long-Period Comets and the Oort Cloud

Paul R. Weissman

Earth and Space Sciences Division
Jet Propulsion laboratory
Pasadena, CA 91109

Correspondence address:

Dr. Paul R. Weissman
Jet Propulsion Laboratory
Mail stop 183-601
4800 Oak Grove Drive
Pasadena, CA 91109

Phone: (818) 354-2636
Fax: (818) 393-4605
E-mail: pweissman@issac.jpl.nasa.gov

To be published in the proceedings of the
United Nations Near-Earth Objects Conference, April, 1995.

Abstract

The long-period comets pose a unique problem for the impact hazard problem. Because of their very long orbital periods and generally large distances from the Sun, they cannot be surveyed and cataloged in the same manner as the near-Earth asteroids and short-period comets. They appear at random, uniformly distributed on the celestial sphere. Current technologies can detect long-period comets at distances of ~5 AU, giving somewhat less than a one year warning time for potential Earth impactors. The mean impact probability for a long-period comet crossing the Earth's orbit is 2.2 to 2.5 x 10-9 per perihelion passage. The mean impact velocity is -52 km See-', but the most probable impact energy is characterized by a velocity of 56 to 58 km sec^{-1}. The estimated current impact rate for cometary nuclei large enough to create 10 km diameter (or larger) craters on the Earth is between 5 x 10-7 and 2.8 x 10^{-6} per year, with a best estimated value of 1.0 x 10"6 per year. Nuclei large enough to initiate global climatic disturbances strike the Earth, on average, every 16 Myr. The impact frequency may be increased substantially for brief periods of time during cometary showers, initiated by major perturbations of the Oort cloud. Improved technologies are needed to detect approaching long-period comets at large heliocentric distances so as to increase the warning time for potential impactors.

introduction

The long-period comets are the least predictable component of the flux of small bedim in Earth-crossing orbits. "1'heir orbital periods, typically 103 to 10^7 years, are in general so long that they have not been observed on previous passages through the planetary system. Although human societies have recorded appearances of comets for over 2,000 years (Hasegawa, 1980; Stephenson et al., 1985; Marsden and Williams, 1996), most of the older observations are of the few comets that were bright enough or came close enough to the Earth to be seen by naked-eye observers, and the positions are not sufficiently accurate 10 determine precise orbits. Current observational programs are not designed to search for long-period comets; a significant fraction of current discoveries are still made visually by amateur astronomers. At present, approaching long-period comets are rarely found at distances beyond the orbit of Jupiter, giving at best a one year warning time for Earth-crossing objects.

The long-period comets thus provide a significant dilemma for those concerned with the hazard posed by comet and asteroid impacts on the Earth. Although the majority of Earth impacts will come from asteroids and defunct short-period comets (Shoemaker et al., 1990; Weissman, 1990; Shoemaker et al., 1995), the lcmg-period comets still contribute between 10 and 30% of the total impactor flux (measured in terms of impact energy), and thus must be considered as a significant component of the impact hazard.

This paper is designed to serve as an introduction to the topic of long-period comets, in particular for individuals who are not planetary astronomers. Section 2 describes the existing, observational record for the long-period comets. Section 3 discusses the Oort cloud, which is the source of the long-period comets. Section 4 reviews the dynamics of long-period comets and their residence lifetimes in the planetary system. Section 5 discusses possible temporal variations in the cometary flux. Section 6 describes estimates of the impact probability of long-period comets on the Earth, and the expected flux of impacting objects. Section 7 summarizes the mate.rial in this paper and points out areas for future work.

The formal definition of a long-period comet is a comet with an orbital period of 200 years or more. This definition is somewhat arbitrary and is based on the fact that the good observational positions needed to determine accurate orbits exist only over the last 200300 years, corresponding in large part with the invention of the telescope. Despite the fact that the actual observational record extends over two millennia, no verified return of' a long-period comet has ever been identified. The orbital periods of most long-period comets are well in excess of 103 years.

More detailed reviews on the dynamics of long-period comets and the Oort cloud can be found in Marsden and Roemer (1982), Weissman (1991), and Fernández (1 994). A good review on the origin of comets is that by Mumma et al. (1993), and useful reviews on short-period comets are by Weissman and Campins (1993) and Shoemaker et al. (1995).

1 mng-period comets are usually named after their discoverer(s). Official catalog designations give the year the comet was discovered and a letter-number code that designates the approximate time of year and order in which each comet was found. For convenience in the following text, long- ant] short-period comets will be referred to as LP and S1' comets, respectivel y.

The Observational Record

The most recent Catalogue of Cometary Orbits (Marsden and Williams, 1996) contains 698 orbits of long-period comets observed through the end of 1995. 1 'he earliest record is for comet C/- 146 P1, observed in 147 B.C., one of many LP comets recovered from ancient Japanese and Chinese records (1 lasegawa, 1980). Only 67 of the orbits are for comets observed earlier than 1610, prior 10 the invention of the telescope. All of those are parabolic orbits only; no orbital period can be assigned. Because of the diffuse nature of cometary comae, pre-telescopic discoveries required the objects to reach a visual magnitude between 3.5 and 4.0, considerably brighter than the limit of $m_v = 6$ for objects that are stellar in appearance, such as supernovae

(Stephenson et al., 1985; Yau et al., 1994; Yeomans et al., 1996).

Seventy-thwc orbits in the catalog arc for 1,1' comets observed between 1610 and 800, with only 3 of those having non-parabolic elements. The quality of orbits gets progress Vely better with time. For the 202 LP comets which were discovered in the] 9th century, 86 have non-parabolic orbits, or 43°/0 of the total. For the 20th century the numbers are 262 non-parabolic orbits out of a total of 3561,1' comets discovered, or 740A.

Of the 6981.1' comets in the catalog, 411 have perihelion distances less than .0 AU and are thus in Earth-crossing orbits (an additional 10 LP comets have perihelia between 1.0 and 1.0 167 AU, the Earth's aphelion distance). Observational selection effects bias discovery statistics to comets with perihelia mar the Earth's orbit (Everhart, 1 967a). Prior to 1900, 245 of 333 discovered LP comets or 74°/0 were in Earth-crossing orbits (not including 5 sun-grazing comets, most of which are fragments of a single disrupted comet: see below). Since 1900, only 142 of341 observed LP comets, or 42% are Earth-crossing (again, not counting 19 sun-grazers), due to the increasing number of photographic and CCD discoveries of LP comets with larger perihelion distances.

Nine of the LP comet orbits in the catalog may be short-period comets, but were too poorly observed to obtain a non-parabolic orbits] solution. Short-period orbits are characterized by low inclinations and perihelion directions near the ecliptic. Three of these nine comets were pre-telescopic discoveries, while three have been found since 1900. Six of these objects were in Earth-crossing orbits, so they may present a hazard to the Earth.

The current discovery rate for LP comets, averaged over the 10-year period 1985-1994 is 7 comets per year (excluding sun-grazing comets: see below). In the same 10-year period an average of 2.4 discovered LP comets per year had Earth-crossing orbits, i.e., they had perihelion distances ≤ 1 AU. However, many 1,1' comets are likely missed due to observational selection effects. For example, comets can be easily missed if they pass perihelion on the opposite side of the Sun from the Earth. Everhart (1967a, 1967b) studied observational selection effects in detail and estimated that -8,0001,1' comets had passed perihelion within 4 AU of the Sun over a 12.7-year period. Everhart also derived corrected absolute magnitude and perihelion distributions for the LP comets; the perihelion distribution is shown in Figure 1. The number of Earth-crossing comets increases linearly with increasing perihelion distance between O and 1 AU. Using Everhart's estimates, one finds that there are ~1O Earth-crossing LP comets per year brighter than absolute magnitude, 11,0 = 11.[1] Comparing this estimate with the observed statistics above, it appears that three-fourths of all Earth-crossing LP comets are currently missed.

The orbits of the LP comets are randomly oriented on the celestial sphere. This is reflected in the orbit element distributions. For random orientations, both the argument of perihelion and the longitude of the ascending node are expected to be uniformly distributed between O and 360°, while the distribution of inclinations is such that the number of comets at any inclination, i, is proportional to sin(i). Although the observed distributions do not match the expected distributions perfectly, Everhart (1 967a) showed that the differences between them could readily be accounted for by observational selection effects. The most notable selection effect is caused by the preponderance of northern hemi sphere observers, which leads to an excess of comets being discovered if they pass perihelion north of the celestial equator. A second notable

---

[1] The absolute magnitude of a comet, 1110, is the total brightness a comet would have, with coma, if it was 1 AU from both the Sun and Earth, and its brightness varied as $1/r^2$ versus geocentric distance, and $1/r^4$ versus heliocentric distance. This brightness law generally works reasonably well for 1,1' comets when they are less than ~3 AU from the Sun. However, the heliocentric exponent can vary bet ween ~2.5 and 6 or more, generally being less for dynamically new comets, and larger for older, more physical l y evolved comets. Based on modeling, by Weissman (1 990), an H_{10} value of 11 corresponds to a nucleus mass of 4×10^{15} g, or a nucleus radius of 1.2 km assuming a bulk density of 0.6 g cm^{-3}.

effect is an excess in the number of retrograde comets discovered, because their retrograde motion is more likely to bring them close to the Earth during the limited time when they arc bright enough to be discovered. The preponderance of northern hemisphere observers also results in seasonal variations in the discovery rate of comets, fewer comets being found in northern hemisphere winter when inclement weather and cold is likely to keep some observers away from telescopes.

Some researchers have identified possible asymmetries in the orbital clement distributions of the 1.1' comets, which they associate with particular theories of the origin of comets. Most notable of these is an alleged clustering of perihelia near the solar apex (e.g., Tyror, 1957; Bogart and Noerdlinger, 1982.). However, Neslušan (1996) showed that the asymmetry and apex clustering is largely a result of the north-south asymmetry in observers. It has also been proposed that a contribution 10 the asymmetries may come from the most recent stellar perturbation of come.ts in the Oort cloud (Biermann et al., 1983; see section 3).

A special case of Earth-crossing LP comets is the sun-grazing comets (Marsden, 1967, 1989). These 24 observed comets have perihelia < 0.0] AU, within one solar radius of the Sun's photosphere. "1'bus, they arc within the Roche limit of the Sun where tidal forces can disrupt the nucleus of a comet. All but one of the 24 sun-grazing comets have very similar orbital elements, though some orbits arc assumed because of limited observations. They arc collectively referred to as the Kreutz group. The similarity of the orbits of the Kreutz group suggest that they arc fragments of a larger parent comet that disrupted on one or more previous ret 111'11s, in recent years, discovery of sun-grazing comets has been greatl y supplemented by spat.cborne instruments, including the SOLWIND experiment and the Solar Maximum Mission, and some fragments have been observed to impact the Sun. in addition to tidal forces, the intense heating of the nucleus and the resulting thermal stresses probably play a role in the disruption of these nuclei.

The Kreutz group comets have semimajor axes on the order of 60 100 All, yielding orbital periods between ~500 and 103 years. 1 lowever, the orbits of the Kreutz group arc inclined -139-144° to the ecliptic and arc oriented such that the fragments cannot make close approaches to the Earth. Repeated passages within the Sun's Roche limit will likely destroy these objects befor c their orbits can evolve very far. '1'bus, they likely play no significant role in the impact hazard on the 1 'arth.

The Oort Cloud

About two-fifths of observed 1,1) comets passing through the planetary region (for which mm-parabolic orbit solutions are possible) arc on osculating (instantaneous) hyperbolic orbits. 1 'arly on, this led to the suggestion that the 1,1' comets came from interstel lar space. However, integration of the orbits backward in time to a point before the comets entered the planetary system, and correction to a barycentric rather than a heliocentric coordinate system, showed that virtually all of the orbits were originally elliptical. '1'bus, the LP comets arc members of the solar system, though their semimajor axes in many cases arc quite large, $\sim 10^4$ AU or more (corresponding to orbital periods $\geq 10^6$ years).

A useful way to display the semimajor axis (distribution of the LP comets is to use the inverse of the semimajor axis of the original orbit, $1/a_o$, prior to the comets having entered the planetary system. The inverse semimajor axis is proportional to the energy of the comet's orbit. Positive values of $1/a_o$ correspond to negative energies, or bound, elliptical orbits. Negative $1/a_o$ values correspond to positive. energies, or unbound, hyperbolic orbits. The distribution of $1/a_o$

for 291 non-parabolic orbits from Marsden and Williams (1996) is shown in Figure 2.

The distribution is characterized by a large 'spike' of comets at near-zero, but bound energies (with semimajor axes > 10^4 AU), and a low continuous distribution of bound orbits at increasing values of $1/a_o$. A modest number of comets have weakly hyperbolic orbits. These hyperbolic orbits are generally discounted as due to errors in the orbit determinations, and due to the effects of nongravitational forces from cometary jetting (see below), which tend to make the orbits appear more eccentric than they actually are.

