THE ASYMMETRIC CRATERING HISTORY OF THE MOON AND TERRESTRIAL PLANETS

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Abstract

By measuring the size-frequency distribution of impact craters on a planetary surface, it is possible to estimate its age. One fundamental assumption used in such analyses is that the cratering rate, while perhaps not uniform in time, is independent of the position on a given planet. However, as the population of asteroids and comets that strikes a planet is not isotropic in space, we have found that a latitudinal dependency of the cratering rate is to be expected. This latitudinal effect has been investigated semi-numerically for Mercury, Venus, the Earth, the Moon, and Mars using as input the orbital distribution of small bodies from [2]. As most of these bolides have low inclinations, and because their encounter kinetic energy contributes more in governing their trajectory than the gravitational attraction of the target planet, the impact flux on the terrestrial planets should generally be larger at the equator than at high latitudes. Even for the case of Mars, where the obliquity variations tend to homogenize this latitudinal effect, the impact flux appears to have been ~20% lower at the poles over the past billion years. In addition, as the mean impact angle from horizontal decreases towards the poles, the resulting crater size will be larger at low latitudes, making this latitudinal effect even stronger in terms of cratering rate.

For the special case of the Moon, whose synchronous rotation was expected to induce other asymmetric effects, numerical simulations have been made in the frame of the restricted three-body problem. In addition to the latitudinal effect, an apex/antapex asymmetry of ~30% has been found, as well as a nearside/farside asymmetry for projectiles with low inclinations and velocities.

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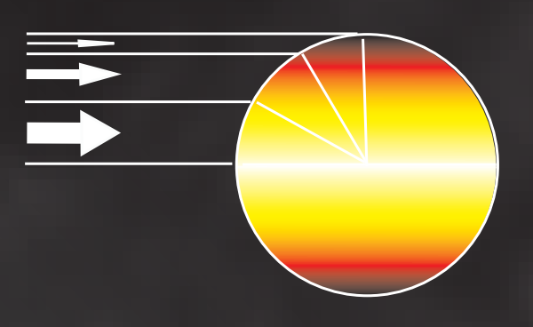
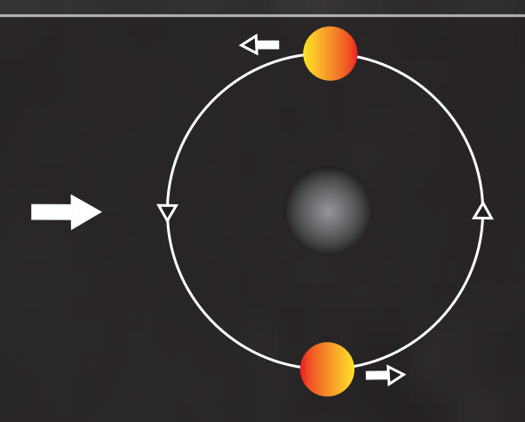
Asymmetric cratering rate

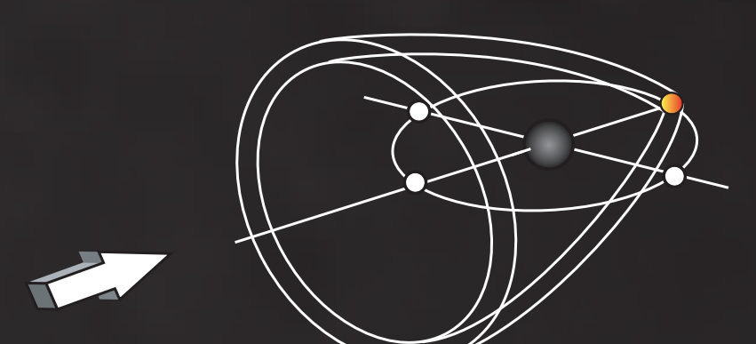


As the path of the projectile is most of the time governed by its encounter kinetic energy, and because in general its inclination is low, the impact flux will be larger around the equator. This figure shows the extreme case of a non graviting body (i.e., projectiles coming with an infinite velocity) experiencing a zero inclinated flux.

Synchronous rotation



Like the rain hitting preferentially the front of a moving car, more impacts will occur on the Moon's leading (or western) hemisphere than on its trailing (or eastern) one.

