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THE FLUX OF SMALL ASTEROIDS NEAR THE EARTH

D. L. Rabinowitz, Lunar and Planetary Laboratory
The University of Arizona, Tucson AZ 85721

Tom Gehrels, Jim Scotti, and I have been scanning for Earth approachers since September of 1990. By Earth approacher (EA), I mean any object that approaches the sun to within 1.3 astronomical units (AU). Information about our scanning technique has been presented elsewhere in these proceedings (Scotti et al. 1991a) and in other publications (Rabinowitz 1991, Gehrels et al 1990). We have discovered fifteen new EAs since September, among them the smallest asteroids on record: 1990 UN, 1991 BA, and 1991 JR, which are in the 10 to 100m size range (Scotti et al. 1991b). For the first time, we can make estimates of the fluxes near the Earth of these small objects, thought to be the immediate parents of meteorites, from direct observation. In this paper, I show that for EAs larger than a few 100m, the magnitude-frequency dependence we observe is consistent with the cumulative magnitude-frequency relation, m(H), established for the main belt asteroids. Assuming this relation extends to smaller sizes, however, the probability for discovering both 1990 UN and 1991 JR was 15%, and for discovering 1991 BA only 1%. Objects smaller than ~100m are therefore increasingly overabundant compared to an extrapolation from larger objects, with this excess increasing with decreasing size. Near 10m, the most probable flux near the Earth is two orders of magnitude higher. This is in agreement with the flux extrapolated from observations of bright meteors and fireballs. It is thus likely that processes other than collisional breakup of asteroidal material begin to supply the population of small objects near the Earth at sizes near 100m. Tantalizing clues from spectral measurements and orbital associations suggest that these objects may be the debris from extinct, short-period comets.

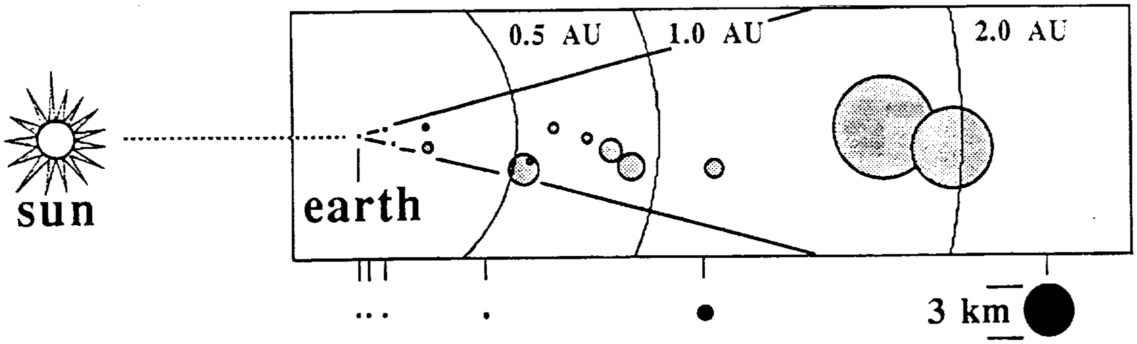

Fig. 1. Opposition geometry at discovery for Earth approachers discovered with the Spacewatch Telescope.

Discovery Geometry

A quick inspection of Fig.1 reveals that the larger EAs observed with the Spacewatch telescope have an incremental size distribution that is nearly proportional d^{-3}, where d is diameter. The figure is to scale, and shows the position in the ecliptic plane relative to the sun-earth line at the time of discovery for nearly all the EAs we have detected since September of 1990. The circles representing each object scale linearly with the estimated sizes. Notice that the the number of objects we find does not depend strongly on object size. We have found EAs larger than 3 km as far as 2 AU from the earth, km-sized objects ~1 AU away, objects of ~200m diameter ~0.5 AU away, and smaller objects at nearer distances. Since the maximum geocentric distance, Δ_L, at which we can detect one of these objects is nearly proportional to d, and the number we detect of a given size goes as $\Delta_L{}^3$

(the search volume), the flatness of the spectrum we observe implies that the true incremental size distribution is proportional to d^{-3}. This same size distribution has been determined for the main-belt population (van Houten et al. 1970).

