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ASTEROID AND COMET FLUX IN THE NEIGHBORHOOD OF THE EARTH; Eugene M. Shoemaker, Carolyn S. Shoemaker, and Ruth F. Wolfe, U.S. Geological Survey, Flagstaff, Arizona 86001.

Significant advances in our knowledge and understanding of the flux of large solid objects in the neighborhood of Earth have occurred since the last Snowbird Conference. We present here our best estimates of the collision rates with Earth of asteroids and comets and the corresponding production of impact craters.

Approximately 80 Earth-crossing asteroids have been discovered through May 1988. The rate of discovery increased to 8 per year in 1986 and 1987, more than double the previous 10-year average. As shown by this high rate, the discovery of Earth crossers is far from complete. Among 42 new Earth-crossing asteroids found in the last decade, two-thirds were discovered from observations at Palomar Observatory and 15 were discovered or independently detected in dedicated surveys with the Palomar 46-cm Schmidt. On the basis of these latter observations and 6 discoveries made in a prior survey using the 46-cm Schmidt [1], we estimate that the population of Earth crossers brighter than absolute V magnitude (H) of 17.7 is about 1100. The estimated populations of each orbital type, based on the proportions of known objects brighter than mag 17.7, is as follows (numbers enclosed in parentheses indicate assumed values):

	Number Discovered	Percent Discovered	Estimated Population
Atens	4	(5)	80 ± 50
Apollos	36	5.1	700 ± 300
Earth-crossing Amors	15	(5)	300 ± 150
Total Earth crossers	55	5	1080 ± 500

Probabilities of collision with Earth have been calculated for about two-thirds of the known Earth-crossing asteroids by the method of Shoemaker et al. [2]; the mean of the calculated collision probabilities is 0.49×10^{-8} yr^{-1}. When multiplied by the estimated population of Earth crossers, this yields an estimated present rate of collision of $(5.2 \pm 2.5) \times 10^{-6}$ yr^{-1} to H=17.7. This estimate is about 65% higher than that reported in [2], owing chiefly to the discovery in the last 10 years of several asteroids with unusually high probabilities of collision. When improved data on the proportion of S- and C-type asteroids, the distribution of impact speeds, and the theoretical distribution of zenith angles of impact are taken into account, we estimate from the above collision rate that the production of asteroid impact craters larger than 10 km in diameter is $(1.6 \overset{\times}{\div} 2) \times 10^{-14}$ km^{-2} yr^{-1}, somewhat lower than that given in [2] and [3].

Present evidence indicates that the discovery of Earth-crossing asteroids is essentially complete at H=13, close to the magnitude of the brightest known objects. Because the completeness of discovery declines for fainter objects, the magnitude-frequency distribution of the population can only be inferred from indirect evidence. For Earth crossers fainter than mag 15, the slope of the magnitude-frequency distribution is assumed to be similar to that of main belt asteroids (cumulative frequency approximately proportional to $e^{-0.9H}$). If so, the frequency evidently drops precipitously for objects brighter than mag 15 (cumulative frequency roughly proportional to e^{-2H}). In this model, the collision rate of Earth crossers to $H<15$ (roughly equivalent to S-type asteroids with diameters greater than 3 km) is about 3×10^{-7} yr^{-1}; the collision rate to $H<13$ (asteroids roughly 8 km in diameter and larger) is about 5×10^{-9} yr^{-1}.

Spectrophotometric data obtained chiefly in the last decade show that the large majority of observed Earth crossers are similar to asteroids found in the inner part of the main belt. The combination of asteroid-asteroid collisions in the main belt, resonant perturbations of the orbits of collision fragments, and further perturbation of asteroid fragments by encounters with Mars appears adequate to replace losses of Earth-crossing asteroids due to collisions with planets as well as ejection from the solar system. The population of Earth crossers to H=17.7 probably has remained steady within about ±5% through most of the last 3 billion years. However, surges of about 25% above the mean level in the population, which were due to breakup of main belt asteroids on the order of 100 km in diameter, probably occurred at average intervals of about half a billion years [4]. Durations of these surges above half maximum are estimated to be about 3×10^{7} years. The number of Earth crossers brighter than mag 13 may have increased by an order of magnitude at the peak of these surges. In addition to these stochastic fluctuations of the population, periodic modulation of the near-Earth asteroid flux has occurred at a frequency of 10^{-5} yr^{-1} as a result of secular variation of the eccentricity of the Earth's orbit. The amplitude of this modulation is estimated to be about ±10% from the mean flux.

