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"THE ORBITS OF ASTEROIDS THAT IMPACT EARTH AND GROUNDBASED DETECTION STRATEGIES"

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Searches for Earth-Crossing asteroids (ECAs) have concentrated towards the solar opposition region. This produces selection effects that are evident in a published analysis of the search effectiveness of the proposed Spaceguard system (Morrison 1992), which will also concentrate its search there. This analysis shows that Spaceguard will recover 90% of all known ECAs but fewer than 50% of the Atens (asteroids with semimajor axes less than 1 A.U. that cross the orbit of Earth). This strongly suggests that Atens are under-represented among known ECAs and that Spaceguard may find significantly fewer than 90% of all ECAs. If the orbits of the ECAs were completely thermalized in close encounters with Earth, half the ECAs would be Atens, which is certainly the upper limit. When Atens impact Earth, they approach it from the direction of an angular cone that is centered on the third-quarter moon (the direction of the Earth's revolution around the sun). Among ECAs that will hit Earth within the next 300 years, we find that a sizeable fraction of Atens and Apollos with small semimajor axes would be missed by searches that are confined to *the solar opposition region. Any groundbased survey needs to cover as much of the sky as possible. A large fraction of the asteroids that will hit Earth during the next 300 years will make close approaches to Earth before impact. We find that they become bright enough to be detected with small telescopes at these close approaches, but they often appear in directions that are far from solar opposition. One quick fix would be to add a battery of small telescopes to the Spaceguard survey that would cover the entire sky (except near the sun) every night. Such a battery would also be very effective in finding asteroids as small as 100 meters in diameter during the final two weeks to impact.*

I. INTRODUCTION

This conference has shown the danger of impacts by Earth-crossing asteroids (ECAs). Asteroids 60 meters in diameter and larger can destroy large cities by airblast, by 200 meters in diameter they produce substantial regional impact damage as well as tsunami that can devastate the shore lines of entire ocean basins, and by 1 km in diameter they may, in addition, perturb the atmosphere enough to produce global mass extinctions (e.g., Hills and Goda 1993).

In this paper we examine strategies for detecting ECAs that may hit Earth within the next few years. We wish to detect asteroids down to 60 meters in diameter in sufficient time to allow them to be deflected or destroyed before Earth impact. A week is sufficient warning to allow a single rocket equipped with a nuclear explosive (using existing rocket boosters and nuclear explosives) to deflect from Earth impact an asteroid with a diameter up to 1-2 km if such a rocket were on standby for this purpose (Canavan 1992, and Canavan & Solem 1992; Arons and Harris 1993). To deflect a larger asteroid requires a lead time of months to years even if rockets to deflect it were on standby.

These lead times suggest that objects less than about 1 km in diameter need only be detected a week or two before impact as part of a terminal defense system. Larger objects need to be detected up to several years before impact. In the next section we shall discuss the orbit characteristics of asteroids that are with a few orbital revolutions of Earth impact. In the section after that we determine the detectability of small asteroids in the final weeks before impact. Next, we discuss the detectability of larger ECAs in the final few years before their impact. This last section is the main thrust of the current paper.

II. ORBITS OF ASTEROIDS THAT IMPACT EARTH

The orbits of asteroids that impact Earth were determined by Hills and Leonard (1995). We briefly summarize their results.

The orbits of all asteroids that suffer head-on collisions with Earth can be mapped in geocentric coordinates by their impact speeds prior to gravitational acceleration by Earth and by their positions on the sky at a given time prior to impact as seen by a hypothetical observer at the center of Earth. Two angles are needed to specify the position on the sky, so three parameters are required to specify the final trajectory. For an object of a given size and composition, the impact speed determines how much damage it can inflict (Hills & Goda 1993). Its position on the sky determines how readily observable it will be prior to Earth impact.

If we treat Earth's orbit as circular, these three geocentric parameters determine three heliocentric orbital elements: the asteroid semimajor axis, a, eccentricity, e, and inclination to the ecliptic, i. The argument of perihelion, ω, is also known from a and e through the equation of an ellipse,

$$r = \frac{a\left(1 - e^2\right)}{1 + e\ cos\left(f\right)}, \tag{1}$$

because at impact with Earth $r = 1$ AU, so the orbital phase or true anomaly $f = \omega$ or $(2\ \pi - \omega)$. A fifth orbital element T, the time of perihelion passage, is determined by the time of impact and the time the asteroid took to go from perihelion to impact, which is known from a, e, and f. The time of year of impact also determines the sixth orbital element Ω, the angle of the ascending node, since Earth crosses the line of nodes at impact. We first specify the orbit of the asteroid in geocentric coordinates and then transform to heliocentric coordinates to determine its position relative to Earth in the days and years before impact.

Asteroid collisions should be equally probable throughout the year if the orbit of Earth were circular, so in a statistical evaluation we may ignore the orbital elements Ω

and T. We need only consider the three heliocentric orbital elements a, e, and i (because ω is known from a and e for Earth impactors) or the three geocentric parameters: relative impact speed, V_{rel}, and the two angular coordinates giving the direction of approach of the impactor at some specified time prior to impact. Specifying all permitted values of either set of three parameters provides an equally satisfactory mapping of all possible asteroid impactors.

The true distribution of orbits of Earth-crossing asteroids (ECAs) is not well known; e.g., their observed distribution is consistent with up to half them being burned-out comets (cf, Wetherill 1988), which have initial orbits that differ considerably from that of classical asteroids. The orbit distribution of ECAs detected to date may be highly biased. Asteroid surveys have tended to be confined to near solar opposition, so the cone in which asteroids are discovered tends to be elongated towards opposition.

Using a geocentric coordinate system to map the distribution of impacting asteroids is simpler than using a heliocentric one. It may also provide a more natural way of estimating the frequency of asteroids in various permitted orbits. Most asteroids make several close approaches to Earth before impact; e.g., an impacting asteroid will have passed within $2R_\oplus$ of Earth about 3 times before its impact (ignoring gravitational focusing). Such a close encounter tends to rotate the velocity vector of the asteroid without affecting its speed, V_{rel}, relative to Earth, so a succession of close encounters tends to randomize its direction of approach to Earth (cf., Hills 1969). If an Aten originated either as a short-period comet or from the asteroid belt, it suffered at least one close encounter with Earth to have had its orbit shrunk below 1 A.U.

If an asteroid has an Earth-approach speed $V_{rel} < V_c \equiv (2^{1/2} - 1)\ V_\oplus = 12.3$ km s^{-1}, where $V_\oplus = 29.8$ km s^{-1} is the orbital speed of Earth around the sun, then it is in a bound orbit around the sun for all possible directions of approach to Earth impact. Repeated close encounters with Earth would tend to cause such low-impact-speed asteroids to evolve towards a near-isotropic distribution of impact directions with respect to the moving Earth. At approach speeds $V_{rel} > V_c$, there has to be a deficiency of objects that approach Earth from directions where they would be in hyperbolic orbits around the sun. This zone of avoidance is an angular cone that points away from the direction of Earth's orbital motion around the sun. Objects are in this cone if they approach Earth from an angle, θ, that is more than

$$\theta_2 = cos^{-1}\left[\frac{\left(\frac{V_{rel}}{V_\oplus}\right)^2 - 1}{2\left(\frac{V_{rel}}{V_\oplus}\right)}\right], \tag{2}$$

away from the direction of Earth revolution. This cone of avoidance increases rapidly with increasing V_{rel}.

For a given approach speed, V_{rel}, the minimum semimajor axis, a, of an impacting ECA occurs at $\theta = 0$ for prograde asteroid orbits ($V_{rel} < V_\oplus$). Within some critical $\theta = \theta_1$, $a < a_\oplus = 1$ AU, so these ECAs are Atens. We find that

$$\theta_1 = cos^{-1}\left(\frac{1}{2}\frac{V_{rel}}{V_\oplus}\right). \tag{3}$$

Objects with $\theta_2 > \theta > \theta_1$ are Apollos, ECA in bound orbits with $a > 1$ A.U.

