THE AGING AND LIFETIMES OF COMETS

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ABSTRACT. The aging of comets is evidenced by a number of observable phenomena: production of gas, dust and meteor particles, splitting of cometary nuclei, nongravitational effects in the comet's motion, sudden and progressive absolute brightness variations, and ultimate disappearance. Statistical data on comet losses, absolute magnitudes and orbits also bear signatures of their aging. The knowledge of potential active lifetimes of individual objects is a prerequisite of any realistic model of the long-term evolution of the whole comet complex. This paper reviews different sources of information on the aging process and summarizes implications for the mean lifetimes of comets, their dispersion and dependence on the orbital parameters. Two alternative end fates of comets - their total disintegration or change into an inactive asteroid-like object - are also discussed.

1. INTRODUCTION

The papers presented at the preceding sessions have shown that we still have a number of competing hypotheses on the origin of comets. The only straightforward way to demonstrate the validity of any of them, is to start from a correct model of the initial state and to trace the evolution forwards to a state compatible with observation. The great progress in modelling experiments with the use of modern computing techniques makes this possible in principle. However, there are three serious impediments :

1. Very incomplete information on the present state. We can only observe comets in the innermost region of their huge system. For the new comets in Oort's sense the period of observation is always less than one millionth of the period of revolution, which again is only about one thousandth of the age of the Solar System. Some short-period comets are observable all around their orbits, but their active lifetimes are apparently less than one millionth of the age of the Solar System. The number of known comet orbits (over 700, including over 100 of short period) constitutes a fairly rich statistical sample. However, in order to compare it with the results of

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modelling experiments, a number of strong selection effects must be taken in account, in particular, those of revolution period, perihelion distance and absolute brightness. We are also not sure whether or not this sample is representative for a quasi-steady state in the inner Solar System, persisting over a considerable part of its lifetime as an equilibrium between source and sink.

2. Uncertainties about the past perturbing environment. These refer to individual perturbing events - encounters of the Solar System with stars and clouds of interstellar matter - the recurrence rate of which may be subject to long-period variations associated with the motion of the Sun within the Galaxy. If the age of the comet system is about the same as that of the planetary system (which is currently the prevailing opinion), then the structural changes of the latter may have played a significant role, especially during the earliest phase of evolution.

3. Progressive disintegration of the comets themselves. This is accompanied by nongravitational effects in their motion, which are often erratic and cannot be extrapolated with confidence outside the period covered by observations. And what is still more important, at some evolutionary stages the rate of physical aging may become much higher than that of the dynamical evolution. Progressive aging of comets introduces a definite asymmetry into the occurrence rate of fundamental perturbing events, which is not borne out by computer simulations of their motion. A comet whose disintegration process was triggered by a decelerating encounter with a planet, may survive not long enough to experience an analogous accelerating encounter. Captures into short-period orbits become more frequent than ejections from them; Jupiter's reflecting barrier thus becomes a partially absorbing barrier, and the quasi-steady state becomes different from a pure dynamical equilibrium.

The purpose of the present paper is to discuss the problems of determination of the active lifetimes of comets, their distribution, and correlation with the orbit type. The other question to be addressed is what happens at the end of the comet's active lifetime and what is the character of its remnants.

2. PHENOMENA ACCOMPANYING THE AGING PROCESS

The aging of comets is borne out by a number of observable phenomena:

-- Production of coma and tail consisting of escaping gas and dust.

-- Splitting of the nucleus and sudden brightness bursts, indicating a temporary acceleration of the mass loss.

-- Nongravitational effects in the comet's motion, produced by jet effects of the escaping matter on the nucleus insolated from one direction.

-- Existence and dispersion of meteor streams occupying the orbits of comets.

-- Progressive decrease of the absolute brightness of short-period comets observed at a number of returns to perihelion.

-- Differences between the absolute brightness of dynamically old (short-period) and young (long-period, especially new) comets.

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-- Failure of the rediscovery of some short-period comets at their expected returns to perihelion.
-- Untimely disappearance of some long-period comets.
-- An appreciable excess of new comets in Oort's sense as compared with other long-period comets.

In principle, each of these effects can assist in estimating the active lifetimes of comets. Unfortunately, each of them has its specific constraints in this respect.

3. THE ABSOLUTE MASS LOSS

The physical lifetimes of comets are evidently determined by the rate of their progressive mass loss. The observable products of the aging process include: (1) gas, (2) icy grains, (3) dust grains, (4) meteor particles, and (5) larger fragments up to long-lived secondary components producing their own comas and tails.

