Icarus **156**, 287–290 (2002)
doi:10.1006/icar.2001.6789, available online at http://www.idealibrary.com on IDEAL®

NOTE

The Near-Earth Asteroid Size–Frequency Distribution: A Snapshot of the Lunar Impactor Size–Frequency Distribution

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Received November 2, 2000; revised August 7, 2001

It is shown that the size–frequency distribution (SFD) of a time-averaged projectile population derived from the lunar crater SFD of Neukum and Ivanov (in *Hazards Due to Comets and Asteroids* (T. Gehrels, Ed.), 1994, pp. 359–416, Univ. of Arizona Press, Tucson) provides a convincing fit to the SFD of the current near-Earth asteroid (NEA) population, as deduced from the results of asteroid search programs. Our results suggest that the shape of the SFD of the impactor flux has remained in a steady state since the late heavy bombardment, so that the current NEA population can be viewed as a snapshot of the flux of impactors on the Moon. The number of bodies in the projectile population with diameters of 1 km or more is 700 ± 130, which is in good agreement with recent estimates of the total number of NEAs in this size range. Our results imply that the contribution to the projectile flux from comets is small for diameters below 10 km. © 2002 Elsevier Science (USA)

Key Words: **near-Earth asteroid; cratering statistics; population estimate.**

1. Introduction. The population of near-Earth asteroids (NEAs) is thought to consist mainly of fragments from collisions between main-belt asteroids, although some NEAs may be the nuclei of extinct short-period comets. Impactors on the Earth–Moon system derive from the population of NEAs, supplemented by comets. Around 170 proven terrestrial impact structures and the heavily cratered surface of the Moon are evidence of a violent past in the development of the terrestrial planets. Assessment of the current risk to civilization posed by NEAs requires knowledge of their total number, their size–frequency distribution (SFD), and their impact probability, or of the average crater production rate derived, for example, from the crater SFD of the Moon.

Here we compare the SFD of the projectile population deduced from the lunar crater SFD (Neukum 1983, Neukum and Ivanov 1994) with the known NEA population in the range where completeness has almost been reached (up to an H value of 14) and with estimates of the total NEA population for $H > 14$ (Rabinowitz *et al*. 2000, D' Abramo *et al*. 2001).

2. The projectile population. The SFD of the projectile population was derived from lunar crater counts described by a polynomial expression of 11th order (Neukum 1983, Neukum and Ivanov 1994), with updated coefficients by Ivanov *et al*. (1999, 2001). The shape of this distribution (Fig. 1) in the form of a so-called R plot (see Arvidson *et al*. 1978) is similar to those of all terrestrial planets (Neukum 1983, Neukum and Ivanov 1994). To compare and characterize the crater population independently of the target, conversion from crater diameter, D_c, to projectile diameter, D_p, is necessary. Our approach is based on the scaling law of Schmidt and Housen (1987), which uses an average impact velocity and an average impact angle of 45° (for details see Neukum and Ivanov 1994), and has been extended by Ivanov *et al*. (2001), who solved the inverse problem of transforming the lunar crater SFD into a projectile SFD, thus deriving a model projectile SFD applicable to the Moon. Empirical scaling parameters corresponding to two different regimes (strength or gravity dominance) during the impact crater formation (Schmidt and Housen 1987), as well as the complex crater collapse model (Croft 1985), are used. Ivanov *et al*. (2001) have demonstrated the applicability of the projectile SFD to all terrestrial planets and some asteroids and have compared it with older estimates for the main belt (Jedicke and Metcalfe 1998) and NEA population (Rabinowitz *et al*. 1994).

We integrated the crater-derived R distribution (Fig. 1) for projectiles by Ivanov *et al*. (1999, 2001) to derive the cumulative number N larger than a certain projectile diameter D_p (Fig. 2). The polynomial fit to the lunar crater size distribution extends to a crater diameter of 300 km, which corresponds to a projectile diameter of 27 km. Finally, we fitted a polynomial to the cumulative curve (see Fig. 2). From the lunar crater SFD and the impact scaling law the number of lunar impacts by projectiles with diameters $D_p \geq 1$ km is $3.2\ (\pm 0.5) \times 10^{-6}$ Gy^{-1} km^{-2} (Neukum 1983, Neukum and Ivanov 1994), which corresponds to an impact probability of $1.3\ (\pm 0.2) \times 10^{-7}$ events per year over the Moon's surface.

