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# A SOLAR ELECTRIC PROPULSION MISSION TO THE MOON AND BEYOND

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## ABSTRACT

The technological development of solar electric propulsion has advanced significantly over the last several years. Mission planners are now seriously examining which missions would benefit most from solar electric propulsion. NASA's Solar System Exploration Division is cofunding with the Advanced Concepts and Technology Division both ground and space qualification tests of components for electric propulsion systems. In response to the impending release of NASA's Announcement of Opportunity for Discovery class planetary missions we have undertaken a prephase A study of a Solar Electric Propulsion mission to the Moon. In this paper we review some of our findings about missions using solar electric propulsion and outline a possible scenario for a lunar mission. Solar electric propulsion can shorten mission flight times, enable launches on smaller rockets, and provide greater flexibility including longer launch windows. Such a mission launched now would enable us to complete the geophysical and geochemical mapping of the Moon left undone by both the Apollo and Clementine missions and to demonstrate a technology of significant importance to both future planetary exploration and the growing commercial space market.

## INTRODUCTION

The exploration of the moon presents us with a paradox. On the one hand the moon can be considered to be our most explored planetary neighbor. The Ranger series of spacecraft took increasingly high resolution pictures of the surface as they hurtled toward their hard landings. Surveyors landed softly on the Moon and analyzed its surface. Lunar Orbiters photographed the surface of the Moon. Explorer 35 measured how the moon interacted with its plasma environment. The Apollo missions not only carried man to the surface and returned lunar samples, but measured geophysical and geochemical properties of the moon from the command module, particles and magnetic fields from subsatellites and the geophysics of the moon from the landed ALSEP packages. On the other hand, when the Apollo program ended, the exploration of the moon was far from complete. The geophysical and geochemical measurements were entirely from low latitudes and certain measurements were not made at all. Further, since no lunar mission for purely scientific purposes could match the excitement of the manned Apollo missions, it was difficult to get approval for new lunar missions. In the mid 1970's plans for the Lunar Polar Orbiter mission were abandoned. In the late 1980's the plans for the Lunar Observer mission were abandoned. In the early 1990's the plans for the Lunar Scout missions were abandoned. In 1994 the Clementine mission was able to take some important lunar measurements but only as a remote sensing demonstration mission and without many of the instruments that should be included in any comprehensive mission.

Thus the US lunar science community is left with a quandary. Clearly to decision makers the moon is no longer an exciting target for space exploration because everything pales before the legacy of Apollo.

Yet there is much to be done in lunar exploration in order to meet our scientific goals. One possible solution to this quandary is to achieve our lunar goals as part of a larger program: one of technology demonstration as was attempted on Clementine or one in which the moon is part of multiple targets of a single spacecraft, again as on Clementine. Solar electric propulsion enables us to pursue such a strategy. It provides us with a new technology whose time for transfer from development to exploitation has arrived and it enables us to explore multiple targets with a single spacecraft. It is the purpose of this paper to review very briefly the history of solar electric propulsion, how it works, its advantages for lunar and planetary exploration and a possible exploration strategy for a lunar mission using solar electric propulsion.

## SOLAR ELECTRIC PROPULSION

The development of ion engines began at NASA Lewis Research Center, the Jet Propulsion Laboratory and TRW in the 1960s and has continued since that time. The original thrusters used mercury propellant but more recently the inert gas xenon has been used instead. Also the thrusters have been derated to operate at a lower thrust than they might ultimately achieve. Thus once solar electric propulsion missions become common place we may expect significant improvements in performance above that planned for the initial generation of missions. Three factors have sparked renewed interest in solar electric propulsion (SEP). First, recent mission studies have shown that solar electric propulsion was compatible with small missions and that it provides life-cycle cost reductions. For example savings in the launch vehicle cost because a solar electric propulsion system is lighter than a corresponding chemical system and savings in operations cost due to shorter trip times for some missions can far outweigh the extra cost of the solar electric propulsion unit. The second important factor sparking renewed interest in SEP is the growth in the potential commercial market. Large communication satellites continue to be placed in geosynchronous orbit and they require propulsion systems for long term station keeping. Solar electric propulsion is ideal for this application. The third important factor is the degree of technical readiness for flight that solar electric propulsion has achieved. Two of NASA's Offices have been cofunding the development of solar electric propulsion under the NSTAR program which stands for NASA Solar Electric Propulsion Technology Applications Readiness program. (For acronym aficionados we note that this is a double second order acronym which uses the first initials of the acronyms NASA and SEP). The NSTAR program has already initiated ground testing of the power processing units and thrusters and a space test is planned possibly as early as 1998.