If the distribution of impacting velocities is isotropic except in the forbidden zone, where the ECAs would be in hyperbolic orbits, then the fraction of impacting ECAs that are Atens is 0.4-0.5 for most impact velocities. While this is undoubtedly an upper limit, it points out that Atens may be under-represented among known ECAs. This may be the result of the tendency of observers to concentrate their searches near solar opposition. Computer simulations of the expected search characteristics of the proposed Spacequard survey (Morrison 1992), which is similar to the search strategies used by most observers today, shows that it would miss a substantially larger fraction of Atens than other NEAs. The degree of under-representation of Atens can only be resolved by observations. We suggest that observers devote some of their telescope time observing near the direction of Earth's revolution around the sun at $\theta = 0$ (approximately the direction of the third-quarter moon).

III. DETECTABILITY OF ECAs DURING THEIR FINAL FEW DAYS TO IMPACT

The detectability of asteroids during their final days to Earth impact was considered in Hills and Leonard (1995). We briefly review that work.

Magnitude

The apparent visual magnitude, V, of an asteroid depends on its distances from Earth, d, and sun, r, diameter, D, visual Bond albedo, A, and reflection phase law, $\phi(\alpha)$. Phase angle α is the angle between the sun and Earth on the sky as observed from the asteroid. Here ϕ is the flux density of the asteroid at phase angle α in units of its maximum value at $\alpha = 0$. We assume that the asteroid is spherical and that $\phi_m(\alpha_m)$ obeys the lunar phase law given by Allen (1974). We find that the visual magnitude of the asteroid is given by the equation

$$V = -5.0 \log_{10}\left[\left(\frac{1.0025695}{r\ (\text{AU})}\right)\left(\frac{10^4}{3.476 \times 10^8}\right)\left(\frac{0.0025695}{d\ (\text{AU})}\right)\right]$$

$$-2.5 \log_{10}\left(\frac{0.2}{0.067}\right) + \Delta V(\alpha) - 5.0 \log\ (D/10^4\ \text{cm}) - 2.5 \log\ (A/0.2) - 12.73, \qquad (4)$$

Figure 1 shows V versus angle from the sun, $\theta_{\odot}$, for model asteroids with $D = 100$ m and $A = 0.2$ that approach Earth at 10 km s^{-1} at 10 days to impact. The reflected light from an asteroid is weak for small $\theta_{\odot}$ due to the phase effect; it would look like a crescent moon if observed with a sufficiently powerful telescope. Objects that approach from the anti-solar direction have $V \lesssim 16$. Asteroids that approach at right angles to the sun have $V \gtrsim 18$ while those within 30° of the sun have $V < 21$, which makes their detection very difficult.

The infrared N-band, as defined by Allen (1974), is centered at 10.2 μm, which is near the peak of the thermal spectrum for asteroids near Earth. We assume that the asteroid is rotating rapidly enough that its surface radiates uniformly in the infrared. The phase effect is not relevant in this case. We also assume that the asteroid radiates as a black body, so its spectrum is determined by its effective temperature, T_{eff}. We adopt our visual Bond albedo, $A = 0.2$, for the bolometric albedo. We use $D = 100$ m for our standard "small" asteroid.

Figure 2 shows the apparent N magnitude versus angle from the sun of 100-m asteroids that approach Earth at 10 km s^{-1} at 10 days to impact. In contrast to visual magnitudes, the asteroids are brightest in the N band when they approach from the solar direction, because they have the highest effective temperatures. Therefore, infrared telescopes may be the most effective ground-based means of detecting impactors that approach Earth from within 30° of the sun.

Parallax

The parallax, in radians, of an asteroid at distance, d, from Earth when viewed over a baseline of one Earth radius, $R_\oplus$, is simply

$$\Pi = \frac{R_\oplus}{d}. \tag{5}$$

Unlike the proper motion, the parallax steadily increases in the final weeks prior to impact. An asteroid that is one to two weeks away from Earth impact has a small proper motion, a large parallax, and is becoming brighter.

At a 10 km s^{-1} impact speed and 10 days from impact, the objects are at a distance of about 8.6×10^6 km = 0.058 AU = 22 times the distance to the moon. Their parallax for two observers at a projected separation of 1 $R_\oplus$ is about 150 arcsec = 2.5 arcmin, which is readily resolved with wide angle cameras. If an asteroid 100 m in diameter or larger hits Earth every 300 years (Shoemaker *et al.* 1990, 1991), then about 6000 such objects pass within 0.058 AU of Earth each year.

Geocentric Proper Motion

The geocentric proper motion of an asteroid is found by subtracting from the position vector of the asteroid relative to Earth at the desired time to impact the corresponding vector from a few minutes earlier. The angle between the two vectors divided by the elapsed time yields the proper motion.

Figure 3 shows daily geocentric proper motion μ versus angle from the sun $\theta_\odot$ for asteroids that approach Earth isotropically at 10 km s^{-1} at 10 days to impact. The maximum μ is small. We note the relatively narrow range of μ in Fig. 3 at each value of $\theta_\odot$. The minimum μ occur at $\theta_\odot = 0°$, 90° and 180° while the maximum μ of about 300 arcsec day^{-1} occurs near $\theta_\odot = 45°$ and 135°. The values of μ are sufficiently small that in a typical 2-minute CCD exposure an asteroid moves less than 0.4 arcsec, so its CCD image appears nearly stellar. To detect the proper motions of these asteroids, we need to observe them a few hours to a few days apart.

An observer on the rotating Earth sees an additional proper motion due to his own motion that is superimposed on the geocentric proper motion. The maximum reflex proper motion due to rotation can be comparable to the maximum geocentric proper motion at 10 days from impact. Because of the vector nature of the geocentric and reflex proper motions, there may be portions of the sky where the total proper motion vanishes when these two components are added together. The maximum summed proper motion is low enough at 10 days to impact that the typical movement across the CCD in a 2-minute exposure is less than 1 second of arc, so the image remains stellar. The reflex proper motion resulting from rotation becomes increasingly important as the object approaches Earth. The additional proper motion due to the finite impact parameter of the object also becomes important as it approaches impact.

Search Strategies for Impacting Asteroids

We have seen that the proper motions of asteroids during their final days to Earth impact are small and may even vanish in certain parts of the sky, so they may be missed by conventional surveys that rely on large proper motions to flag promising candidates. However, their parallaxes are easily detected with wide-angle (low-resolution) telescopes observing over a baseline of a few thousand kilometers. The major challenge is to correlate, in near real time, pairs of images from two or more sites to find promising candidates that would then be observed for proper motions. A large parallax and a low proper motion indicates a promising candidate, whose orbit would then be determined by further observations.

Relatively small telescopes are adequate to observe asteroids 100 m or more in diameter during their final days to Earth impact. A 5-inch, f/5 telescope would reach a saturation magnitude of 17.7 in a 2-minute exposure using the Spacewatch CCD array, which would cover a field $\approx 5^\circ$ across. This limiting magnitude will allow detection of a 100-m diameter asteroid 10 days from impact if it approaches Earth anywhere in the hemisphere centered on solar opposition. A 10-inch, f/5 telescope would reach a limiting magnitude of 19.2, which would allow it to detect these asteroids if they approach farther than 70° from the sun while a 16-inch, f/5 telescope would detect them farther than 40° from the sun. A 36-inch, f/5 telescope with a limiting magnitude of 22 could observe them if they approach no closer than 25° to the sun, which is about as close to the sun as twilight would allow observations under the best of circumstances. Alternatively, to reach the desired limiting magnitudes, we could use larger telescopes, e.g., 1-meter, that are rapidly scanned near opposition and more slowly scanned closer to the sun.