For the determination of the average impact probability *per asteroid* we used the Öpik formulas (Öpik 1951), as refined by Wetherill (1967) for elliptical target and projectile orbits. It was assumed that all positions of the asteroid orbit with respect to that of the Earth in a cycle of orbital precession have the same probability. Application of this procedure to known NEAs with absolute magnitude $H \leq 18$ yields an average lunar impact probability of $1.86\ (\pm 0.04) \times 10^{-10}$ per year. Orbital elements were taken from the file astorb.dat at http://asteroid.lowell.edu.

The derivation of the average lunar impact probability is discussed in detail by Ivanov (2001), who also addresses the question of the bias in the perihelion distribution.

Dividing the average annual impact rate on the Moon of projectiles with diameters of 1 km or more, as derived from crater counts $(1.3\ (\pm 0.2) \times 10^{-7})$,

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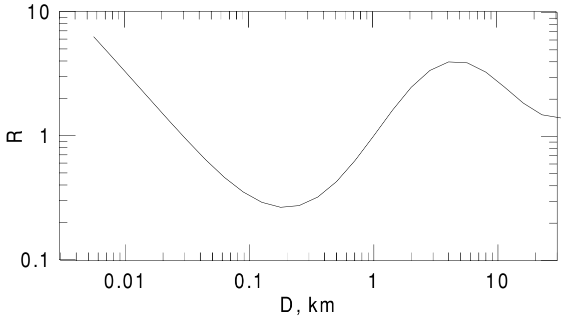

FIG. 1. The relative lunar crater size–frequency distribution in the form of an R plot. R is defined as $D^3 \times dN/dD$, where N is the cumulative number of craters per unit area with diameters larger than D.

by the average impact probability per asteroid, as derived from Öpik's formulation (1.86 ($\pm$0.04) $\times 10^{-10}$), we obtain a total of 700 ± 130 for the number of objects with diameters $D \geq 1$ km in the time-averaged population of projectiles that produced the observed lunar cratering record.

The time-averaged projectile population may not be exactly equivalent to the current population of NEAs due to variability in the rate at which objects are delivered from the main belt to the inner Solar System. Furthermore, our estimate of the average impact probability per asteroid is based on the population of *known* NEAs, which is probably significantly biased in favor of objects that make relatively frequent close approaches to the Earth and are therefore more likely to be detected. However, such objects are also those that are more likely to impact on the Earth and Moon. Hence our estimate of the average impact probability per asteroid applies to that fraction of the total NEA population that is most significant from the point of view of detection and lunar cratering. The value of 700 quoted may be a significant underestimate of the *total* NEA population, but it is the number relevant here for comparison with results from NEA search programs.

3. Observational constraints on the current NEA population. It is possible to estimate the total NEA population in a given range of absolute magnitude, H, by considering the rate of redetection of known objects with H values in that range. As a search program progresses the ratio of redetections to all detections, R, increases asymptotically toward unity. At any stage in the search program, division of the number of known objects by R, measured over a suitable time interval, gives an estimate of the total number of objects in the chosen H range. This method is described in detail by D'Abramo *et al.* (2001), who applied it to the LINEAR (Lincoln Near-Earth Asteroid Research) search program results.

For the total number of NEAs with $D \geq 1$ km (corresponding to $H \leq 18$, assuming a value of 0.11 for the geometric albedo, p_v—see the next paragraph), D'Abramo *et al.* (2001) obtained 855 ± 101. This result agrees within the uncertainties with that derived above for the time-averaged population of projectiles responsible for cratering on the Moon.

To compare the overall projectile population size distribution with that of the NEA population it is necessary to relate H values to diameters via albedo. The diameter, geometric albedo, and H value are related by (e.g., Fowler and Chillemi 1992)

$$D_p\,(\text{km}) = 10^{-H/5}\,1329/\sqrt{p_v}.$$

Unfortunately, accurately determined albedos exist for only a small number of NEAs. As discussed in the following, NEA albedos may be higher on average than those derived for main-belt asteroids, although observational results may be significantly biased toward high albedos by selection effects (Luu and Jewitt 1989). As is evident from the IRAS Minor Planet Survey (Veeder and Tedesco 1992) the albedos of asteroids cover a wide range ($p_v = 0.01$–0.6), and the albedo distribution of the NEA population is incompletely known. Therefore, to facilitate a comparison of the lunar impactor SFD with that of the current NEA population, we follow previous authors in assuming that NEAs have a mean geometric albedo of 0.11 (corresponding to a diameter of 1 km for $H = 18$), which is near the mean of the albedos associated with C-type and S-type asteroids (e.g., Luu and Jewitt 1989 and references therein). In the following section we also consider the possibility that small NEAs have a higher mean albedo.

