DID A LARGE IMPACT REORIENT THE MOON?

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Summary. The Moon is currently locked in a spin-orbit resonance of synchronous rotation, of which one consequence is that more impacts should occur near the Moon's apex of motion (0° N, 90° W) than near its antapex of motion (0° N, 90° E) [1-4]. Several of the largest lunar impact basins could have temporarily unlocked the Moon from synchronous rotation, and after the re-establishment of this state the Moon would have been left in either its initial orientation, or one that was rotated 180° about its spin axis. We show that there is less than a 2% probability that the oldest lunar impact basins are randomly distributed across the lunar surface. Furthermore, these basins are preferentially located near the Moon's antapex of motion (contrary to what might be expected), and this configuration has less than a 0.3% probability of occurring by chance. We postulate that the current "near side" of the Moon was in fact its "far side" when the oldest basins formed. One basin with the required size and temporal characteristics to account for a 180° reorientation is the Smythii basin.

Reorientation of the Moon by Impacts. When asteroids and comets collide with the lunar surface, the angular momentum and spin rate of the Moon are altered instantaneously. Since the relative change in angular momentum is small, the Moon will continue to rotate approximately about its prior spin axis, but with the axis of its minimum moment of inertia librating back and forth in longitude like a pendulum [5,6]. The maximum angular extent of these librations depends upon the change in angular momentum along the lunar rotation axis, and if the impulse delivered by the impactor were large enough, the libration amplitude could exceed 90°. If this were to happen, the Moon would rotate non-synchronously, allowing both faces to be seen from the surface of the Earth over a period of about a year. At this point, tidal torques would act to once again bring the Moon into synchronous rotation, but it would be only a matter of chance as to whether the same face of the Moon would be directed towards the Earth as before the impact [5,7].

We calculate the minimum sized bolide required to unlock the Moon from synchronous rotation as a function of impact velocity [see 7]. Results assuming an average impact geometry are shown in Figure 1, as well as the corresponding crater size using crater-scaling laws in the gravity regime. These results depend upon the assumed Earth-Moon separation, for which we chose two representative extremes of 25 and 50 Earth radii (the present separation is 60 Earth radii), as well as the bolide density.

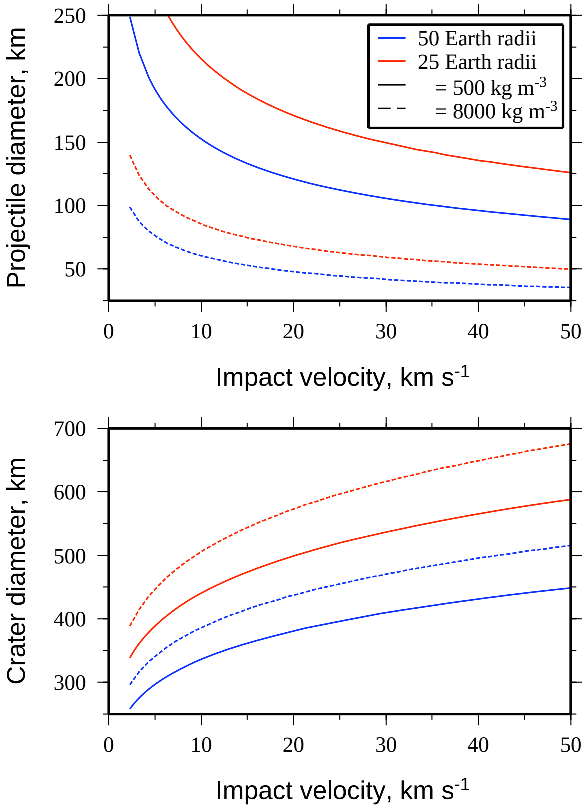

Figure 1. Minimum projectile diameter (top) and minimum crater diameter (bottom) required to unlock the Moon from synchronous rotation as a function of impact velocity for the case of an average impact geometry. The average impact velocity with the Moon is about 19 km/s.

For the case where the semimajor axis of the Moon is close to its present value, any impact crater greater than about 300 km in diameter could have unlocked the Moon from synchronous rotation. In contrast, if the semimajor axis of the Moon was closer to 25 Earth radii, the crater diameter would have to be greater than about 350 km for the minimum impact velocity, and greater than about 500 km for the average impact velocity. As originally noted by Melosh [5], there are several impact basins that could have temporarily unlocked the Moon from synchronous rotation and which might have led ultimately to a 180° reorientation about the lunar spin axis.

Evidence for Reorientation. One of the consequences of synchronous rotation is that more impact events should occur near the Moon's apex of motion on its western hemisphere than the antapex of motion on its eastern hemisphere. At the present time, the difference in impact rate between these two points is about 29%, but this would have been greater in the past when the Moon was closer to the Earth and its orbital velocity was higher. If one or more impact events unlocked the Moon from synchronous rotation, and if the geographic locations of the apex and antapex of motion were subsequently switched, one might expect to find a surplus of craters within a certain age range located near the current antapex of motion on the eastern hemisphere of the Moon.