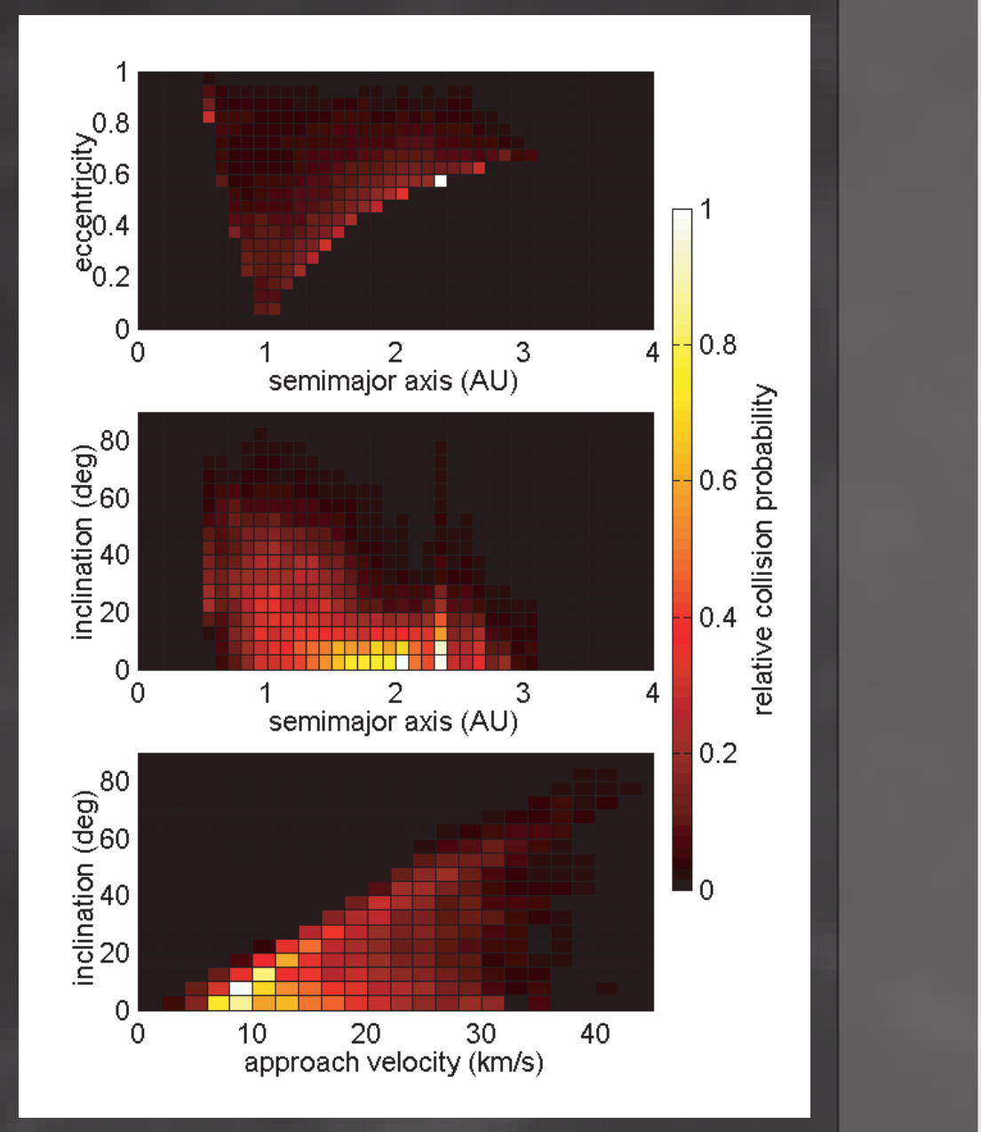


Because of the Earth's gravitational field, which acts as a focusing lens, more impacts will occur on the Moon's nearside than on its farside when it cross the focal point beyond the Earth, as previously proposed by [7].

3

NEO collision probability

For each planet, the probability of an impact and its corresponding encounter velocity have been calculated as a function of the orbital elements *(a,e,i)* using a modification of Kessler's method as detailed in [1]. The impact probability of each orbital element bin was then weighted by the relative number of asteroids or comets in that bin as estimated by Bottke et al. [2]. This model assumes that the population of small bodies is currently in steady state, which is probably a reasonable assumption for the past 3 Ga. The resulting impact probability for each *(a,e,i)* bin was then transformed into an impact probability as a function of inclination *i* and encounter velocity *u*. The probability of each *(u,i)* bin was then used as an input for estimating the impact flux distributions.



Estimates of the collision probability with the Moon.

Most of the impactors possess low inclinations

4

Latitudinal effect

Ignoring a possible true polar wander, the impact flux on a planetary body should depend only on the latitude as a result of its rotation, except for the case of a synchronous satellite, where a longitudinal effect arises. Within the approximation of a two-body problem, the target planet experienced an impact flux whose variations with latitude are depending only on the encounter parameters of a given kind of bolides (approach velocity *u* and mutual inclination *i*) and on the mass and size of the planet (respectively *M* and *R*). Indeed, the impact flux Φ produced by a given *(u,i)* population can be fully described by the non dimension number $\Gamma = GM/Ru^2$.