IV. DETECTABILITY OF ECAs DURING THEIR FINAL FEW YEARS TO IMPACT

Objects larger than 1 km in diameter need to be detected months to years before impact to allow time for deflection away from Earth. Proposed surveys for finding them, such as Spaceguard (Morrison 1992), will attempt to find all ECAs of this size rather than just those that will hit Earth in the next few years. They plan to concentrate their search towards solar opposition, as have most surveys to date. This limitation in sky coverage may produce severe selection effects, as is evident in the preliminary analysis of the detection capabilities of the Spaceguard survey (Morrison 1992). It showed that the survey would find 90% of all Near-Earth asteroids (NEAs) larger than 1 km in diameter after 25 years of searching if undiscovered NEAs have orbits similar to those of known ones. However, the survey would find only about 50% of the Atens, ECAs with semimajor axes less than 1 A.U. Since *existing* surveys such as Spacewatch concentrate their search towards opposition, they are likely to suffer the same selection effect, so Atens are under-represented among known ECAs.

ECAs that will hit Earth in the next few years should be easier to detect than other ECAs because they approach much closer to Earth. Any ECA, which is defined to have its perihelion (closest approach to the sun) within the orbit of Earth and its aphelion (farthest distance from the sun) beyond it, can *eventually* hit Earth. When impact occurs, the distance of the ECA from the sun equals that of Earth at one of the two points where the orbit of the asteroid intersects the orbital plane of Earth (the nodes). For a given ECA this happens at two different values of the argument of perihelion, the angle at the sun between the ascending node and the perihelion of the asteroid. In a purely two-body problem, this angle is invariant, but perturbations by the planets cause it to precess (rotate) by 2π radians on time scales of about 2×10^4 years. Twice per precession cycle, or about every 10^4 years, the distance from the sun at the node equals 1 A.U., so the ECA can collide with Earth if the orbit phasing permits it. The mean time to a collision is about 2 $\times 10^8$ years, so the orbit of the asteroid intersects that of Earth about 2×10^4 times before the asteroid collides with Earth. The mean closest approach of the ECA to Earth during each orbit crossing within the precession cycle is about $(2 \times 10^4)^{1/2} R_\oplus = 141 R_\oplus = 2.3$ times the distance to the moon = 0.006 A.U. If the object is destined to hit Earth, we expect close approaches of this order during the orbit revolutions immediately proceeding the one that leads to impact. The object will be much brighter than average during these close approaches. During the remainder of the precession cycle, the ECA orbit does not pass nearly as close to Earth especially if its perihelion lies well inside the orbit of Earth and its aphelion lies well outside it. ECAs in such non-intersecting orbits are much harder to detect, but they are of no immediate danger to Earth.

These orbit intersections within the precession cycle of the line of apsides are times of crisis for Earth. The close approaches during these times make the ECAs easier to observe, but they also make their orbits much more chaotic. We need to detect all objects that are in near-intersection orbits and then track them sufficiently well to assure that they will not hit Earth before precession again causes their orbits to diverge from that of Earth. In this paper we examine the observability of objects in near Earth-intersection orbits. If we define an Earth-intersecting asteroid (EIA) as one whose orbit is within +-200 years of intersection with the orbit of Earth due to planetary perturbations, then EIAs constitute about (2*200)/(20,000/2) = 4% of the ECA population. If there are 2000 ECA with diameters exceeding 1 km, then there are about 80 EIAs with such diameters. There should be nearly 10^5 EIAs with diameters exceeding 100 meters.

Orbital precession assures that a representative sample of Earth-crossing objects are now in orbits that pass near Earth. (These EIAs are, fortunately, the easiest ones to explore in detail including with the use of space probes.) There is no hidden ensemble of objects that may eventually hit the Earth, unless they are very rare. An extreme case of such a rare object may be Comet Hale-Bopp. It is reportedly 10 times the size and 1000 times the mass of Comet Halley or of the impactor responsible for the demise of the dinosaurs. This object may be massive enough to sterilize Earth. Fortunately, the chance of such an object hitting Earth is very small. A normal long-period comet hits Earth every 10^8 years (e.g., Hills 1981) with about 5 such comets intersecting the orbit of Earth each year. If this is the comet of the century, it is about 500 times rarer than the average long-period comet, so such an Armageddon comet would hit Earth about every 5×10^{10} years. Since the dawn of life on Earth, there has been about a 10% chance that such a comet would have hit. Except for such long-period comets, we should find a representative number of the various types of Earth-impacting objects among the current-day EIAs.

In this paper we consider the detectability of ECAs that will impact Earth in the next few years. We show that the currently proposed searches will systemmatically under-discover Atens and will not find Apollos as efficiently as they could. We show that these deficiencies can be corrected by changes in observing strategy.

Test Orbits

To study the observability of Earth-Intersection Asteroids (EIAs), we considered an ensemble (usually 1000) of them having a fixed impact velocity with respect to Earth. We used Monte Carlo sampling to place them isotropically, except for the forbidden zone corresponding to hyperbolic orbits, on a shell centered on Earth at 1 day from Earth impact. We found the heliocentric orbit of each and ran it and the orbit of Earth back through time for several years to find the position and magnitude of the EIA with respect to Earth prior to impact. We took our standard asteroid to have a diameter of 1 km, an albedo of A = 0.2, and a lunar phase law. The results are trivially scaled to other albedos and diameters.

To sharpen our intuition, we shall consider the detailed observational properties of a few representative impactors from the ensemble before looking at it statistically. Column 1 of Fig. 4 shows the magnitude and angle from the sun of typical Atens that have impact velocities of 15 km/s prior to gravitational acceleration by Earth while Column 2 shows their position on the sky. Fig. 5 shows representative Apollos. The points in both plots are given at one-day intervals for the final 10^4 days prior to impact. Column 2 of each figure is a Mercator projection in which the vertical axis is the angular distance from the north ecliptic pole. The horizontal axis is the angular distance in the ecliptic plane away from the instantaneous direction of Earth's motion around the sun. The sun is always located at ecliptic longitude 90^o (and polar angle 90^o) while the solar opposition point is at ecliptic latitude 270^o (and polar angle 90^o).

The loops to brighter magnitudes shown in Fig. 4 and 5 occur during close approaches to Earth. The objects can be very bright during these close approaches especially the Atens, which can reach magnitude 10 during some close approaches as shown in Fig. 4. We see that most Atens do not approach near enough to the solar opposition point to be found by existing and proposed ECA surveys despite their becoming quite bright during these close approaches. When the Atens are 180^o in ecliptic longitude away from the sun, they tend to be near the north or south ecliptic poles. This is due to their being relatively close to Earth at these times, so they tend to have a high ecliptic latitude even if they have a relatively small orbital inclination to the ecliptic. While Apollos can produce loops that dip down to comparably bright magnitudes, they make fewer revolutions around the sun per unit time than the Atens, so there is less probability of catching them when they are exceptionally bright. We note that the loops do not occur when the Apollos are near solar opposition, so to detect them when they are bright requires a survey that scans most of the sky. Apollos, with diameters of 1 km and albedos of 0.2, are generally about magnitude 18 during a typical close approach loop.

The last pair of plots in Fig. 5 is than of an Apollo that hits Earth on the first pass after observations begin rather than making several close approaches before it impacts. It is typical of long-period Apollos and long-period comets. We note that it is very faint until the final few months. It approaches the threshold of detetectability of magnitude 22 (characteristic of the proposed Spacequard system and typical of larger ground-based systems) at an angular distance of about 110^o from the sun or 70^o from opposition and never strays very far from it until impact. This is well outside the observing window centered on opposition proposed for Spaceguard or carried out currently by existing surveys such as Spacewatch. Such surveys would clearly miss the object. It points out the desirability of a survey that covers the entire sky to faint optical magnitude.