In order to test the hypothesis, we make use of the known impact basins as tabulated by Wilhelms [8] and Spudis [9], of which there are 46. These basins have been grouped into 15 relative age classes (with 1 being the youngest and 15 the oldest) and we ignore the oldest and largest basin (South Pole-Aitken) since this event might have altered the moments of inertia of the Moon, and hence, its stable orientation.

To quantify the distribution of lunar impact basins, we use the statistic

$$\bar{\mathbf{r}} = 1/N \sum_{i=1}^{N} \mathbf{r}_i$$

where N is the number of impact basins and $\mathbf{r}_i$ is a unit vector pointing in the direction of the ith basin. If the basin locations were randomly distributed, the expectation value of this statistic would be identically zero. The observed direction and magnitude of this statistic for a given set of basins are thus indicators of any spatial asymmetry that might have existed in the cratering rate. We determine the probability that a spatially uniform cratering rate could have given rise to the observed value of $\mathbf{r}$ by performing Monte Carlo simulations.

The upper image of Figure 2 shows the locations of the impact basins used in this study, and the lower image shows the direction of $\mathbf{r}$ for all basins younger and contemporary to a given age group (blue), or older and contemporary to a given age group (red). As is seen, the younger basins are, as expected, preferentially located on the western hemisphere of the Moon. In contrast, when considering only those basins that are older or equal to a given age group, it is seen that the older basins are preferentially located on the eastern hemisphere of the Moon. The simplest hypothesis to explain this observation is that the youngest basins formed when the Moon was in its current orientation, but that the oldest basins formed when it was in an orientation rotated 180° about its spin axis.

The next question to address is whether the magnitudes of the observed asymmetries in basin locations are statistically significant, or if a uniform cratering rate could have given rise to these by chance. When considering all those basins younger and contemporary to a given age group (blue), we find that there is a high probability that the magnitudes of $\mathbf{r}$ could have occurred by chance. In contrast, when basins older and contemporary to a given age group are considered (red), we find that there is less than a 5% probability for the magnitude of $\mathbf{r}$ to be as large as observed. In particular, the probability that basins are randomly distributed for age groups older or equal to 11, 12, and 13 is 3.3, 1.6 and 1.3%, respectively.

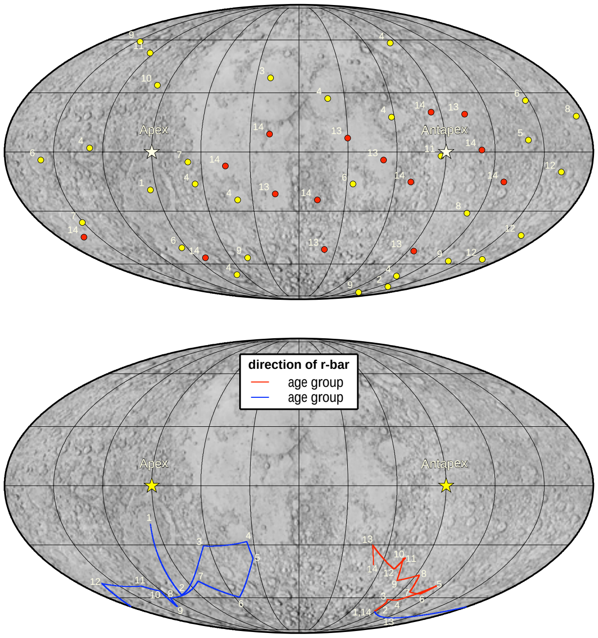

Figure 2. (top) Locations of lunar impact basins, with numbers indicating the relative age group (age group 1 is the youngest and age group 14 is the oldest). Basins younger and contemporary to group 11 are plotted in yellow, whereas older basins are plotted in red. (bottom) Position on the lunar surface of the vector $\mathbf{r}$ for all basins younger and contemporary to (blue), or older and contemporary to (red), a given age group.

In addition to testing whether the lunar basins are randomly distributed or not, we also investigate whether the observed magnitude and direction of the observed asymmetry are consistent with having a higher cratering rate near either the Moon's apex or antapex of motion. We find that there is less than a 0.27% probability that the observed magnitude of $\mathbf{r}$ and angular distance between $\mathbf{r}$ and the Moon's antapex of motion could have occurred by chance for age groups greater or equal to 12 and 13.

References: [1] G Horedt, G Neukum, Icarus 60, 710, 1984; [2] K Zahnle et al., Icarus 153, 111, 2001; [3] T Morota, M Furumoto, EPSL, 206, 315, 2003; [4] T Morota et al., Icarus 173, 322, 2005; [5] HJ Melosh, EPSL, 26, 353, 1975; [6] S Peale, JGR, 80, 4939, 1975; [7] J Lissauer, JGR 90, 11289, 1985; [8] D Wilhelms, USGS 1348, 1987 [9] P Spudis, The geology of multi-ring impact basins, 1993.