For projectiles with $i = 0$

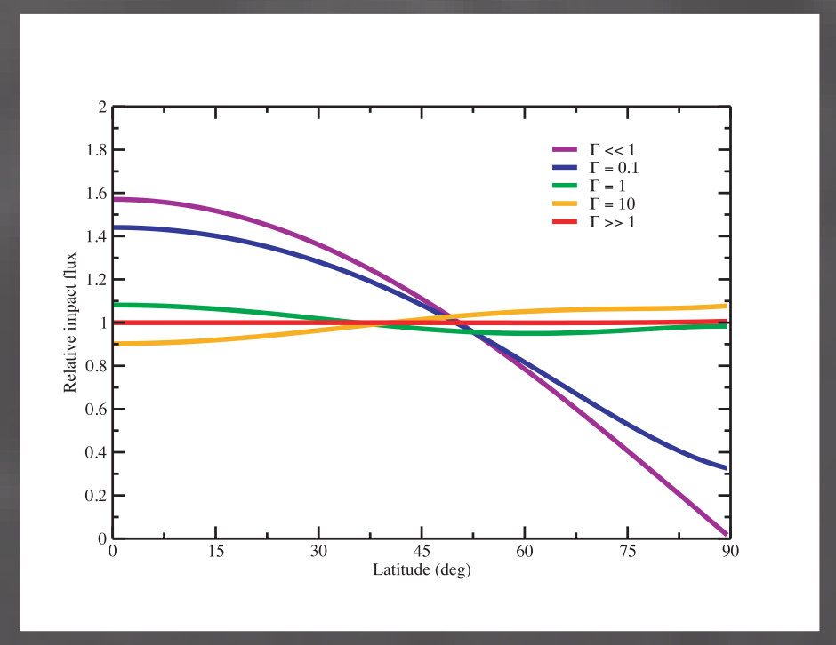
$$\Phi'^2(\lambda) = \cos^2(\lambda) + f(\Gamma)\sin^2(\lambda)\left(1 + e^{-\left(\frac{\Gamma - \frac{0.6}{f(\Gamma)}}{20}\right)^2}\sin(\lambda)\right)$$

