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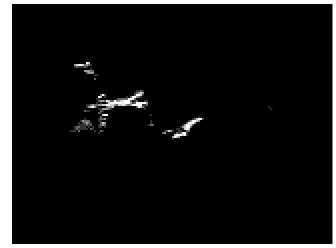
Hot Idea Update posted June 4, 2003


Ben Bussey, APL

The Moon's Dark, Icy Poles

--- Permanently shadowed regions on the Moon--where frozen water could be trapped--are more abundant and more widely distributed than originally thought.

Written by Linda M. V. Martel
Hawai'i Institute of Geophysics and Planetology

Water ice is trapped in permanently shadowed areas at the lunar poles. This prediction is consistent with data from the Clementine [see **PSRD** article: Ice on the Bone Dry Moon] and Lunar Prospector missions and radar measurements with the Arecibo radio telescope. What we know for sure is that concentrations of hydrogen are associated with permanently shadowed craters. We don't know the total concentration of hydrogen or whether or not the hydrogen is surely in water ice or some other form. [See **PSRD** article: The Moon Beyond 2002.] But researchers are zeroing in on these zones of permanent darkness because knowing their size and distribution would tell us where and how much water ice could be found in cold traps--an obvious advantage for human settlement of the Moon.

Lacking images of the lunar poles through every season, researchers turned to computer simulations to model the illumination of simple craters to watch how the shadows change with time. Ben Bussey (Johns Hopkins University Applied Physics Lab) and colleagues (at APL, University of Hawaii, Northwestern University, and Q & D Programming) studied simple craters with diameters less than 20 km and used results from their simulations to predict the minimum amount of permanent shadow in the north and south polar regions. Their predictions, 7500 km^2 around the north pole and 6500 km^2 around the south pole, are significantly larger than any previous estimates.

Reference:

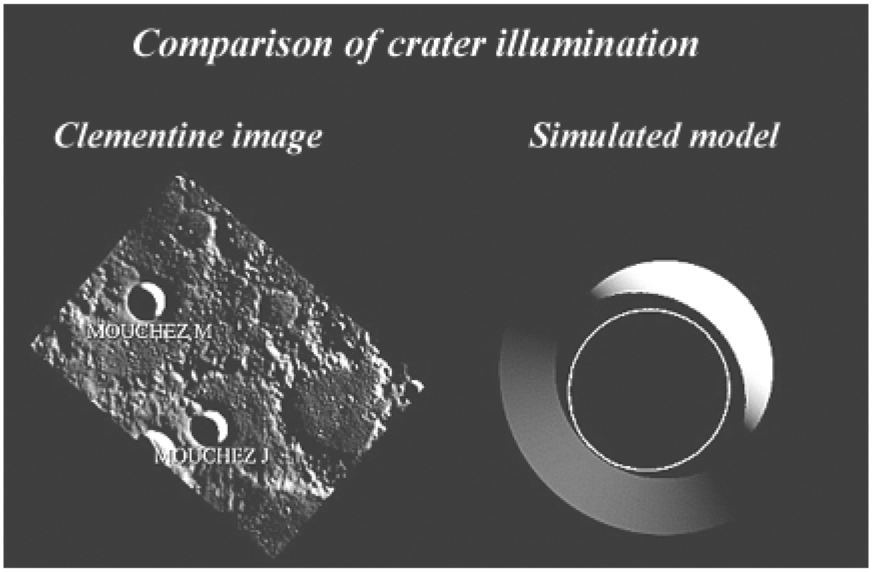
Bussey, D.B.J., Lucey, P.G., Steutel, D., Robinson, M.S., Spudis, P.D., and Edwards, K.D. (2003) Permanent shadow in simple craters near the lunar poles, *Geophysical Research Letters,* v. 30(6), 1278, doi: 10.1029/2002GL016180.

The graphic at the top of the page, produced by Ben Bussey of Applied Physics Lab, is a collection of Clementine images of the south polar region taken during one lunar day.