Estimates of the gas production rates are currently available for about ten brighter comets observed since 1970. They are based on quantitative measurements of emission line and band strength, combined with the lifetimes of individual species. In view of the high prevalence of the H_2O parent molecules (Delsemme, 1982), the relevant data are provided by UV measurements from satellites and sounding rockets. The results summarized by Feldman (1982) and Ney (1982), if converted under reasonable assumptions into the total loss of H_2O per revolution, yield 10^{10} to 5×10^{10} kg for short-period comets (1.5×10^{11} kg for P/Halley according to Delsemme, 1976) and up to 8×10^{11} kg for long-period comets. The addition of other volatiles should not increase these rates appreciably. Just on the contrary, since the measurements were made on relatively bright comets at smaller solar distances, one has to expect considerably smaller mass loss rates for comets of low absolute brightness or large perihelion distance. There is no dependable information as to the loss of volatiles at larger solar distances, including the formation and removal of icy grain halos. However, since most of the mass loss takes place along the perihelion arc of the orbit (e.g., definitely at $r < 2$ AU for $q = 1$ AU, which is about the median value for known comet orbits), any deviations from the r^{-2} dependence of the mass loss seem to be immaterial for those comets which are aging rapidly. Irregular fluctuations may affect the result more seriously.

Estimates of the dust production rates are mainly based on IR measurements of type II tails of bright comets and refer to micron-sized particles (Ney, 1982). They indicate that the dust production per revolution is 2×10^{10} kg to 5×10^{11} kg for bright long-period comets, and less than 10^9 kg for P/Encke. Thus the dust-to-gas mass ratio is normally between 1:10 and 1:1, the only case where the dust seems to have prevailed, in a ratio of 5:3, being that of 1957 III Arend-Roland (Finson and Probstein, 1968).

Estimates of the production of larger solid particles are only possible when the comet approaches the Earth's orbit close enough to give rise to a meteor shower. While in such cases it is possible to determine the space density of meteor particles, problems arise when it is to be converted into the mass loss. First, we only have one-dimensional sounding along the Earth's path through the stream; in order to reconstruct a three-dimensional picture, extrapolation is necessary. That along the comet's path is possible for permanent meteor streams, making use of the annual recurrence of the shower; that perpendicular to it depends on the distance of the passage from the stream's centre, and on the specific pattern of dispersion produced by perturbations. In the only detailed analysis of this kind published so far and relating to P/Halley, McIntosh and Hajduk (1983) find a highly anisotropic distribution with a flattening of 1:10 perpendicular to the comet's orbital plane. They find 5×10^{14} kg as the total mass of the stream, and suggest that this has been assembled in the course of about 1500 revolutions of the comet, i.e. at an average rate of 3.3×10^{11} kg per revolution. Taking in account the inevitable losses by progressive destruction and hyperbolic escape, the figure appears unexpectedly high. However, in spite of its long revolution period, P/Halley is a much stronger source of meteoroids than other comets (Whipple, 1967; Kresák, 1979a), and was apparently an exceptionally large object in the past.

Splitting of cometary nuclei is another phenomenon which can reduce at once their potential survival time. Present statistics indicate an average rate of one observed split per 25 apparitions for long-period comets, and one per 170 apparitions for short-period comets (Whipple, 1978a). Taking in account the limited periods of observability, values about twice as large are obtained, relating to non-tidal splits during the whole revolution: one per 12 revolutions for long-period comets, and one per 90 revolutions for short-period comets (Kresák, 1981a). The earlier finding that splits are more frequent for new comets in Oort's sense than for other long-period comets (Stefanik, 1966), is apparently due to their longer periods of observability; the difference becomes statistically insignificant when corrections for observational selection are applied (Kresák, 1981a). As we shall see later, the observed rate implies that many comets, and possibly their majority, experience at least one splitting during their active lifetime. The effect of these events on the lifetime would decrease with increasing mass ratio of the fragments. The differential nongravitational effects indicate that the mass ratio is often very high (Sekanina, 1982); smaller fragments tend to fade out very early, having apparently no major effect on the lifetime of the main component.

The distribution of orbits of long-period comets does not bear out the presence of groups or pairs indicative of persistent components of split comets (Whipple, 1977a; Kresák, 1982b; Lindblad, 1985). The only exception is the Kreutz group of sungrazing comets, which probably experience splitting by solar tides at every perihelion passage (Kresák, 1981a) - a branching process continuing over a number of revolutions of the original object which must have been extraordinarily large. For short-period comets the process is much easier to overview, because checking is possible at every return. A few recorded cases cover the whole range of possibilities. In the case of P/Biela, both components persisted over two revolutions and disappeared almost simultaneously. In the case of P/Brooks 2 (tidal disruption by Jupiter), two minor fragments disappeared just during their first perihelion passage, while the main component is still observable after 14 revolutions. P/Taylor got lost just after its first apparition during which it had experienced splitting, but the main component was rediscovered 9 revolutions later. P/DuToit-Hartley was observed as a single comet in 1945 and as a double comet in 1982. There is only one pair of short-period comets which strongly suggests that we have to do with persistent components of a single progenitor: P/Neujmin 3 and P/Van Biesbroeck (Carusi et al., 1984). Backward computations indicate that both large fragments of the original nucleus have already made 12 and 11 revolutions, respectively, as two separate objects. P/Neujmin 3 was last observed in 1972, P/Van Biesbroeck in 1978. An alternative, less probable explanation is that these two comets originally constituted a binary system of marginal stability, which was dissolved by differential perturbations during the close encounter with Jupiter in 1850.

