EARTH-CROSSING ASTEROIDS, 1989; E.M. Shoemaker, C.S. Shoemaker, R.F. Wolfe, and H.E. Holt, U.S. Geological Survey, Flagstaff, AZ 86001.

The year 1989 marked a high point in the discovery of Earth-crossing asteroids. Thirteen new Earth crossers were found during the year, five of them in one remarkable dark-of-the-Moon observing period in late October and early November. These new discoveries increase the total of known Earth crossers to 96, including 9 Atens, 61 Apollos, and 26 Earth-crossing Amors. Of these asteroids, 59 have precisely determined orbits and are now numbered, 10 are lost, and most of the remainder have been discovered too recently to have been observed on a second apparition.

Two discoveries in 1989 of special interest were 1989 AC and 1989 FC. Found on January 4 by J.-L. Heudier, R. Chemin, A. Maury, and C. Pollas at Caussols, France, 1989 AC is the sixth brightest known Earth crosser (H=14.2). It was followed at about 20 observatories around the world. An early preliminary orbit permitted C.S. Shoemaker to find and measure prediscovery positions from films taken by H.R. Holt and T.A. Rodriquez at Palomar on July 17, 1988. This increase in the length of the observed arc enabled C.M. Bardwell to link 1989 AC with 1934 CT, which was observed on two nights in February, 1934, at Uccle, Belgium. Hence, 1989 AC was actually the second Apollo asteroid to be observed at the telescope.

1989 FC was discovered at Palomar by H.E. Holt and N.G. Thomas on March 31, 1989, eight days after it had passed within about 690,000 km of the Earth. This is the closest known approach of any asteroid to Earth. A campaign of observations organized by E. Bowell of Lowell Observatory resulted in a good preliminary orbit based on a 66-day arc; this orbit should be sufficient to permit recovery observations of 1989 FC in 1990, which are needed to assure that this very faint object will not be lost. At H=21.0, 1989 FC and 1988 TA are the faintest known asteroids with relatively accurate orbits. If they are S-type asteroids, as are the majority of known Earth crossers, they are about 200 m in diameter.

Our estimate of the population of Earth-crossing asteroids to H=17.7, based on discoveries to date, is as follows:

	Number Discovered ($H \leq 17.7$)	Percent Discovered	Estimated Population ($H \leq 17.7$)
Atens	5	(5.8)	90 ± 40
Apollos	40	5.8	690 ± 300
Earth-crossing Amors	15	(5.8)	260 ± 130
Total Earth crossers	60	5.8	1040 ± 470

The total population is based on the rate of discovery of Apollos with the 46-cm Schmidt camera at Palomar Observatory, and the proportions of Atens, Apollos, and Earth-crossing Amors is based on their proportions among the discovered objects. Present evidence suggests that the discovery of Earth-crossing asteroids is complete at H=13.24, the magnitude of the brightest known object. For Earth crossers fainter than mag 15.8, the slope of the magnitude-frequency distribution is assumed to be similar to that of main-belt asteroids (cumulative frequency approximately proportional to $e^{0.92H}$), as shown in Fig. 1. The frequency evidently drops precipitously for objects brighter than mag 15.8 (cumulative frequency roughly proportional to e^{2H}).

A check on the inferred magnitude-frequency distribution of the Earth-crossing asteroids is provided by the frequency with which Earth crossers have been accidently rediscovered. About 8 have been rediscovered or recovered without deliberate search. Examples are (1627) Ivar, (2100) Ra-Shalom, (2201) Oljato, (3573) 1986 TO, (4179) 1989 AC, and (4183) 1959 LM, all of which were lost after their first detection. The accidentally rediscovered asteroids are all brighter than H=16.25; most are mag 15 or brighter. The number of discovered objects brighter than mag 16.25 is 37; the fraction of rediscoveries (6/37) suggests that discovery is about 16% complete and that the population is about $37/0.16 \approx 230$ to mag 16.25. This number is close to the estimate of 270 indicated by the dashed line in Fig. 1. At H=15.0, 4 out of 12 known objects have been accidentally rediscovered, which suggests that completeness of discovery at this magnitude is about 33%; the completeness indicated in Fig. 1 is 35%. The brightest Earth crosser, (1627) Ivar, was discovered in 1929, then lost, rediscovered in 1957, and serendipitously recovered in 1985 with the Palomar 46-cm Schmidt. Another Earth-crossing asteroid as bright as or brighter than Ivar is unlikely to have escaped detection.

We have updated our estimates of probabilities of collision with the Earth for Earth-crossing asteroids, using the equations of Shoemaker et al. [1]. Where we were unable to derive the collision parameters from secular perturbation theory, we used the equations of Opik [2]. The frequency distribution of collision probabilities is strongly skewed (Fig. 2): half a dozen asteroids have collision probabilities substantially

exceeding $10^{8}\,yr^{-1}$. Mean probability of collision is $10.7 \times 10^{9}\,yr^{-1}$ for Atens, $4.1 \times 10^{9}\,yr^{-1}$ for Apollos, and $1.4 \times 10^{9}\,yr^{-1}$ for Earth-crossing Amors. The grand mean probability of collision obtained for all categories of Earth-crossing asteroids is $4.2 \times 10^{9}\,yr^{-1}$. The uncertainty in this estimate probably is about 40%.

