National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

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Dear Dr. Suggs and Dr. DeStefano,

This memo describes a brief analysis we have conducted to estimate the flux of small asteroids and comets (those between about 0.1 and 1000 meters in diameter) onto the lunar surface. We have based this analysis on the Brown et al. (2002) large impactor flux at the Earth and the impact velocity distribution of bolides reported by the Center for Near Earth Object Studies (CNEOS).[1] Both of these data sources are kinetic-energy-limited and correspond to the impact flux at the same location: the Earth's atmosphere.

Large impactor flux

Brown et al. (2002) use a combination of bright bolide data, infrasound and acoustic data, satellite observations, and telescopic observations of small asteroids to construct a power law describing the cumulative flux of large objects onto the Earth:

$$\log_{10} N = a - b \log_{10} \mathrm{KE} \tag{1}$$

where KE is the kinetic energy of the impactor in kilotons TNT equivalent (4.184×10^{12} J), N is the number of objects impacting the Earth per year with a given kinetic energy or greater, and the constants are $a = 0.5677$ and $b = 0.9$.

We convert this flux to MKS units by assuming that the Earth has an effective radius of 6471 km (including 100 km of atmosphere capable of ablating meteoroids). The resulting kinetic-energy-limited flux per square meter per year is:

$$f_{\oplus}(\mathrm{KE}) = 7.023 \times 10^{-15}\, \mathrm{KE}^{-0.9} \tag{2}$$

To obtain Eq. 2, we have divided by the surface area of the Earth. Thus, $f_{\oplus}$ reports the flux per unit surface area. One can convert Eq. 2 to a flux per cross-sectional area, if desired, by multiplying by 4.

Gravitational focusing

The Earth's gravity "pulls" objects in and increases its effective impact cross section. As a result, the mass-limited flux of objects onto the Earth is greater than that onto the Moon. Furthermore, the Earth also accelerates incoming objects to higher speeds, increasing their kinetic energy. As a result, there will be an even larger disparity in the kinetic-energy-limited flux at the Earth and the Moon.

Overall, gravitational focusing increases the (mass-limited) flux onto the Earth by the following factor:

$$\xi_{\infty} = \frac{v_{\mathrm{atm}}^2}{v_{\mathrm{atm}}^2 - v_{\mathrm{esc},\oplus}^2} \tag{3}$$

[1] https://cneos.jpl.nasa.gov/fireballs/

Here, ξ_∞ is the ratio of the flux on the top of the Earth's atmosphere to that in interplanetary space, v_{atm} is the speed of the impactor as it enters the Earth's atmosphere, and $v_{\mathrm{esc},\oplus}$ is the escape velocity at the Earth. By dividing by a similar expression for the Moon, one can obtain the ratio of the flux at Earth to that at the Moon:

$$\xi = \frac{v_{\mathrm{atm}}^2}{v_{\mathrm{atm}}^2 - v_{\mathrm{esc},\oplus}^2 + v_{\mathrm{esc},☾}^2} \tag{4}$$

We assume $v_{\mathrm{esc},,\oplus} \simeq 11.1$ km s^{-1}; this is the escape velocity at an altitude of 100 km above the Earth's surface. Many of the CNEOS bolides were measured at lower altitudes than this, where the local escape velocity could be up to 0.1 km s^{-1} higher. However, because the CNEOS speeds can have large uncertainties (as large as 40%; Devillepoix et al., 2019), the use of a constant value of 11.1 km s^{-1} is reasonable in this context.

Lunar surface flux

In order to convert kinetic energy to diameter, Brown et al. (2002) assume an average speed of 20.3 km s^{-1} and a bulk density of 3000 kg m^{-3}. However, because the effects of gravitational focusing depend non-linearly on speed, we cannot use the average speed to account for this effect. Instead, we use the measured speeds of bright bolides reported by CNEOS. Out of 822 bolides, speeds are reported for 221 objects. Out of these 221, three have speeds that are lower than the escape velocity. We discard these three, leaving us with a data set consisting of 218 impactors.

