THE ASYMMETRIC CRATERING HISTORY OF THE MOON.

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The geologic history of the Moon plays a key role in planetary science as it is the only body for which geologic units have been sampled and dated. By calibrating the observed size-frequency distribution of impact craters at the Apollo sites to their radiometric ages, it is possible to determine the ages of other geologic units on the Moon and other planetary bodies. The Moon, however, is not so neutral a reference body as one would hope. Because it is locked in a synchronous rotation about the Earth, we have found that it experiences a significant asymmetry in its cratering rate, and that this asymmetry may induce dramatic errors when dating surfaces far from the Apollo landing sites.

The crater counting method.
As a result of the measured radiometric ages of samples returned by the Apollo and Luna missions, an empirical relationship has been obtained between the age of a geologic unit and its size-frequency distribution of impact craters [1]. The shape of this curve, the production function, is commonly assumed to be independent of both time and location on the lunar surface. By using the vertical offset of a measured production curve, the age of geologic units far from the landing sites can thus be estimated, including, after extrapolation, other planetary bodies such as Mars and satellites of Jupiter and Saturn [e.g., 2]. As we have no samples from other planets with a known geologic context, the method of crater counting is the only technique available for the dating of other planetary surfaces.

While this method is in common use within the planetary science community, it is important to realize that the obtained ages are valid only if at a given point in time, the flux of impactors (i.e., asteroids and comets) is homogeneous over the entire surface of the Moon. However, because of the Moon's synchronous rotation, we have found that a significant asymmetry of the lunar impact cratering rate could arise. Two phenomenon that are applicable to any synchronously locked satellite are involved here.
Firstly, like the rain hitting preferentially the front of a moving car, more impacts will occur on its leading (or western) hemisphere than on its trailing (or eastern) one. Secondly, because of the Earth's gravitational field, which acts as a focusing lens, more impacts will occur on the Moon's nearside than on its farside. When the Moon cross the "focal point" beyond the Earth, its nearside hemisphere will experience a greater flux of projectiles than its farside.

While the leading-trailing cratering dichotomy has been partially investigated [e.g., 3, 4, 5], the nearside-farside asymmetry was only preliminary investigated in a single paper [6]. The purpose of this study is to quantify the leading/trailing and nearside/farside cratering asymmetries, and to develop crater-counting methods that take these into account.

Impact simulations.
By performing numerical simulations, we have investigated the influence of the Earth-Moon separation and the velocity of the incoming projectiles on the Moon's cratering rate. For simplicity, we initially assumed that the lunar orbit, lunar spin axis, and incoming projectiles all possessed an inclination of zero.

Figure 1 illustrates the Earth's gravitational focussing effect, by showing the initial positions of the projectiles launched in our simulations that eventually hit the Moon. As is seen, in addition to those projectiles that lie within the Earth-Moon plane, gravitational focusing by the Earth causes some projectiles initially located above this plane to impact the Moon as well. This is quantified in figure 2 which shows the impact cratering rate as a function of position on the lunar surface. As is seen, the Earth-Moon distance has only a small effect on this distribution. The asymmetry is more pronounced for small initial projectile velocities, but remains significant for higher velocities. Due to the two sources of asymmetry mentioned above, the maximum cratering rate is located on the equator between the nearside and leading hemispheres. On average, the cratering rate is about a factor of four greater on the nearside than the farside, and the cratering rate at the poles is almost a factor of 10 less than average.
As a result of the large predicted spatial variations in the cratering rate, this effect must be included when applying the technique of crater counting to the Moon. While crater count ages obtained for sites close to the Apollo landing sites should not be too much in error, as one moves away from these calibration sites, the error will increase.

As the above results assumed that the inclinations of the lunar orbit, lunar spin axis, and incoming projectiles was zero, we have performed some cursory simulations to see if the above measured asymmetry disappears when more realistic conditions are employed. Following [7, 8], we have taken into account the inclination of lunar orbit and spin axis for a few typical values of the Earth-Moon separation. While this effect slightly reduces the asymmetry effects, a prominent nearside/farside asymmetry is still found to exist.
We are currently implementing a more realistic model of the near Earth asteroid orbital parameters which includes their inclination and velocity distributions[9, 10]. Using these probability distributions as input to out model, we are in the processes of calculating the probability that these enter the Earth's Hill sphere, and then continuing our simulations as described above.

Geological consequences.
Figure 3 illustrates the canonical crater density versus age plot that is used in many crater counting studies. As is illustrated by the red curve, a change in the cratering rate (which corresponds to a change in the total number of craters found on a unit) by a factor of 2 could bring about dating errors of up to 1 Gyr in worst case scenarios. Due to the flatness of the curve between about 1 and 3 Gy, errors will be largest during this time period. Indeed, we note that an error of 1 Gy could easily change the epoch of some geologic units,.
In particular, we suspect that the apparently young Eratosthenian lava flows within the Smythii basin, and which are far from the confines of the Procellarum KREEP Terrane, are in fact much older, possibly being

Imbrian in age. We further note that the results of this study will be of importance for interpreting correctly the ages of samples that will be obtained from the SPA basin, as this basin is located on the southern farside hemisphere, where the impact flux is predicted to be less from that of the Apollo landing sites.