The existence of such systems was suggested by Van Flandern (1981), and associated by Whipple (1983a, 1984) with the violent double outbursts of P/Holmes in 1892 and P/Tuttle-Giacobini-Kresák in 1973. Whipple interprets these events as a grazing encounter of the components after reduction of their minimum distance by differential nongravitational forces, followed by a collision one revolution later, which destroys the secondary. This scenario may certainly be questioned, but there is so far no other explanation of the recurrence of two bursts in an interval of a few weeks. Collisions of double comets may represent another instantaneous process of aging, though much less frequent than spontantaneous splits. Only two known examples would imply a collision rate of one per 500 revolutions, with a considerable margin of uncertainty. On the other hand, the inherent mass loss may be substantial for the survival time. The integrated radiation output during the two outbursts of P/Tuttle-Giacobini-Kresák was equivalent to that over about 80 normal revolutions (Kresák, 1974b). This comet counts among the faintest known objects; for typical comets with a much higher normal activity level a similar effect might be less drastic but not negligible. Unlike splitting, the binary collisions would only occur in a fraction of comets, without a preference for long-period comets. Both the cases on record refer to the Jupiter family of comets, but it would be too daring to imply that there is any systematic difference on the basis of such poor statistics. Non-catastrophic collisions with small asteroids are evidently much too rare to affect the aging of a significant fraction of comets. The question of unobserved interplanetary boulders (Harwit, 1967; Kresák, 1978) still remains open.

4. THE RELATIVE MASS LOSS

The total masses of comets are even more difficult to estimate than their mass losses. As related to observable quantities, the diameters D and masses M of cometary nuclei can be tentatively expressed by the equations

$$D = c\ 10^{-0.2\ H} \quad (1)$$

$$M = C\ 10^{-0.6\ H} \quad (2)$$

where H is the absolute magnitude of the comet (the total apparent magnitude reduced to a distance of 1 AU both from the Sun and Earth, assuming brightness variations with the inverse fourth power of the heliocentric distance and with the inverse square of the geocentric distance). The scaling factor c involves the brightness ratio of the nucleus to the coma at 1 AU, and the albedo of the nuclear surface. The factor C involves, in addition, the mean density of the nucleus, the shape of which is assumed nearly spherical.

Using Vsekhsvyatskij's (1958) scale of absolute magnitudes H, Öpik (1963 and 1973) originally assumed c = 150 km, C = 2.2×10^{18} kg, ρ = 2 gcm^{-3}, including deviations from a spherical shape. However, in his later paper he already pointed out that there is good reason to revise c to 75 km and C to 2.6×10^{17} kg. A more recent revision by Whipple (1978a) suggests c = 32 km and C = 2.5×10^{16} kg, with ρ = 1.5 gcm^{-3}. Thus each of the revisions has put the mass estimates one full order of magnitude lower which, if related to the mass loss rates, would put the lifetimes one order of magnitude higher.

The point is that direct evidence is available neither on the contribution of the light reflected by the nuclear surface to the total brightness of the comet, nor on the albedo and density of the nucleus. The product of its diameter and the square root of its albedo can be determined from observations at extreme solar distances with large long-focus telescopes, provided that the contribution of the coma can be neglected under such circumstances (Roemer, 1966; Kresák, 1973). Another function of diameter and albedo can be determined from the vaporization rate of H_2O production at small solar distances, provided that the whole surface is covered by water ice (Delsemme and Rudd, 1973). Solving these two equations, Whipple (1978a) finds rather high values for the albedos (over 0.6) and determines the diameters of some cometary nuclei, which are in fair agreement with his scaling factor in Eq. (1). Another approach suggested by him is the mass determination based on the radial acceleration by nongravitational forces. This procedure, applicable only to short-period comets, requires some assumptions about quantities which are not measurable directly; nevertheless, results roughly consistent with other independent estimates could be obtained for some comets. In their analysis of the rotation, nongravitational deceleration and sublimation of P/Encke, Whipple and Sekanina (1979) estimate its current relative mass loss by sublimation at 0.09 per cent per revolution, but point out substantial temporal variations of this value.

