

Permanent shadow in simple craters near the lunar poles

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[1] An analysis of simple craters in the lunar polar regions has produced new values for the minimum amount of permanent shadow in these areas, 7500 km² and 6500 km², for the north and south pole respectively. These values were obtained by conducting illumination simulations of realistically shaped simple craters, <20 km in diameter, to investigate the size and latitudinal extent of permanently shadowed regions near the lunar poles. Craters as far as 20° from the pole still contain significant amounts of permanent shadow. Larger simple craters have slightly more relative permanent shadow than smaller craters. Seasonal effects are independent of crater size and latitude, with a crater having 15% more of its interior shadowed during a lunar day in winter than in summer. *INDEX TERMS:* 5462 Planetology: Solid Surface Planets: Polar regions; 5464 Planetology: Solid Surface Planets: Remote sensing; 6250 Planetology: Solar System Objects: Moon (1221). **Citation:** Bussey, D. B. J., P. G. Lucey, D. Steutel, M. S. Robinson, P. D. Spudis, and K. D. Edwards, Permanent shadow in simple craters near the lunar poles, *Geophys. Res. Lett.*, 30(6), 1278, doi:10.1029/2002GL016180, 2003.

1. Introduction

[2] Knowledge of the size and extent of permanently shadowed regions near the lunar poles has important ramifications for understanding the amount and locations of environments favourable for ice deposits. The Moon's spin axis is nearly perpendicular to the ecliptic (1.5°), causing locations near the pole to experience extreme illumination conditions. Topographic lows, such as the floors of impact craters, may be in permanent shadow, whilst high areas may receive near constant solar illumination. The temperatures inside a permanently shadowed crater have been estimated to be low enough (~50 K) that any water molecule in a polar cold trap will not have the thermal energy to escape [Watson *et al.*, 1961; Arnold, 1979; Ingersoll *et al.*, 1992; Vasavada *et al.*, 1999]. Results from the Clementine [Nozette *et al.*, 1997, 2001] and Lunar Prospector [Feldman *et al.*, 2000, 2001] missions as well as Earth based radar observations [Stacy, 1993] all indicate the possible presence of water ice near the lunar poles, although none of the results is conclusive.

[3] The two main imaging datasets of the lunar polar regions, obtained by the Clementine and Lunar Orbiter IV missions, only collected data during winter in the southern

hemisphere and summer in the northern hemisphere. Therefore neither mission data permit an investigation of the seasonal variations of illumination conditions.

2. Simulations

[4] Lacking seasonally complete imaging, one method of expanding our knowledge of the lunar polar illumination conditions, particularly seasonal variations and identifying regions of insolation extremes, is to simulate the illumination of topography, looking at the position of shadows and sunlit regions and their changes with time. This technique permits all possible illumination scenarios to be investigated.

[5] Topographic data for the lunar poles have been derived from a number of different sources. Interferometry of Arecibo radar data have been used to generate topographic information of the polar regions [Margot *et al.*, 1999]. These products have the benefit of relatively high resolution (150 m spatial, 50 m vertical) but have the disadvantage that spatial coverage is limited exclusively to portions of the Moon that are visible from Earth. A second data set that exists is topography derived from stereo analysis of Clementine UVVIS images [Cook *et al.*, 2000; Rosiek *et al.*, 1999; Wählisch *et al.*, 1999]. An advantage of stereo derived topography is that it has excellent farside coverage, but it has a lower resolution (1 km spatial, 100 m vertical) and is noisier than the radar derived topography. An initial study of these datasets, involving illumination conditions that match Clementine images, determined that they can both be used to produce reasonably realistic simulations [Bussey *et al.*, 2001, 2002]. The radar topography resulted in simulated illumination conditions that more closely matched those of direct imaging, but was limited to nearside illumination direction due to the sparse farside topography coverage.

[6] Pike [1977] quantitatively characterized key parameters of simple craters as a function of diameter for craters smaller than 15 km. These parameters include depth, rim height, rim width, and flat floor diameter. Craters with diameters between 15 and 20 km fall into a transition zone, they can either be simple or complex. Pike [1980a] states that the transition diameter for highland simple craters is 21 km and also Pike [1980b] states that simple craters up to 25 km in diameter can exist that obey the parameter equations for simple craters as described in Pike [1977]. We therefore use the Pike [1977] equations for craters in the 15 to 20 km diameter range that appear to be simple craters, recognizing that this assumption may not be valid in some individual cases. On the basis that such analyses may be statistically treated to infer typical lunar topography, we use these parameters to produce digital elevation models of idealized craters with shapes dictated by the statistics of Pike [1977]. Simulating the lighting conditions of these model craters

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permits a detailed study of how the areas of permanent shadow in a simple crater varies as a function of crater location, crater size, and season.

