "Early Robotic Missions to the Moon" was convened by Mike Griffin and his Exploration Programs Office as JSC. The purpose of this workshop was to effectively inventory possible instruments for orbiting missions to the Moon in 1995 and 1996. The first orbiter will be called "Lunar Geodetic Scout" and the second, "Lunar Resource Mapper". Each would have but three instruments, e.g., gamma-ray spectrometer, soft x-ray spectrometer, and spectral reflectance spectrometer. If all goes as planned, an "Artemis" lander would follow these orbiters in 1997.

**SDI/NASA Mission to the Moon**

Early this year (1992), the Strategic Defense Initiative Office (SDIO) of the Department of Defense announced project "**Clementine**" with plans to send a flight package into space in order to perform a long-life test of the sensitivity of SDI instrumentation to space conditions (e.g., vacuum, temperature extremes, cosmic/galactic/solar radiation, micrometeorite impacts). A "near-Earth asteroid" flyby will provide a realistic test of sensors and autonomous navigation. NASA has proposed that certain remote-sensing instruments also be carried aboard this craft and that initially it be put into orbit about the Moon - effectively a lunar polar orbiter. After about two months of data gathering at the Moon, the spacecraft could be powered out of orbit and sent into outer space for a rendezvous fly-by of the near-Earth asteroid "Geographos". The proposed launch date which SDIO plans is between January and April of 1994, with the fly-by occurring in August of that year.

If this combined SDI/NASA mission comes to fruition which seems likely as we go to print, NASA Exploration will be able to accomplish some of the goals of the "Lunar Geodetic Scout" and "Lunar Resource Mapper". Specifically, data on surface chemistry and mineralogy will be gathered, as well as near-side gravity from tracking data. A laser altimeter will map the global figure of the Moon simultaneously with acquisition of imaging and spectral data. In addition, the fly-by of "Geographos" will provide some of the data that was planned for the Comet Rendezvous Asteroid Fly-by (CRAF) Mission that has recently been canceled.

**Summary**

In spite of the great success of Apollo, major unanswered questions about the Moon abound. A substantial research effort should be made to improve our knowledge of the Moon. This should begin with global geochemical remote sensing by a "lunar observer mission", followed by more localized studies, such as a detailed study of materials that can be collected at a lunar outpost, higher resolution remote sensing, "rover-transported" geochemical sensing, and sample collection from regions determined from the global surveys to be promising. These studies are part of the basic geoscientific characterization of the Moon as a planet, as well as a means of finding the Moon's best available resources. Such studies will affect our general understanding of the nature and origin of the Moon and of its resources. Most of the homework has been done for a timely return to the Moon. It remains to be done.