with $f(\Gamma) = \frac{0.7\Gamma}{1 + 0.7\Gamma}$

In the general case

$$\Phi(\lambda) = \frac{1}{\pi}\int_0^{\pi} \Phi'(\lambda_i)d\phi$$

with $\sin\lambda_i = \sin\lambda\cos i + \cos\lambda\sin i cos\phi$



Projectiles in the equtorial plane

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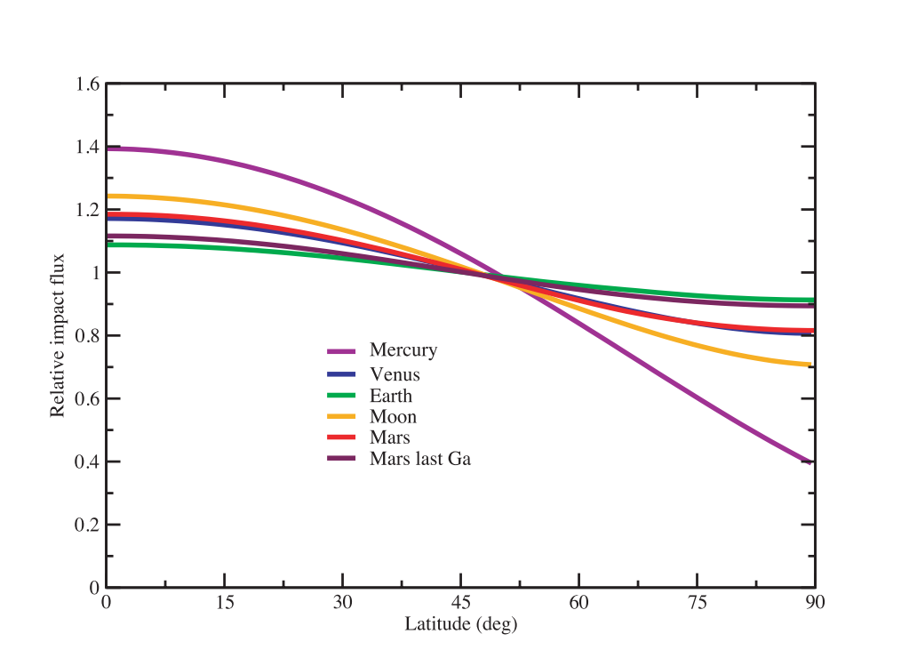
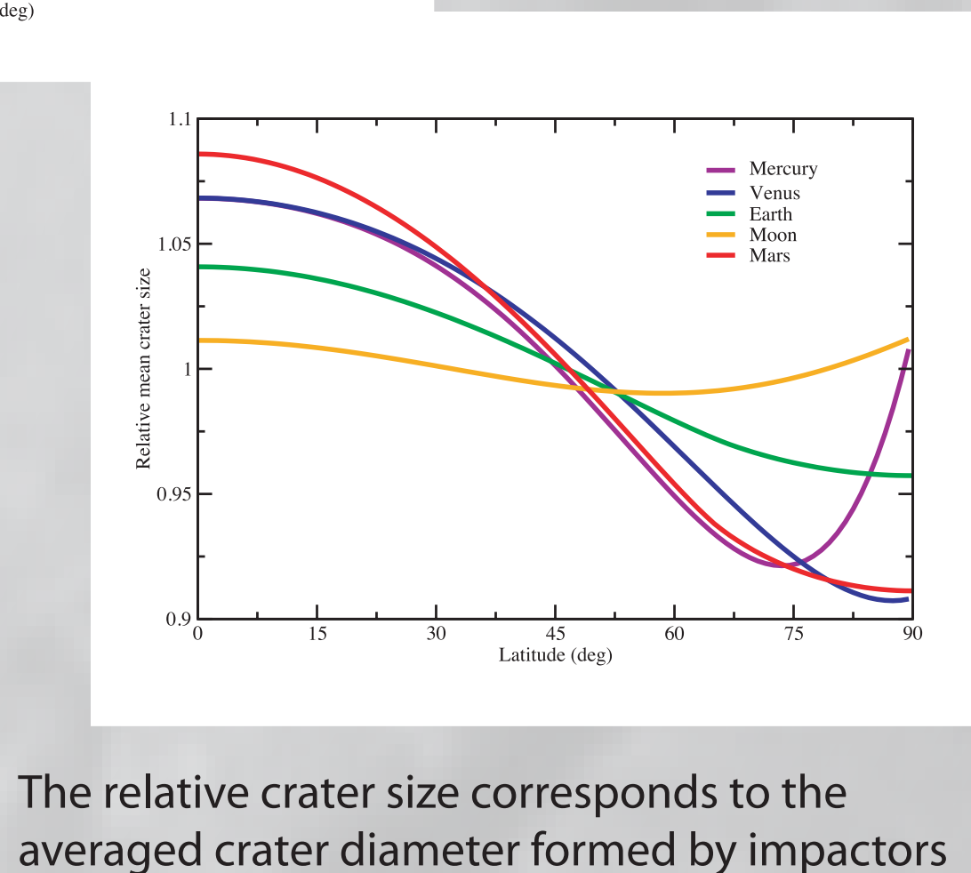
Terrestrial planets

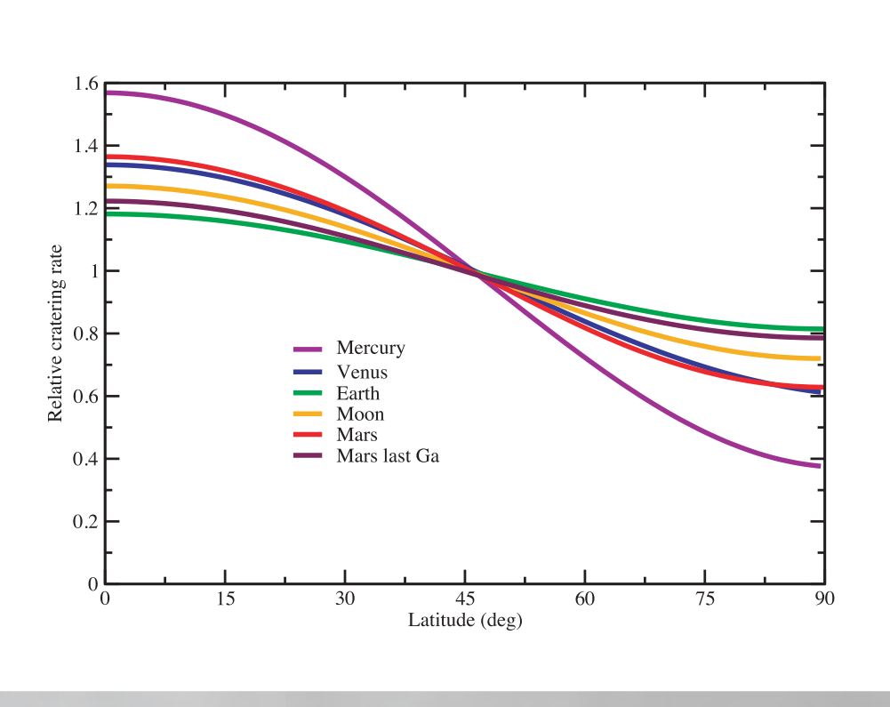
By combining the *(u,i)* distribution of impact probability (see 3) with the analitycal expression of the latitudinal effect (see 4), the resulting impact flux and cratering rate have been estimated over the terrestrial planets and on the Moon. Note that the Moon is considered here to orbit around the Sun at 1 u.a.
For the special case of Mars, whose obliquity variations are large, the time spent at a given obliquity over the last Ga [3] has been used. By summing theoretical impact distributions for each obliquity, weighted by the amount of time the planet spends there, the net latitudinal effect was determined. Even taking into account this strong homogenizing effect, it has been found that a significant latitudinal variation is still predicted to exist.