[7] Even though these equations are quoted for “fresh” simple craters, *Pike* [1980b] shows that simple craters keep their described shapes for long periods of time; both Eoarchean and late Imbrian craters (i.e., those forming after ~ 3 b.y. ago) may retain nearly pristine morphology. Thus, a crater may look fresh, and therefore have a shape described by the *Pike* [1977] equations, but it may be more older than 2–3 billion years old, certainly old enough to possibly have experienced the deposition of water molecules.

3. Results From Simulated Topography

[8] A systematic study has been undertaken to investigate how the amount of permanent shadow in a crater varies as a function of crater location, and crater size. Model simple craters with parameters derived using the *Pike* [1977] equations are superposed onto a 1738 km sphere (the mean lunar radius). We have produced DEMs for craters with diameters ranging from 2.5 up to 20 km. In order to test the validity of the results, a simulation was conducted using illumination conditions that correspond to a Clementine UVVIS image. Figure 2 shows Clementine image lub1812r.051 and a simulation result for a 17.5 km crater. Lub1812r.051 contains the craters Mouchez M (17.5 km diameter) and Mouchez J. Figure 1 shows that the actual and simulated illuminations are similar.

[9] The only parameter changed during a run of simulations is the incoming subsolar longitude, which is altered by 5° between each simulation. In order to determine the amount of permanent shadow in a crater, a subsolar latitude of 1.5° , representing the highest possible elevation of the Sun, is used for all simulations. This is done, rather than using subsolar latitude and longitude corresponding to a day in summer, because analysis of ephemeris details for the Moon shows that the subsolar longitude for mid summer (i.e. the instant in time when the Sun reaches its highest elevation) occurs over all longitudes. The result from a typical simulation is shown in Figure 1. The results from all

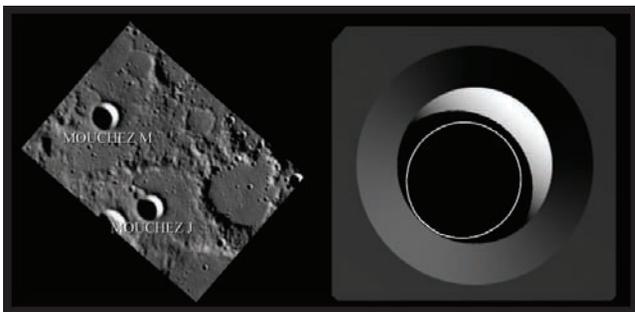


Figure 1. The image above left is the Clementine UVVIS frame lub1812r.051. It contains the 17.5 km simple crater Mouchez M ($80.2^\circ\text{N } 49.3^\circ\text{W}$). The image above right is the result of running a simulation on a model 17.5 km simple crater produced using the *Pike* [1977] parameters. The illumination conditions for the simulation match those for lub1812r.051. The white circle shows the extent of the permanent shadow within the crater.

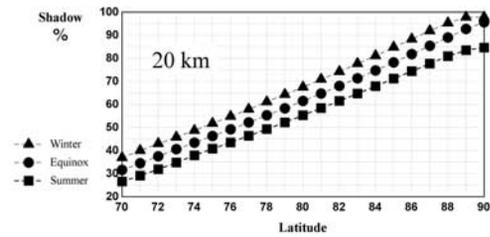


Figure 2. These graphs show how the amount of shadow varies as a function of latitude for 20 and 5 km craters. Illuminations were simulated for days in winter, equinox and summer. The amount of permanent shadow corresponds to the value for a day in summer, shown by the circles. Seasonal variations are indicated by the difference between the amount of shadow for a winter, and a summer day. This is independent of crater size and latitude and is equal to approximately 15%.

72 simulations are merged to determine the amount of permanent shadow in a crater.

[10] In order to investigate how the amount of permanent shadow varies as a function of size, simulations were run for craters with diameters of 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, and 20.0 km. For each crater size, simulations were run on craters placed at 1° latitude increments from 70° to 90° . Finally, seasonal variations were investigated by moving the subsolar point 1.5° above or below the equator, to represent summer and winter for the northern hemisphere.

[11] Other basic assumptions are that there are no regional slopes, all craters are fresh and there are no unusual morphologies. The existence of regional slopes would either lower or raise the Sun facing crater rim, thus affecting the amount and shape of the internal shadow. It is assumed that all craters are primary, not secondary, and that they are fresh, i.e. do not have degraded rim heights. Both secondary and degraded craters would have depth diameter ratios that are less than those in *Pike* [1977] and would therefore have less internal shadow.