Probability of Detection

Fig. 6a shows the probability of detecting an ensemble of Earth-intersecting Atens with impact velocity 15 km/s during the interval from 10^4 to 10^3 days to impact. It shows the fraction of objects detected by a survey that observes all the sky farther than a certain angle from the sun to a given limiting magnitude. A detection is assumed if the object is visible for 5 or more days in the observing window. The limiting magnitudes of the surveys are 14,16,18,20, and 22. The near superposition of the surveys for all magnitudes onto one curve shows saturation, so that any survey with a magnitude limit of 14 or fainter would equally be able to detect the objects. The main limit is the geometric one. A survey limited to 45^o of opposition would only find about 0.4 of the Atens while one that extends to at least 90 degrees from opposition would find them all. The lack of dependence on magnitude is due to the loops to brighter magnitudes shown in Fig. 4, which occur in close approaches to Earth. The importance of close encounters is evident by the contrast with the discovery probabilities given in Fig. 6b where we have taken the same objects as in Fig. 6a and randomized their arguments of perihelia, so they more closely resemble the general Aten population rather than just those Atens that hit Earth. We note from Fig. 6b that a survey to find all Atens will not be complete unless its limiting magnitude is at least 18 rather than 14. The survey is also not complete unless it extends farther than 90^o from opposition.

Fig. 7a shows the detection probability of Earth-intersecting Apollos with impact velocities of 15 km/s when observed 1000 to 10,000 days to impact. The situation is not as favorable as for the Atens. An all-sky survey would find fewer than 60% of the Apollos if its limiting magnitude is 14 and under 90% if it is 16. At magnitude 18 about 98% would be discovered. Even allowing for albedos much darker than 0.2, it is likely that a survey with a magnitude limit of 20 would find at least 98% of the objects with diameters greater than 1 km. This survey would have to cover the entire sky farther than 90^o from the sun. Fig. 7b shows the detection probability if the line of apsides of these objects were rotated by random amounts so that they represent better the general ECA population. Again, a survey would find a smaller fraction of objects than if only Apollos with Earth-intersection orbits were considered, but the differences are not as large as they are for Atens.

Long-period objects, 1 km in diameter, such as the last one shown in Fig. 5 cannot be detected 1000 days before impact at a limiting magnitude of 22. That object does not approach the threshold of magnitude 22 until the last few months to impact, an it only reaches magnitude 14 during the last two weeks to impact. Such objects can only be detected years to impact by going to much fainter than magnitude 22, as is evident from the last plot in Fig. 5. Because of such objects, even the faintest survey does not reach unity in Fig. 7a. Because the sky background is about 22 magnitudes/(arc sec)^2 the only practical way of going to fainter magnitudes is to observe from space where the diffraction limit of even moderate aperture telescopes is less than 1 sec. This suggests an observing triage where the initial all-sky surveys would only go down to magnitude 18-20, but would cover the entire sky a few times a week. This would find more than 90% of the Earth-crossing asteroids in Earth-Intersection orbits. It does not make much sense to go down much further than this at high marginal cost unless the survey addresses the detection of long-period comets, which, like the last object in Fig. 5, needs to be detected at much fainter than magnitude 22 to be found years to impact. A wide-field 2-meter space telescope would go down to magnitude 27 before sky saturation, which would be adequate to detect these objects a few years to impact. This would require long exposures on each field, so it would only make, say, annual observations of each field. Two or three exposures on each field separated by a few days would be enough to show the proper motion of these distant objects. Likely objects would then have to followed with another space telescope to determine the orbit. The second space telescope would not have to have a wide field, unlike the discovery telescope. It could probably do this follow-up work as part of its other activities.

To discover more Earth-Intersection asteroids, particularly Atens, with present equipment, such as Spacewatch, it may be desirable to use it during the bright moon, when it is not currently used. It can do very rapid scans to magnitude 16-18, which is well above the sky background during the full moon, so the telescope will not be hampered by moonlight. During these times the telescopes should look at the part of the sky far from opposition, which is then occupied by the (near) full moon. The change in procedure would not reduce the current discovery rate of these telescopes at opposition, but it would allow additional EIAs to be detected far from opposition, at some increase in manpower.

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FIGURE CAPTIONS

Figure 1. Magnitude V of the intruding asteroid as a function of angle from the sun. The model asteroid has diameter $D = 100$ m, albedo $A = 0.2$, and obeys the lunar phase law. It approaches Earth at 10 km s^{-1} and is observed at 10 days to impact.

Figure 2. The apparent N magnitude versus angle from the sun of 100-m asteroids that approach Earth at 10 km s^{-1} at 10 days to impact.

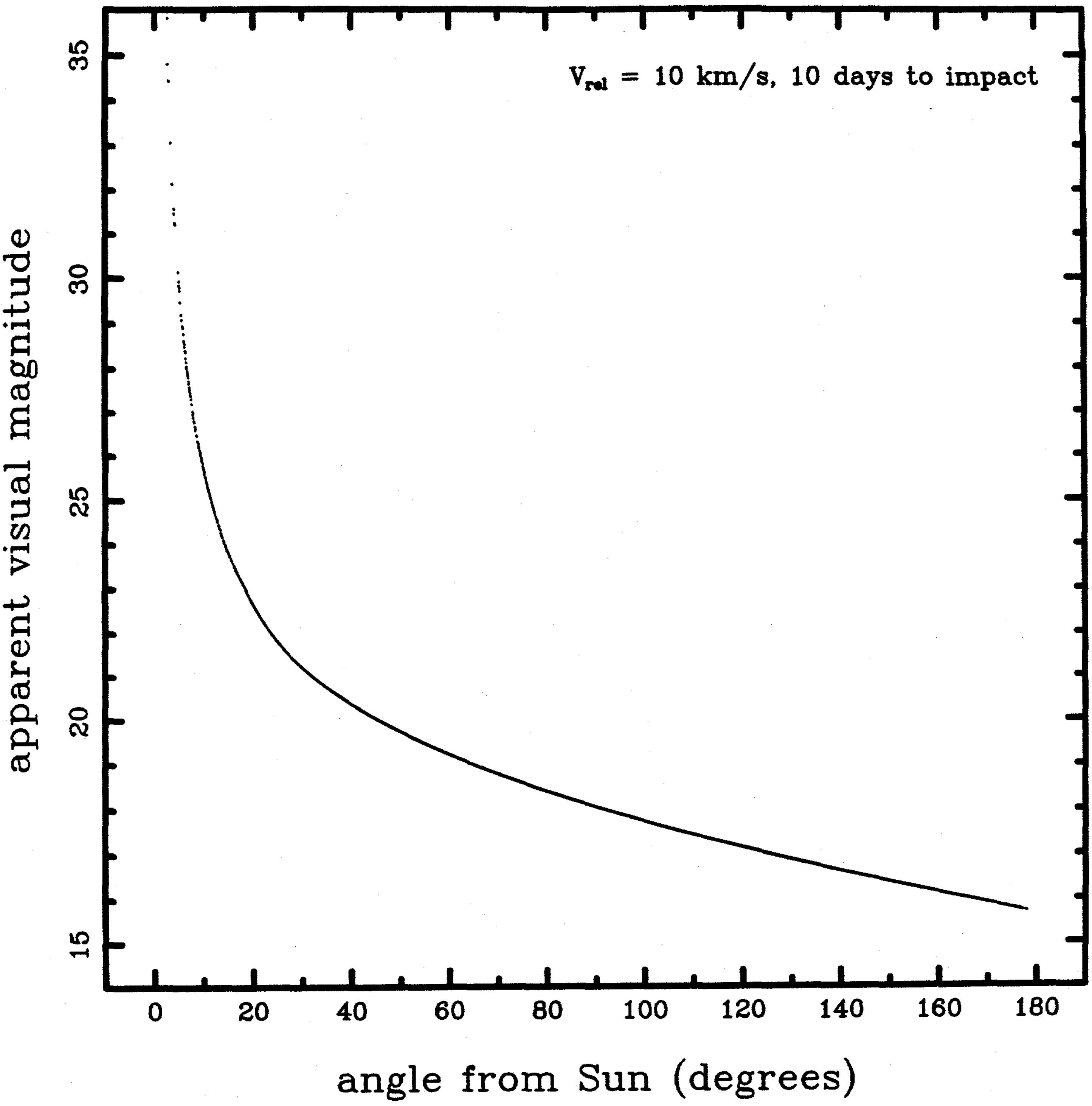
Figure 3. The daily geocentric proper motion μ versus angle from the sun of asteroids that approach Earth isotropically at 10 km s^{-1} at 10 days to impact.