A xenon ion SEP system works as follows. Solar panels generate about 5 to 10 kW of power for a moderate (Discovery class) planetary mission at 1AU. Such a solar array is comparable to that on a typical 1990s communication spacecraft. This power is used to ionize xenon gas. This ionized plasma is accelerated and focused electrostatically exiting the ion engine at exhaust velocities of thousands of meters per second. At the exit plane electrons are added to the ion beam to make it a neutral plasma. Two thrusters each with an exit plane aperture of 30 cm generate 180 millinewtons of thrust with a 2.3 kW power input. A single thruster can operate continuously for at least one year. Solar electric propulsion provides ten times more thrust per kilogram of fuel than does chemical propulsion and can maintain thrusting over a much longer interval. The ability to thrust continuously and efficiently enables distant targets to be reached more quickly. Since solar arrays are used in today's electric propulsion systems, thrusting is limited to within about 3AU of the sun. However, large velocities can be achieved within this region and distant objects may be reached. For example mission design studies have been completed for a solar electric Pluto fast flyby mission.

Some of the advantages of solar electric propulsion over chemical propulsion have been mentioned above. However, we wish to re-emphasize some of these points in terms of our solar system exploration program. First, SEP can enable missions that cannot be performed with chemical systems. The order of magnitude higher efficiency can reduce the required propellant mass to a launchable quantity. Second, SEP can shorten the flight time for many missions. Factors of 2 to 3 shorter missions are possible for a comet rendezvous mission for example. This significantly lowers operations costs. Furthermore SEP by providing a more efficient propulsion system enables the spacecraft to be launched from a smaller vehicle. Whereas a chemical mission might require an Atlas II rocket, a corresponding SEP mission would require only a Delta II rocket. A corollary of this savings is that a larger number of solar system objects become accessible targets and can be explored with a new class of affordable, smaller planetary spacecraft. In particular the exploration of small bodies i.e. comets and asteroids, will benefit greatly from SEP.

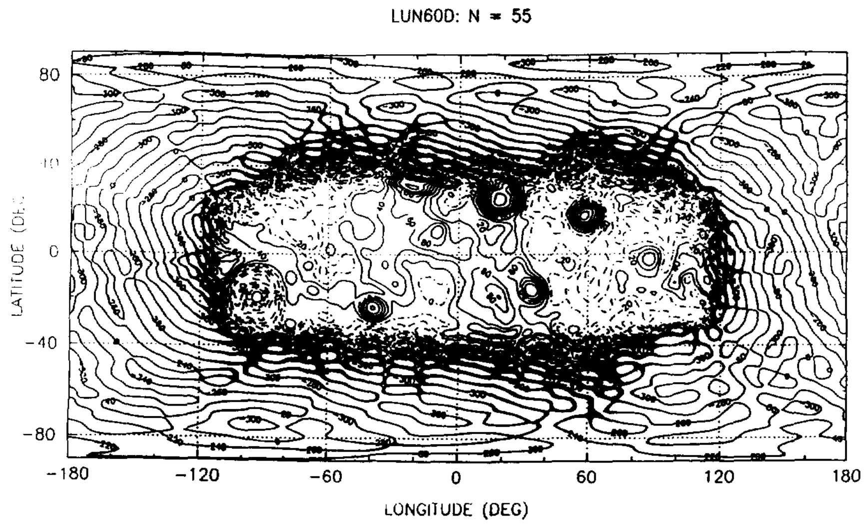

Fig. 1 The radial acceleration in milligals mapped over the full surface of the moon for the best existing lunar gravity model using no a priori constraints /1/.

