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## Small spacecraft exploration of the Moon

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### Abstract

The Clementine and Lunar Prospector missions to the Moon have greatly increased our knowledge of the Moon, in particular the Moon's polar regions. These latest findings indicate that several new data sets should be obtained. Because the Moon is close, much of these data can be obtained using small, low-cost spacecraft.

One of the more intriguing discoveries is the likely presence of water ice deposits in the permanently dark areas near the lunar poles. These deposits represent a valuable resource and expanding our knowledge of their extent and properties is the next logical step in lunar exploration. Such exploration can be achieved by using instruments on a small satellite to characterize the polar regions. An imaging experiment could map the lighting conditions surrounding the poles to determine the extent of permanent darkness (where water ice would be stable) and permanent sunlight (where surface operations could be easily supported).

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### 1. Polar illumination extremes

The Moon's spin axis is nearly perpendicular, inclined at  $1.5^\circ$ , to the ecliptic plane which can result in unusual lighting conditions at the lunar poles. Areas which have low elevation, such as the floors of impact craters, may never see the Sun, i.e. they are permanently shadowed, whilst regions of high elevation, relative to the local terrain, may be permanently illuminated.

Areas of extreme insolation are interesting for both scientific and operational reasons. Permanently shadowed areas are likely cold enough to represent thermal traps for any water molecules entering. It has been

modeled that the temperature in these cold traps can be less than 100 K [1]. Thus over a period of time, water molecules reaching the Moon, from cometary and asteroid impact, could produce a sizable deposit. Both the Clementine and Lunar Prospector missions identified probable ice deposits at the lunar poles. Obviously the presence of water ice at both poles has huge implications for the possibility of supporting a manned infrastructure on the Moon.

Areas of constant illumination are valuable for two reasons. Firstly, they represent places which would permit abundant solar energy generation, possibly negating the need for RTGs. Secondly, it has been modeled that the temperature in a region with constant grazing illumination is approximately  $220 \pm 10$  K, a benign thermal environment relative to the temperature extremes experienced by the rest of the Moon (typically  $250 \pm 140$  K) [2].

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## 2. Current knowledge

### 2.1. Lunar south pole

The Clementine spacecraft spent 71 days in a 5 h polar orbit. During that time it imaged each pole every alternate orbit, producing a snap shot of the illuminations at both poles once every 10 h for a little more than 2 lunar days. During the period when the data were acquired, it was winter in the southern hemisphere and summer in the northern hemisphere. These data represent the best systematic imaging data of the lunar poles. Lunar Orbiter did acquire a few frames of the poles but these were obtained during the same seasonal conditions as the Clementine data.

An analysis of the lunar south polar lighting using Clementine UVVIS imaging data revealed some interesting illumination conditions in this region [3]. No place on the surface, at the resolution of the Clementine UVVIS data (500 m/pixel), appears to be permanently illuminated. However, several regions exist which are illuminated for greater than 70% of a lunar day in winter. A map of the south polar illumination conditions is shown in Fig. 1.

Two of these regions (labeled A & B in Fig. 1), which are only 10 km apart, are collectively illuminated for more than 98% of the time.

Analysis of Clementine high-resolution data ( $\sim 40$  m/pixel) revealed more details of the physical nature of these highly illuminated regions (Fig. 2).

Areas A and B lie at opposite ends of a ridge emanating from the rim of Shackleton crater. Area C corresponds to a small hill superposed onto the rim of De Gerlache crater. A high-resolution mosaic of the south polar region is shown in Fig. 2.

### 2.2. Extent of permanent shadow

An important piece of knowledge is the location and extent of permanently shadowed regions near both lunar poles. Such regions are likely extremely cold and represent the most likely locations for deposits of water ice, the existence of which has been suggested by both Clementine and Lunar Prospector.

Modeling the illumination inside simple impact craters has revealed that there is a lot more permanent shadow, associated with these features, surrounding both lunar poles than previously thought, at least 7500

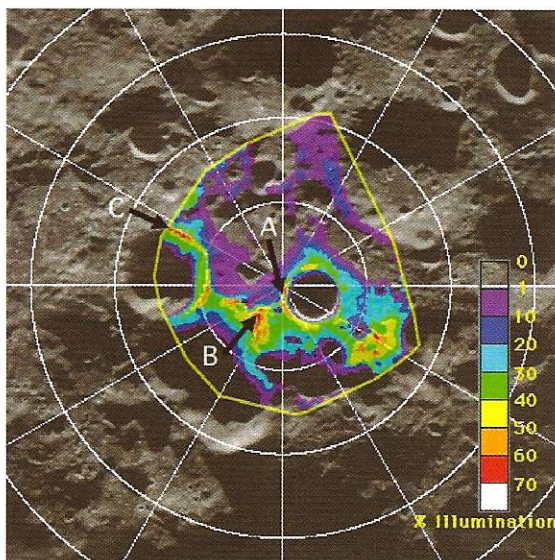


Fig. 1. Illumination map covering the region within approximately  $2.5^\circ$  latitude of the Moon's south pole. The three most illuminated regions are identified by the letters A, B, & C.