Figure 4. Column 1 shows the apparent V magnitude and angle from the sun of typical Atens that have impact velocities of 15 km/s prior to gravitational acceleration by Earth. Column 2 shows the positions of these objects on the sky. The data points are at one-day intervals during the final 10^4 days to impact.

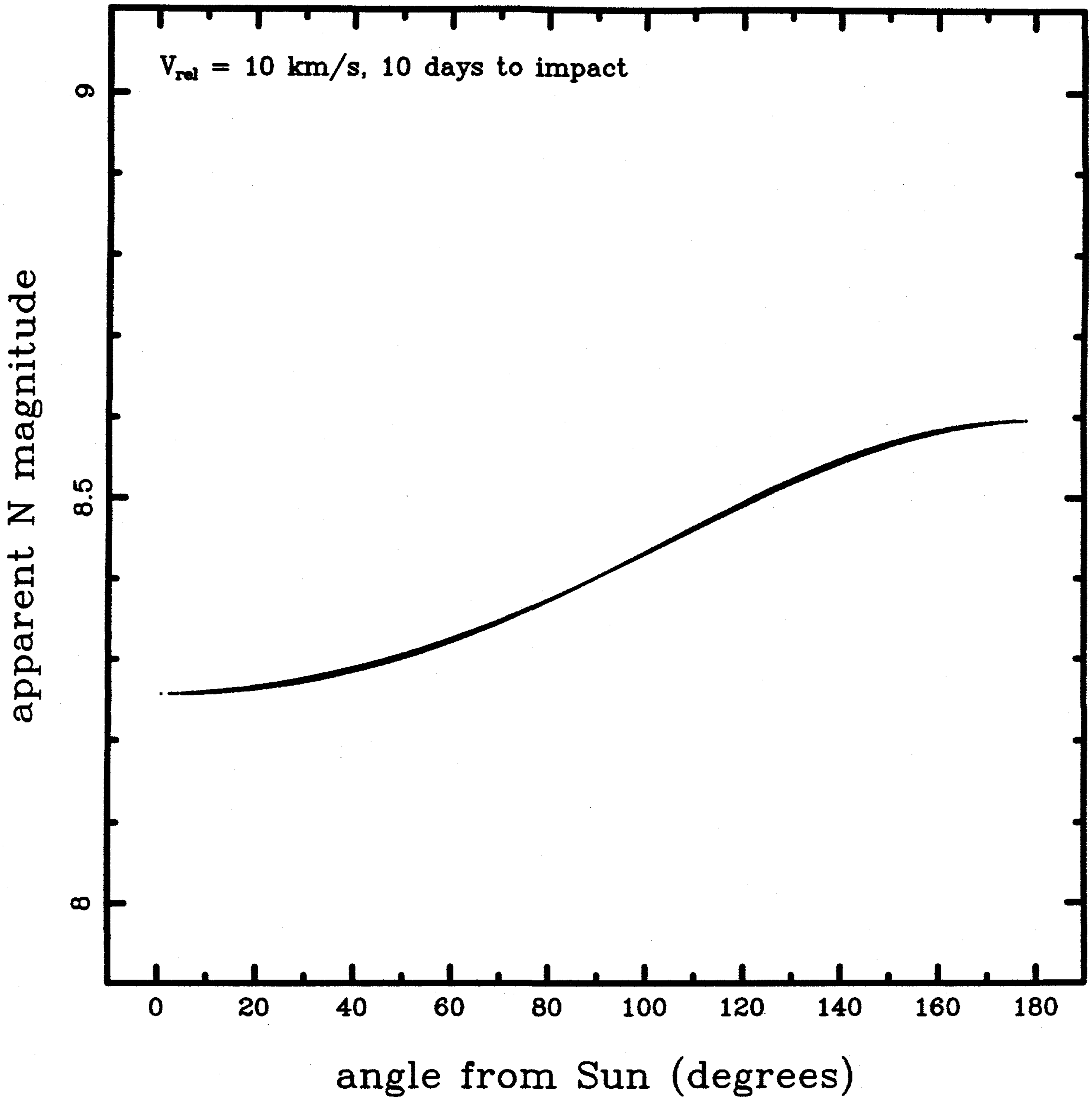
Figure 5. Same as Fig. 4, but for representative Apollos.

Figure 6. Here 6a gives the probability of detecting an ensemble of Earth-intersecting Atens with impact velocity 15 km/s during the interval from 10^4 to 10^3 days to impact. The probabilty is the fraction of objects detected by a survey that observes all the sky further than a given angle from the sun to a given limiting magnitude. A detection is assumed if the object is visible for 5 or more days in the observing window. The limiting magnitudes of the surveys are 14,16,18,20, and 22. The near superposition of the probabilities onto one curve shows that any survey to limiting magnitude 14 or better would be equally able to detect these objects. Here 6b estimates the probability of detecting the general ECA population of Atens. This was found by randomizing the arguments of perihelia of the objects used in constructing Fig. 6a.

Figure 7. Same as Fig. 6 but for Apollos rather than Atens. The curves are for limiting magnitudes 14, 16, 18, 20, and 22. Unlike Fig. 6, it shows that the surveys are not complete at the brighter limiting magnitudes.