4. Results and discussion. In Fig. 3 the projectile population SFD (see Section 2), converted to an H-value frequency distribution as described in Section 2, is shown superimposed on a plot of $N(H)$ for the NEA population at $H < 14$, where it is practically complete, and estimates of $N(H)$ for the total NEA population at $H \geq 14$ derived by D'Abramo *et al.* (2001) and Rabinowitz *et al.* (2000). The projectile SFD provides a convincing fit to the NEA population for $H < 20$, assuming $p_v = 0.11$. For $H > 20$ the results of Rabinowitz *et al.* (2000) match the steepening projectile curve, although their points lie somewhat above the curve in this range. This may indicate that the number of small objects ($D < 500$ m) in the current NEA population is larger than that in the time-averaged projectile population. The crater SFD represents an average flux over the last 1 to 3 Gyr and both the transformation from crater size to projectile size and the bias correction in the total number estimates of Rabinowitz *et al.* (2000) are subject to modeling uncertainties. While the significance of this discrepancy is not clear at present, we considered the possibility that the albedos of subkilometer-sized NEAs are systematically higher than those of larger asteroids. Since small NEAs are probably mostly fragments from collisions in the main belt, they may exhibit fresher, less space-weathered, and therefore more reflective surfaces than larger, older asteroids. There is some evidence for higher visual geometric albedos among small NEAs from thermal-infrared and radar observations (see, for example, Harris *et al.* 1998, Harris and Davies 1999, Benner *et al.* 1999, Mahapatra *et al.* 1999). While it is possible that such results are entirely due to observation selection effects and/or modeling uncertainties, it is nevertheless interesting to note that if $p_v = 0.25$ is used to convert the projectile SFD to an H-value frequency distribution (corresponding to a diameter of 1 km for $H = 17.1$) the dashed curve shown in Fig. 3 is obtained, which produces a much better match to the $N(H)$ estimates of Rabinowitz *et al.* (2000) for $H > 20$.

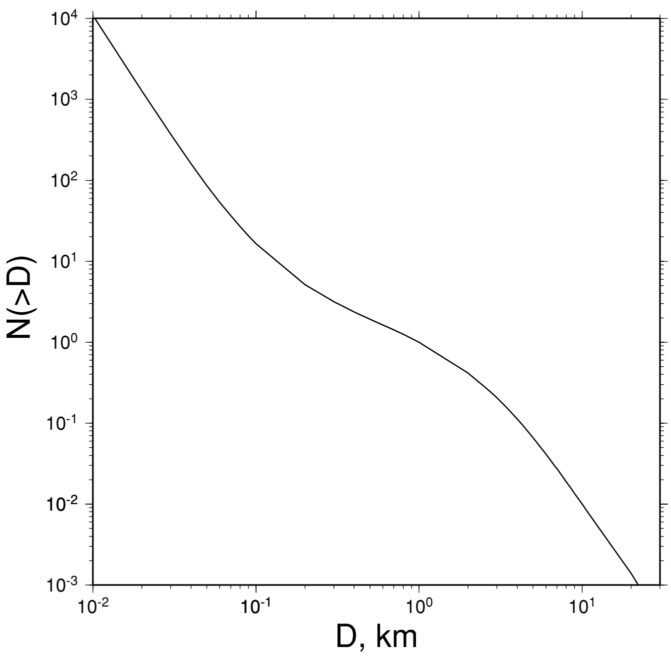

FIG. 2. The cumulative size–frequency distribution of the projectile population derived from the lunar crater distribution. The curve is arbitrarily normalized to $N = 1$, $D = 1$ km.