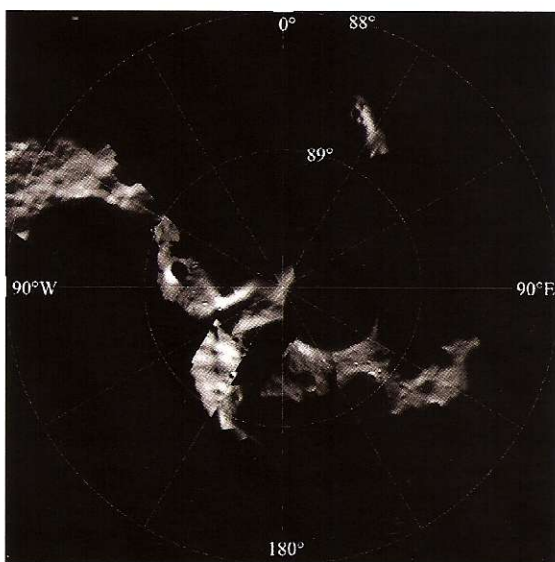


Fig. 2. High-resolution mosaic of the Moon's south polar region.

and  $6500 \text{ km}^2$  at the north and south poles, respectively [4]. An additional finding was that permanent shadow exists in craters more than  $10^\circ$  latitude away from a pole (Fig. 3). There is therefore the potential for more cold traps and volatile deposits.

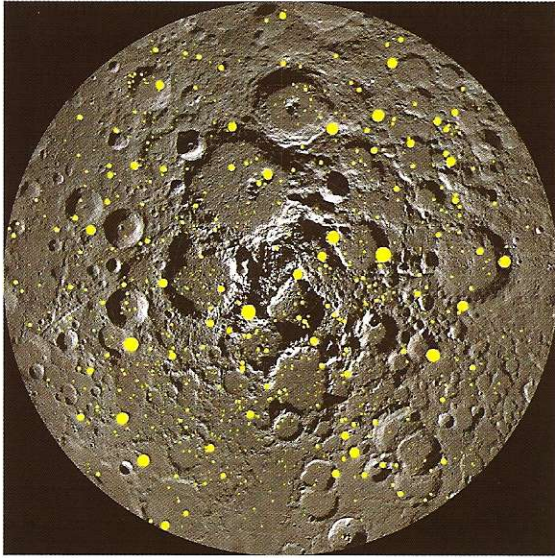


Fig. 3. A map showing the region from  $78^\circ$  to the north pole. Simple craters which contain permanent shadow are shown in yellow.

The numbers quoted above for the areas of permanent shadow represent minima as they refer to shadow inside the simple bowl-shaped craters. Significant amounts of permanent shadow, at least several thousand square kilometers, is likely inside the larger complex craters close to each pole.

### 2.3. Topography data

The Clementine laser altimeter experiment provided near global topography data at a scale of a few kilometers. Unfortunately no laser data were obtained at either lunar pole due to an altitude constraint on the instrument.

Polar altitude knowledge comes from Clementine stereo image analysis and Arecibo radar data. Products based on the radar data [5] have the benefit of relatively high resolutions (150 m spatial and 50 m vertical) but have the disadvantage that surface coverage is limited to parts of the Moon which can be seen from Earth. Therefore, farside coverage is limited.

A second topography data set is derived from stereo analysis of Clementine UVVIS images [6]. Stereo derived topography has the advantage that it has excel-

lent farside coverage, but it has a lower resolution (1 km spatial, 100 m vertical) than the radar derived topography and is also noisier.

An analysis of these datasets, simulating lighting conditions that match a Clementine UVVIS image indicated that neither topography dataset is accurate enough to be confidently used to simulate unknown lighting conditions [7,8].

### 2.4. Lunar volatiles

Both the Clementine and Lunar prospector missions provided evidence that deposits of water ice exist in the permanently shadowed regions near both lunar poles.

An innovative experiment using the Clementine communication antenna was conducted to do a bistatic radar investigation of the polar regions [9]. The result of this experiment was the indication of ice deposits inside dark areas surrounding the south pole.