Solar electric propulsion enables mission operations that might otherwise be viewed as too costly, such as multiple or continuous maneuvers. A spacecraft can explore an entire volume of space as it spirals through it, rather than occupy a few orbits around an object. In addition, plane changes might be considered to increase coverage over specific targets. Solar electric propulsion also increases mission flexibility and increases the length of launch windows. Thrusting operations become safer because they are done over a longer period. On a planetary mission, the two way light time often is much longer than the thrust time so a critical thrust cannot be terminated once initiated even if a problem is discovered. On a SEP mission, close coupling of the control center with the spacecraft during maneuvers is easily maintained.

In summary solar electric propulsion not only is an important new technology for the commercial space sector, but it will open up a new era of future planetary exploration even in an environment of declining budgets for space exploration.

## LUNAR SCIENCE OBJECTIVES

Although lunar exploration has not captured the imaginations of those who have guided our solar system exploration over the last two decades for a variety of programmatic reasons, the science community is firmly committed to a renewed program of lunar exploration because the origin of the Moon is inextricably linked to the earliest evolution of the Earth. Because the Moon has preserved its primordial crust it is arguably the best place in the solar system to study the evolution of a terrestrial planet immediately following accretion. In addition, the Moon has retained a record of its near-post-accretional impact history. The Lunar Exploration Science Working Group (LExSWG) has stated its priorities for science objectives on lunar orbital missions as follows.

- Constrain models of lunar origin by estimating the refractory element content and magnesium number of the crust. (Magnesium number is the ratio of magnesium to the sum of magnesium and iron).
- Estimate the composition and structure of the lunar crust in order to model its origin and evolution.
- Determine the origin and nature of the lunar magnetic field and estimate the size of the lunar core.
- 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.

We can illustrate the present state of our knowledge of some of these areas with a few figures. Figure

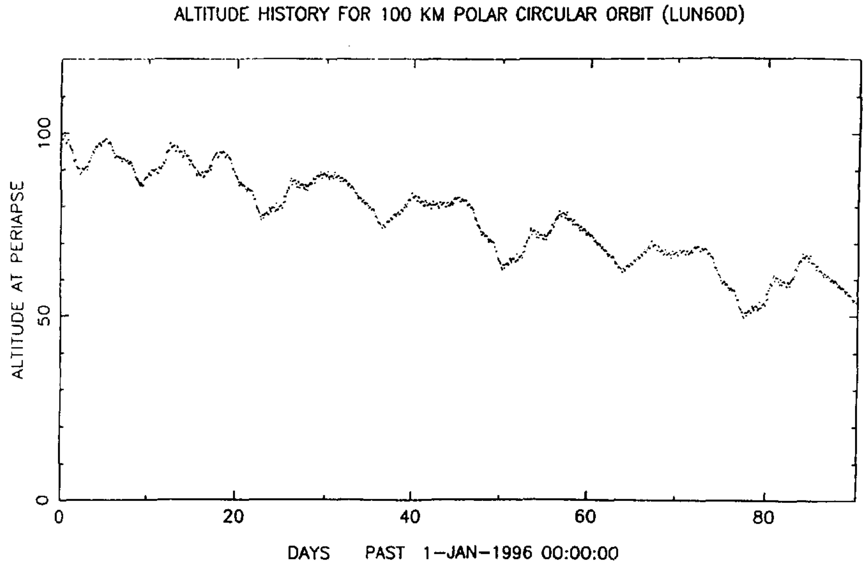

Fig. 2 The altitude history of periselene for a 100 km polar circular orbit using the best available lunar gravity model /1/.

1 shows the radial acceleration over the lunar surface according to the best pre-Clementine model based on Lunar Orbiter and Apollo data using no a priori constraints /1/. The good coverage extends slightly over the limbs on to the farside of the moon at low latitudes but we have little information about farside gravity elsewhere. Even on the nearside there is little information above 40° and below - 40° latitude. This raises the question as to whether it is safe to operate at low altitudes above the surface of the moon. Figure 2 shows the variation of periselene for a lunar polar orbiter mission initially in a circular orbit. Even with some uncertainty in the gravitational field this orbit is safe for a mission with SEP that has plenty of orbit adjust capability. However, to operate at different altitudes or inclinations it may be necessary to determine the gravitational field better before entering such an orbit. Reduction of the Clementine Doppler data will aid in this respect but Clementine was in an eccentric orbit with a periselene at or above 400 km.