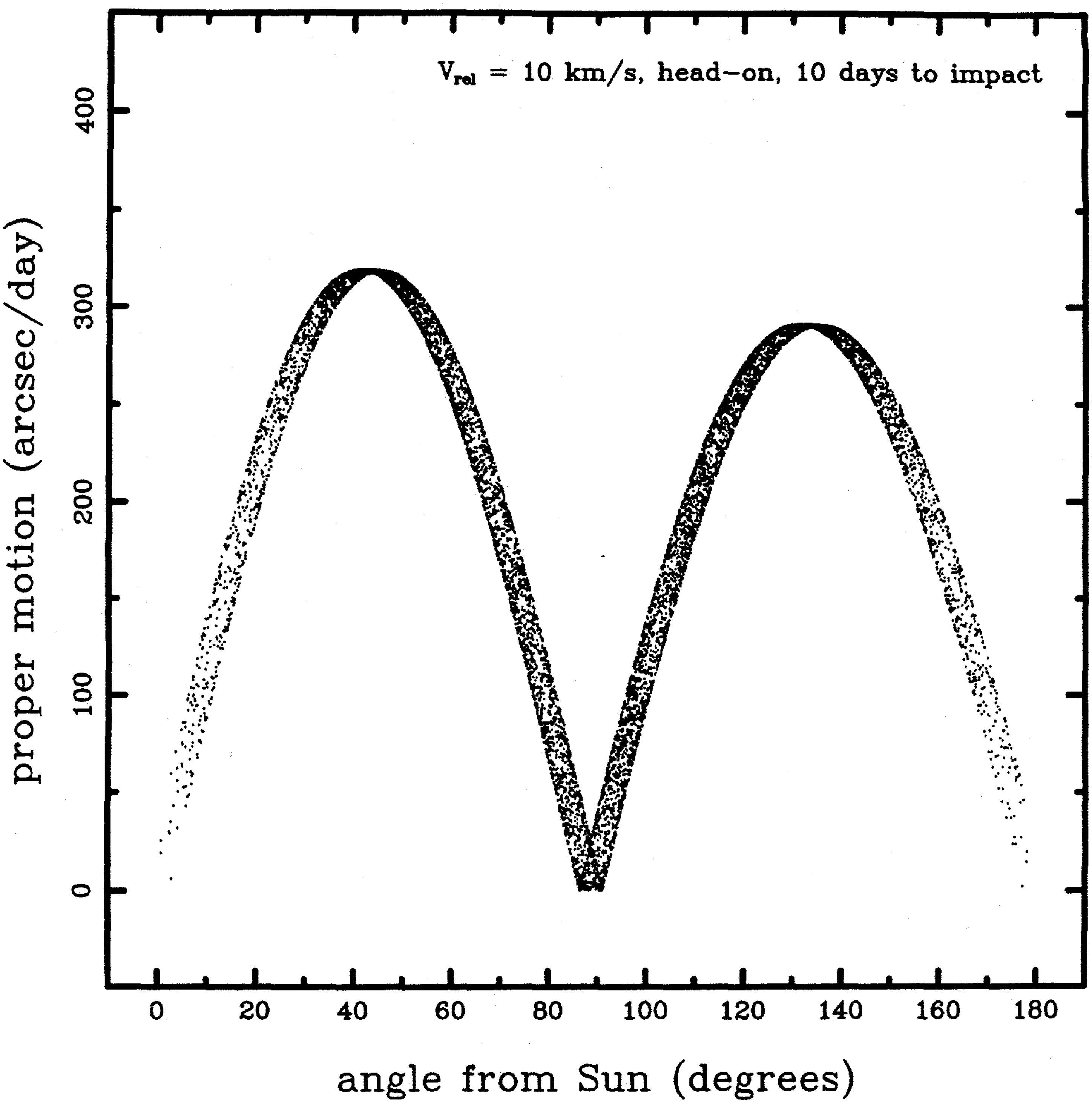


V_{rel} = 10 km/s, 10 days to impact
apparent visual magnitude
35
30
25
20
15
0
20
40
60
80
100
120
140
160
180
angle from Sun (degrees)



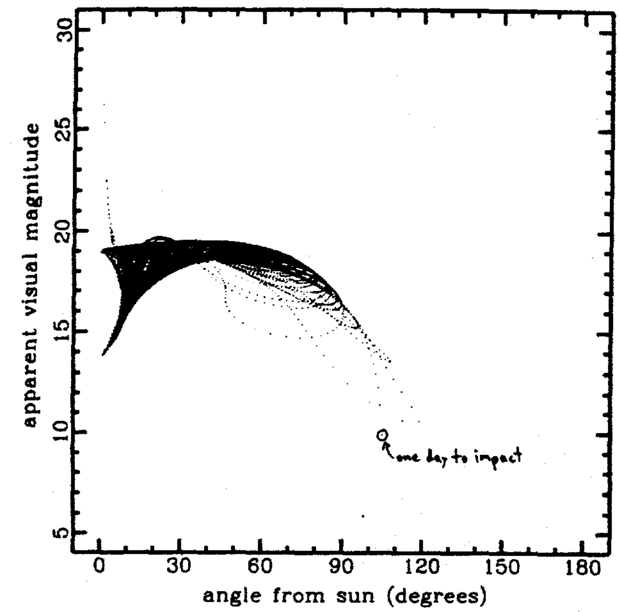
V_{rel} = 10 km/s, 10 days to impact
apparent N magnitude
9
8.5
8
0
20
40
60
80
100
120
140
160
180
angle from Sun (degrees)

Fig. 2

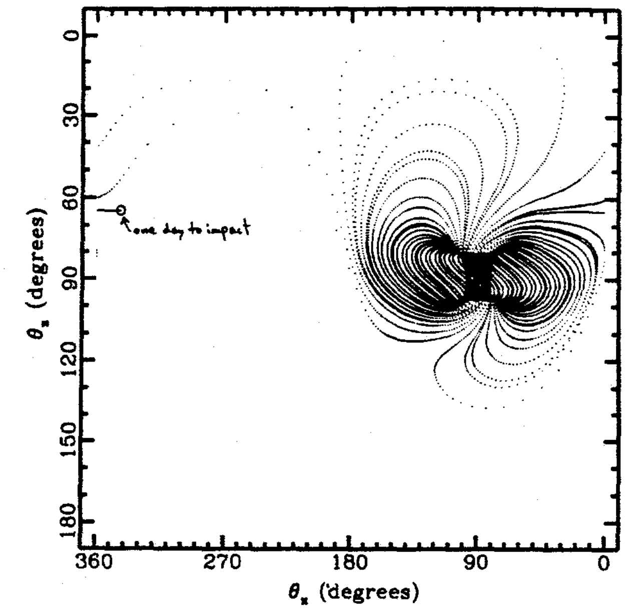


V_{rel} = 10 km/s, head-on, 10 days to impact
proper motion (arcsec/day)
0
100
200
300
400
0
20
40
60
80
100
120
140
160
180
angle from Sun (degrees)

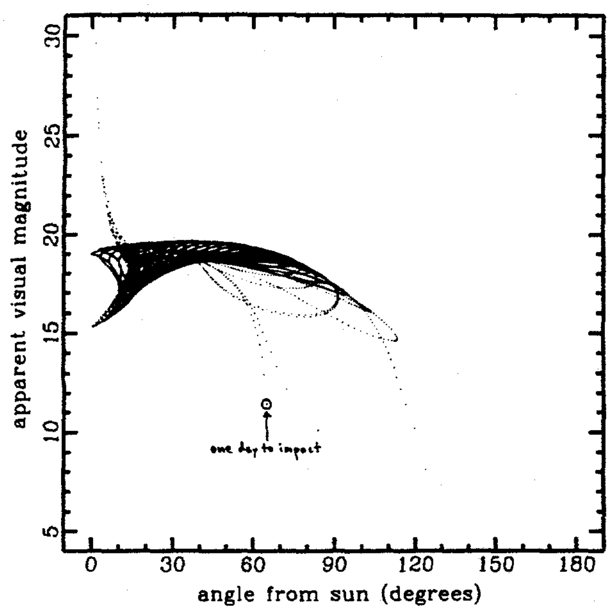
Final 10^4 days of Aten 3 ($a = 0.586$ AU, $e = 0.745$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



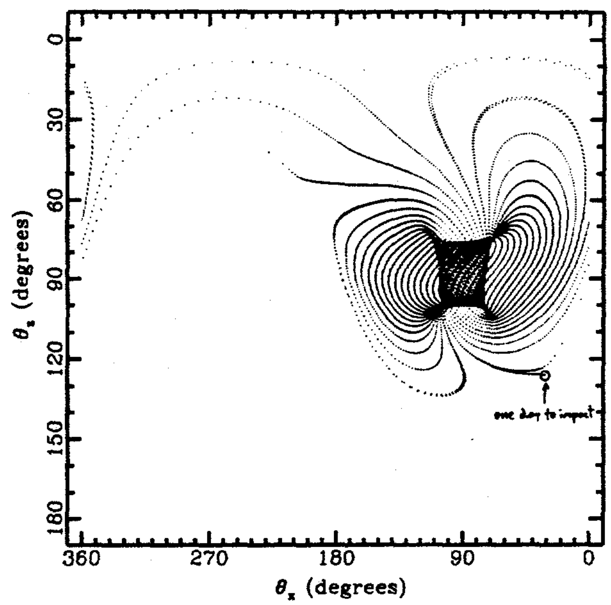
Final 10^4 days of Aten 3 ($a = 0.586$ AU, $e = 0.745$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



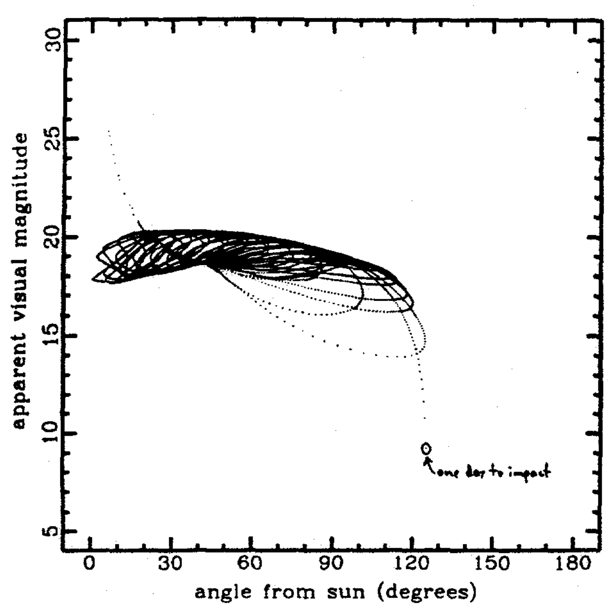
Final 10^4 days of Aten 4 ($a = 0.673$ AU, $e = 0.591$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