Lunar Prospector carried a neutron spectrometer that measured the energy spectrum of neutrons emitted from the lunar surface. Both poles had a dearth of epithermal neutrons [10]. This is indicative of an elevated amount of hydrogen, probably in the form of water ice. These regions of increased hydrogen content appear to be correlated with the permanent dark regions near the poles, supporting the idea that the hydrogen is in the form of water ice.

## 3. Required future data

Whilst the recent lunar missions have greatly expanded our knowledge of the Moon's polar regions, so too have they raised a number of questions that need answering. Several key data sets are required, many of which could be obtained by lightweight instruments on a small satellite. A typical mission could consist of an appropriately instrumented spacecraft in a near polar orbit for a period of approximately 12 months. A discussion of the data needed is shown below.

### 3.1. Lunar poles illumination conditions

Current data have shown that extreme illumination conditions do exist in locations near the lunar poles. However they do not provide all the information

we need. The south pole maps only cover the region within approximately  $2.5^\circ$  of the pole while the north pole map covers an even smaller area. Also Clementine only mapped for the poles for a total of 71 days. We currently lack seasonal knowledge for the polar regions.

What is required is the full characterization of the illumination conditions at the lunar poles. Compared to current data a much larger area needs to be analyzed and mapping of all possible lighting conditions should be undertaken, so that seasonal effects can be understood.

This could be achieved using a wide angle camera (to ensure enough regional coverage) orbiting the Moon for 12 months. Such a camera could be fairly simple, and therefore light and inexpensive. A single wavelength is adequate for this task as multi-spectral data is essentially useless due to the high phase angles and long shadows associated with polar images.

A snap shot of each pole obtained every 5–10 h would be an optimal goal. Additionally it is important that enough of the Moon is continually imaged. Our research has shown that interesting lighting conditions can occur at several degrees latitude from the pole. Therefore a synoptic lighting map should ideally cover the region within  $10^\circ$  of each pole. Spatial resolution is of secondary importance compared with areal coverage, a resolution of 500 m/pixel would be adequate.

The brightness dynamic range of the moon is large enough that a 12 bit camera is needed. Clementine an 8 bit system by taking pairs of images with different gains. This is less than optimal and a 12 bit system would negate the need for such a system.

Data for both poles is desirable as current data indicates that permanent shadow exists in both places and the Lunar Prospector spacecraft detected hydrogen deposits at both poles.

### 3.2. Polar temperatures

The temperatures quoted for the polar regions ( $< 100$  K in permanent shadow and 220 K for permanently illuminated) are all based on modeling, not direct measurements. Several other factors exist that could affect these numbers. One example is how cold are doubly shadowed regions, e.g. a crater within a crater? Such places could be much colder than a singly

shadowed region and thus may extend latitudinally how far from the pole an ice deposit could exist.

Polar temperatures could be obtained from orbit using a cryogenically cooled IR bolometer. Not only is temperature measurement useful in determining where volatiles would be stable, but it also provides information on the composition of the Moon. The temperature in a permanently shadowed region is due primarily to the internal heat flow in the Moon, produced by radioactive decay. Therefore knowing the temperature in these regions provides an insight into how much radioactive elements are in the bulk Moon.

### 3.3. Detection of lunar volatiles

The next logical step in exploring the polar regions should include mapping of the location and extent of the volatile deposits that are believed to exist in the permanently shadowed regions near the lunar poles. To accomplish this instruments are required that have high spatial resolution (e.g.,  $< 1$  km) to see inside the small permanently shadowed regions. One such instrument is an orbital radar experiment that could operate in both scattering and imaging modes. As a scatterometer, it could identify the location and approximate volume of ice deposits; while in imaging mode, it could image the morphology and topography of the surface, including the floors of permanently dark craters.

Several important parameters, such as the molecular and isotopic composition of lunar polar deposits, can only be determined from surface measurements. A small analytical laboratory could be fitted onto a landing small spacecraft (either a soft or hard lander) and dispatched to the permanently dark areas of the poles. There, this spacecraft could conduct in situ analyses to characterize the volatile deposits, their physical and chemical states, and the nature of the local environment. The combination of knowledge from these small missions will completely characterize the unusual polar deposits and tell us much about both lunar history and the history of volatile elements in the inner Solar System.

## 4. Conclusions

The characterization of the lunar polar regions could be adequately achieved using suitably instrumented

small satellites. A spacecraft with an imager, a radar instrument and an IR bolometer could definitively answer the quandary of is there ice on the Moon, where is it, and how much of it is there?

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