The large spike of comets at near-zero energies does not appear in the distribution of osculating orbits of comets passing through the planetary region, or in the distribution of future orbits of comets integrated forward in time until they have passed well beyond the gravitational perturbations of the individual planets. Oort (1950) recognized that the spike in the original energy distribution represents the source of the long-period comets, a vast spherical cloud of comets surrounding the planetary system at very large heliocentric distances, -50,000 150,00 AU, but still gravitationally bound to the Sun. Most of the comets in the 'spike' are making their first perihelion pass through the planetary region. Oort showed that on subsequent returns, planetary perturbations scatter the comets in orbital energy, allowing them to diffuse in $1/a_o$ and forming the low continuous distribution in Figure 2.

Oort also showed that the orbits of comets in the cometary cloud were so weakly bound to the Sun that they were perturbed by random passing stars. On the order of 6 10 stars pass within 1 parsec of the Sun every million years (Weissman, 1980a; Fernández, 1980). Stellar perturbations cause the perihelia of the very eccentric cometary orbits in the cloud to random walk back into the planetary region where they can be observed as 'dynamically new' long-period comets. Once a comet enters the planetary region, its motion tends to be dominated by distant planetary perturbations, primarily by Jupiter, causing the orbits to random walk in orbital energy, $1/a_0$, and thus diffusing comets to larger or smaller semimajor axes.

The typical Jupiter energy perturbation is ±630 x 10^{-6} AU^{-1}, or more than six times the width of the spike in Figure 2. Thus, comets rapidly diffuse away from the 'Oort cloud' to either more tightly bound, shorter period orbits, or to unbound, hyperbolic orbits where they are ejected to interstellar space. About one-half of the 'dynamically new' comets from the Oort cloud, that is, comets making their first perihelion passage through the planetary region, are ejected to hyperbolic orbits and do not return, The other half are scattered to smaller semimajor axes where they return some time in the future, to be scattered in orbital energy once again. A small fraction, 5%, are returned to orbits with semimajor axes in the Oort cloud. The motion of the comets is thus a random walk in $1/a_0$, diffusing both to the left and to the right in Figure 2, but being lost if they achieve negative values of $1/a_0$.

The few 'hyperbolic' comets in Figure 2 are most likely the result of small errors in their orbit determinations, or unmodeled nongravitational forces resulting from jetting of volatiles on the. surfaces of the cometary nuclei (which make the orbits appear more eccentric than they actually are, as shown by Marsden et al., 1973). Since the Sun and solar system are moving with a velocity of ~16.5 km sec^{-1} with respect to the local stars, interstellar comets entering the planetary system would be expected to have comparable hyperbolic excess velocities. The largest hyperbolic excess velocity for any of the comets represented in Figure 2 is 0.81 km sec^{-1} for comet Sato, C/1975 X 1. That comet had a perihelion distance of 0.864 AU and the errors in its orbit could easily be due to unmodeled nongravitational forces, which were not included in its orbit solution, Kresák (1992) pointed out other problems with the orbit solution, including the very short interval over which comet 1975 X 1 was observed (less than 2 months), the lack of a central condensation in the coma, and the intrinsic faintness of the coma (11,0 = 11 .2.). Similar problems exist with many of the other hyperbolic original mbit solutions. Thus, it is highly doubtful thal any of the observed LP comets arc on truly hyperbolic orbits.

Oort proposed that the cloud of comets had been created by material dynamically ejected from the planetary region by the growing proto-planets. Oort showed that as objects were driven to larger and larger orbits by close encounters with the planets, achieving aphelia of -2 x 10^4 AU or more, perturbations by random passing stars would become significant. The stellar perturbations have two effects. First, they cause the perihelion distances of the comets to random walk, with many perihelia increasing to distances greater than the semimajor axes of the giant planets, effectively detaching the cometary orbits from the planetary region. Second, stellar perturbations randomize the inclinations of the cometary orbits, which arc initially close to the ecliptic plane, creating a spherical Oort cloud.

Once the comet orbits become detached from the planetary region, they continue to evolve under the influence Of random stellar perturbations. In addition, giant molecular clouds (GMC's) in the galaxy, unknown at the time of Oort's work, serve as a second major perturber of the comet cloud. GMC encounters arc much less frequent than stellar encounters, occurring perhaps once every 3 x 108 years, but can be quite significant because of the huge mass of interstellar material in the GMC's (Hut and Tremaine, 1985).

Repeated stellar and GMC perturbations cause the orbits of the comets to diffuse in velocity phase space, slowly increasing the energy anti angular momentum of tile Oort cloud comets and causing the cometary perihelia to diffuse away from the planetary region. However, a third important perturbation comes from the integrated mass of the galactic disk, known as the galactic tide, causing the perihelia and inclinations of the orbits to oscillate (Byl, 1983; Heisler and Tremaine, 1986). The galactic tide can thus drive the perihelia of orbits back into the planetary region. Stellar and GMC perturbations also contribute to the random walk of the perihelia back into the planetary region, though the galactic tide appears to dominate the process.

Although Oort suggested that the original source of the comets was the asteroid belt, Kuiper (1951) pointed out that the icy nature of comets required that they had formed farther out from the Sun, among the giant planets, where it was cold enough for volatile ices to condense. Subsequent work by Safronov (1969) showed that comets formed in the Jupiter-Saturn zone tended to be ejected to interstellar space by these massive giant planets, rather than placed on distant ellipses which could be captured into the Oort cloud. However, Safronov also showed that the smaller masses of Uranus and Neptune resulted in fewer ejections and more efficient capture into distant orbits. Thus, the Uranus-Neptune zone is generally recognized as the source of the Oort cloud comets, though some contribution from the Jupiter and Saturn zones is possible.

The dynamical evolution of LP comets from the Oort cloud is illustrated by the scatter diagram in Figure 3, which plots each observed LP comet as a function of its perihelion distance and inverse original semimajor axis (omitting those comets for which only parabolic orbital solutions are available). The dynamically new, Oort cloud comets appear as a horizontal band of objects near zero 1/a. . As comets are perturbed by the giant planets they random walk vertically in the Figure (planetary perturbations on the perihelion distance, q, are typically small unless a very close approach occurs). However, if a comet random walks to a negative value of $1/a_o$, it escapes the solar system and does not return.

An important observational selection effect is illustrated in Figure 3. Although Oort cloud comets are quite bright and have been discovered with perihelion distances up to 6 AU and more, returning LP comets (ones with $1/a_o > 10^{-4}$ AU^{-1}) are rarely discovered unless their perihelion distances are less than 3 AU (the recently discovered comet 1 lale-Bopp, C/1 99501, which will pass perihelion on April 1, 1997 is a notable exception to this rule). Three AU is the distance at which water ice begins to sublimate at a sufficient rate to produce an easily visible coma 'J'here is no dynamical mechanism which will selectively remove returning 1.1' comets with perihelia > 3 AU, so the effect must be one of observability, as first noted by Marsden and Sekanina (1973),

Several explanations have been proposed for the anomalous brightness of dynamical] y new LP comets from the Oort cloud. Whipple (1978) proposed that the comets were covered with a 'frosting' of highly volatile interstellar molecules, accreted during the comets' long residence time in the Oort cloud. 1 lowever, Stern (1 990) showed that micro-cratering by interstellar dust grains will likely erode away this frosting faster than it can form. in addition, galactic cosmic rays and solar protons (Johnson et al., 1987) will sputter this volatile material away.

A more plausible explanation of the anomalous brightening of new comets involves the conversion of amorphous water ice in the cometary nuclei to crystalline ice, which occurs as the nucleus surface is warmed to temperatures between 1 10 and 150 K (Prialnik and Bar Nun, 1987). This occurs at about 5-8 AU as the comet is inbound to the Sun for the first time. If comets formed cold in the outer solar system, at temperatures < 60 K, then the water ice in the nuclei was initially in an amorphous state. The conversion from amorphous to crystalline ice is an exothermic reaction, so it is somewhat self-sustaining, though it eventually dies out because of the presence of other, non-volatile material in the comet's icy-conglomerate matrix. Typically, a 1 aycr several meters thick on the nucleus surface is converted to crystalline ice, and cometary materials may be blown off the surface. in addition, volatile gases such as CO in the near surface layers of the nucleus will be liberated during the conversion process, and wil 1 carry entrained dust off the nucleus surface, leading to a visible cometary coma. This greatly increases the brightness of the comet over that of its bare nucleus, and thus increases the chance of discovery by terrestrial observers.

Oort estimated a population for the cometary cloud of 1.9 x 1011 comets. However, using Everhart's (1967b) estimates of the flux of LP comets corrected for observational selection effects, and more detailed modeling of the Oort cloud by Weissman (1985) and Heisler (1990), the population is now estimated to be $\sim 10^{12}$ comets with $H_{10}<11$ (Weissman, 1991; $H_{10}<11$ corresponds to nuclei with radii > 1.2 km; see below).

Oort proposed that there would be no come.ts in the comet cloud with orbital semimajor axes less than --104 AU, because of the declining effect of stellar perturbations on orbits that Close to the sun. However, the recognition that the galactic tidal field also plays a role in perturbing the perihelia of distant comets caused a re-appraisal of Oort's conclusion. Duncan et al. (1 987) modeled the dynamical evolution of comets ejected out of the proto-planetary region under the influence of planetary, galactic, and stellar perturbations. They showed that comets with semimajor axes as small as $\sim 3 \times 10^3$ AU could have their perihelia raised out of the planetary region by the galactic tide. These comets would be captured into the Oort cloud and would continue to diffuse in velocity phase space, slowly increasing their orbital energies as well as randomizing their orbital inclinations. Duncan et al. showed that the inner Oort cloud retains some flattening for comets with semimajor axes less than -6×10^3 AU, but that beyond that distance the orbital inclinations of the comets are essentially random.

Duncan et al. (1 987) estimated that the population of the inner Oort cloud was about five times that of the outer Oort cloud, or about 5 x 10]2 comets, given the Oort cloud population estimates above. Taking Weissman's (1 990) estimate of an average cometary nucleus mass of

3.8 x 10^{16} g, the total mass in the inner and outer Oort clouds would be -2.3 x 1029 g, or 38 Earth masses. A hypothetical illustration of the Oort cloud, using the orbital energy distribution found by Duncan et al., is shown in Figure 4.

Physical and Dynamical Evolution of Long-Period Comets

Dynamical simulations by Weissman (19'79a) and Fernández (1 982) showed that the average LP comet makes five peri helion passages through the planetary system before being removed by one of several physical and dynamical processes. About 65% of all LP comets are ejected to interstellar space or to semimajor axes beyond's the Sun's sphere of influence (a > 10S AU). Another 8% of all LP comets are returned to orbits with aphelion distances in the Oort cloud, where stellar and galactic perturbations can once again raise their perihelion distances out of the planetary region. About 10/0 of LP comets are perturbed to perihelion distances within one solar radius of the Sun, where they will likely be tidally disrupted, as has been observed for the Kreutz group of comets. The mean lifetime of a LP comet is -6 x10^{5} years following its first perihelion passage (Weissman, 1 979a).

Additionally, 27°A of LP comets are lost to random disruption, i.e., splitting of nuclei. Random disruption is a poorly understood process, Although likely associated with heating of the nuclei during their perihelion passages, disruption events do not show a strong correlation with time of perihelion, passage through the ecliptic plane, or any other easily recognized element of the comets' orbits. Based on observed events, Weissman (1980b) estimated that about 10°/0 of dynamically new LP comets from the Oort cloud randomly disrupted, while only 4% of returning 1.1' comets broke up, and only 1 % of short-period comets, per perihelion passage. These statistics suggest some sort of binding mechanism or gradation of cometary strengths, such that weak comets break up rather soon after first appearing, whereas stronger comets continue to return and can survive the many returns necessary to evolve to short-period orbits.

This scenario is complicated by the fact that most splitting events do not appear to involve disruption of the entire nucleus, but rather the breaking off of ma]] fragments from a main nucleus (Sekanina, 1982). Although the minor fragments typically fade and disappear in a few weeks to months, the main nucleus usually persists, and in the case of SP comets, may continue to make regular returns. One famous exception to this was comet Biela, an Earth-crossing S1' comet which was first observed in 1772. in 1846 it was observed to have split into two comets. Both comets returned in 1852 but were never seen again, despite repeated searches. However, there were massive displays of the comets' associated meteor shower, the Andromedids, in later years.

This raises the question of the physical end-states of cometary nuclei, which is an important one for the hazard problem. If cometary nuclei disintegrate entire] y into relatively small, meteoroidal particles, they will no longer pose a significant hazard to the Earth. However, it has been suggested that comets can evolve to dormant, asteroidal objects due to the build-up of non-volatile lag deposits on their surfaces (Brin and Mendis, 1979; Fanale and Salvail, 1984; Weissman et al., 1989). Levison and Duncan (1 994) estimate that SP comets are active for only ~10% of their dynamical lifetimes in the planetary region; the remainder of the time they are likely dormant, asteroidal objects. These 'dead' or 'extinct' comets will continue to orbit the Sun and pose a hazard to the Earth. Up to 500/o of the near-Earth asteroids are estimated to be extinct cometary nuclei (Wetherill, 1 991).