Detailed Analysis

The size distribution revealed by Fig.1 can be tested by a more rigorous analysis of the EAs discovered with the Spacewatch Telescope. I use a computer to simulate an arbitrarily large population of EAs with the same distribution of orbital elements, a, e, and i, as the population of known EAs, but random arguments of perihelion and ascending nodes. For each simulated EA, the computer assigns a random mean anomaly, solves for position and velocity, and evaluates the offset from apparent to absolute magnitude, V-H. Given an assumed form for m(H), it can then predict the incremental number of simulated EAs, $\Delta n(H)$, that would be observed with the Spacewatch Telescope as a function of H. I then use the ratio of the actual number detected, $\Delta N(H)$, to the predicted number to correct m(H) and arrive at the true magnitude-frequency for the Earth approachers, $m^*(H)$:

$$m^*(H) = \frac{\Delta N(H)}{\Delta n(H)}\, m(H) \tag{1}$$

This method of determining $m^*(H)$ is reliable to the extent that the orbits for the known EAs faithfully represent the true population. For example, an over-representation of orbits which are near to the orbit of the Earth, such as Aten-type orbits with low inclinations, would cause $\Delta n(H)$ to be over-estimated for large H values; hence, an under-estimate for $m^*(H)$. This is because the smallest objects are only observable near the Earth.

In order to determine the cumulative impact rate at the Earth, F(H), I must normalize the above expression for $m^*(H)$ by an independent estimate for the impact rate, $F(H_0)$, at some fixed absolute magnitude, H_0:

$$F(H) = \frac{m^*(H)}{m^*(H_0)}\, F(H_0) \tag{2}$$

I can estimate $F(H_0)$ from the discoveries of the Spacewatch Telescope with $d \gtrsim 1.0$km ($H_0 \lesssim 20.0$). Assuming the EAs have a constant velocity relative to the Earth, v, their incremental impact rate at the Earth, $\Delta F(H)$, is given by:

$$\Delta F(H) = \frac{\Delta N(H)}{\Omega(H)}\, 4\pi\rho^2 K v \tag{3}$$

where $\Omega(H)$ is the volume of space searched in order to find the asteroids of magnitude H, ρ is the radius of the Earth, and K is the flux enhancement due to gravitational attraction. As discussed above, $\Omega(H) \propto \Delta_L{}^3$, and is the volume of a sphere with radius Δ_L scaled by the fraction of the sky scanned by the Spacewatch Telescope. For the larger EAs observed near opposition and far from the Earth, it is straight forward to calculate Δ_L for the Spacewatch Telescope as a function of H and the limiting magnitude, V_L. Evaluating $\Delta F(H)$ for magnitude intervals $H-\Delta H/2$ to $H+\Delta H/2$ and summing over the range spanned by the observations represented in Fig. 1 with $H<H_0$ yields $F(H_0)$.

Results

Fig. 2 shows F, as determined by equations (1) - (3) with ρ=6400km, K=1.8 (Kresák 1978), v= 20km/s (Shoemaker 1983), V_L=20.5, and ΔH=2.5, plotted as a function of the impacting mass, m (black squares). The vertical error bars show the uncertainty owing to counting statistics. There is an additional systematic uncertainty of a factor of 2 owing to the uncertainty in the calculated normalization, $F(H_0)=4.6\times10^{-6}y^{-1}$ at H_0=18.8. I have converted from F(H) to F(m) assuming uniform spheres with density 3500 kg/m^3 and geometric albedo 0.12±0.07. The horizontal error bars show the uncertainty in this transformation. Also shown in Fig. 2 are the impact rates determined by other authors from observations of bright meteors (Ceplecha 1988), photographic surveys for asteroids (Shoemaker et al. 1990), and the size distribution of craters in lunar maria (Shoemaker 1983).

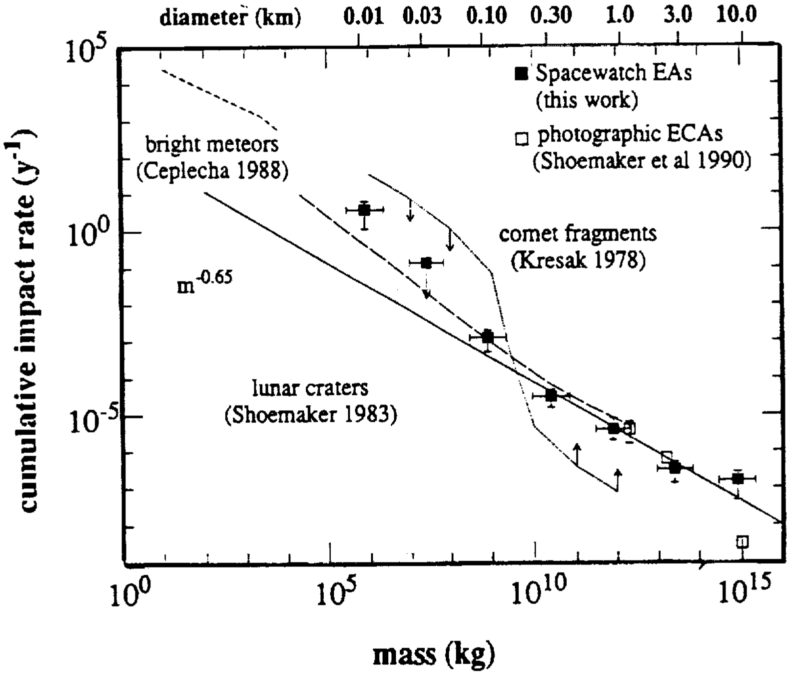

Fig. 2. The cumulative impact rate at the Earth as a function of impacting mass.

