long-Period Comets and the Oort Cloud

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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 \times 10^{-9} per perihelion passage. The mean impact velocity is ~52 km See^{-1}, 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 \times 10^{-7} and 2.8 \times 10^{-6} per year, with a best estimated value of 1.0 \times 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 bodies in Earth-crossing orbits. Their orbital periods, typically 10^3 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 (Iasegawa, 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 to 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 long-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 material 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 200-300 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 (1994). 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).

Long-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- and short-period comets will be referred to as L.P. and S1' comets, respectively.

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. The earliest record is for comet C/146P1, observed in 147 B.C., one of many L.P comets recovered from ancient Japanese and Chinese records (Iasegawa, 1980). Only 67 of the orbits are for comets observed earlier than 1610, prior to 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
Seventy-three orbits in the catalog are for 1.1\ comets observed between 1610 and 1800, with only 3 of those having non-parabolic elements. The quality of orbits gets progressively better with time. For the 2021 P comets which were discovered in the 19th century, 86 have non-parabolic orbits, or 43\% of the total. For the 20th century the numbers are 262 non-parabolic orbits out of a total of 3561, 1\ comets discovered, or 740\%.

Of the 6981, 1\ comets in the catalog, 411 have perihelion distances less than 1.0 AU and are thus in Earth-crossing orbits (an additional 10 J.P 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 near the Earth’s orbit (Everhart, 1967a). Prior to 1900, 245 of 333 discovered J.P comets or 74\% 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 of 341 observed J.P comets, or 42\% are Earth-crossing (again, not counting 19 sun-grazers), due to the increasing number of photographic and CCD discoveries of J.P comets with larger perihelion distances.

Nine of the J.P comet orbits in the catalog may be short-period comets, but were too poorly observed to obtain a non-parabolic orbit 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 J.P 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 J.P 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. Ivorhart (1967a, 1967b) studied observational selection effects in detail and estimated that ~8,000,1’ comets had passed perihelion within 4 AU of the Sun over a 12.7-year period. Ivorhart also derived corrected absolute magnitude and perihelion distributions for the 1P comets; the perihelion distribution is shown in Figure 1. The number of 1 Earth-crossing comets increases linearly with increasing perihelion distance between 0 and 1 AU. Using Ivorhart’s estimates, one finds that there are ~101 Earth-crossing 1P comets per year brighter than absolute magnitude, M_0 = 11.¹ Comparing this estimate with the observed statistics above, it appears that three-fourths of all Earth-crossing 1P comets are currently missed.

The orbits of the 1P 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 0 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, Ivorhart (1967a) 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 hemisphere 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, M_0, is the total brightness a comet would have, with coma, if it was 1 AU from both the Sun and 1 Earth, and its brightness varied as 1/r² versus geocentric distance, and 1/r 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 between ~2.5 and 6 or more, generally being less for dynamically new comets, and larger for older, more physical 1 y evolved comets. Based on modeling, by Weissman (1990), an H_1 value of 11 corresponds to a nucleus mass of 4 x 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 are 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 element 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 to the asymmetries may come from the most recent stellar perturbation of comets in the Oort cloud (Biermann et al., 1983; see section 3).

A special case of 1.1' crossing 1.1' comets is the sun-grazing comets (Marsden, 1967, 1989). These 24 observed comets have perihelia < 0.01 AU, within one solar radius of the Sun's photosphere. "They are 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 are assumed because of limited observations. They are collectively referred to as the Kreutz group. The similarity of the orbits of the Kreutz group suggest that they are fragments of a larger parent comet that disrupted once or more previous returns. In recent years, discovery of sun-grazing comets has been greatly supplemented by spaceborne instruments, including the SOI WIND 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 AU, yielding orbital periods between ~500 and 103 years. However, the orbits of the Kreutz group are inclined -139-144° to the ecliptic and are 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 before their orbits can evolve very far. ‘1’bus, they likely play no significant role in the impact hazard on the Earth.

The Oort Cloud

About two-fifths of observed 1,1) comets passing through the planetary region (for which mm-parabolic orbit solutions are possible) are on osculating (instantaneous) hyperbolic orbits. Early on, this led to the suggestion that the 1,1’ comets came from interstellar 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 1,1P comets are members of the solar system, though their semimajor axes in many cases are quite large, ~10⁴ AU or more (corresponding to orbital periods ≥10⁶ years).

A useful way to display the semimajor axis (distribution of the 1,1P comets is to use the inverse of the semimajor axis of the original orbit, 1/a₀, 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/a₀ correspond to negative energies, or bound, elliptical orbits. Negative 1/a₀ values correspond to positive energies, or unbound, hyperbolic orbits. The distribution of 1/a₀
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 > 104 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 to 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 'dynamical by 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, and thus diffusing comets to larger or smaller semimajor axes.