Estimated distributions in latitude of the impact flux, mean crater efficiency and cratering rate on the terrestrial planets and the Moon. The obliquities of the planets are set to their present values, except for the case of Mars during the past billion years.



The relative crater size corresponds to the averaged crater diameter formed by impactors of the same mass, depending only on the impact angle and impact velocity.



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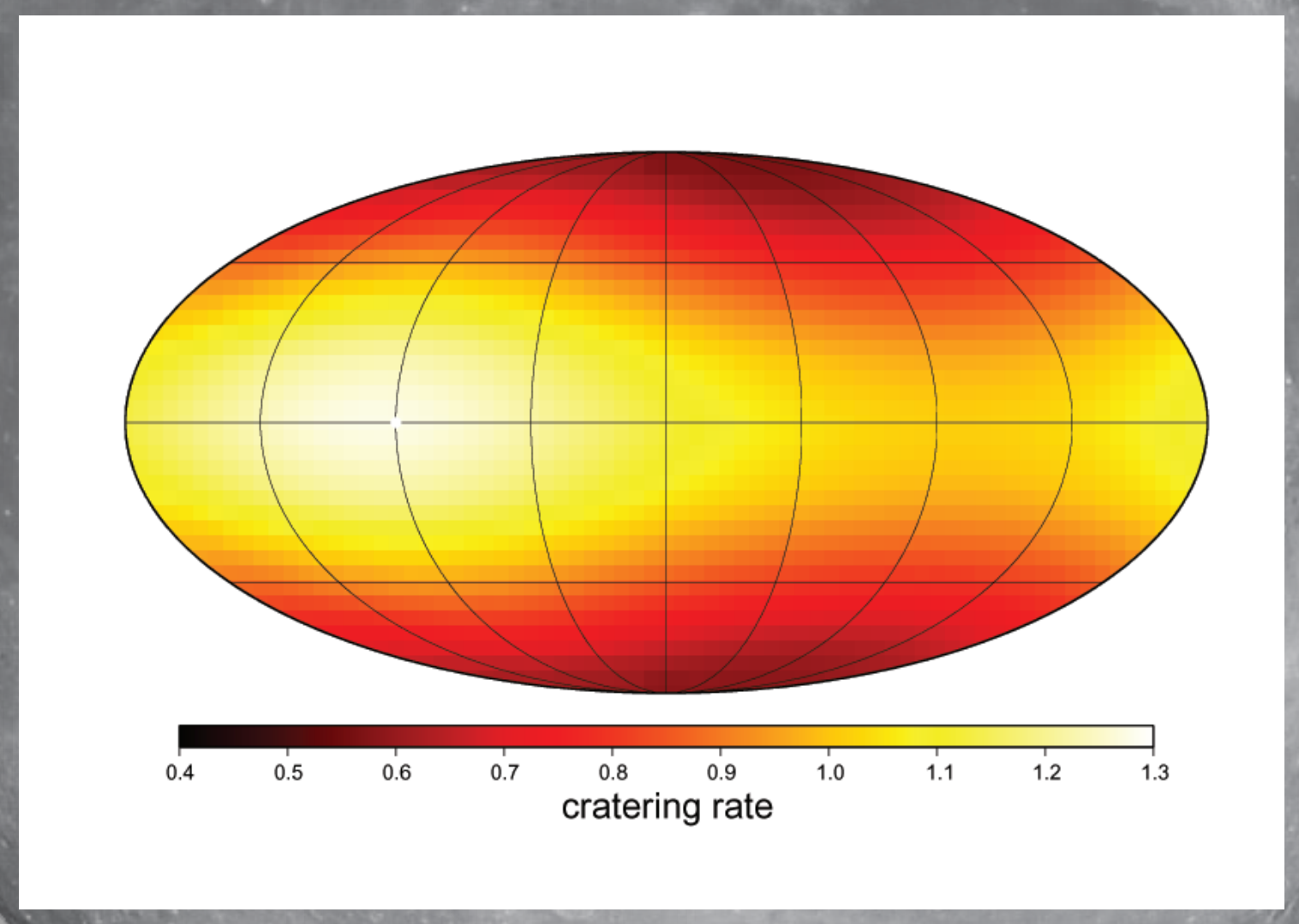
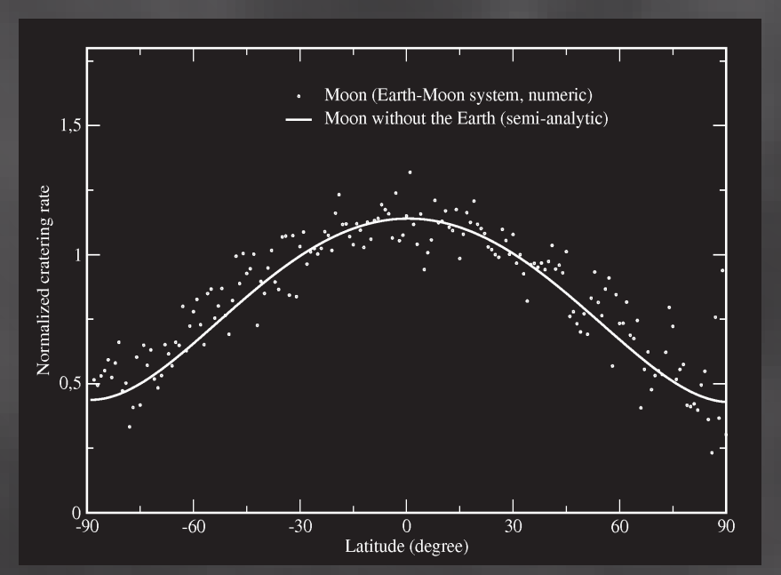
The Moon