Examination of Fig. 2 shows that the values for F derived in this paper are within a factor of 2 of the results of photographic surveys (Shoemaker 1990) near $m=1.0\times10^{12}$ and 3.2×10^{13} kg (d~1km and d~2 km, respectively). These estimates, and the estimates from this paper for F at $m=3.2\times10^{10}$ and 1.0×10^{15} kg are fit well by a line with slope -0.65 (the solid line labeled "$m^{-0.65}$" in the figure). This is the same m dependence seen in the population distribution of the main-belt asteroids, and revealed by Fig. 1. For $m<3.2\times10^{10}$ kg (d<150m), however, it is clear that the fluxes derived in this paper deviate significantly from the main-belt relation, with values 3 and 100 times larger than an $m^{-0.65}$ extrapolation would predict at $m=1.0\times10^9$ and 1.0×10^6 kg, respectively. A similar deviation is seen in the fluxes derived from the size distribution of lunar craters, beginning at $m=3.2\times10^{10}$ kg (d~200m) and continuing towards lower masses, but the deviation is smaller. The greatest deviation from the $m^{-0.65}$ extrapolation is shown by the fluxes of bright meteors, which are more than two orders of magnitude higher for $m<10^4$ kg. An extrapolation of the meteor curve to larger masses matches the flux reported in this paper at $m=1.0\times10^6$ kg.

In addition to the measured flux curves plotted in Fig. 2, there is a curve showing the flux of cometary fragments predicted by Kresák (1978). As indicated by the vertical arrows, this curve is an upper limit below 10^9 kg, and a lower limit above 10^9 kg. The fluxes of Spacewatch EAs with masses $< 10^{10}$ kg approach this upper limit, suggesting that they are the cometary fragments envisioned by Kresák. This suggestion is supported by the orbital characteristics of 1991 BA (Q=3.77, q=0.71 i=2.0°) and 1991 JR (Q=1.77, q=1.04, i=10.1°). Though not decisively cometary, the orbit of 1991 BA explores the outer reaches of the asteroid-belt. In this respect, it is similar to the orbit comet P/Encke. The orbit of 1991 JR has been found to be clearly associated with the Φ Boötes meteor stream (J. Drummond, personal communication), which is a good indication that its source is cometary. 1991 JR also has a featureless C-type spectra (Mueller, 1991; E. Howell, personal communication), like that of (3200) Phaethon, which has an F-type spectrum (Tholen 1989) and is strongly associated with the Geminid meteor stream.

Conclusions

The Spacewatch Telescope is finding kilometer-sized Earth-approachers when they are farther than 1AU from the earth and asteroids with diameters of 10 to 100m within 0.1AU of the Earth. A broad size spectrum has thus been sampled, allowing the first determination of the magnitude-frequency relation for the Earth-approacher population from direct observation. This relation is well described by a power law in mass with exponent -0.65 for the cumulative distribution of asteroids larger than a few hundred meters. This is the distribution observed for the main-belt asteroids, and it is therefore likely that the larger Earth-approachers are collisionally derived from this population. The number of smaller asteroids, however, is significantly enhanced above this power law spectrum. At 10m they are 100 times more numerous. A possible explanation for this over-abundance, supported by preliminary spectral measurements and orbital analysis, is that small asteroids are mostly fragments of decayed comets.

note added in proof: Two more small EAs have recently been discovered with the Spacewatch Telescope: 1991 TT (~25 to 50m) and 1991 TU (~10m). These discoveries reduce the statistical uncertainties in the fluxes reported here for masses between 10^6 and 10^8 kg to less than a factor of 2.

Credit for the success of the Spacewatch Telescope goes to T. Gehrels, J. Scotti, R. McMillan and M. Perry at the Lunar and Planetary Laboratory (LPL). I also thank B. Marsden at the Minor Planet Center, B. Mueller at Kitt Peak National Observatory, E. Howell at LPL, and J. Drummond, formerly of LPL, whose efforts strengthened this work considerably.

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