Shadow Permanence

A permanent shadow in a crater on the Moon is defined as an area on the surface of the Moon that never receives sunlight. This happens at the poles because the Moon's axis of rotation is nearly perpendicular to the plane of its orbit around the Sun, so the Sun is always low, close to the horizon, casting long shadows off the crater rims or any other high point [see **PSRD** diagram Plane of Moon's Orbit].

In their simulations of lunar topography, Bussey and colleagues superimposed the shapes of simple craters onto a sphere the size of the Moon. The figure below illustrates the similarity between the lighting of a 17.5 km simulated crater with actual lunar craters in a Clementine image.



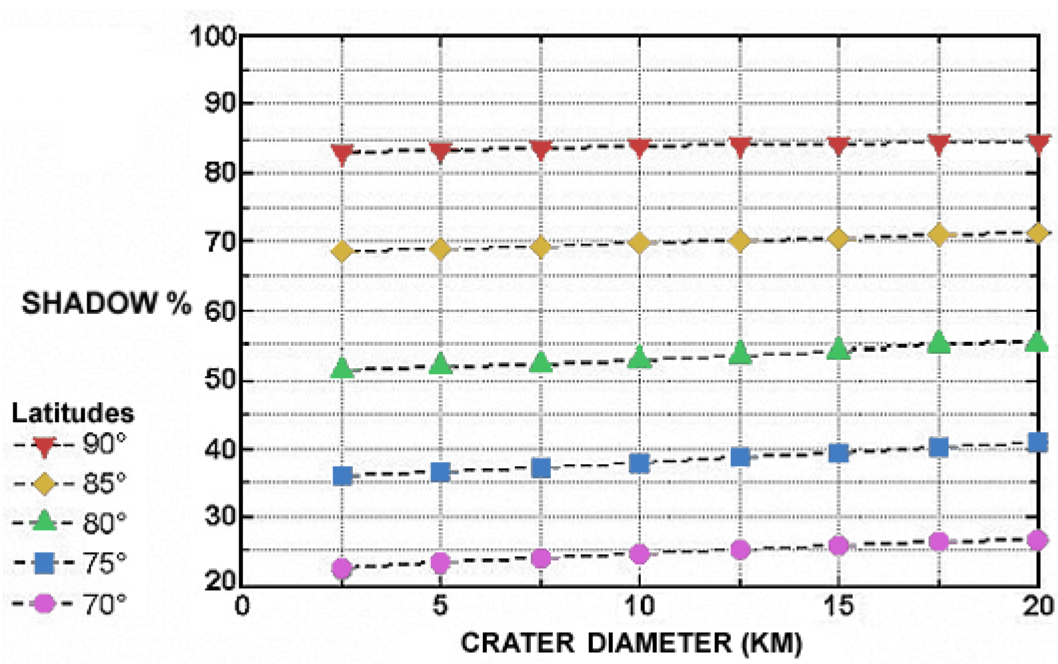
(Bussey et al., 2003, Geophysical Research Letters, v. 30, Fig. 1.)

The white circle on the simulated crater shows the extent of its permanent shadow.

Simulations were run for craters ranging in diameter from 2.5 km to 20.0 km, in 2.5 km increments, in order to see how the amount of permanent shadow varies with crater size. For each size, simulations were run on craters placed at latitudes from 70° to 90° at 1° increments. Seasonal variations were studied by moving the subsolar point (position of the Sun's vertical or direct ray) 1.5° above or below the equator, to represent summer and winter for the northern hemisphere. The researchers assumed in their simulations that the craters were fresh and primary (not secondary) and that there were no regional slopes. Slopes would expose a crater rim to more (or less) sunlight, thus affecting the size and shape of the internal shadow.