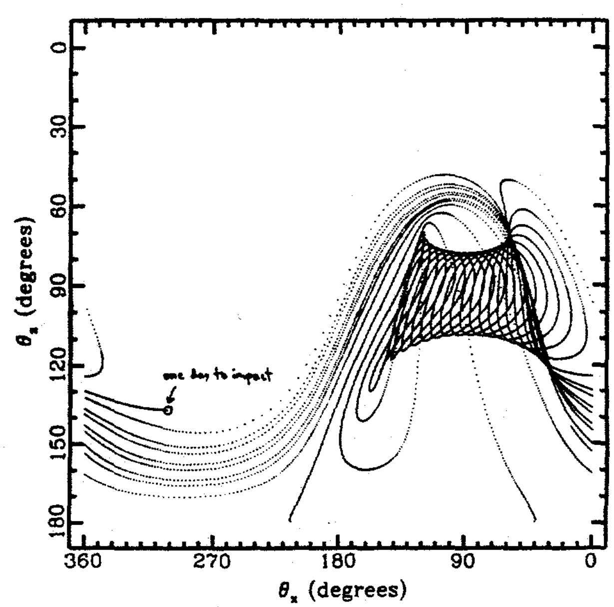
Final 10^4 days of Aten 4 ($a = 0.673$ AU, $e = 0.591$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



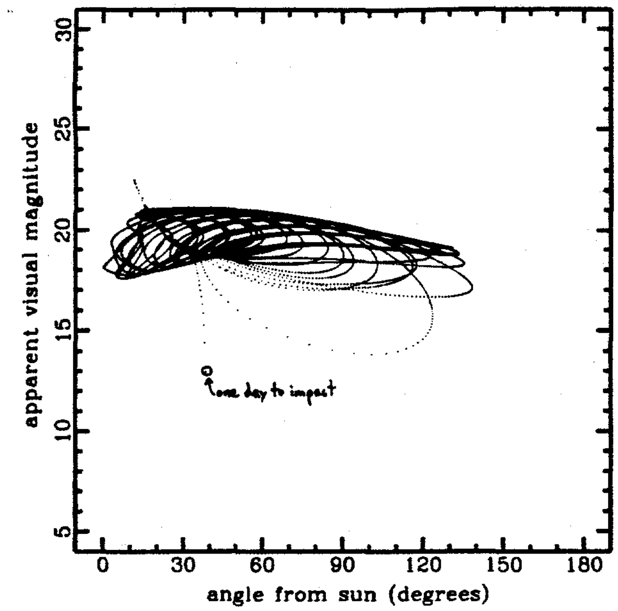
Final 10^4 days of Aten 7 ($a = 0.973$ AU, $e = 0.397$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



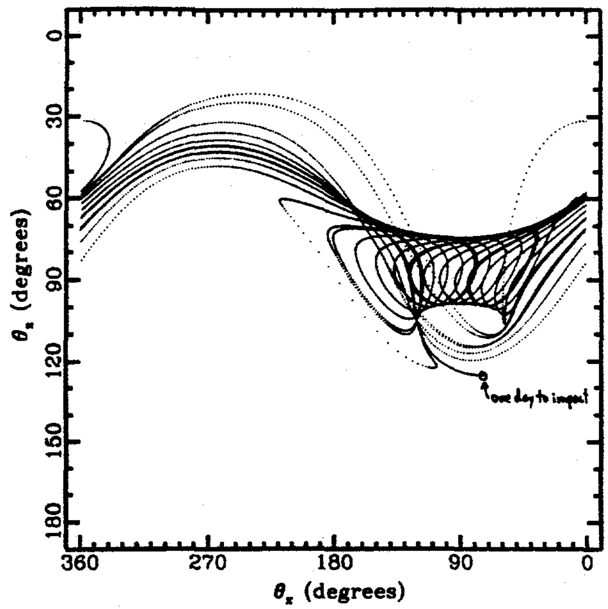
Final 10^4 days of Aten 7 ($a = 0.973$ AU, $e = 0.397$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



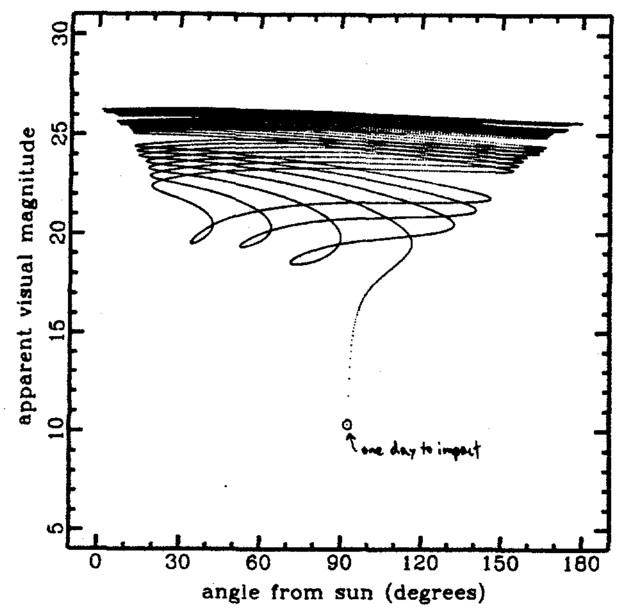
Final 10^4 days of Apollo 4 ($a = 1.151$ AU, $e = 0.505$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



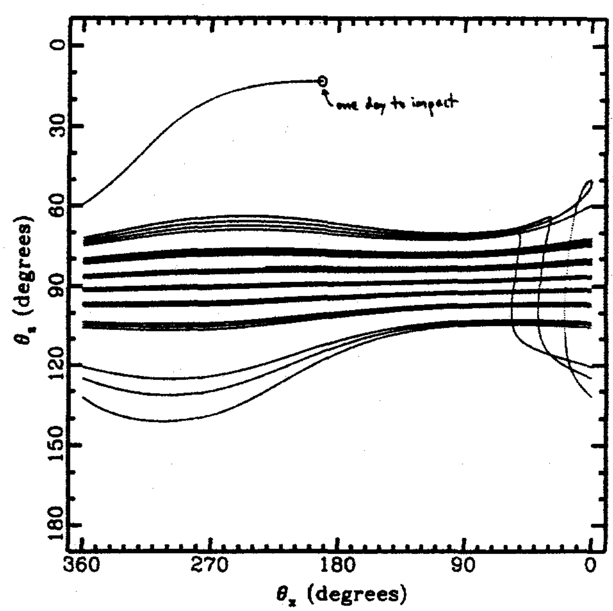
Final 10^4 days of Apollo 4 ($a = 1.151$ AU, $e = 0.505$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



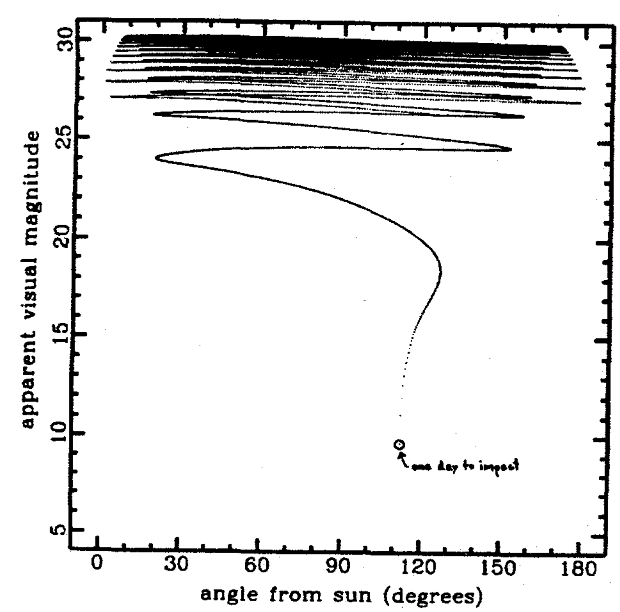
Final 10^4 days of Apollo 7 ($a = 4.034$ AU, $e = 0.752$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