Another important objective for lunar science is the investigation of the deep electrical conductivity of the moon to determine if it has a metallic core. Figure 3 shows the exclusion of a vacuum magnetic field by a lunar core in an environment such as the lobe of the Earth's tail. A positive indication of such an effect was found on the Apollo 15 and 16 subsatellite missions but there was insufficient accuracy in the measurements to determine if the induced currents were steady or were slowly decaying which would enable us to determine the depth at which the currents flowed /2/.

In addition to induced currents and their associated magnetic field, the lunar crust contains remanent magnetization. Although there are several possible mechanisms by which the lunar crust could have become magnetized the correlation of the strength of the remanent field with geologic age suggests that an internal dynamo was responsible for the magnetizing field /3/. In order to obtain accurate maps of the crustal remanent magnetic field, orbital measurements must be obtained at fairly low altitude and with a low noise level. Figure 4 shows the altitude dependence of the lunar magnetic field over 4 sectors of the Moon obtained on the Apollo 16 mission /4/. At the noise level obtained on this mission the lunar field began to be detected routinely at about 100 km altitude. Figure 5 shows a map of the radial component of the magnetic field at 100 km as measured by the Apollo 15 and 16 subsatellite magnetometers /3/. This map illustrates both the complexity of the fine scale field and also how little of the magnetic field has been mapped.

As mentioned above, the Clementine mission recently addressed some of the objectives of the lunar science community but not all of them. It made no attempt to measure gamma rays, x-rays, farside gravity, magnetic fields or the lunar atmosphere. It did provide a global digital imaging data base, some topography and some spectral mapping information. However, the topography data was spotty due to

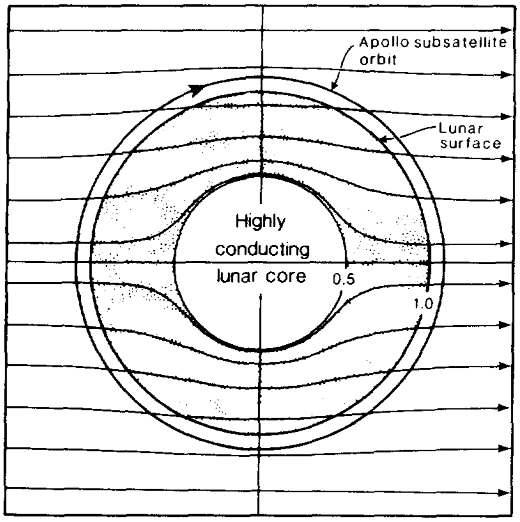

Fig. 3 The effect of a conducting lunar core on a uniform external magnetic field in a vacuum.

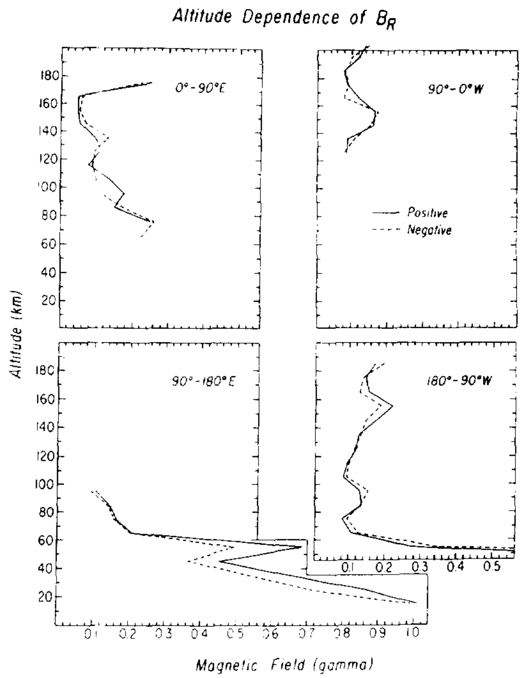

Fig. 4 The altitude profile of the radial component of the lunar magnetic field as measured by the Apollo 16 subsatellite /3/.

both a low sampling rate and a low signal to noise ratio. The spectral data had only modest resolution, insufficient to provide the mineral identifications required in many studies. Thus, while the Clementine data were welcomed by the lunar science community, these data are insufficient to address the outstanding questions of lunar formation and evolution.