At present there is no clear estimate of the proportion of comets arriving at each of these two physical end-states. However, this is a less important concern for the LP comets because they are dynamically removed on a relatively rapid time scale, before they can physically evolve to dormant objects.

Nongravitational forces from jetting of volatiles can also perturb the orbits of the LP comets, in particular if they have perihelia < 0.5 AU. However, Weissman (1979a, b) showed that nongravitational forces likely do not play a systematic role in the long-term dynamical evolution of the LP comet orbits. Weissman did propose that nongravitational forces could provide an explanation for the unusually small semimajor axes of the Kreutz group of sun-grazing comets.

Nongravitational forces also make it difficult to predict accurately the return of LP comets and to estimate their precise paths through the planetary region. This uncertainty adds to the dilemma posed by the LP comets for the impact hazard problem, because of the difficulty in predicting the difference between a near-miss and a potential impact, and the difficulty in intercepting the comet with a destructive device.

Temporal Variations

Current estimates of the flux of long-period comets crossing the Earth's orbit are based on the observed flux over the last 200 years, a relatively short time interval as compared with the orbital periods of the comets or the dynamical timescales for gravitationally perturbing the Oort cloud. Thus, it is worth considering how the cometary flux may vary with time, and whether the current flux is indeed typical, or possibly perturbed.

Hills (1981) suggested that stars passing through the Oort cloud could initiate showers of comets into the planetary region, particularly if the Oort cloud had a dense inner core of comets, the inner Oort cloud. The effect of the star passage is to perturb so many comets in perihelia that the comets fill the 'loss cone,' the region in velocity phase space where the comet orbits have perihelia in the planetary region.]n effect, the inner planetary region is flooded with comets. The perihelion distribution becomes uniform with heliocentric distance, and the number of comets at any perihelion distance is given by (Hills, 1981)

$$f = 2q/a\,(1 - q/2a) \approx 2q/a \qquad \text{for } q \ll a\ , \qquad (1)$$

where f is the fraction of the comet population with semimajor axis, a, that has perihelion distance < q, and q is the perihelion distance. Given an outer Oort cloud population of 10'? comets (Weissman, 1991) and a typical semimajor axis of 2.2 x 104 AU (Marsden et al., 1978), Equation 1 predicts a uniform perihelion distribution in the planetary region of 28 dynamically new comets per AU per year. This is 14 times the current estimated flux of dynamically new comets (see section 2).

If the star passage severely perturbs the inner Oort cloud, assuming a population of 5 x 10^{12} comets and a typical semimajor axis of 3×10^3 AU, the density of perihelia predicted by Equation 1 is 3.3 x 10^9 AU^{-1}. Because that semimajor axis corresponds to an orbital period of ~1.6 x 105 years, the flux versus time is ~2.0 x 104 $AU^{-1}yr^{-1}$, about 700 times the value obtained above for perturbing only the outer Oort cloud. However, Weissman (1990) showed that even a close penetrating stellar passage is typically not sufficient to fill the loss cone for inner Oort cloud comets, and the peak increase in the LP comet flux at the Earth's orbit would be by a factor of ~300.

Hut et al. (1987) and Fernández and Ip (1 987) modeled the dynamical evolution of cometary showers. The most intense showers would be caused by stars penetrating the Oort cloud to ~3×10^3 AU, which would only be expected to occur about once every 5 x 108 years. More modest showers might occur from star passages at 104 AU, which would occur on average every 5 x 107 years. The relative number of shower comets passing per helion and the number of surviving comets versus time for a major shower is shown in Figure 5 from Hut et al. (1987). The excess comets in the shower are dynamically removed due to planetary perturbations in about 2 to 3×10^6 years.

Weissman (1990) estimated that cometary showers raised the total integrated flux at the Earth's orbit by about a factor of three over the history of the solar system, assuming that the solar system is currently not in a cometary shower. Fernández (1994) suggested that the fact that the signature of the galactic tide is observable in the distribution of long-period comet orbits is evidence that the solar system is currently not experiencing a cometary shower (the signature is a deficit of dynamically new LP comets with aphelion directions towards galactic latitudes of 0° and ±90°, as pointed out by Delsemme and Patmiou, 1986). Weissman (1993) reached the same conclusion based on the $1/a_0$ distribution for the LP comets, which shows no evidence of a recent stellar perturbation of the inner Oort cloud.

Heisler (1990) simulated the dynamical evolution of comets in the Oort cloud using a Monte Carlo model which included both random stellar perturbations and the galactic tide, modeling the flux of comets into the planetary region versus time. An example is shown in Figure 6 which gives the relative number of dynamically new comets passing within 2 AU of the Sun versus time. The large spikes in the flux are the result of close stellar passages: the largest spike is for a star passing at only 7,200 AU from the Sun. The small scale variations in the steady-state flux of comets in Figure 6 are most likely due to the statistics of the Monte Carlo model, and probably do not reflect real variations in the comet flux.

A second mechanism for varying the cometary flux from the Oort cloud was investigated by Matese et al. (1995). They estimated a factor of four variation in the cometary flux due to the solar system's harmonic motion above and below the galactic plane, which currently carries the planetary system ~75-85 parsecs out of the galactic plain. As the solar system moves into less dense regions of the galactic disk above and below the central plane, it experiences a smaller galactic tidal force, resulting in fewer comets being perturbed into the planetary region. This sinusoidal variation has a period of ~64 68 Myr (Bahcall and Bahcall, 1985).

Matese et al.'s dynamical mode] did not include stellar perturbations. It is possible that stellar perturbations act to mitigate the variation in the galactic tidal perturbations, though they actual l y may accentuate the variation due to the similar] y varying space density of stars above and below the galactic plane. At present the solar system has just passed through the galactic plane in the last few million years, so the current steady-state flux is likely at a local maximum. '1 'his then suggests that the current steady-state LP comet flux is t wice the long-term average flux.

An alleged periodicity in the times of biological extinction events on the Earth (Raup and Sepkoski, 1984; Sepkoski, 1990) led researchers to suggest several hypotheses to produce periodic perturbations on the Oort cloud, in order to initiate periodic cometary showers into the planetary region. These include: 1) an unseen, dwarf companion star to the Sun passing through the Oort cloud (Whitmire and Jackson, 1984; Davis et al., 1984), 2) the Sun's harmonic motion above and below the galactic plane (Schwartz and James, 1984; Rampino and Stothers, 1984), and 3) a 10th planet in a precessing orbit beyond Neptune (Whitmire and Matese, 1985). 'J'here arc substantial dynamical problems with all of these hypotheses and many of the.ir implications arc clearly not borne out. If periodic extinctions arc real, the physical mechanism for invoking them has not yet been identified. The reader is referred to Tremaine (1986) and Weissman (1 986, 1991) for more detailed discussions of these issues.

Terrestrial Impact Probabilities and Fluxes

The potential hazard posed by the impact of comets on the Earth was first pointed out by Halley (1705) in his classic paper on comets that included the first catalog of 24 cometary orbits. Writing about a comet which had passed near the Earth's orbit a short distance ahead of the Earth in its motion, Halley speculated,

> *"But what might be the consequences of so near an appulse; or of a contact; or lastly, of a shock of the celestial bodies, (which is by no mean impossible to come to pass) I leave to be discussed by the studious of physical matters."*

It is a tribute to Halley's genius that he foresaw the attention today focussed on the threat of comet and asteroid impacts on the Earth. Halley also suggested that the comets in his catalog, for which he could only derive parabolic orbits, were likely members of the solar system and revolving in very long-period ellipses around the Sun. Of course, Halley's 1705 paper is best remembered for his recognition that the similar orbits for the comets of 1531, 1607, and 1682 were one and the same comet returning at periodic intervals, now known as Comet Halley.

The probability that any long-period comet will impact the Earth can be calculated as a function of the comet's orbital elements using equations derived by Öpik (1951, 1976). The probability of impact, p, per perihelion passage is given by

$$p = s^2 U / \pi \sin i \, |U_x| \qquad (2)$$

where s is the capture radius of the target planet, U is the hyperbolic encounter velocity of the comet relative to the planet (in units of the planet's circular orbital velocity about the Sun), i is the inclination of the comet's orbit to the plane of the planet's orbit, and U_x is the component of the hyperbolic encounter velocity in the radial (i. e., heliocentric) direction. The parameters U, U_x, and s are given by

$$U = [\, 3 - 1/a - 2\sqrt{a(1 - e^2)} \cos i \,]^{1/2} \qquad (3)$$

$$U_x = [\, 2 - 1/a - a(1 - e^2) \,]^{1/2} \qquad (4)$$

$$s = (R/a_o)(1 -1 v_e^2/U^2)“2 \qquad (5)$$

where a, c, and i arc respectively the semimajor axis (in units of the target planet's semimajor axis, a_o), eccentricity, and inclination of the comet's orbit, and R, a_o, and v_e arc the radius, semimajor axis, and escape velocity of the target planet. Equation 5 includes the effect of gravitational focussing by the target planet to "pull" comets onto collision paths. Note that in the case of a comet in a near-parabolic orbit, i.e., a long-period comet with eccentricity close to 1, the quantity $a(1-c^*) = a(1-c)(1+c) \approx 2q$, where q is the comet's perihelion distance.

Öpik's equations assume that the target planet is in a circular orbit, a reasonable assumption for the Earth whose orbital eccentricity is only 0.0167. They also assume that the planet itself is spherical. in addition, the perihelion distance of the comet must be less than or equal to the planet's semimajor axis.

A weakness in Öpik's equations is that the impact probability goes to infinity as the inclination of the comet's orbit approaches 0° or 180°, or as the perihelion distance of the comet approaches the semimajor axis of the planet, i.e, as q -> 1 AU for the Earth. Additionally, Öpik's equations do not allow for the eccentricity of the orbit of the target planet. More accurate (though also more complex) methods for calculating impact probabilities were devised by Wetherill (1 967) and Kessler(1981) involving the volumes swept out by the planet and the comet in their orbits. However, Öpik's equations perform satisfactorily so long as grazing orbits, 0.98 < q < 1 AU, and orbits close to the ecliptic, i < 1') and i > 179° arc excluded.

Long-period comet impact probabilities on the Earth have been calculated by a number of researchers. Weissman (1 982) found a mean impact probability of 2.2 x 10-9 pcr cometary perihelion passage, using Öpik's equations to average 2.5 x 105 random cometary orbits, uniformly distributed in perihelion distance between 0.00S (the radius of the Sun) and 0.99 AU.

Marsden and Steel (1995) used Kessler's method to find a similar mean impact probability of 2.21 x 10-9. Zimbelman (1984) found values of 1.33×10^{-9} and 1.48 x 10“9 using analytic and numerical approximations to Öpik's equations. An examination of Zimbelman's calculations (Steel, 1993) showed that he erred and somehow lost a factor of n/2 (the mean value of sin i evaluated from O to 1800), which would then bring his estimates into general agreement with those above.

Shoemaker (1984) found a higher impact probability of 3.3 x 10'9 by averaging encounter probabilities for the observed Earth-crossing LP comets. However, the observed LP comets are a biased sample, and the same factors which lead to an increased discovery probabil it y also I cad to an increase in the impact probabi 1 ity for LP comets. The observed sample is biased towards comets with perihelia near the Earth's orbit and inclinations c1osc to the ecliptic plane, and the resulting mean impact probability is substantially higher than the true average. Similar results for 411 observed LP comets were found by Marsden and Steel (1 995), shown in Figure 7.

The mean hyperbolic encounter velocity for the LP comets is 50.5 km sec^{-1}, and the man impact velocity (considering the Earth's escape velocity of 11.2 km sec^{-1}) is 51.8 km sec^{-1} (Weissman, 1982). However, the most relevant parameter for the impact hazard is the energy of the impactor, proportional to its impact velocity squared. Onc can also weight the impact energy by the probability of an impact by a comet on that particular orbit. Doing so yields a representative impact velocity of 56.4 km scc-' for the most probable LP comet impactor energy on the Earth. These values all assume a uniform perihelion distribution and randomly inclined cometary orbits.

As noted in Section 2, the perihelion distribution of the LP comets is likely not uniform interior to 1 All. Weissman (1985) showed that the perihelion distribution of the LP comets rises sharply throughout the planetary region because Jupiter and Saturn act as a dynamical barrier to the diffusion of LP comets into the inner planets region. If one assumes the perihelion distribution found by Everhart (1967b), shown in Figure 1, then the mean impact probability rises to ?.4 x 10^{-9} and the most probable impact energy corresponds to a velocity of 56.7 km s^{-1}. Using a perihelion distribution that varied as $q^{1/2}$ (Fernández, 1981), Marsden and Steel (1995) found a mean impact probability of 2.5 x 10^{-9}.

The variation of impact probability and impact velocity versus perihelion distance and orbital inclination is shown in Figure 8 (from Marsden and Steel, 1995). It can be seen that the impact probability increases as the comet's perihelion distance approaches 1 AU, and as the plane of the comet's orbit approaches the ecliptic. impact velocity increases with increasing orbital inclination. Also, note that impact probabilities are generally slightly higher for retrograde orbits versus direct orbits. It is this correlation between impact probability and impact velocity which leads to the most probable impactor velocity being somewhat higher than the mean impact velocity.