We thus have 218 values of v_{atm}, which we will denote v_i, where $i = 1, ..., 218$. These values constitute our top-of-atmosphere, kinetic-energy-limited speed distribution. In other words, we presume that these meteors contribute equally to the kinetic-energy-limited flux:

$$f_\oplus(\mathrm{KE})|_{v_{\mathrm{atm}}=v_i} = \frac{1}{218} f_\oplus(\mathrm{KE}) \tag{5}$$

These top-of-atmosphere meteoroid speeds do not, however, contribute equally to the mass-limited flux at the lunar surface. Let us use g to denote a mass-limited, rather than kinetic-energy-limited, flux. Recall also that the ratio of the mass-limited flux at the lunar surface to that at the Earth is ξ, and let us use ξ_i to denote $\xi(v_{\mathrm{atm}} = v_i)$. Then,

$$\begin{aligned}
g_☾(m) &= \sum_{i=1}^{218} g_☾(m)|_{v_{\mathrm{atm}}=v_i} && (6)\\
&= \sum_{i=1}^{218} \frac{1}{\xi_i} g_\oplus(m)|_{v_{\mathrm{atm}}=v_i} && (7)\\
&= \sum_{i=1}^{218} \frac{1}{\xi_i} f_\oplus(\tfrac{1}{2} m v_i^2)|_{v_{\mathrm{atm}}=v_i} && (8)\\
&= \frac{1}{218} \sum_{i=1}^{218} \frac{1}{\xi_i} f_\oplus(\tfrac{1}{2} m v_i^2) && (9)
\end{aligned}$$

With this methodology, we determine that the flux at the lunar surface is:

$$g_☾(m) = 2.89 \times 10^{-11}\,\mathrm{m}^{-2}\,\mathrm{yr}^{-1} \cdot m^{-0.9} \tag{10}$$

where m is the mass of the impactor in kg.

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Lunar surface speed distribution

Each top-of-atmosphere speed corresponds to a lower lunar-surface speed:

$$v_{☾,i}^2 = v_i^2 - v_{\mathrm{esc},\oplus}^2 + v_{\mathrm{esc},☾}^2 \tag{11}$$

From Eq. 9, we can see that each speed carries a weight w_i, where

$$w_i = \frac{1}{\xi_i} f_\oplus(\tfrac{1}{2} m v_i^2) \tag{12}$$

We therefore construct a lunar surface speed distribution by generating a histogram of $v_☾$ using these weights. The resulting distribution is shown in Fig. 1.

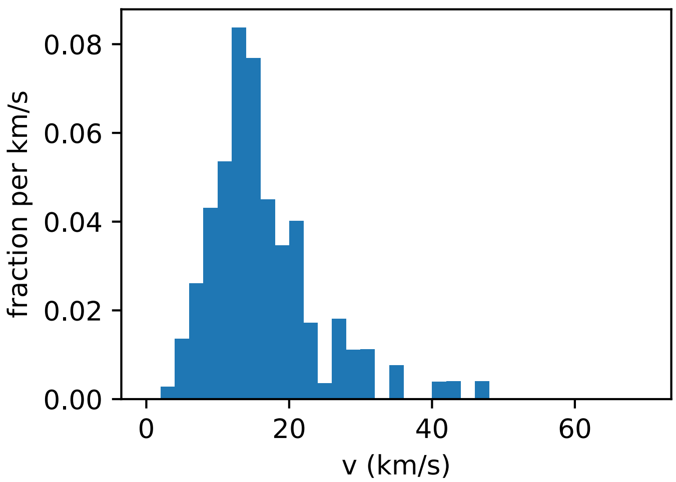

Figure 1. Mass-limited speed distribution at the lunar surface.

We have provided the speed bin midpoint values and fraction of the flux per bin in a separate text file. Because the size of the bins is 2 km s^{-1}, the fraction per bin (in the text file) is twice the fraction per km s^{-1} (in Fig. 1). Note also that because the flux is a power law, this speed distribution is independent of limiting mass.

Sincerely,

Althea Moorhead

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cc: William Cooke, EV44

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References

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