4. Results

[12] Figure 2 shows the results from the simulations of 20 and 5 km craters that looked at how the latitude of an impact crater affects the amount of permanent shadow. For each crater size, simulations were conducted from 70° to 90° latitude in 1° increments. Figure 2 shows that even 20° away from a pole, a significant amount of permanent shadow is present, which is located in the poleward facing wall and floor of the crater. As an example, a 20 km diameter simple crater located at 70° contains $\sim 27\%$, or 84 km^2 of permanent shadow. Permanent shadow is defined as the area within a crater which receives no sunlight when the Sun is at its highest elevation, for all azimuths. The results for 10 km diameter craters match well with the results from a similar analysis of 10 km craters by *Vasavada et al.* [1999].

[13] Figure 3 shows the percentage of the interior of a crater that is permanently shadowed as a function of size, at a constant latitude. Larger simple craters contain slightly more relative permanent shadow, this is probably due larger simple craters having slightly higher raised rims. This effect is enhanced at lower latitudes, for example, at 90° a 20 km

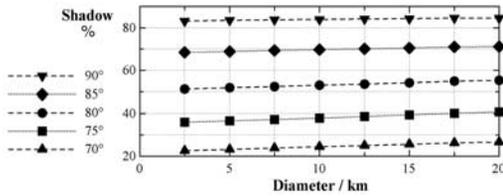


Figure 3. This graph shows the affect of crater size on the amount of permanent shadow in a crater. Larger craters have slightly more relative permanent shadow than smaller craters. This affect is more pronounced at lower latitudes.

crater has 2% relative more shadow than a 10 km crater, whilst at 70° this number increases to 9%. However size is a much less important parameter than latitude in affecting the amount of permanent shadow.

[14] Figure 2 also shows the results of the investigation into seasonal variations. Results from 20 and 5 km craters are displayed. The difference between the amount of shadow during a day in winter and the amount of shadow for a day in summer is approximately 15%. Seasonal affects appear to be independent of both crater size and latitude.

5. Estimate of Amount of Permanent Shadow in the Polar Regions

[15] We use these results to determine a new estimate for the amount of permanent shadow in simple craters near the lunar poles. The results from all our simulations for summer (i.e. amount of shadow can be assumed to be permanent) can be expressed by equation 1 which permits the amount of permanent shadow to be calculated as a simple function of latitude and crater size.

$$S = (0.9465 \times D) + (0.0202 \times \theta^2) - (0.009258 \times \theta \times D) - 78.06 \quad (1)$$

where S is the percentage of the interior of the crater that is permanently shadowed, D is the crater diameter in kilometers and θ is the latitude in degrees. The equation works well for the latitude range 70° to 89° with an absolute error of better than 1%. By utilizing equation 1 we can infer model topography and therefore calculate the amount of permanent shadow associated with a fresh simple crater of a given size.

6. North Pole

[16] A detailed analysis of all fresh looking simple craters larger than 1 km within 12° of the pole was undertaken. The total number of craters mapped was 832 (Figure 4). These craters have a total surface area of approximately 12,500 km² representing roughly 3% of the lunar surface poleward of 78°. Using equation 1 to calculate the amount of permanent shadow associated with these craters yields 7500 km². This number is significantly larger than the previous estimates of 530 km² [Nozette et al., 1996] and 2650 km² [Margot et al., 1999]. Our value of 7500 km² is a lower limit for the total amount of permanent shadow as it only represents shadow in simple craters between 1 and 20 km in diameter. The contribution of poleward facing walls of complex craters will also contribute large amounts of area to the overall permanent shadow budget. Specifically three complex craters, Lovelace E (82.1°N 94°W, 23 km diameter),

Rozhdestvensky K (82.7°N 145°W, 42 km diameter), and Rozhdestvensky U (85.3°N 152°E, 44 km diameter) are all likely to contain large permanently shadowed areas, probably totaling >1000 km². Additionally the highland area approximately defined by the boundaries 80–90°N, 90–180°W appears to contain copious small shadowed areas that may be permanently shadowed [Vasavada et al., 1999].

7. South Pole

[17] A detailed analysis of all fresh looking simple craters larger than 1 km, within 12° of the pole identified 547 craters. These craters have a total area of 11,200 km² which represents just under 3% of the total lunar surface south of 78°S. Using equation 1 to calculate the amount of permanent shadow associated with these craters yields a lower limit of permanent shadow of 6500 km². This compares with 3300 km² [Bussey et al., 1999], and 5100 km² [Margot et al., 1999]. Our new value is a lower limit for a number of reasons. As was stated for the north pole above, this number only reflects shadow in simple craters 1 to 20 km in diameter. A number of complex craters in the 20–35 km diameter range exist in the south polar region e.g., Scott E (81.1°S 36°E, 28 km diameter), Idelson L (84.2°S 116°E, 28 km diameter), and Weichert J (85.6°S 177°W, 34 km diameter). These are all likely to have large amounts of permanent shadow. Additionally for the south polar region, the fact that it was winter in the southern hemisphere when the data were collected means that significant amounts of the surface are in shadow. These regions contain craters that have permanent shadow, for example Faustini (87.3°S 77.0°E 39 km diameter) and Shoemaker (88.1°S 44.9°E 51 km diameter), that have not been included in the 6500 km² figure quoted above. An upper limit for the amount of permanent shadow in the south polar region has been obtained by measuring the actual shadow seen, 15000 km² [Nozette et al., 1996], as well as calculating the