A more difficult problem is that of estimating the actual impactor flux and crater production rate by LP comets on the Earth. This is because of the very poor present knowledge of the size and mass distributions of the LP comets. Cometary nuclei are difficult to observe directly since when they are close to the Sun they are enveloped in bright dust and gas comae, whereas when they are inactive they are usually too far from the Sun to be easily observed. Also, it is not always clear when nuclei are inactive as comae can be unresolved at the large distances involved. Unresolved comae can still contribute to both the visual and thermal radiation from the comets, making accurate determinations of nucleus dimensions and albedos quite difficult.

Nevertheless, several researchers have attempted to derive the size distribution of cometary nuclei. One example by Weissman (1990) is shown in Figure 9. Weissman used the observed distribution of LP comet absolute magnitudes, H_{10}, corrected for observational selection effects, as found by Everhart (1967b). By comparing, the H_{10} values for specific comets with observations of their nuclei at large heliocentric distances when they were presumably inactive, Weissman obtained the relationship

$$\log M = 20.0 - 0.4\, H_{10} \tag{6}$$

where M is the nucleus mass in grams and a density of 0.6 g cm^{-3} was assumed. Using the magnitude distribution in Figure 9, the average cometary nucleus brighter than $H_{10} = 11$ has a mass of 3.8×10^{16} g. Bailey and Stagg (1988) derived a similar mass-magnitude relationship

$$\log M = 19.9 - 0.5\, H_{10} \tag{7}$$

though with a steeper slope such that mass decreases more sharply with increasing absolute magnitude. The cometary size distribution has also been estimated by Shoemaker and Wolfe (1982).

The size distribution in Figure 9 is known as a broken power law distribution, where the number of comets in any logarithmically spaced size bin can be expressed as a power of the mass or radius of the cometary nuclei, and the size distribution is broken into two ranges with different characteristic exponents, A broken power law size distribution was recently suggested for Kuiper belt comets (comets in a ring beyond the orbit of Neptune) by Weissman and Levison (1996). It has also been suggested by models of the accretion of planetesimals in the early solar system by Greenberg et al. (1984) and Wetherill and Stewart (1993).

Weissman (1982, 1990) used Shoemaker's (1977) crater-energy scaling relationship to estimate crater sizes on the Earth for LP comets hitting at the most probable impact energy representative velocity of 56.4 km sec^{-1}. He showed that a comet with a mass of 1.9 x 1013 g was required to form a crater 10 km in diameter. Such a comet would have a radius of 0.20 km, assuming a bulk density of 0.6 g cm^{-3}. Using the crater scaling relationship of Melosh (1989) one finds a similar mass, 2.1 x 10^{13} g, required for a LP comet to form a 10 km crater on the Earth. Using the mass-magnitude relationship in Equation 6, Weissman (1 990) showed that the mass of 1.9 x 1013 g corresponded to an absolute magnitude of 11,0 = 16.8. By then using the size distribution shown in Figure 9 and the estimate from Everhart's work of ~10 Earth-crossing LP comets per year brighter than 11,0 = 11, Weissman found that there were -415 LP comets per year which could create 10 km craters if they impacted the Earth. Combining this with the mean impact probability from assuming Everhart's perihelion distribution in Figure 1, one finds that a LP comet creates a 10 km diameter or larger crater on the Earth, on average, once every 1.0 x 10^{6} years. in terms of the surface area of the Earth, this works out to a cratering rate of 0.20 x 10^{-14} km^{-2} yr^{-1}. For comparison, Shoemaker et al. (1990) found a mean impact interval for Earth-crossing asteroids creating 10 km or larger craters of 1.1 x 105 years, or a rate of 1.8 x 10-14 km^{-2} yr^{-1}. Thus, LP comets constitute ~1 O% of the present cratering flux on the Earth.

As noted in the previous section, approximately two-thirds of all LP comets passing through the inner planets region arrive as part of cometary showers. Thus, the long-term integrated cratering rate from LP comets is ~3 times the value found above, equal to 0.59 x 10"'4 km^{-2} yr^{-1}, or one impact every 3.3 x 10^{5} years, on average. Since we are not currently in a cometary shower (Weissman, 1993; Fernández, 1994), and the onset time for a cometary shower is on the order of 10^{5} years, the appropriate value to use in evaluating the current impact hazard is that found above for the steady-state flux of one impact every 106 years.

Shoemaker et al. (1990) find a somewhat higher impact frequency of a LP comet creating a 10 km diameter crater every 3.6×10^5 years, or a cratering rate of 0.55 x 10“’4 km^{-2} yr^{-1}. Unfortunately, Shoemaker et al. (1 990) do not explain all the steps in their calculation so it is not possible to determine why their result is different from Weissman's above. However, Shoemaker et al. also noted that the relative] y modest sized comets required to form 10 km craters would probably not survive atmospheric entry intact. Modeling of atmospheric entry for asteroidal and cometary objects by Chyba et al. (1993) showed that at the sizes necessary to match the characteristics of the 1908 Tunguska event, cometary nuclei would explode at altitudes of 20 40 km, which would result in relatively little effect at ground level.

1'. Thomas (personal communication) has estimated that a cometary nucleus with a diameter of about 350 meters is required for the object to reach the Earth's surface before exploding. This is only slightly smaller than the size estimated above to form a 10 km crater. ']'bus, comets of this dimension may burst just above or at the surface of the Earth, creating either a modest or indistinct crater, as has been observed for many crater-like structures on Venus (see for example, Herrick and Phillips, 1994). Onc possibility illustrated by the Venus data is that the comet may disrupt into several large fragments during atmospheric entry and form multiple, overlapping craters.

Olsson-Steel (1967) found that LP comets accounted for 6% of impacts forming craters with diameters ≥ 10 km on the Earth, which suggests a mean impact interval of 2.2×10^6 years. Again, the details of Olsson-Steel's calculation arc not completely explained in his paper so it is difficult to assess why his results arc different from those above. Marsden (1993) estimated that LP comets constitute only 2°/0 of the Earth impactor flux by number, based on the statistics of observed close approaches by comets to the Earth. This implies an impact interval of -5 x 10^6 years. Marsden did not consider observational selection effects which may have prevented the discovery of some close approaching comets, or the possibility that the flux includes small LP comets too faint to detect, but still sufficiently large enough to form 10 km craters. Both these factors contribute to the lower impact frequency found by Marsden. Also, note that Marsden stated his estimate in terms of the number of impactors, and did not normalize for the much higher impact velocities of the LP comets.

A potential weakness in all of these crater rate estimates (except Marsden's) involves the extrapolation of the cometary size distribution down to the relatively small, faint nuclei required to form 10 km craters on the Earth. Comets with that mass, $M \approx 2 \times 10^{13}$ g, are approximately two orders of magnitude smaller than the faintest LP comets currently observed (if we can believe the size distributions in Equations 6 or 7). Some researchers have proposed that there are lower limits to the sizes of cometary nuclei (e.g., Sekanina and Yeomans, 1984), but it is difficult to identify whether the failure to observe such objects is real or only an observational selection effect.

One can also estimate the minimum mass LP comet that might cause a global climatic disturbance. Morrison et al. (1995) find the most likely threshold energy for such an event is 3 x 10$ megatons, or 1.3×10^{28} ergs. For a LP comet impacting at the most probable impact velocity of 56.4 km sec^{-1}, this corresponds to a mass of 8 x 10’4 g, or a radius of -0.7 km. Using the size distribution in Figure 9, such a comet would have an absolute magnitude of 12.7, The Earth-crossing flux would be -26 such comets per year and the mean impact interval would be --1.6 x 107 years.

In summary, the current mean impact rate of LP comets sufficiently massive to create 10 km or larger craters on the Earth is estimated to be between 5 x 10-7 and 2.8×10^{-6} per year, with a most likely value of $\sim 1.0 \times 10^{-6}$ per year. The most probable impact energy corresponds 10 velocities of 56 58 km sec^{-1}.

Discussion

The long-period comets pose a unique dilemma for the impact hazard problem. Because of their very long orbital periods and large distances from the Sun (most of the time) they cannot be surveyed and catalogued in the same manner as the near-Earth asteroids and short-period comets. Even with current astrometric capabilities, returns of comets with periods greater than 200 years cannot be predicted with the accuracy necessary to know whether a comet will pose a significant threat to the Earth. At it's mean orbital velocity of 29.78 km sec^{-1}, the Earth moves through its own diameter in only 7.1 minutes, so the difference between a very close approach and an impact event is truly very small.

A long-period comet approaching the inner planets region will move from Jupiter's orbit to 1 AU in a time interval of just under 1 year. In general, LP comets are relatively inactive at the distance of Jupiter's orbit, unless they are dynamically new comets making their first passage through the planetary system. The problem is one of detecting small, low albedo objects at 5 AU or more. A 1 km radius nucleus with an albedo of 0.04, viewed at opposition (0° phase), would have an R magnitude of $m_R = 23.7$ at 5 AU from the Sun. This is just within the capabilities of current CCD cameras on large aperture ground-based telescopes. An additional problem with regard to the LP comets is the fact that their orbits are randomly oriented on the sky, as opposed to the near-ecliptic inclinations of most near-Earth asteroids. Thus, the entire sky must be surveyed continuously in order to detect approaching LP comets at the earliest possible moment.

The problem of searching for LP comets is discussed in more detail in Marsden and Steel (1995). They estimate that LP comets on impact trajectories would pass opposition ~250 500 days prior to Earth encounter for prc-perihelion impacts (ignoring comets which reach opposition < '?5 days before impact), and -100-425 days for post-perihelion impacts. 'J'bus, possible warning times would range from a little over 3 months to approximately 16 months. Marsden and Steel also emphasize the need to search al 1 ec iptic latitudes in order not to miss any LP comets.

Since no such deep searches for LP comets a 'e currently underway, actual warning times found from current discoveries are typically much smaller. (holy 12!40 of all LP comets were discovered more than 100 days prior to perihelion (Marsden and Steel, 1995), though that number is improving as photographic and CCD discoveries pla y a larger and larger role. Some Earth-approaching LP comets have had remarkably short warning times. 'The recent bright, naked-eye comet Hyakutake, C/1996 B2, was found 8 weeks prior to closest approach, and made a close approach to the Earth of only 0.102 AU. Comet IRAS-Araki-Alcock, C/1983 H1, was discovered only 15 days prior to a close approach to within 0.031 AU from the Earth. This diffuse cornet was di scovered by the IRAS spacecraft but was not reported to the Central Bureau for Astronomical Telegrams until a week later, when it was independently discovered by two ground-based observers, only 8 days before closest approach ! The nucleus of comet IRAS-Araki-Alcock was estimated to have a radius of -4 km (Hanner et al., 1985) so it would have likely resulted in a major global catastrophe if it had struck the Earth.

In contrast, the recent bright LP comet Hale-Bopp, C/1995 01, which is on an Earth-crossing orbit, was found more than 20 months before perihelion at a heliocentric distance of 7.15 AU. Although the large estimated radius for this nucleus, 10 20 km, makes it a major potential hazard, its closest approach distance to the Earth will be 1.32 AU, quite far away.

The long-period comets will continue to present a difficult problem for those concerned about the possibility of a major cometary impact on the Earth. Warning and response times will, in general, remain much shorter than for other potential impactors. Current technologies arc insuffi cient to permit early detection, say at the edge of the planetary system, 30 AU, where the infall time is -12 years. On the other hand, the mean interval of 10^6 years between significant impacts, and the 16 x 10^6 years mean interval between potential 1 y catastrophic 1.1' comet impacts, makes the likelihood of an impact quite low in the next century. During that time, routine improvements in sevel al different technologies may make this problem trivial to solve.

Acknowledgement: The author thanks Brian Marsden and Alan Harris for useful discussions during the course of this work. Brian Marsden also provided a very helpful review of an car] icr draft of this paper. The author thanks John Remo for his encouragement and his patience. This work was supported by the NASA Planetary Geology and Geophysics Program. The research reported herein was performed at the Jet Propulsion Laboratory, under contract with the National Aeronautics and Space Administration.

References

Bahcall, J. N., and Bahcall, S. 1985. The Sun's motion perpendicular to the galactic plane. *Nature* 316, 706-708.

Bailey, M. A., and Stagg, C. R. 1988. Cratering constraints on the inner Oort cloud and implications for cometary origins. *Mon. Not. Roy. Astron. Sot.* 23S, 1-32.

Biermann, L., Huebner, W. F., and Lüst, Rh. 1983. Aphelion clustering of "new" comets: Star tracks through the Oort cloud. *Proc. Natl. Acad. Sci. USA* **80**, 5151-5155.

Bogart, R. S., and Noerdlinger, P. D. 1982. On the distribution of orbits among long-period comets. *Astron. J.* **87**, 911-917.

Brin, G. D., and D. A. Mendis 1979. Dust release and mantle development in comets. Astrophys. J. **229**:402-408.