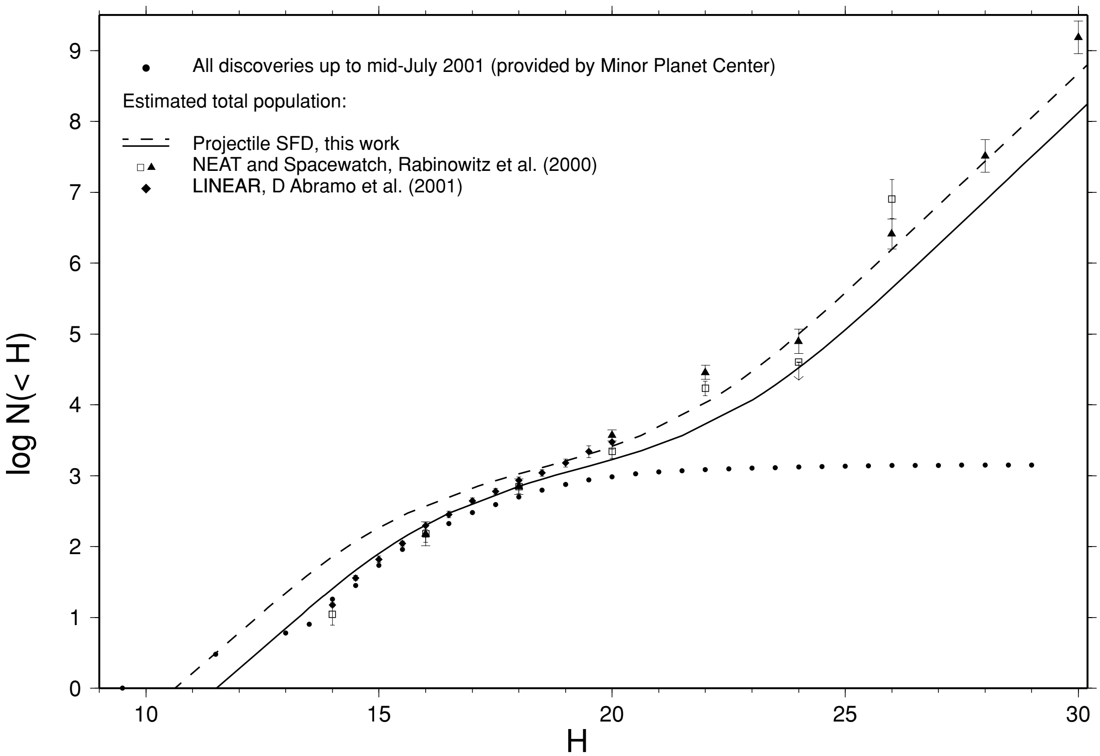

FIG. 3. The filled circles represent the cumulative number (log $N(<\mathrm{H})$) of known NEAs up to mid-July 2001. Squares and filled triangles show the complete population estimates from bias corrections to the NEAT and Spacewatch surveys, respectively, according to Rabinowitz *et al.* (2000). Diamonds show the complete population estimates of D'Abramo *et al.* (2001). The curves are derived from the lunar projectile SFD based on the polynomial expression formulated by Neukum and Ivanov (1994) with improved coefficients (Ivanov *et al.* 2001). For the conversion from diameter to absolute magnitude, H, albedo values of $p_v = 0.11$ (solid) and $p_v = 0.25$ (dashed) have been used. The curves are normalized to $N(<H) = 700$ at $H = 18$ (see Section 2) for $p_v = 0.11$ and to $N(<H) = 700$ at $H = 17.1$ for $p_v = 0.25$.

Another uncertainty is the contribution from comets to the crater record of the Moon and terrestrial planets. The fact that a projectile population derived from lunar cratering statistics can successfully describe the size–frequency distributions of craters on other terrestrial planets and some asteroids (see Section 2) suggests that the same time-averaged population of projectiles is responsible for the cratering on all these bodies. Moreover, the good agreement between the SFD of the projectile population and that of the current NEA population demonstrated in Fig. 3, in terms of both the shape of the distribution and absolute numbers of bodies, is convincing evidence that the projectile population originates in the asteroid belt and contains relatively few comets. Therefore, unless comets are also collisionally evolved and mimic the SFD of the NEA population, our results imply that comets have played a secondary role compared to asteroids in cratering the surfaces of the terrestrial planets.

The good agreement in Fig. 3 extends to NEAs with sizes of up to 10 km ($H > 13.0$). Beyond this size the number of NEAs is insufficient to allow a reliable comparison with the projectile curve and a significant contribution from comets cannot be ruled out on the basis of our results.

5. Conclusions. Our results show that there is remarkable agreement between the size–frequency distribution of a time-averaged projectile population derived from the lunar cratering record and that of the current NEA population derived from observational data, in terms of both shape and absolute numbers. Thus the current NEA population can be viewed as a snapshot of the flux of impactors on the Moon. These results suggest that the SFD of objects in near-Earth orbits has remained in a steady state over the period of lunar cratering from the time of the late heavy bombardment, and the contribution of comets to the projectile population in the diameter range below 10 km is probably small.

ACKNOWLEDGMENTS

The authors thank the two anonymous referees for their very helpful comments. S. C. Werner acknowledges the financial support of the Munich Re-Insurance Company.

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