The number of discovered Earth-crossing comets is more than 4 times greater than the number of known Earth-crossing asteroids, but reliable data on the sizes of comet nuclei are sparse. Photographic observations of comets, obtained when they were relatively far from the sun, and the record of comet discoveries have been used to estimate the magnitude-frequency distribution and flux of the nuclei [5]. The near-Earth flux is found to be dominated by long period comets. After correction for contamination of the observations by unresolved coma, the estimated present rate of collision with the Earth of comet nuclei brighter than absolute B magnitude 18 is about 10^{-7} yr^{-1}.

Several lines of evidence suggest that the albedos of comet nuclei generally are very low; this inference has been confirmed from spacecraft images of the nucleus in the case of P/Halley [6]. Adopting a geometric albedo of 0.03 in the B band [5], we calculate the diameter of comet nuclei to be 2.5 km at absolute B magnitude 18 and 10 km at mag 15. At the rms speed of 57.7 km sec^{-1}, found for long period comets, and a modal zenith angle of impact of 45°, comet nuclei of B magnitude 18 are estimated to produce craters 40 to 50 km in diameter, if their densities are in the range of 0.5 to 1.2 gm cm^{-3}. Craters of this size are comparable with those produced by S-type asteroids of absolute V magnitude 14.2 to 14.8 (diameters of 3.3. to 4.5 km) impacting at the rms speed of 17.5 km sec^{-1} found for Earth-crossing asteroids.

At the present comet flux, the estimated rate of collision with Earth of comet nuclei ≥10 km diameter is 10^{-8} yr^{-1}, and the corresponding mean rate at which these objects pass the Earth at a distance of 4.67×10^6 km (0.0312 AU), the miss distance of comet IRAS-Araki-Alcock (1983 VIII), is about once per 200 years. The geometric mean diameter of the elongate nucleus of IRAS-Araki-Alcock, determined from radar and infrared observations, is 9.3 km [7]. We conclude that the close approach of this large comet, during the ~20-year period in which the radar observations of its nucleus could have been made, either was a stroke of luck (probability ~0.1) or our estimate of the present flux of comets about 10 km in diameter is conservative.

The flux of comets almost certainly has been highly variable over late geologic time, owing to the random perturbation of the Oort comet cloud by stars in the solar neighborhood. Monte Carlo studies [8] suggest that surges in the near-Earth flux from 3 to more than 30 times the mean background occurred at typical intervals of a few tens of millions of years. The majority of comet impacts probably occurred during these surges or comet showers. Even the background flux probably has varied by factors of about 2 over time intervals of 10^7 years, and it is not known from direct observations of comets whether the present flux lies close to the mean background or whether it might represent a shower or possibly a comet "drought."

The record of terrestrial impact craters and impact glass suggests that a mild comet shower may have occurred at ~35 Ma, and a weak shower may have peaked at ~1 Ma [9]. On the basis of bounds on the total crater production set by the Copernican crater record of the Moon [10], we suggest that the present comet flux is about twice the mean background for the last billion years; comet impacts probably account for no more than half the Phanerozoic impact craters larger than 20 km in diameter. During the late Phanerozoic, the mean rate of collision with the Earth of 10-km-diameter and larger objects capable of producing craters larger than ~150 km in diameter may have been about 1 to 2×10^{-8} yr^{-1}. Production of these giant craters probably was dominated by comet impact.

Our best estimate of the production of terrestrial impact craters over the last 100 million years is as follows:

	Crater Diameters						
	≥10 km	≥20 km	≥30 km	≥50 km	≥60 km	≥100 km	≥150 km
Asteroid impacts	820	180	73	10	4.5	0.3	0
Comet impacts	(270)	60	24	8	5.3	1.7	1
Total crater production	(1090)	240	97	18	10	2	1

The uncertainty to be attached to each of the above figures is at least a factor of 2. Production by comet impact of craters smaller than 20 km in diameter may have been suppressed by atmospheric breakup of comet nuclei [11]. To obtain the approximate number of craters expected to have formed on the continents, the figures given above should be divided by 3. The estimated total cratering rate to 20-km crater diameter is $(4.7 \overset{\times}{\div} 2) \times 10^{-15}$ km^{-2} yr^{-1}, which is very close to the rate of $(5.4 \pm 2.7) \times 10^{-15}$km^{-2} yr^{-1} estimated by Grieve [12] from the geologic record of impact for the last 120 million years. On the other hand, the corresponding number of craters larger than 30 km in diameter expected to have been produced on the Moon from the beginning of the Eratosthenian period (the last 3.3 billion years) is about twice the number of Copernican and Eratosthenian craters mapped by Wilhelms [10]. We repeat the observation [2,12] that the mean cratering rate may have increased in late geologic time. An increase by as much as a factor of 2 could be most readily explained by an increase in the mean comet flux, but only if more than half the production of craters >20 km diameter during the last 100 million years is due to impact of comets (including extinct comets, which would be recognized at the telescope as asteroids).

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