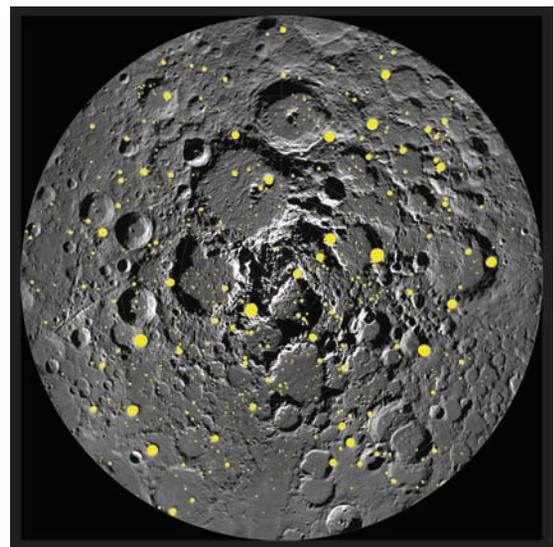


Figure 4. A mosaic of the northern polar region, from 78°N to the pole. Craters included in our analysis are shown in white. They represent approximately 3% of the total surface area shown, and collectively contain roughly 7500 km² of permanent shadow.

combination of shadow together with the amount of surface not imaged, 30,000 km² [Shoemaker *et al.*, 1994].

8. Implications for Hydrogen Deposits

[18] Based on results from the Lunar Prospector neutron spectrometer, Feldman *et al.* [2000] quote a figure for the mass fraction of H₂O in the permanently shadowed regions of 1.5%. If all permanently shadowed terrain does contain water ice at the concentration suggested by Feldman *et al.* [2000] then new values for the minimum amount of water ice are 3.9×10^8 and 4.5×10^8 metric tons for the south and north poles respectively. Based on the non detection of hydrogen by the Lunar Prospector gamma ray spectrometer Feldman *et al.* [2000] quote an upper limit for the amount of water ice in permanently shadowed areas in the north polar region of 10.4 wt.%. Our increased value for the amount of permanent shadow reduces this upper limit to 6.7 wt.%. This number will decrease further when permanent shadow associated with complex craters is included. If this upper limit approaches the value of 1.5 wt.%, estimated from measurements obtained by the neutron spectrometer, it becomes increasingly likely that not all permanent shadow contains ice. This would be consistent with the idea that larger craters are more likely than smaller craters to maintain low enough temperatures to permit ice to persist over extended periods of time [Vasavada *et al.*, 1999].

[19] It should be noted that the existence of permanent shadow is not in itself enough to allow water ice to exist on the lunar surface. Work by several researchers [Vasavada *et al.*, 1999; Hodges, 1980] has suggested that permanent shadow in simple craters at lower latitudes is not cold enough to act as cold traps for water molecules. However doubly shielded (e.g. a crater within a crater) regions might be cold enough to allow ice to exist at lower latitudes than that calculated for simple craters [Hodges, 1980; Carruba and Coradini, 1999]. Therefore the fact that simple craters collectively represent a large area of permanent shadow is relevant to searching for ice deposits. Whilst not all permanent shadow can contain ice, all the ice must be located in permanent shadow.

9. Conclusions

[20] Illumination simulations of topography have greatly increased our knowledge of the amount and location of permanently shadowed regions near the pole. We have shown that latitude, rather than diameter, is the dominant parameter in determining the amount of permanent shadow in a simple crater. Craters as far out as 20° from a pole still contain significant amounts (22–27%) of permanent shadow. Results from the simulations have been used to provide a convenient equation that predicts the amount of permanent shadow in a simple crater, given the crater's latitude and diameter. An analysis of fresh simple craters in both polar regions produced new lower limits for the amount of permanent shadow, 7500 km² for the north pole and 6500 km² for the south pole, which represent significant increases compared to previous estimates. Our polar analysis has also shown that in addition to being large in total area, permanent shadowed regions are widely distributed and copious in number. We have therefore shown that there

are many more potential cold traps, distributed over a wider area, that could harbor water ice, than previously identified.

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