## A POSSIBLE MISSION TO THE MOON

The strategy for a successful lunar mission was laid down two decades ago in the planning phase of the never executed Lunar Polar Orbiter mission. This mission consisted of a main spacecraft at low altitudes accompanied by a subsatellite in high orbit to relay Doppler data from the far side of the moon. An all chemical mission would have to deploy the satellite and subsatellite into an elliptical orbit, and then lower the main spacecraft into a low altitude circular orbit requiring multiple burns of the injection engine. The solar electric counterpart would simply drop off the subsatellite at the optimum circular orbit as it spiralled down to low altitudes. The subsatellite would then be distant from the lunar mascons for the entire orbit and not just at aposelene. A polar orbiting spacecraft obtains repeated coverage at the poles. To spread the coverage of the lunar surface so that more uniform statistics are obtained, plane changes during the mission are desirable. On a chemical mission these are very expensive of fuel, perhaps prohibitively so. Solar electric propulsion can dramatically reduce the fuel required to accomplish plane changes as well as other maneuvering. Similarly, on chemical missions, orbit maintenance can be very fuel intensive for low orbit operations. If orbits with altitudes less than 100 km are desired, solar electric propulsion would be the propulsion system of choice. Finally, if a spacecraft with a chemical propulsion system were to be sent to a second body such as the one to which Clementine was to be sent, mission compromises would have to be made such as an eccentric orbit rather than a circular orbit and an altitude higher than desired. With the fuel efficiency of solar electric propulsion, compromises of the measurement objectives would be limited or completely unnecessary.

In short it is possible with solar electric propulsion to execute the full lunar mapping mission, planned by the lunar community over 20 years ago and retain sufficient reserves to explore a second small body within the Discovery mission constraints. This mission would include a relay subsatellite in an optimized orbit, adaptive selection of an optimum low altitude circular orbit, and plane changes to optimize

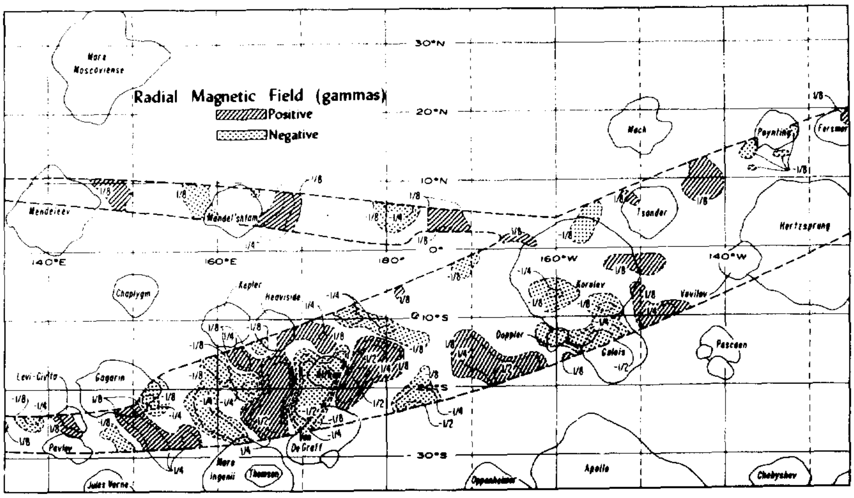

Fig. 5 A map of the radial component of the lunar magnetic field over 100° longitude over the lunar farside at 100 km altitude as measured by the Apollo 15 and 16 subsatellites /3/.

statistical sampling of the surface. The spacecraft could then spiral upwards to escape lunar gravity and proceed to a second target for exploration.

## CONCLUSIONS

There is a strong desire in the lunar community to complete our geophysical and geochemical mapping of the Moon but we will not gain approval of such a mission unless it achieves several other objectives as well and does so in a cost effective manner. Solar electric propulsion can enable us to execute a multiple target mission and reduce launch and operations costs with a smaller launch vehicle and a shorter trip time. Moreover, by using the same spacecraft and payload for two high priority planetary targets the costs of achieving each of the targets is approximately halved. Fortunately solar electric propulsion will be ready for flight when needed by the Discovery program. The NSTAR program to assess the technical readiness of SEP is underway now with a goal of flight readiness in 1998. The time has come for a science demonstration flight of solar electric propulsion.

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