Byl, J. 1983. Galactic perturbations on nearly parabolic cometary orbits. *Moon & Planets* 29, 121-137.

Chyba, C. F., Thomas, P. J., and Zahnle, K. J. 1993. The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid. *Nature* 361, 41-44.

Davis, M., Hut, P., and Muller, R. A. 1984. Extinction of species by periodic comet showers. *Nature 308, 71s-717.*

Delsemme, A. H., and Patmiou, M. 1986. Galactic tides affect the Oort cloud: An observational confirmation. In *20th ESLAB Symposium on the Exploration of Halley's Comet*, eds. B. Battrick, E. J. Rolfe, and R. Reinhard, ESA SP-250, 2, 409-412.

Duncan, M., Quinn, "J'., and Tremaine, S. 1987. The formation and extent of the solar system comet cloud. *Astron. J. 94.* 1330-1338.

Everhart, E. 1967a. Comet discoveries and observational selection. *Astron. J. 72,* 716-726.

Everhart, E. 1967b. intrinsic distributions of cometary perihelia and magnitudes. *Astron. J.* 72:1002-1011.

Fanale, F. P., and J. R. Salvail 1984. An idealized short-period comet model: surface insolation, H_2O flux, dust flux, and mantle evolution. *Icarus* 60:476-51 I.

Fernández, J. A. 1980. Evolution of comet orbits under the perturbing influence of the giant planets and stars. *Icarus* 42.406-421.

Fernández, J. A. 1981. New and evolved comets in the solar system. *Astron. Astrophys.* 96, 26-35.

Fernández, J. A. 1982. Dynamical aspects of the origin of comets. *Astron. J.* 87, 1318-1332.

Fernández, J. A. 1994. Dynamics of comets: Recent developments and new challenges. in *Asteroids, Comets, Meteors 1993*, eds A. Milani, M. Di Martino, and A. Cellino, (Dordrecht: Kluwer), pp. 223-240.

Fernández, J. A., and Ip, W.-}]. 1987. Time dependent injection of Oort cloud comets into Earth-crossing orbits. *Icarus* **71**, *46-56.*

Greenberg, R., Weidenschilling, S. J., Chapman, C. R., and Davis, 1). R. 1984. From icy planetesimals to planets: Numerical simulations of collisional evolution. *Icarus* S9, 87-113.

Hanner, M., Aitken, D. K., Knacke, R., McCorkle, S., Roche, P. F., and Tokunaga, A. '1'. 1985. Infrared spectrophotometry of comet IRAS-Araki-Alcock (1983d): A bare nucleus revealed? *Icarus* 62, 97-109.

Halley, E. 1705. *A Synopsis of the Astronomy of Comets.* London, 24 pp.

Hasegawa, I. 1980. Catalogue of ancient and naked-eye comets. *Vistas in Astron. 24, 59-102.*

Heisler, J. 1990. Monte Carlo simulations of the Oort cometary cloud. *Icarus* **88**, 104-121.

Heisler, J., and Tremaine, S. 1986. The influence of the galactic tidal field on the Oort comet cloud. *Icarus* 6S, 13-2.6.

Herrick, R. R., and Phillips, R, J. 1994. implications of a global survey of venusian impact craters. *Icarus* 111,387-416.

Hills, J. G. 1981. Comet showers and the steady-state infall of comets from the Oort cloud. *Astron. J.* **86,** 1730-1740.

Hut, 1'., and Tremaine, S. 1985. Have interstellar clouds disrupted the Oort comet cloud? *Astron. J.* 90, 1548-1557.

Hut, P., Alvarez, W., Elder, W. P., Hansen, '1'., Kauffman, E. G., Keller, (i., Shoemaker, E. M., and Weissman, 1'. R. 1987. Comet showers as possible causes of stepwise mass extinctions. *Nature* 329, 118-126.

Johnson, R. E., J. F. Cooper, 1,. J. Lanzerotti, and G. Strazzula 1987. Radiation formation of a non-volatile comet crust. *Astron. Astrophys.* **187**:889-892.

Kessler, D. J. 1981. Derivation of the collision probability between orbiting objects: The lifetimes of Jupiter's outer moons. *Icarus* 48, 39-48.

Kresák, L. 1992. The peculiar orbit of comet 19761 Sate. *Astron. Astrophys.* 2S9, 692-695.

Kuiper, G. P. 1951. On the origin of the solar system. In *Astrophysics*, ccl. J. A. Hynek (New York: McGraw Hill), pp. 357-424.

Levison, 11. 1:., and Duncan, M. J. 1994. The long-term dynamical behavior of short-period comets. *Icarus* **108**, 18-36.

Marsden, B. G. 967. The sun-grazing comet group. *Astron. J.* 72, 1170-1183.

Marsden, B. G. 989. The Sun-grazing comet group. 11. *Astron. J.* 98, 2306-232

Marsden, B. G. 1993. To hit or not to hit. In *Near-Earth Objects Interception Workshop,* eds. G. H. Canavan, J. C. Solem, and J. 1). G. Rather (Los Alamos: Los Alamos National laboratory), pp. 67-71.

Marsden, B. G., and Roemer, E. 1982. Basic information and references. In Comets, ed. 1,. L. Wilkening (Tucson: Univ. Arizona Press), pp. 707-733.

Marsden, B. G., and Sekanina, 2,.1973. On the distribution of "original" orbits of comets of large perihelion distance. *Astron.* ,1.78, 1118-1124.

Marsden, B. G., Sekanina, Z., and Yeomans, D. K. 1973. Comets and nongravitational forces. V. *Astron. J.* **78**, 211-225.

Marsden, B. G., Sekanina, Z., and Everhart, E. 1978. New osculating orbits for 110 comets and the analysis of the original orbits of 200 comets. *Astron J.* 83, 64-71.

Marsden, B. G., and Steel, D. I. 1995. Warning times and impact probabilities for long-period comets. In *Hazards Due to Comets and Asteroids*, ed. T. Gehrels (Tucson: Univ. Arizona Press), pp. 221-239.

Marsden, B. G., and Williams, G. V. 1996. *Catalogue of Cometary Orbits*. 11th Edition (Cambridge: Smithsonian Astrophysical observatory), 110 pp.

Matese, J. J., Whitman, P. G., Innanen, K. A., and Valtonen, M. J. 1995. Periodic modulation of the Oort cloud comet flux by the adiabatically changing galactic tide. *Icarus* 116, 255-268.

Melosh, H. J. 1989. *Impact Cratering: A Geologic Process* (New York Oxford Univ. Press), 284 pp.

Morrison, D., Chapman, C. R., and Slovic, P. 1995. The impact hazard. In *Hazards Due to Comets and Asteroids,* ed. T. Gehrels (Tucson: Univ. Arizona Press), pp. 59-91.

Mumma, M. J., Stern, S. A., and Weissman, P. R. 1993. Comets and the origin of the solar system. in *Planets* and *Protostars 11),* eds. E. H. Levy and J. I. Lunine (Tucson: Univ. Arizona Press), pp. 1177-1252.

Neslušan, L. 1996. Perihelion point preferred direction of long-period comets and the north-south asymmetry of comet discoveries from the Earth's surface. *Astron. & Astrophys. 306, 981-990.*

olsson-Steel, D. 1987. Collisions in the solar system - IV. Cometary impacts upon the planets. *Mon. Not. Roy. Astr 0)?, Soc.* 227, 50] -524.

Oort, J. H. 1950. The structure of the cloud of comets surrounding the solar system and a hypothesis concerning its origin. *Bull. Astron. Inst. Neth.* 11, 91-110.

Öpik, E. J. 1951. Collisional probabilities with the planets and the distribution of interplanetary matter. *Proc.* Roy *Irish. A cad. A 54, 165-199.*

Öpik, E. J. 1976. *Interplanetary Encounters* (Amsterdam, Elsevier), 155 pp.

Prialnik, D., and Bar-Nun, A. 1987. On the evolution and activity of cometary nuclei. *Astrophys. J.* 313, 893-905.

Rampino, M. R., and Stothers, R. B. 1984. Terrestrial mass extinctions, cometary impacts, and the sun's motion perpendicular to the galactic plane. *Nature 308,* 709-712.

Raup, D. M., and Sepkoski, J. J. 1984. Periodicity of extinctions in the geologic past. *Proc. Natl. Acad. Sci. USA 81, 801-805.*

Safronov, V. S. 1969. *Evolut ion of the Protoplanetary Cloud and Formation of the Earth and Plan ets*, (Moscow: Nauka Press) (NASA TT-F-677, 1972).

Schwartz, R. D., and James, P. B. (1 984) Periodic mass extinctions and the Sun's oscillation about the galactic plane. *Nature* 308, 712-713.

Sekanina, Z. 1982. The problem of split comets in review. In *Comets*, *cd.* L. L. Wilkening (Tucson: Univ. Arizona Press), pp. 251-287.

Sekanina, Z., and Yeomans, D. K. 1984. Close encounters and collisions of comets with the Earth. *Astron.* .1, **89**, 154-161.

Sepkoski, J. J. 1990. The taxonomic structure of periodic extinction. I n *Global Catastrophes in Earth History*, eds. V. L. Sharpton and P. I). Ward, Geol. Sot. Amer. SP 247, pp. 33-44.

Shoemaker, E. M. 1977. Astronomically observable crater forming projectiles. In *impact and Explosion Cratering*, eds. D. J. Roddy, R. O. Pepin, and R. B. Merrill (New York: Pergamon) pp. 6 17-628

Shoemaker, E. M. 1984. Large body impacts through geologic time. in *Patterns of Change in Earth Evolution*, eds. H. D. Holland and A. F. Trendall (Berlin: Springer-Verlag), pp. 1 5-40.

Shoemaker, E. M., and Wolfe, R. F. 1982. Cratering time scales for the Galilean satellites. in *Satellites of Jupiter*, cd. D. Morrison (Tucson: Univ. Arizona Press), pp. 277-339.

Shoemaker, E. M., Wolfe, R. F., and Shoemaker, C. S. 1990. Asteroid and comet flux in the neighborhood of 1 Earth. 1 n *Global Catastrophe.v in Earth History*, eds. V. L. Sharpton and P. D. Ward, Geol. Sot. Amer. SP 247, pp. 155-170.

Shoemaker, E. M., Weissman, P. R., and Shoemaker, C. S. 1995. 't'he flux of periodic comets near Earth. in *Hazards Due to Comets and Asteroids*, cd. 'I'. Gehrels (Tucson: Univ. Arizona Press), pp. 313-335

Steel, D. I. 1993. Collisions in the solar system - V. Terrestrial impact probabilities for parabolic comets. *Mon.* Not. Roy. *Astron. Sot.* 264, 813-817.

Stephenson, F. R., Yau, K. K. C., and 1 lunger, 11. 1985. Records of Halley 's comet on Babylonian tablets. *Nature* **314**:587-592.

Stern, S. A. 1990. ISM induced erosion and gas dynamical drag in the Oort cloud. *Icarus* **84**, 447-466.

Tremaine, S. 1986. Is there evidence for a solar companion, 1 n *The Galaxy and* the *Solar System*, eds. R. Smoluchowski, J. N. Bahcall, and M. S. Matthews (Tucson: Univ. Arizona Press), pp. 409-416.

Tyror, J. G. 1957. The distribution of the directions of perihelia of long-period comets. *Mon. Not. Roy. Astron. Soc.* **11** 7, 370-379.

Weissman, 1'. R. 1979a. Physical and dynamical evolution of long-period comets. in *Dynamics of the Solar System*, cd. R . 1>. Duncombe (Dordrecht: D. Reidel), pp. 277-282.

Weissman, P. R. 1979b. Nongravitational perturbations of long-period comets. *Astron. J.* 84, 580-584.

Weissman, 1'. R. 980a, Stellar perturbations of the cometary cloud. *Nature 288, 242-243.*

Weissman, P. R. 980b. Physical loss of long-period comets. *Astron. Astrophys. 85:191-196.*

Weissman, P. R. 1982. Terrestrial impact rates for long and short-period comets. in *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, eds.],. T. Silver and I'. H. Schultz, Geol. Sot. Amer. SP 190, pp.] 5-24.

Weissman, 1'. R. 1985. Dynamical evolution of the Oort cloud. In *Dynamics of Comets: Their Origin and Evolution*, eds. A. Carusi and G. I). Valsecchi (Dordrecht, D. Reidel), pp. 87-96.

Weissman, 1'. R. 1986. The Oort cloud and the galaxy: Dynamical interactions. In *The Galaxy and the Solar System*, eds. R. Smoluchowski, J. N. Bahcall, and M. S. Matthews (Tucson: Univ. Arizona Press), pp. 204-237.

Weissman, 1'. R. 1990. The cometary impactor flux at the Earth. 1 n *Global Catastrophes in Earth History*, eds. V. L. Sharpton and 1'. I). Ward, Geol. Sot. Amer. S1' 247, pp. 171-180.

Weissman, I'. 1<. 1991. Dynamical history of the Oort cloud. in *Comets in the Post-Halley Era*, eds. R. L. Newburn Jr., M. Neugebauer, and J. Rahe (Dordrecht: Kluwer), 1, 63-486.