The Jovian system.

Because of tidal interactions, the satellites which orbit the gas giant planets in the outer solar system are similarly in a state of synchronous rotation as the Moon. Since the gravitational attraction of these planets is considerably larger that that of the Earth, it seems probable that these satellites will likewise experience a nearside/farside cratering asymmetry rate. . We are currently quantifying this effect by running similar simulations as above, and initial results seem to indicate that this effect will need to be considered when employing the crater counting method to the Jovian moons.

REFERENCES: [1] Neukum, G., Ivanov, B. A., Hartmann, W. K., 2001, *Cratering Chronology and the Evolution of Mars*, 96, 55-86; [2] Hartmann, W. K. and Neukum, G., 2001, *Space Sci. Rev.*, 96, 165-194; [3] Horedt, G. P., Neukum, G., 1984, *Icarus*, 60, 710-717; [4] Zahnle, K., Schenk, P., Sobieszczyk, S., Dones, L., Levison, H., F., 2001, *Icarus*, 153, 111-129; [5] Morota, T. and Furumoto, M., 2002, *Sci. Rep. Kanasawa Univ.*, 47, 49-58; [6] Wood, J. A., 1973, *The Moon*, 5, 73-103; [7] Ward, W. R., 1975, *Science*, 189, 377-379; [8] Touma, J. and Wisdom, J., 1994, *Astron J.*, 108 (5), 1943-1961; [9] Stuart, J., S., 2001, *Science*, 294, 1691-1693; [10] Greenberg, R., 1982, *Astron. J.*, 87, 184-195.

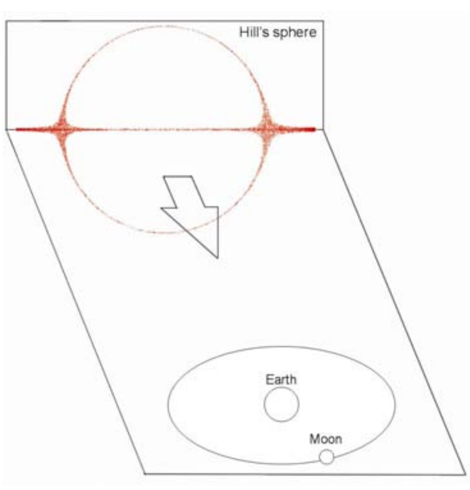

Figure 1. Example of the initial spatial distribution of projectiles, launched from the Earth's Hill sphere, that eventually hit the Moon. While a portion of the projectiles that are launched within the Earth-Moon plane are seen to impact the Moon, because of the Earth's gravitational focussing effect, projectiles launched far from this plane impact the Moon as well.

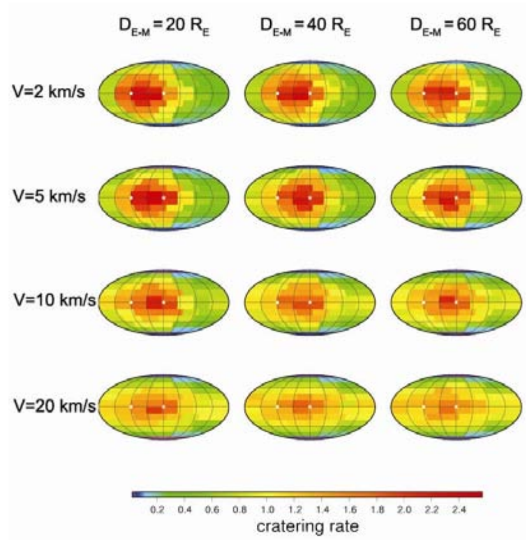

Figure 2. Lunar impact crater density (normalized to the average value) as the function of the initial asteroid velocity, V, and the Earth-Moon separation, D_{E-M}, measured in term of the Earth's radius, R_E (the current Earth-Moon separation is about 60 R_E). In this Mollweide global projection, the sub-Earth point is shown by a star, and the apex (90°W, 0°N) of the leading hemisphere is shown by a circle. The cratering rate is about a factor of two greater than normal on the nearside hemisphere.

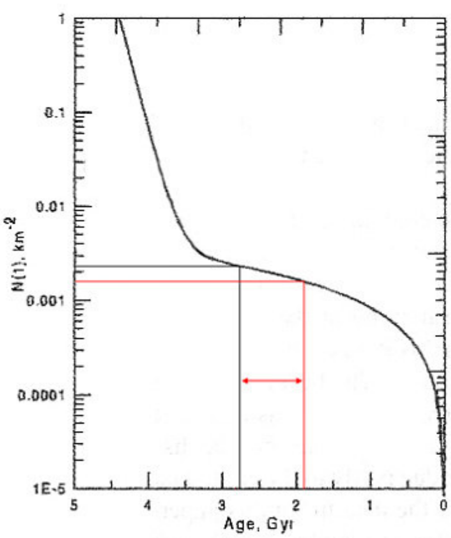

Figure 3. Due to the shape of the production function, large errors may occur when trying to give an age to areas between 1 and 3 Gyrs without considering the asymmetric impact distribution. In this example, two hypothetical geologic units with the same age, but with a crater density different by a factor 2, are shown. The ages given by the dating method are almost 1 Gyr different.