The typical Jupiter energy perturbation is $\pm 630 \times 10^{-6}$ AU, 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, diffusing both to the left and to the right in Figure 2, but being lost if they achieve negative values of 1/a.

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 Sate, 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 orbit solutions. Thus, it is highly doubtful that any of the observed IPC comets are 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 are 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 are much less frequent than stellar encounters, occurring perhaps once every 3 x 10^8 years, but can be quite significant because of the huge mass of interstellar material in the GMC’s (Lut and Tremaine, 1985).

Repeated stellar and GMC perturbations cause the orbits of the comets to diffuse in velocity phase space, slowly increasing the energy and angular momentum of the 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; Leisler
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 J.P comets from the Oort cloud is illustrated by the scatter diagram in Figure 3, which plots each observed J.P 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 $1/a$, 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 $6 \, \text{AU}$ and more, returning J.P comets (ones with $1/a > 10^{-4} \, \text{AU}^{-1}$) are rarely discovered unless their perihelion
distances are less than 3 AU (the recently discovered comet 1 Ialc-Bopp, C/199501, 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. There 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 dynamically new 1.1 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. However, Stern (1990) 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 110 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 layer 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 will 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 $1.9 \times 10^{11}$ comets. However, using Livermore's (1967b) estimates of the flux of 1P comets corrected for observational selection effects, and more detailed modeling of the Oort cloud by Weissman (1985) and Weissman (1985) and Weissman (1990), the population is now estimated to be $\sim 10^{12}$ comets with $11_{10} < 11$ (Weissman, 1991; $11_{10} < 11$ corresponds to nuclei with radii $> 1.2$ km; see below).

Oort proposed that there would be no comets in the comet cloud with orbital semimajor axes less than $\sim 104$ 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. (1987) 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 $6 \times 10^3$ AU, but that beyond that distance the orbital inclinations of the comets are essentially random.

Duncan et al. (1987) estimated that the population of the inner Oort cloud was about five times that of the outer Oort cloud, or about $5 \times 10^{12}$ comets, given the Oort cloud population estimates above. Taking Weissman's (1990) estimate of an average cometary nucleus mass of
$3.8 \times 10^{16}$ g, the total mass in the inner and outer Oort clouds would be $-2.3 \times 10^{29}$ 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 (1979a) and Fernández (1982) showed that the average L.P comet makes five perihelion passages through the planetary system before being removed by one of several physical and dynamical processes. About 65% of all L.P comets are ejected to interstellar space or to semimajor axes beyond the Sun’s sphere of influence ($a > 10$ AU). Another 8% of all L.P 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% of L.P 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 L.P comet is $-6 \times 10^5$ years following its first perihelion passage (Weissman, 1979a).

Additionally, 27% of L.P 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% of dynamically new L.P comets from the Oort cloud randomly disrupted, while only 4% of returning L.P 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 many 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 S1’ 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 entirely 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 (1994) estimate that SP comets are active for only \( \sim 10\% \) 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, 1991).

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 L.P comets because they are dynamically removed on a relatively rapid time scale, before they can physically evolve
Nongravitational forces from jetting of volatiles can also perturb the orbits of the L,P 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 L,P 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 L,P comets and to estimate their precise paths through the planetary region. This uncertainty adds to the dilemma posed by the L,P 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. In 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)

\[ f = 2q/a \left(1 - q/2a\right) \approx 2q/a \quad \text{for} \quad q \ll a, \quad (1) \]

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 \( 10^{12} \) comets (Weissman, 1991) and a typical semimajor axis of \( 2.2 \times 10^4 \) 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 \( 5 \times 10^{12} \) comets and a typical semimajor axis of \( 3 \times 10^3 \) AU, the density of perihelia predicted by equation 1 is \( 3.3 \times 10^9 \) AU\(^{-1}\). Because that semimajor axis corresponds to an orbital period of \( \sim 1.6 \times 105 \) years, the flux versus time is \( \sim 2.0 \times 104 \) 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 10ss cone for inner Oort cloud comets, and the peak increase in the J.P comet flux at the Earth's orbit would be by a factor of \( \sim 300 \).

Hut et al. (1987) and Fernández and Ip (1987) modeled the dynamical evolution of cometary showers. The most intense showers would be caused by stars penetrating the Oort cloud to \( \sim 3 \times 10^3 \) AU, which would only be expected to occur about once every \( 5 \times 108 \) years. More modest showers might occur from star passages at \( 104 \) AU, which would occur on average every \( 5 \times 107 \) 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 Iltut et al. (1987). The excess comets in the shower are dynamically removed due to planetary perturbations in about 2 to $3 \times 10^5$ 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 de Leissemme and Patmioiu, 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.

Leissemme (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 ~6468 Myr (Bahcall and Bahcall, 1985).