Multiplying the mean collision probability by the estimated population at H = 17.7, we estimated the present rate of collision for Earth-crossing asteroids to be $(4.3 \pm 2.6) \times 10^{6}\,yr^{-1}$, about 30% higher than that reported by Shoemaker et al. [1]. The colliding flux consists of about 65% Apollos, 25% Atens, and 10% Amors. Using improved data on the proportion of S- and C-type asteroids and the rms impact speed, weighted according to collision probability, of 17.9 km s^{-1}, we estimate that the production rate of asteroid impact craters larger than 10 km in diameter is $(1.4 \pm 0.7) \times 10^{-14}\,km^{-2}\,yr^{-1}$, somewhat lower than that given by Shoemaker et al. [1] and Shoemaker [3]. The collision rate of Earth crossers to H = 15.8 (roughly equivalent to S-type asteroids with diameters greater than 2 km) is about $7 \times 10^{7}\,yr^{-1}$; the rate to H = 13 (asteroids roughly 9 km in diameter and larger) is about $3 \times 10^{9}\,yr^{-1}$.

References: [1]Shoemaker, E.M., Williams, J.G., Helin, E.F., and Wolfe, R.F., 1979 in Gehrels, T., ed., Asteroids, Tucson, Univ. Arizona Press, p.253-282. [2]Opik, E.M., 1951, Proc. Roy. Irish Acad. 54A, p. 165-199. [3]Shoemaker, E.M., 1983, Ann. Rev. Earth Planet. Sci., v. 11, p. 461-494.

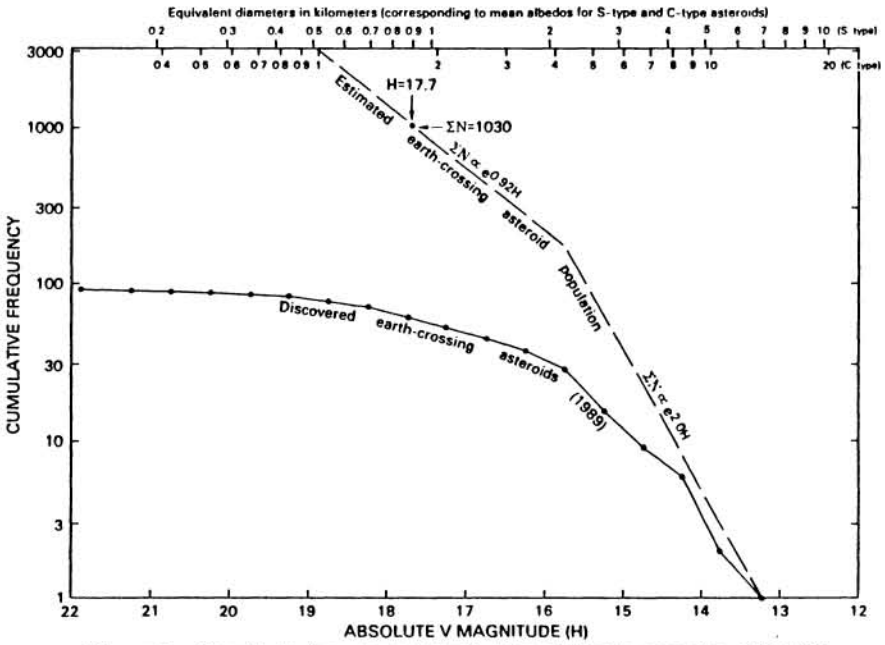

Figure 1. Magnitude-frequency distribution of Earth-crossing asteroids

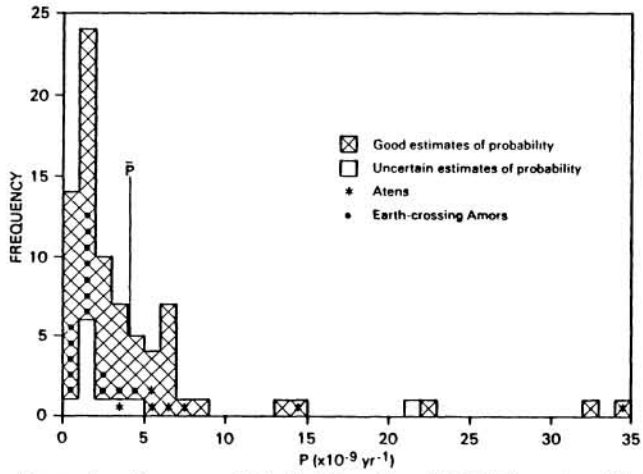

Figure 2. Frequency distribution of probabilities of collision with Earth for Earth-crossing asteroids