Weissman, P. R. 1993. No, we are not in a cometary shower. *Bull. Amer. Astron Sot.* 25, 1063 (abstract).

Weissman, 1'. R., A'Hearn, M. F., McFadden, L. A., and Rickman, H. 1989. Involution of comets into asteroids. in *Asteroids II*, eds. R. P. Binzel, T. Gehrels, and M. S. Matthews (Tucson: Univ. Arizona Press), pp. 880-920.

Weissman, P. R., and Campins, H. 1993. Short-period comets. In *Resources of Near-Earth Space*, eds. J. Lewis, M. S. Matthews and M. Guerrieri (Tucson: Univ. Arizona Press), pp. 569-617.

Weissman, P. R., and Levison, 11. F. 1996. The size distribution of cometary nuclei. *Lun. Planet. Sci. Conf. 27, 1409-]410* (abstract).

Wether ill, G. W. 1967. Collisions in the asteroid belt, *J. Geophys. Res.* 72, 2429-2444.

Wetherill, G. W. 1991. End products of cometary evolution: Cometary origin of Earth-crossing bodies of asteroidal appearance. In *Comets in the Post-Halley Era*, eds. R. L. Newburn, J. Rahe, and M. Neugebauer (Dordrecht: Kluwer), pp. 537-556.

Wetherill, G. W., and Stewart, G. R. 1993. Formation of planetary embryos: Effects of fragmentation, low relative velocity, and independent variation of eccentricity and inclination. *Icarus 106,* 190-209.

Whipple, F. L. 1978. Cometary brightness variation and nucleus structure. *Moon & Planets* 18, 343-359.

Whitmire, D. P., and Jackson, A. A. 1984. Are periodic mass extinctions driven by a distant solar companion? *Nature* 308, 713-71 S.

Whitmire, 1). 1'., and Matese, J. J. 1985. Periodic comet showers and planet X. *Nature* 313, 36-38.

Yau, K., Yeomans, D., and Weissman, 1'. 1994. The past and future motion of comet Swift-Tuttle. *Mon. Not. Roy. Astron. Soc.* 266, 305-316.

Yeomans, D. K., Yau, K., and Weissman, P. R. 1996. The impending approach of periodic. comet Tempel-Tuttle and the Leonid meteors. *Icarus*, in press.

Zimbelman, J. R. 1984. Planetary impact probabilities for long-period comets. *Icarus* 57, 48-54.

Figure Captions

Figure 1. The perihel ion distribution of long-period comets, corrected for observational selection effects, by Everhart (1967b). The distribution is not well determined for q > 1 All. However, Fernández (1981) and Weissman (1985) showed that the number of comets likel y continues to increase with increasing heliocentric distance.

Figure 2. The distribution of inverse original semimajor axis, $1/a_o$, for 291 long-period comets. Data from Marsden and Williams (1996). The tall spike at the left represents long-period cornets from the Oort cloud making their first perihelion passage through the planetary system.

Figure 3. Scatter diagram in perihelion distance and inverse original semimajor axis for the observed lmg-period comets. The horizontal band of comets at near-zero $1/a_o$ are comets making their first perihelion passage from the Oort cloud. Comets diffuse up and down in the diagram as a result of planetary perturbations, primarily by Jupiter. Data from Marsden and Williams (1996).

Figure 4. Hypothetical view of the Oort cloud of comets surrounding the solar system, based on the orbital energy distribution found by Duncan et al. (1987).

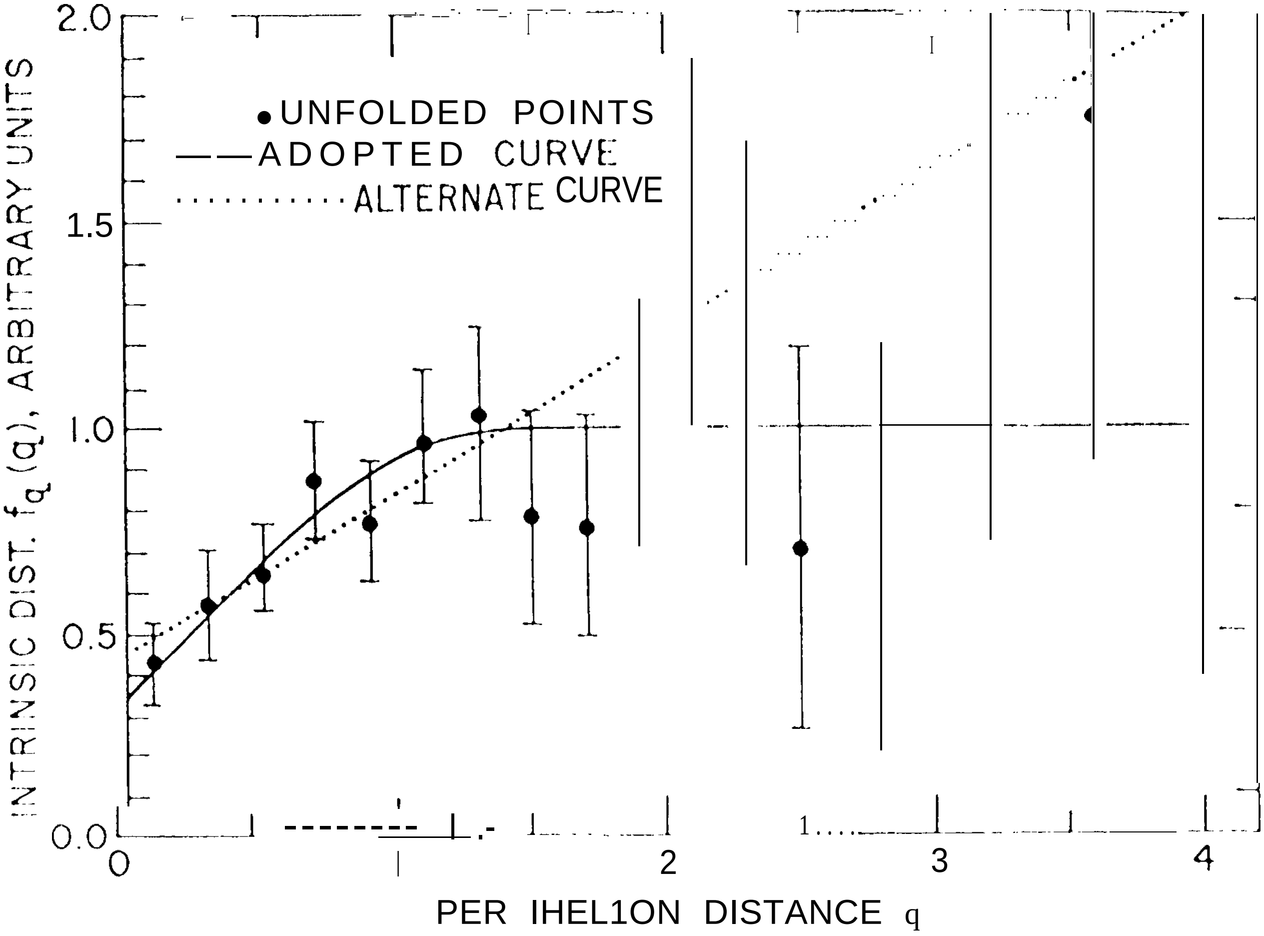
Figure 5. Dynamical evolution of the flux of comets through the planetary system during a major cometary shower, caused by a penetrating stellar passage through the inner Oort cloud. The solid histogram shows the relative number of comets passing perihelion versus time. The clashed curve gives the number of comets from the shower still dynamically evolving through the system. From 1 Iut et al. (1 987).

Figure 6. 1 lypothetical flux of dynamically ncw comets into orbits with perihelia < 2 AU as found by Heisler (1 990). The large spikes arc comet showers resulting from close stellar passages.

Figure 7. impact probability y on the Earth versus orbital inclination for 411 observed long-period comets. From Marsden and Steel (1995).

Figure 8. impact probability on the 1 Earth versus impact velocity for long-period comets in near- parabolic orbits, as a function of perihelion distance, q, and orbits] inclination, i. From Marsden and Steel (1995).

Figure 9. The mass distribution of the long-period comets as found by Weissman (1 990), using Everhart's (1 967b) distribution of the number of comets as a function of their absolute magnitudes, H_{10}, corrected for observational selection effects. The mass scale assumes a bulk density for the nuclei of 0.6 g cm^{-3}.



UNFOLDED POINTS
ADOPTED CURVE
ALTERNATE CURVE
INTRINSIC DIST. $f_q(q)$, ARBITRARY UNITS
PER IHEL1ON DISTANCE q
2.0
1.5
1.0
0.5
0.0
0
2
3
4

Figure 1.

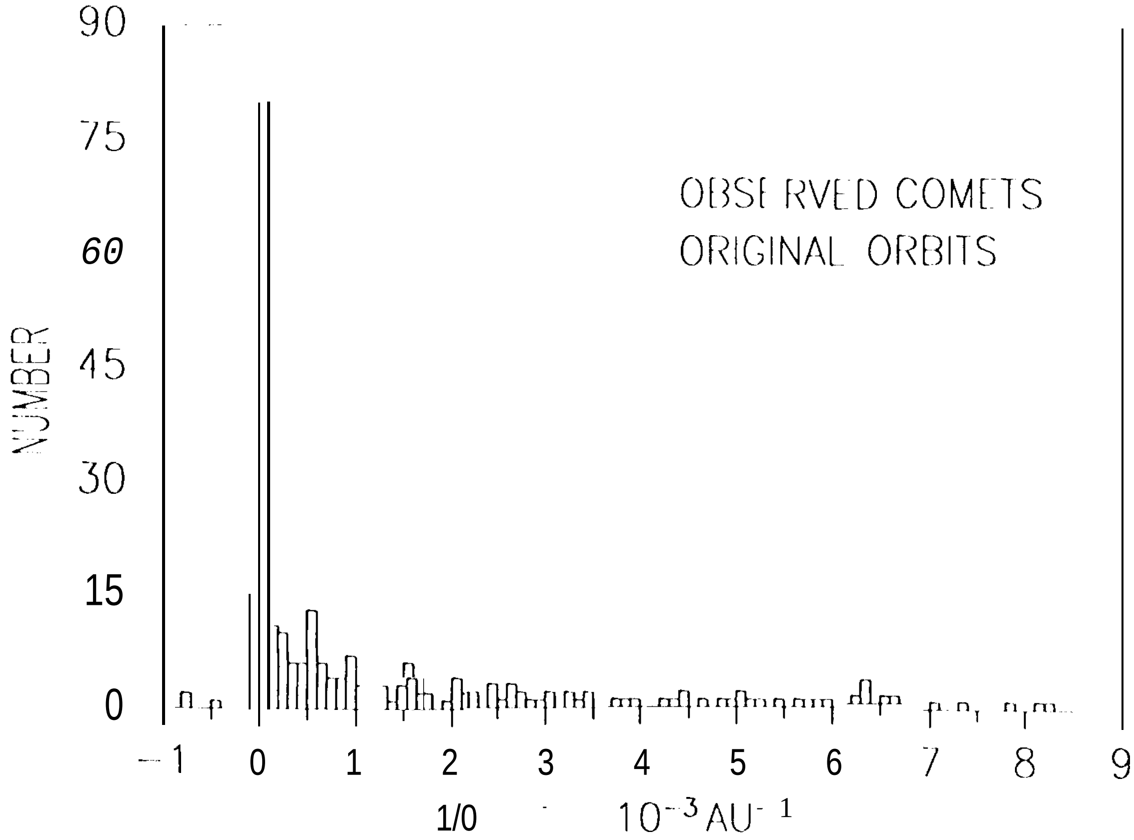

90
75
60
45
30
15
0
NUMBER
OBSERVED COMETS
ORIGINAL ORBITS
−1
0
1
2
3
4
5
6
7
8
9
1/a 10⁻³ AU⁻¹

Figure 2.