Matese et al.’s dynamical model did not include stellar perturbations. It is possible that stellar perturbations act to mitigate the variation in the galactic tidal perturbations, though they actually may accentuate the variation due to the similarly 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. This then suggests that the current steady-state Jovian comet flux is twice 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). There are substantial dynamical problems with all of these hypotheses and many of their implications are clearly not borne out. If periodic extinctions are real, the physical mechanism for invoking them has not yet been identified. The reader is referred to Tremaine (1986) and Weissman (1986, 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 means 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 closed orbits 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

\[
p = \frac{s^2 U}{\pi \sin i \left| U_x \right|}
\]

(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

\[
U = \left[ 3 - \frac{1}{a} - 2 \sqrt{a(1 - C^2) \cos i} \right]^{1/2}
\]

(3)

\[
U_x = \left[ 2 - \frac{1}{a} - a(1 - C^2) \right]^{1/2}
\]

(4)
\[ s = \left( \frac{R}{a_0} \right) (1 - 1 - \frac{v_e^2}{U^2})^{-2} \]  

where \( a, e, \) and \( i \) are respectively the semimajor axis (in units of the target planet's semimajor axis, \( a_0 \)), eccentricity, and inclination of the comet's orbit, and \( R, a_0, \) and \( v_e \) are 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 \( a(1 - c^*) = a(1 - c)(1 + c) \approx 2 q \), 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 \( q \to 1 \text{AU} \) 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 (1967) 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, \( 0.98 < q < 1 \text{AU} \), and orbits close to the ecliptic, \( i < 1^\circ \) and \( i > 179^\circ \) are excluded.

Long-period comet impact probabilities on the Earth have been calculated by a number of researchers. Weissman (1982) found a mean impact probability of \( 2.2 \times 10^{-9} \) per cometary perihelion passage, using Öpik's equations to average \( 2.5 \times 10^5 \) random cometary orbits, uniformly distributed in perihelion distance between 0.005 (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 x 10^{-9} and 1.48 x 10^{-9} using analytic and numerical approximations to Opik's equations. An examination of Zimbelman's calculations (Steel, 1993) showed that he erradand somehow lost a factor of n/2 (the mean value of sin i evaluated from 0 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 1.P comets. However, the observed 1.P comets are a biased sample, and the same factors which lead to an increased discovery probability also lead to an increase in the impact probability for 1.P comets. The observed sample is biased towards comets with perihelia near the Earth's orbit and inclinations close to the ecliptic plane, and the resulting mean impact probability is substantially higher than the true average. Similar results for 411 observed 1.P comets were found by Marsden and Steel (1995), shown in Figure 7.

The mean hyperbolic encounter velocity for the 1.P comets is 50.5 km sec^{-1}, and the mean 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. One 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 sec^{-1} for the most probable 1.P 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 1.P comets is likely not uniform interior to 1 AU. Weissman (1985) showed that the perihelion distribution of the 1.P comets rises
sharply throughout the planetary region because Jupiter and Saturn act as a dynamical barrier to the diffusion of 1.P 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 $7.4 \times 10^{-9}$ and the most probable impact energy corresponds to a velocity of 56.7 km s$^{-1}$. Using a perihelion distribution that varied as $q^{12}$ (Cernández, 1981), Marsden and Steel (1995) found a mean impact probability of $2.5 \times 10^{-9}$.

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 1.P comets on the Earth. This is because of the very poor present knowledge of the size and mass distributions of the 1.P 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 J.P comet absolute magnitudes, \( m_{10} \), corrected for observational selection effects, as found by Verhart (1967b). By comparing, the \( m_{10} \) values for specific comets with observations of their nuclei at large heliocentric distances when they were presumably inactive, Weissman obtained the relationship

\[
\log M = 20.0 - 0.4 m_{10}
\]  

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 \( m_{10} = 11 \) has a mass of \( 3.8 \times 10^{16} \) g. Bailey and Stagg (1988) derived a similar mass-magnitude relationship

\[
\log M = 19.9 - 0.5 m_{10}
\]