To take into account the synchronous rotation of the Moon, the probability of each *(u,i)* bin was used as an input in the frame of the restricted three-body problem. The resulting global spatial distribution of the impact flux is well described by the addition of two independent effects: a leading-trailing asymmetry that depends on the Earth-Moon distance, and a latitudinal asymmetry.

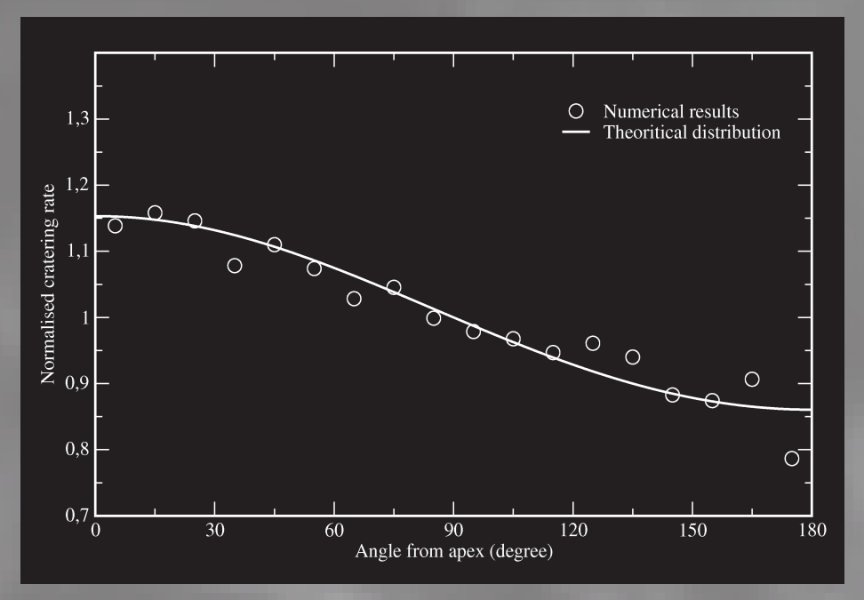


Normalized impact flux on the Moon. The Earth-Moon separation is taken at its present value. The white dot represents the apex of motion.

7 The latitudinal effect is well described by the method ignoring the gravitational influence of the Earth (see **5**).



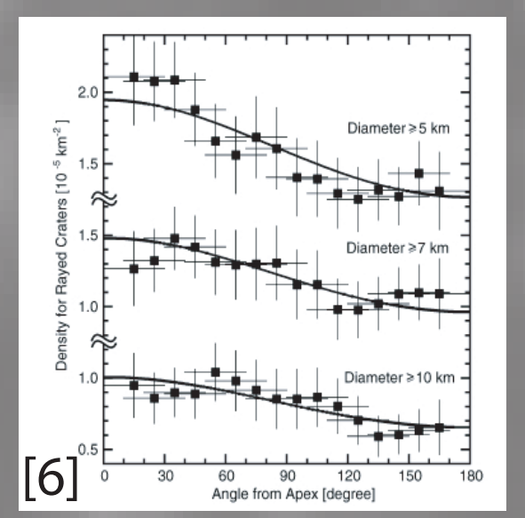
8 The leading-trailing asymmetry, found to be ~30%, is consistent with the data of rayed craters from [6], although our mean approach velocity is estimated to be larger.