Shadow Amounts

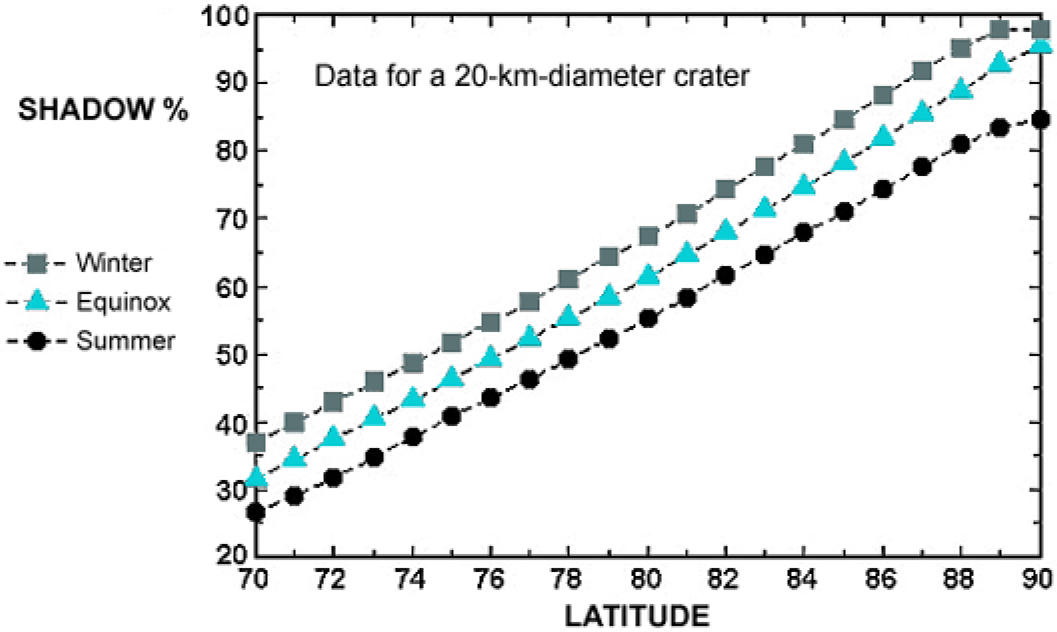
Bussey and co-researchers found that for a given latitude (nearly horizontal lines on the graph below), larger craters have slightly more relative permanent shadow in them than smaller craters. This happens simply because larger craters have higher rims.



(From Bussey *et al*, 2003, *GRL*, v. 30, Fig. 3.)

Especially at lower latitudes (see the 70° purple line), larger craters have slightly more relative permanent shadow than smaller craters. Craters nearer a pole (see the 90° red line) contain a larger percentage of shadow than craters at 70°.

But more than crater size, they found that latitude is the dominant parameter affecting the amount of permanent shadow in a simple crater. Craters as far as 20° away from a pole still have significant amounts (22% to 27%) permanent shadow.