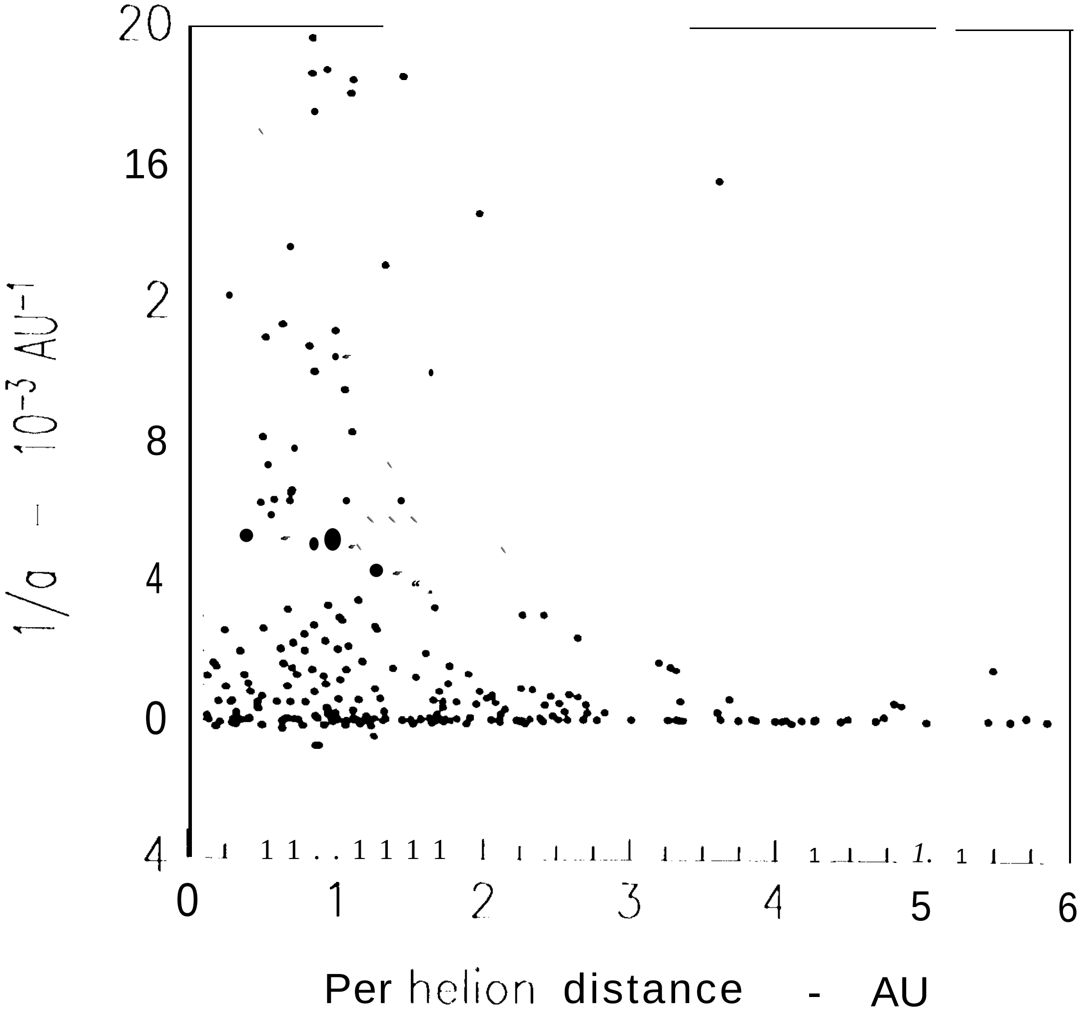


Figure 3.

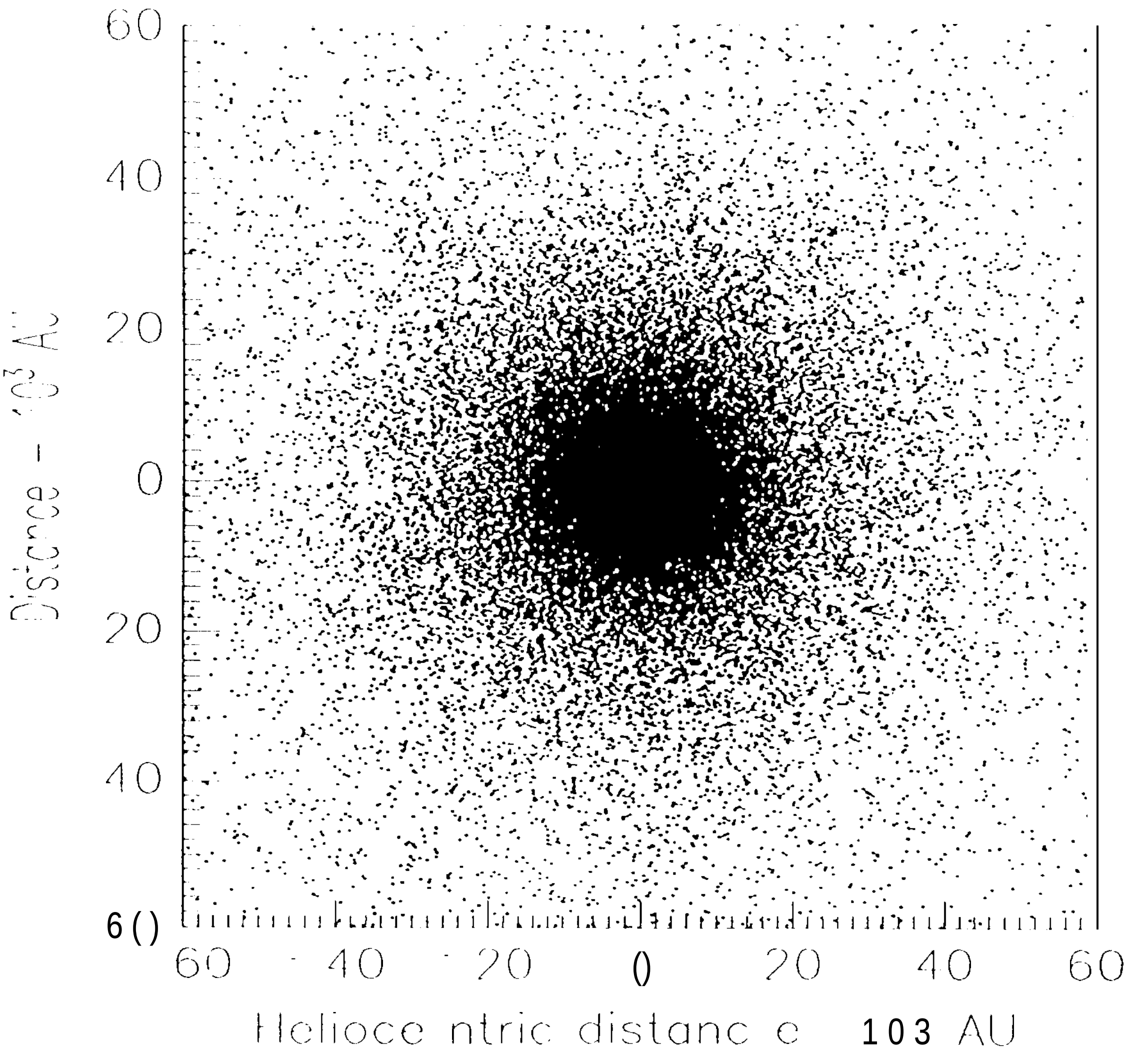

60
40
20
0
20
40
6()
Distance - 10³ AU
60
40
20
0
20
40
60
Helioce ntric distanc e 103 AU

Figure 4.

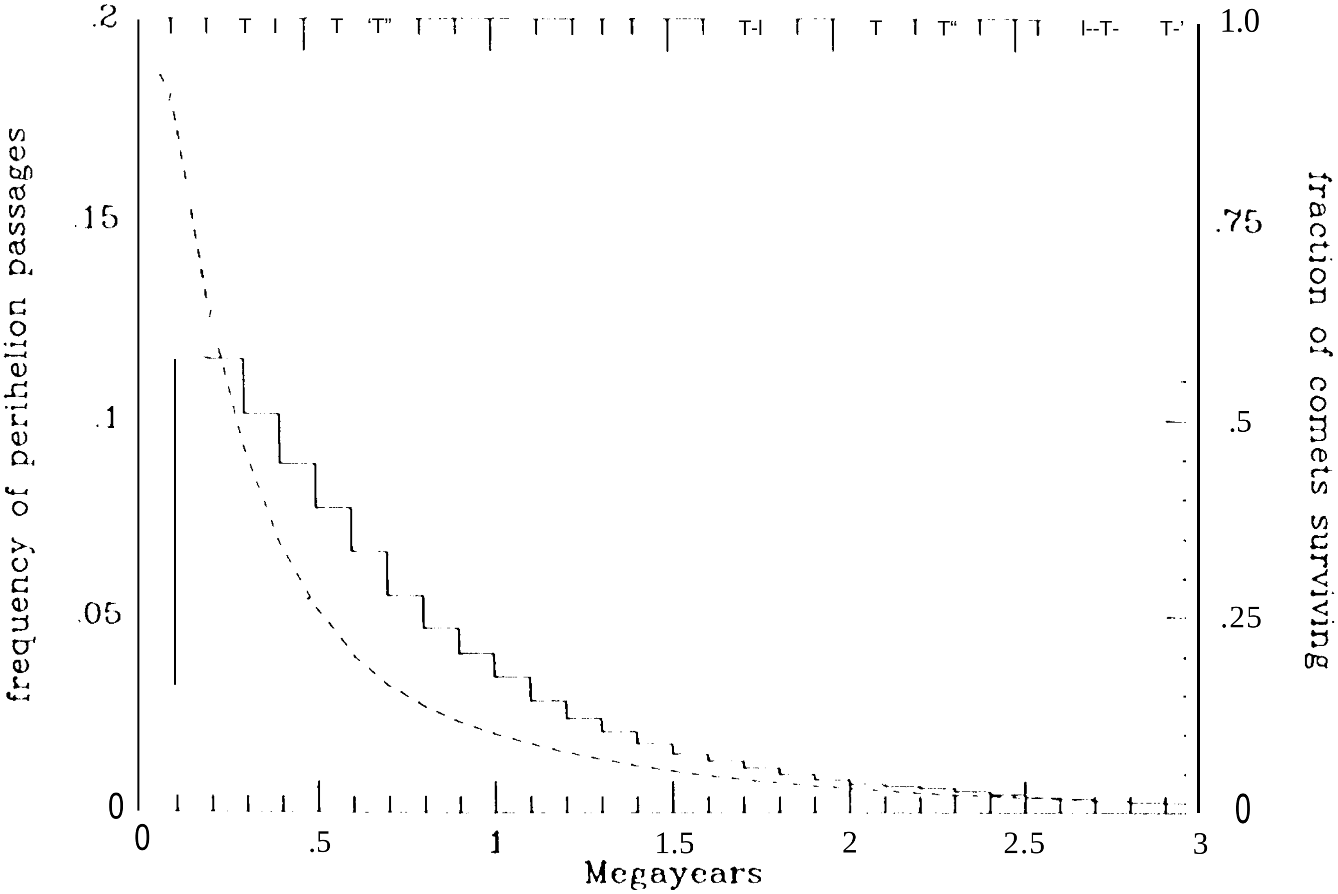

frequency of perihelion passages
fraction of comets surviving
Megayears
.2
.15
.1
.05
0
1.0
.75
.5
.25
0
0
.5
1
1.5
2
2.5
3

Figure 5.

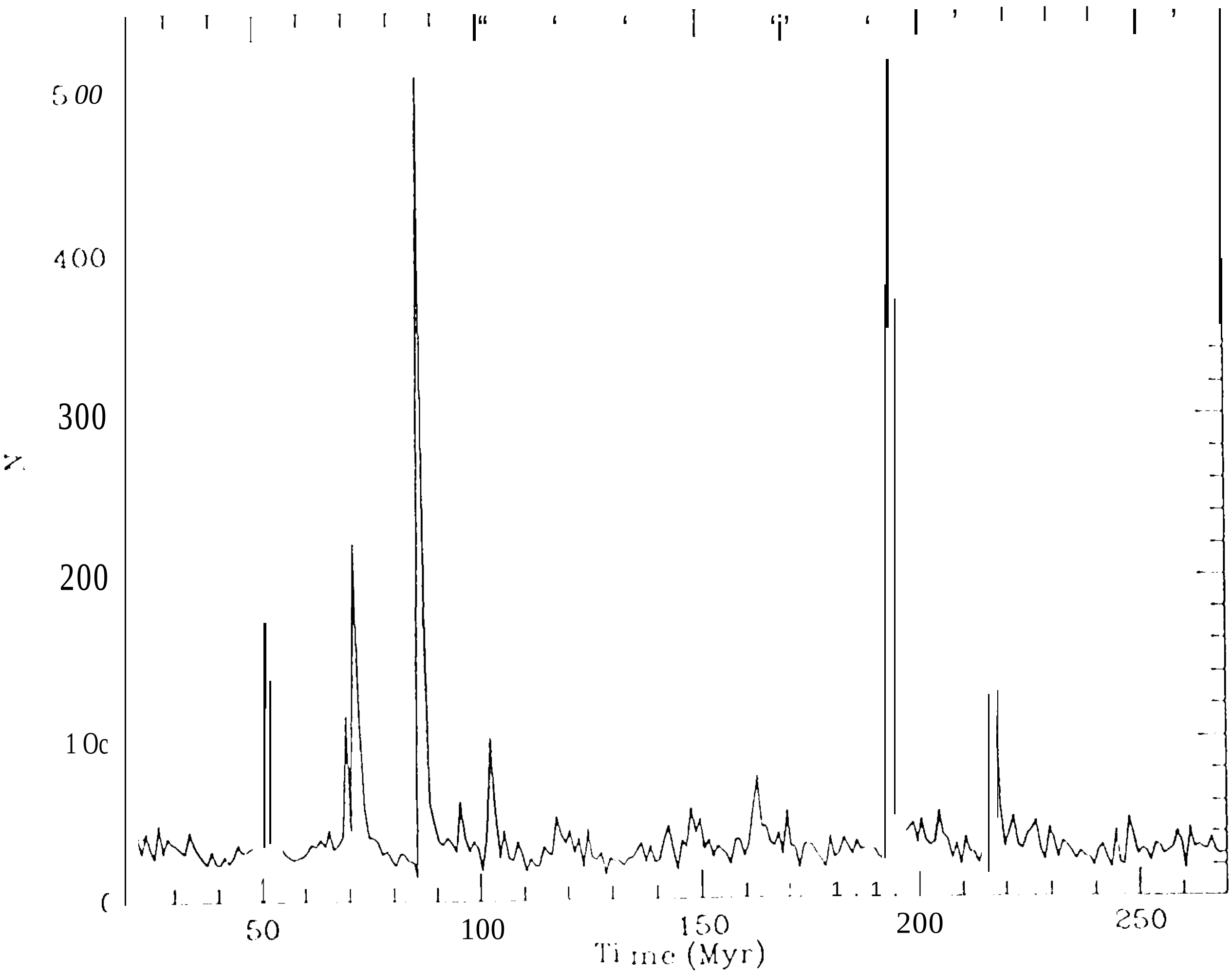


Figure 6.