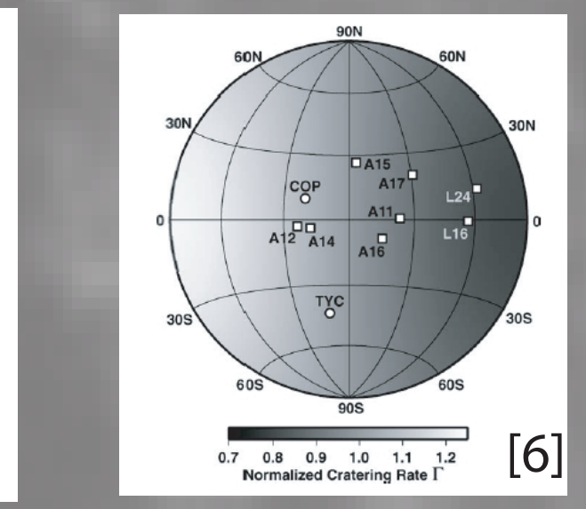
$\langle v_\infty \rangle = 20km/s$

$b = 0.58 \pm 0.03$

$$\dot{N}(\beta) = \left(1 + \frac{v_{orb}}{\sqrt{2v_{orb}^2 + v_\infty^2}}\cos(\beta)\right)^{2.0+1.4b}$$ [5]

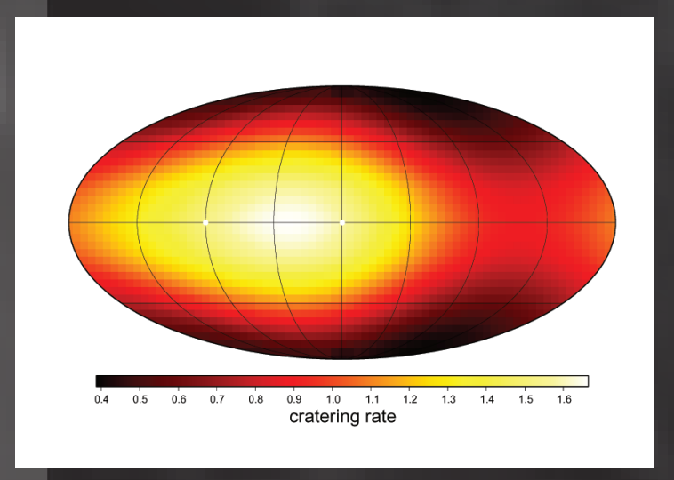


[6]



[6]

9 For low velocity and inclination projectiles, a nearside/farside asymmetry arises. This may locally change the shape of the SFD.