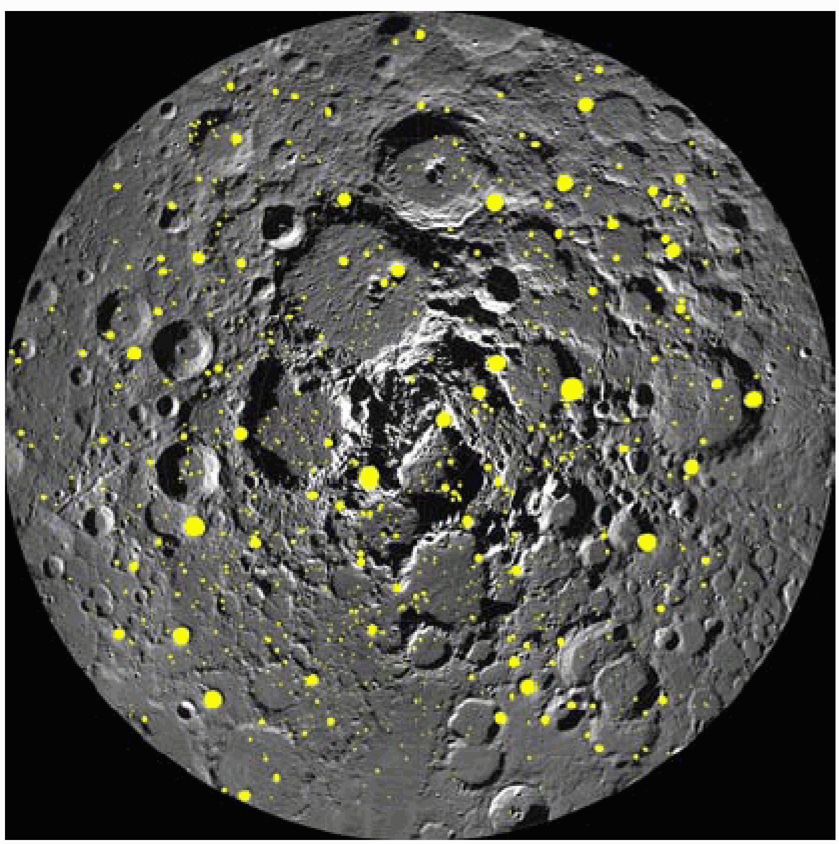
(From Bussey *et al*, 2003, *GRL*, v. 30, Fig. 2.)

Illumination of a 20-km-diameter crater was simulated for winter, equinox, and summer days. The amount of permanent shadow inside the crater corresponds to the value for a day in summer, shown by the black circles. The difference between the winter and summer curves represents the difference between the amount of shadow in a crater for a winter and summer day (~15%) and is independent of crater size and latitude.

Based on these simulation results, the researchers created a "permanent darkness" equation that permits them to figure out shadow amounts as a function of latitude and crater size.

Their next step was to examine images of the Moon and identify all the fresh looking simple craters larger than 1 km within 12° of each pole. By measuring the diameters of these craters and using the "permanent darkness" equation they calculated the amount of permanent shadow.

Craters in the lunar north pole area containing permanent shadow

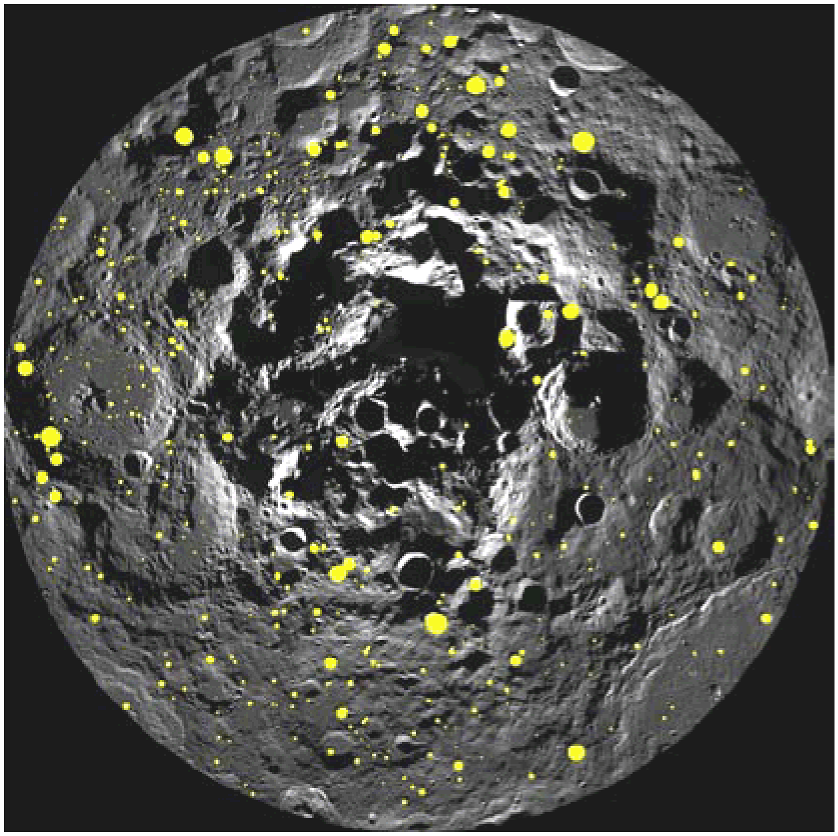


(From Bussey *et al*, 2003, *GRL*, v. 30, Fig.4 .)