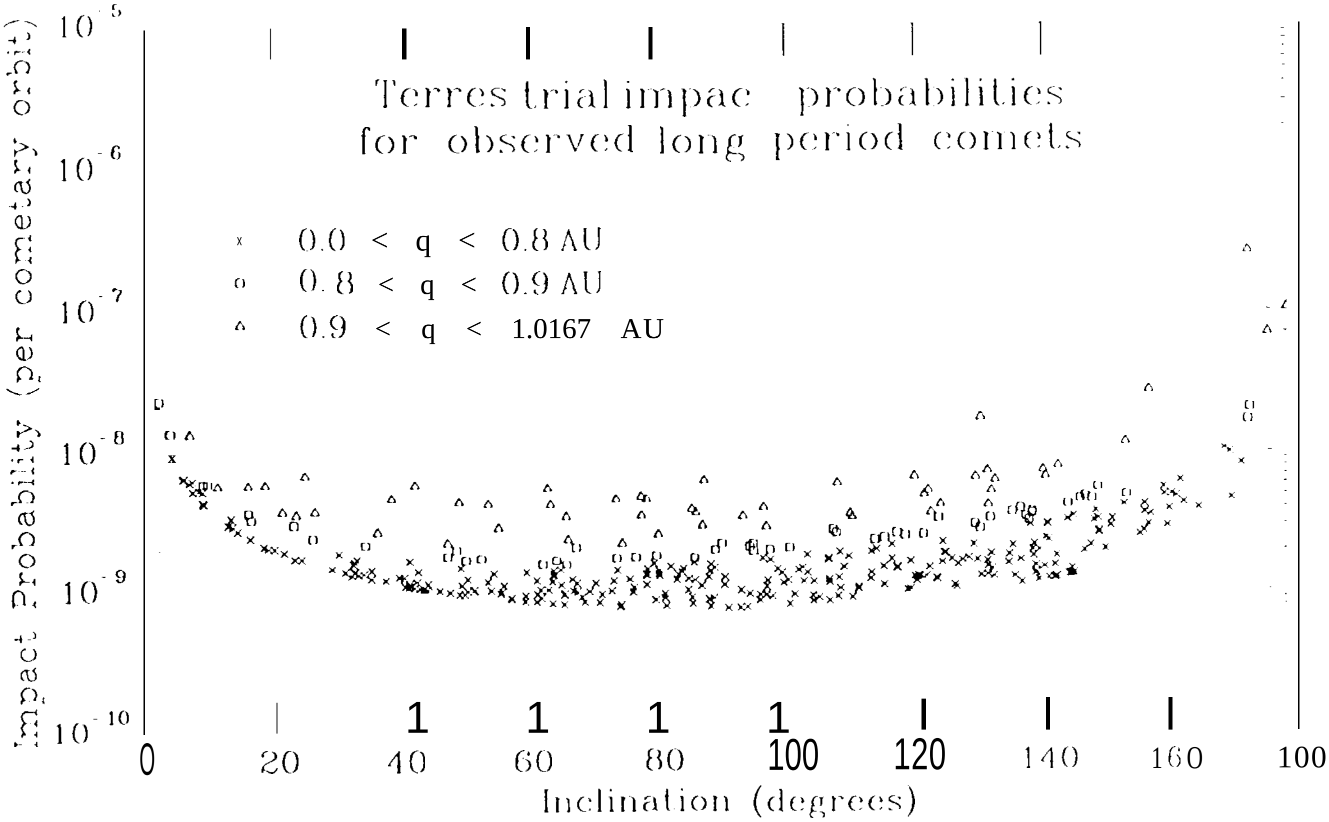

Terrestrial impact probabilities
for observed long period comets
0.0 < q < 0.8 AU
0.8 < q < 0.9 AU
0.9 < q < 1.0167 AU
Impact Probability (per cometary orbit)
Inclination (degrees)

Figure 7.

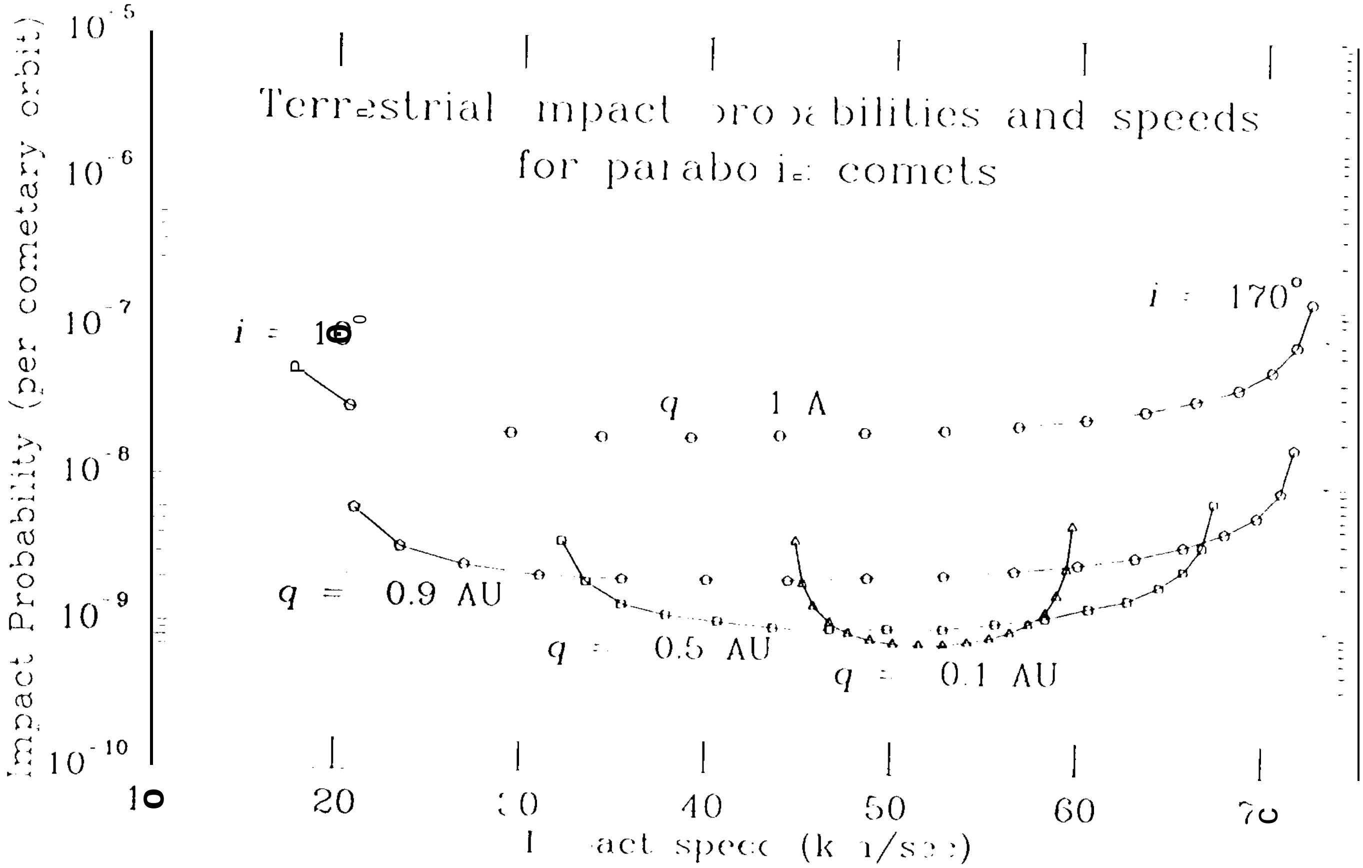
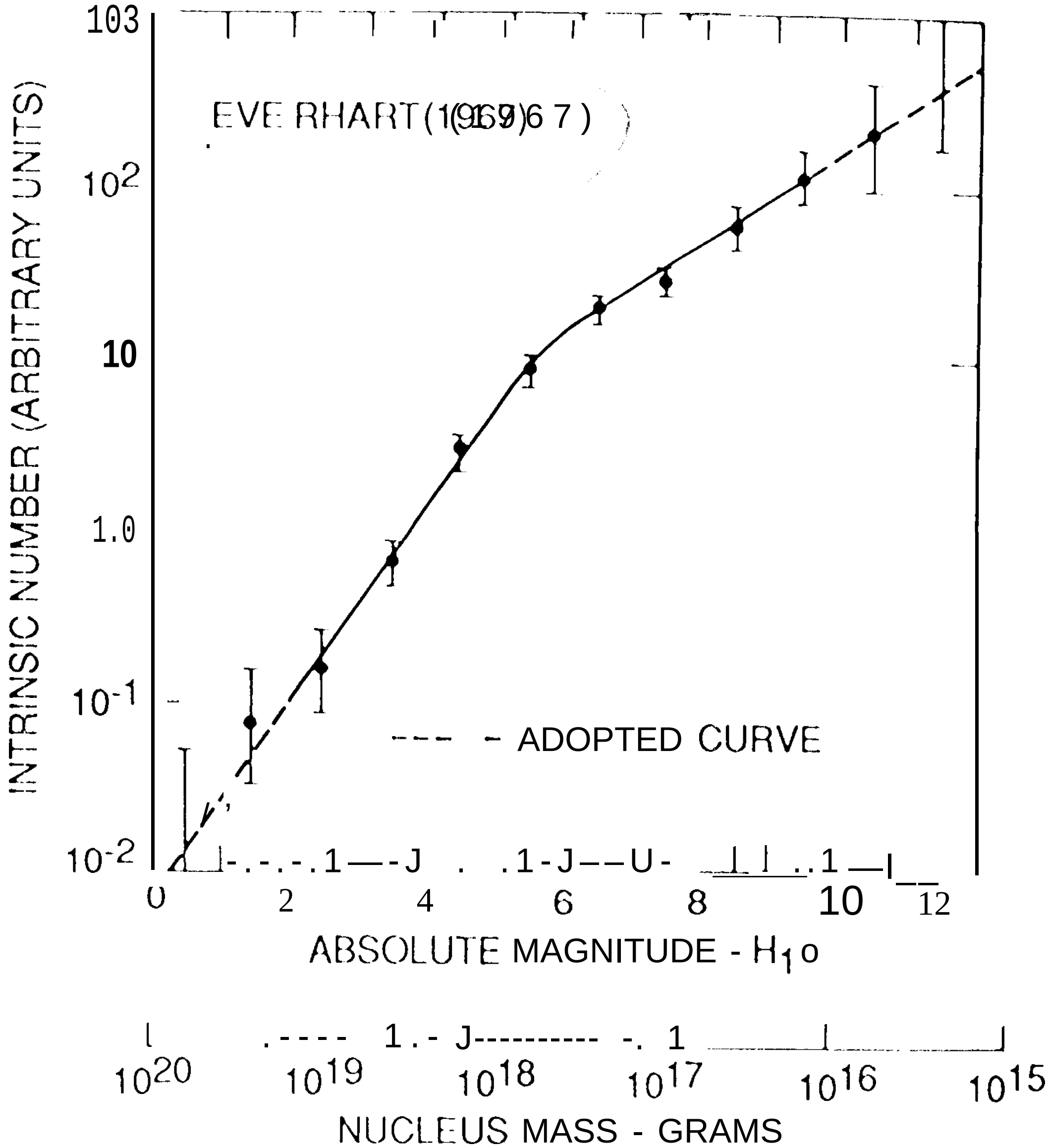

Terrestrial impact probabilities and speeds
for parabolic comets
Impact Probability (per cometary orbit)
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
i = 10°
i = 170°
q = 0.9 AU
q = 0.5 AU
q = 0.1 AU
10
20
40
50
60

Figure 8



EVERHART (1967)
INTRINSIC NUMBER (ARBITRARY UNITS)
10^3
10^2
10
1.0
10^{-1}
10^{-2}
ADOPTED CURVE
0
2
4
6
8
10
12
ABSOLUTE MAGNITUDE - H_{10}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
NUCLEUS MASS - GRAMS

Figure 9.