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 1 Earth for J.P comets hitting at the most probable impact energy
representative velocity of $56.4 \text{ km sec}^{-1}$. 11c showed that a comet with a mass of $1.9 \times 10^{13} \text{ g}$ 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 $0.6 \text{ g cm}^{-3}$. Using the crater scaling relationship of McLoish (1989) one finds a similar mass, $2.1 \times 10^{13} \text{ g}$, required for a LP comet to form a 10 km crater on the Earth. Using the mass-magnitude relationship in equation 6, Weissman (1990) showed that the mass of $1.9 \times 10^{13} \text{ g}$ corresponded to an absolute magnitude of $M = 16.8$. By then using the size distribution shown in Figure 9 and the estimate from Verhart’s work of ~10 Earth-crossing LP comets per year brighter than $M = 11$, 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 Verhart’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 $1.0 \times 10^{6}$ years. In terms of the surface area of the Earth, this works out to a cratering rate of $0.20 \times 10^{14} \text{ km}^{2} \text{ yr}^{-1}$. For comparison, Shoemaker et al. (1990) found a mean impact interval for Earth-crossing asteroids creating 10 km or larger craters of $1.1 \times 105$ years, or a rate of $1.8 \times 10^{-14} \text{ km}^{2} \text{ yr}^{-1}$. Thus, LP comets constitute ~10% 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 $0.59 \times 10^{-14} \text{ km}^{2} \text{ yr}^{-1}$, or one impact every $3.3 \times 10^{5}$ 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 $3.6 \times 10^5$ years, or a cratering rate of $0.55 \times 10^{-4} \text{ km}^2 \text{ yr}^{-1}$. Unfortunately, Shoemaker et al. (1990) 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 relatively 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.

't. 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. 'I'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). One 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 $\geq$ 10 km on the Earth, which suggests a mean impact interval of $2.2 \times 10^6$ years. Again, the details of Olsson-Steel's calculation are not completely explained in his paper so it is difficult to assess why his results are different from those above. Marsden (1993) estimated that LP comets constitute only 2% 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 $5 \times 10^6$ 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 I.P 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 I.P 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 I.P 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 Yomans, 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 1,1' comet that might cause a global climatic disturbance. Morrison et al. (1995) find the most likely threshold energy for such an event is $3 \times 10^6$ megatons, or $1.3 \times 10^{28}$ ergs. For a I.P comet impacting at the most probable impact velocity of $56.4 \text{ km sec}^{-1}$, this corresponds to a mass of $8 \times 10^4 g$, or a radius of $0.7 \text{ km}$. Using the size distribution in Figure 9, such a comet would have an absolute magnitude of $\sim 2.7$. The Earth-crossing flux would be -26 such comets per year and the mean impact interval would be $\sim 1.6 \times 10^7$ years.

In summary, the current mean impact rate of I.P comets sufficiently massive to create 10 km or larger craters on the Earth is estimated to be between $5 \times 10^{-7}$ and $2.8 \times 10^{-6}$ 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 its 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, 1.1’ 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 1.P 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. ‘1’bus, the entire sky must be surveyed continuously in order to detect approaching 1.P comets at the earliest possible moment.

The problem of searching for 1.1’ comets is discussed in more detail in Marsden and Steel (1995). They estimate that 1.P comets on impact trajectories would pass opposition \( \sim 250,500 \)
days prior to Earth encounter for pre-perihelion impacts (ignoring comets which reach opposition < 25 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 at 1 cciptic latitudes in order not to miss any 1.0 comets.

Since no such deep searches for 1.0 comets are currently underway, actual warning times found from current discoveries are typically much smaller. (holy 12!40 of all 1.0 comets were discovered more than 100 days prior to perihelion (Marsden and Steel, 1995), though that number is improving as photographic and CCD discoveries play a larger and larger role. Some 1.0 Earth-approaching 1.0 comets have had remarkably short warning times. One recent bright, naked-eye comet Hyakutake, C/1996 H2, 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 I 11, was discovered only 15 days prior to a close approach to within 0.031 AU from the 1.0 Earth. This diffuse comet was discovered by the I. RA 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 1.1 comet Hale-Bopp, C/1995 O1, 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 are insufficient 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 $16 \times 10^6$ years mean interval between potential 1 y catastrophic I.I’ comet impacts, makes the likelihood of an impact quite low in the next century. During that time, routine improvements in several different technologies may make this problem trivial to solve.

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References


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


Figure Captions

Figure 1. The perihelion distribution of long-period comets, corrected for observational selection effects, by Liverhart (1967b). The distribution is not well determined for q > 1 AU. However, Fernández (1981) and Weissman (1985) showed that the number of comets likely 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 comets 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 long-period comets. The horizontal band of comets at near-zero \(1/a_o\) arc 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. A 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 I I It et al. (1987).

Figure 6. A hypothetical flux of dynamically new comets into orbits with perihelia < 2 AU as found by Heisler (1990). The large spikes are comet showers resulting from close stellar passages.

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

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

Figure 9. The mass distribution of the long-period comets as found by Weissman (1990), using van Houten’s (1967b) distribution of the number of comets as a function of their absolute magnitudes, H10, corrected for observational selection effects. The mass scale assumes a bulk density for the nuclei of 0.6 g cm⁻³.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Terrestrial impact probabilities for observed long period comets

- $0.0 < q < 0.8 \text{ AU}$
- $0.8 < q < 0.9 \text{ AU}$
- $0.9 < q < 1.0167 \text{ AU}$

Impact probability (per cometary orbit)

Inclination (degrees)

Figure 7.
Figure 9.