u < 10 km/s
i < 10˚

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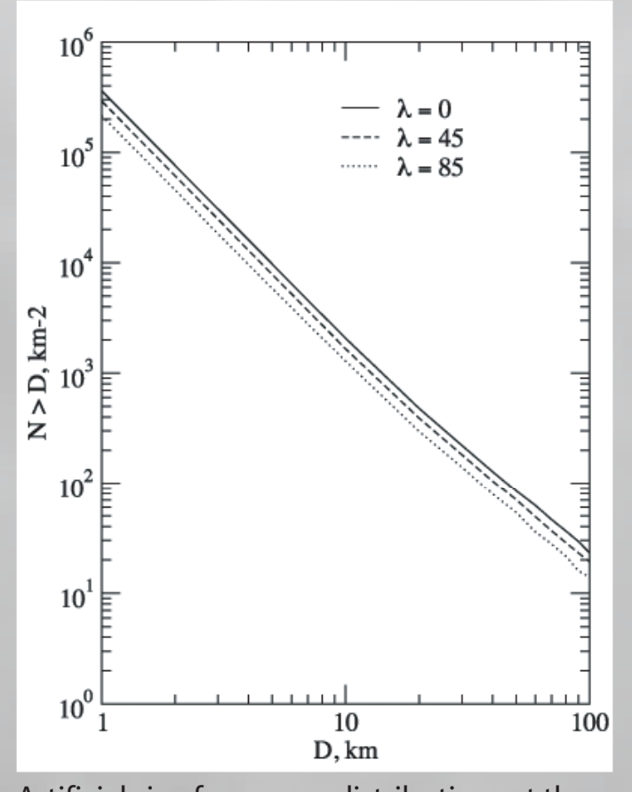
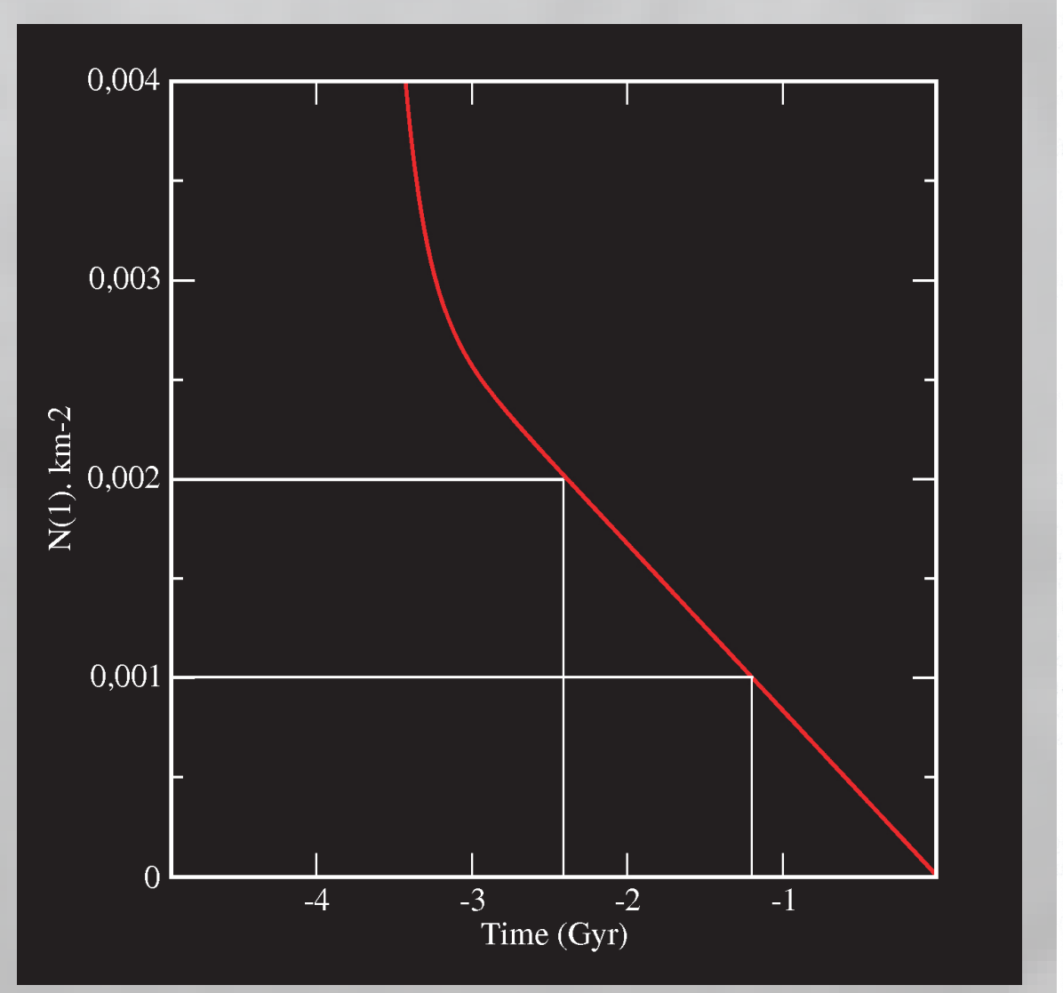
Implications for surface chronology

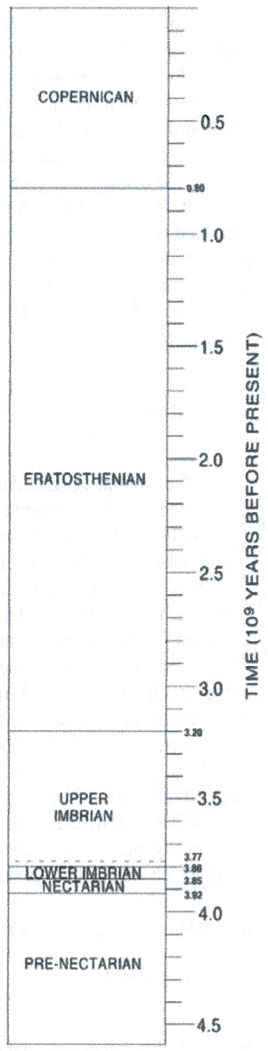
As the dating of planetary surfaces by the method of crater counting considers that the crater density is only a function of time [8,9], the neglect of spatial variations could significantly bias the obtained age estimates. The Moon is not so neutral a reference body as one would hope, possessing an asymmetric cratering history as a result of its synchronous rotation. More generally, the terrestrial planets should also show a latitudinal variation of the impact flux. As the cratering rate has been relatively constant over the past 3 Ga, a given variation in crater production between two locations on the planet simply translates to a bias in age of the same value when this effect is not taken under consideration.



Artificial size-frequency distributions at three different latitudes, on the Moon. The offsets between the curves correspond to the relative variations of the cratering rate, and not to the relative ages.



Bias in age for a cratering rate lower by a factor 2 because of the location of the area considered.



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[2] Bottke, W. F. and 6 others, 2002, Icarus, **156**, 399-433;
[3] Laskar, J. and 5 others, 2004, Icarus, **170**, 343-364;
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