This image is centered on the north pole of the Moon and extends to 78°N. The yellow dots represent 832 fresh looking simple craters containing permanent shadow used in the study.

The 832 craters at the north pole have a total surface area of approximately 12,500 km^2 (about 3% of the surface shown). The amount of permanent shadow calculated by the "permanent darkness" equation is 7,500 km^2. This value is a lower limit and is based solely on the simple craters. More shadow is contributed by poleward facing walls of complex (multi-ringed) craters.

Craters in the lunar south pole area containing permanent shadow



(From Bussey *et al.* 2003, *Lunar and Planetary Science XXXIV*, abstract 1897, Fig.5.)

This image is centered on the south pole of the Moon and shows the area out to 78°S. The yellow dots show the 547 fresh looking simple craters containing permanent shadow used in the study.

The 547 craters identified at the south pole have a total area of 11,200 km^2 (again representing about 3% of the lunar surface shown). This area, when used in the equation, yields 6,500 km^2 of permanent shadow. As is true for the north pole, this value is based only on permanent darkness in the simple craters and is a lower limit; permanent shadow in larger complex craters was not modeled or included in the value.

Why the Shadows Matter

Because temperatures in these polar shadows do not exceed about -230°C (40K) they act as effective cold traps--holding frozen water molecules that do not have the thermal energy to escape. How did the ice get there in the first place? They call it random walk migration (literally hopping along) by water molecules arriving by impacting comets long ago, billions of years ago. Lunar ice mixed in the regolith of polar cold traps would be an important resource for people living and working on the Moon.

The study by Bussey and colleagues has shown that permanently shadowed regions on the Moon are more numerous and distributed over a wider area than we thought. This means there are many more potential cold traps that could hold water ice. We do not know how much water is trapped in the shadowed areas. However, if all the permanently shadowed regions contain water ice at a concentration suggested by Lunar Prospector data, about 1.5 wt%, then the volume of ice might be nearly one cubic kilometer, enough to fill a lake perhaps 2 km x 2 km and 200 meters deep or more than 100 major league football and baseball stadiums. If larger complex craters and areas farther away from the poles are taken into account, the amounts of permanent shadow and potential water ice would be even larger.

Bussey's discovery of large amounts of permanently shadowed areas has implications for scientific understanding of the amount, nature, and transport of volatiles, and for future human settlement of the Moon. We do not know whether the hydrogen trapped in polar shadows comes from the solar wind or from the impact of millions of comets. If from comets, these regions might contain a record of the cometary compositions and perhaps how they changed through time. Space scientists have started to look at prospective landing sites at the lunar south pole where future robotic rovers could access and examine the ice [see Leonard David's summary]. Furthermore, human settlers might benefit from vast stores of ice at the poles. Ongoing studies are looking at the feasibility and economics of melting lunar ice for use by habitants or converting lunar ice into hydrogen and oxygen for rocket fuel [see, for example, the abstracts and papers from Space Resources Roundtable workshops].

Additional Resources

Bussey, D.B.J., Lucey, P.G., Steutel, D., Robinson, M.S., Spudis, P.D., and Edwards, K.D. (2003) Permanent shadow in simple craters near the lunar poles, *Geophysical Research Letters,* v. 30(6), 1278, doi: 10.1029/2002GL016180.

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Spudis, P.D. (1996) Ice on the Bone Dry Moon. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Dec96/IceonMoon.html

Taylor, G.J. (2002) The Moon Beyond 2002. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Oct02/moon.html

psrd@higp.hawaii.edu
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