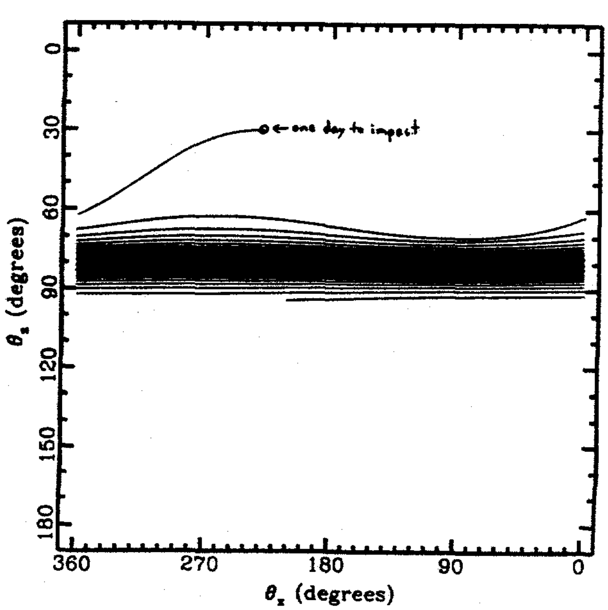
Final 10^4 days of Apollo 7 ($a = 4.034$ AU, $e = 0.752$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



Final 10^4 days of Apollo 3 ($a = 9.599$ AU, $e = 0.899$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



Final 10^4 days of Apollo 3 ($a = 9.599$ AU, $e = 0.899$, $V_{rel} = 20$ km s^{-1}, $D = 1.0$ km, $A = 0.2$)



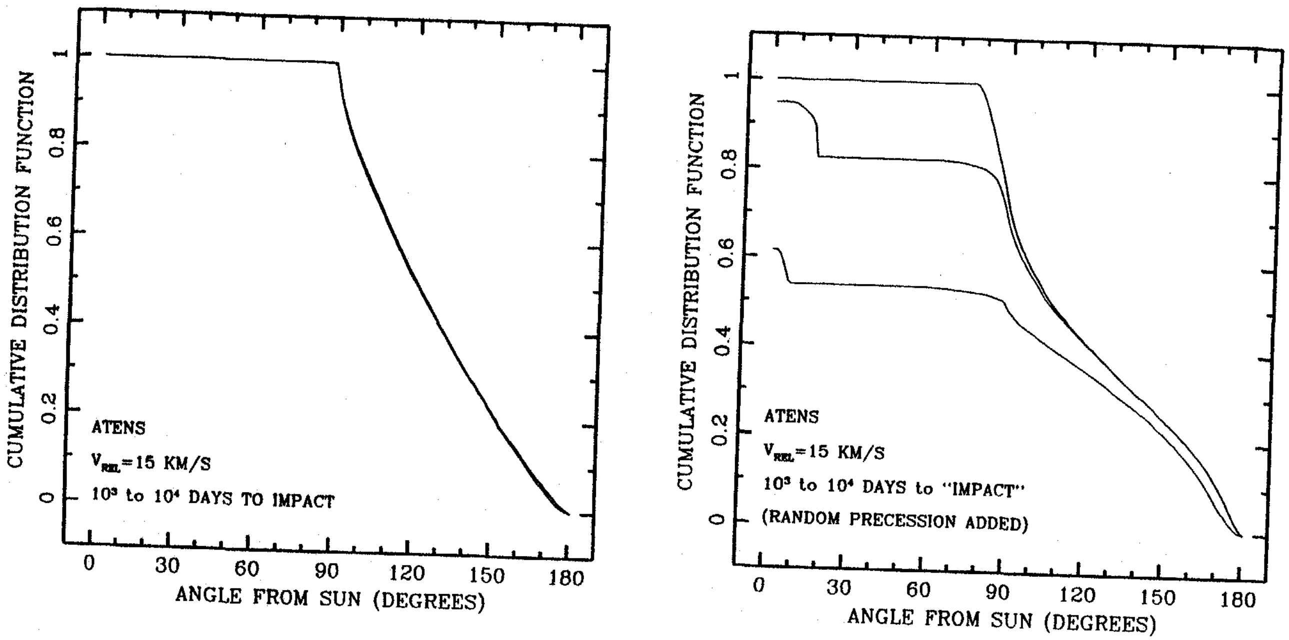

CUMULATIVE DISTRIBUTION FUNCTION
ANGLE FROM SUN (DEGREES)
ATENS
V_{REL}=15 KM/S
10^3 to 10^4 DAYS TO IMPACT
CUMULATIVE DISTRIBUTION FUNCTION
ANGLE FROM SUN (DEGREES)
ATENS
V_{REL}=15 KM/S
10^3 to 10^4 DAYS to "IMPACT"
(RANDOM PRECESSION ADDED)

Fig. 6

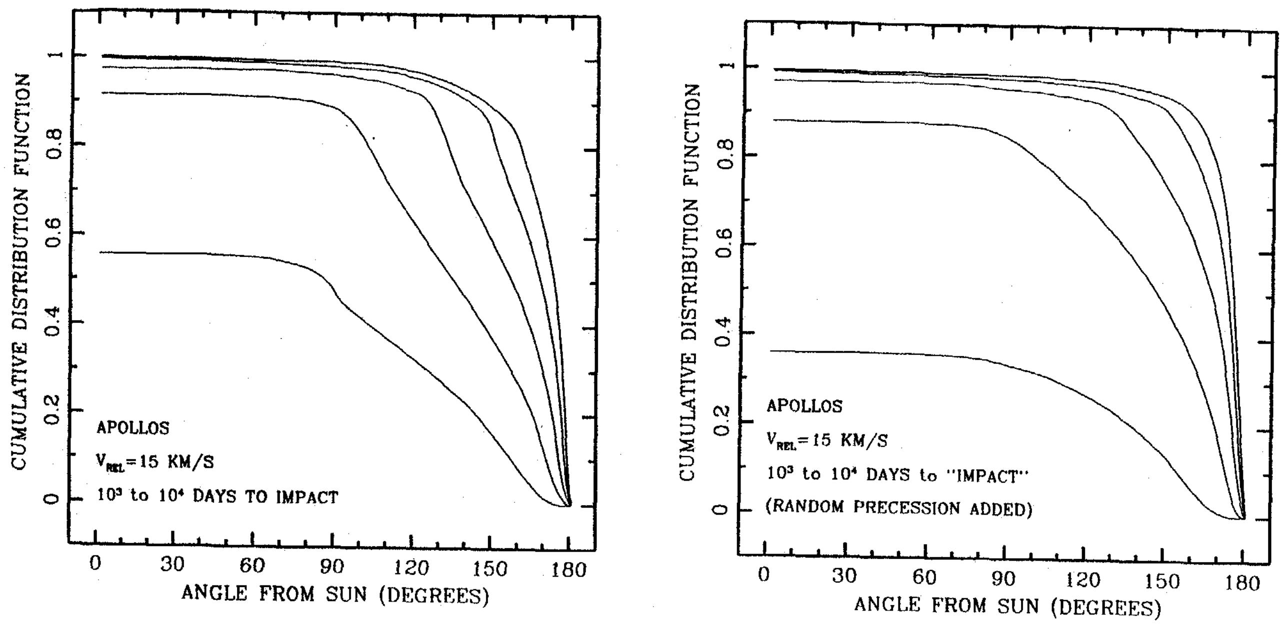

CUMULATIVE DISTRIBUTION FUNCTION
APOLLOS
V_{REL}=15 KM/S
10^3 to 10^4 DAYS TO IMPACT
ANGLE FROM SUN (DEGREES)
CUMULATIVE DISTRIBUTION FUNCTION
APOLLOS
V_{REL}=15 KM/S
10^3 to 10^4 DAYS to "IMPACT"
(RANDOM PRECESSION ADDED)
ANGLE FROM SUN (DEGREES)

Fig. 7