Now, if we assume the validity of (2) with Whipple's scaling factor and one half of the nucleus (by mass) being composed of H_2O, potential lifetimes of comets can be obtained by dividing M by the H_2O production rate per two revolutions, as discussed in Section 3. There are only ten comets for which this is possible. For seven long-period comets (1970 II, 1973 XII, 1975 IX, 1976 VI, 1978 XV, 1979 I and 1980 XII) the result ranges from 1 to 50 revolutions, with the median at 12 revolutions. These are mostly comets of small perihelion distance, and reducing the mass loss rates to q = 1 AU a median of 18 revolutions is obtained. For the three short-period comets the result is entirely misleading: 1.5 revolution for P/Encke, 4 revolutions for P/Tuttle and P/Stephan-Oterma. In fact, P/Encke has already made 60 revolutions since its discovery, P/Tuttle 15 revolutions, and none of them shows signatures of approaching an early disappearance.

It must be concluded that the assumptions involved in this mass determination are invalid. Evidently, both c and C in Eqs. (1) and (2) are appreciably higher for short-period comets than for long-period comets, which is most probably due to a considerable reduction of their effective surface area by a non-volatile crust (Shul'man, 1972). It may also be noted that the diameter of P/Encke, as determined from (1) with c = 32 km and H = 9.8 (Meisel and Morris, 1982) comes out D = 0.35 km. Radar detection of this comet (Kamoun et al., 1982a) sets the limits of D at 0.8 to 8 km. Other estimates, as assembled by Whipple (1978a) and by Kamoun et al. (1982b) yield different values, but all within the above radar range. The uncertainty of 1:10 in size means one of 1:1000 in lifetimes computed by comparison of the total mass with the mass loss. Hence, the resulting limitation to between 20 and 20,000 revolutions covers all possibilities which may be reasonably admitted, and no progress is possible without making the size estimates much sharper. It is hoped that the spacecraft missions to P/Halley will provide a fundamental improvement of our knowledge about its size, composition and surface properties, and will make possible some calibration of the data on other comets, including the factors c and C in equations (1) - (2).

5. THE SECULAR BRIGHTNESS DECREASE

The aging of comets is inevitably accompanied by a progressive decrease of their absolute brightness. The slow rate of change makes this only detectable on short-period comets observed at a number of revolutions. The effect was most thoroughly investigated by Vsekhsvyatskij, who has spent much effort in processing photometric data on comets, and has produced comprehensive annotated lists of their absolute magnitudes at different apparitions (Vsekhsvyatskij, 1958, 1966, 1967, 1979; Vsekhsvyatskij and Il'chishina, 1974).

Under some oversimplified assumptions (a homogeneous nucleus of nearly spherical shape, with a constant depth of the surface layer removed during each revolution), the trend of the brightness changes can be predicted by a simple function with a single unknown parameter. Accordingly, the absolute brightness H should decrease by $\Delta H = +1.5$ magn. during the first half of the comet's lifetime, by the same amount during the first half of the remaining period, etc. If the acceleration of ΔH can be measured, the death date can be predicted under the above provisions. Then, assuming that short-period comets are, on the average, observed in the middle of their active lifetime, its mean duration can be estimated.

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This approach, however, leads to gross underestimates of the computed lifetimes, as evidenced by continuing observations of seven short-period comets which were predicted to disappear between 1958 and 1971: P/Pons-Winnecke, P/Tuttle, P/Wolf, P/Kopff, P/Brooks 2, P/Faye and P/Whipple (Whipple, 1964; Whipple and Douglas-Hamilton, 1966). The reasons of the failure are explained in detail elsewhere (Kresák, 1974a) and can be summarized as follows:

First, the absolute brightness of comets is subject to irregular fluctuations the amplitude of which varies substantially from one object to another. If the comet is decelerated by Jupiter into an orbit of appreciably smaller perihelion distance - and such captures are responsible for about 20% of short-period comet discoveries (Kresák, 1982a) - the change in the insolation regime makes them absolutely brighter for one or two apparitions (Kresák, 1973). Also, if there are major brightness variations from one revolution to another, it is more probable that the comet will be discovered at an increased activity level. Thus the first apparitions cannot be relied upon in determining the general rate of fading. As shown by Svoreň (1979), just the removal of the discovery apparitions is sufficient to reduce the average brightness decrease from 0.36 to 0.22 magnitude per revolution.

Second, and in particular, the photometric data on short-period comets, covering nearly two centuries, bear definite signatures of the development of observing techniques. However paradoxical it may appear, the instrumental effects make the comets fainter with time. This is because the detection threshold is improving, and large telescopes tend to record only the central condensation of the coma. A striking example of instrumental effects producing a systematic difference of over 7 magnitudes, or a ratio of almost 1:1000 in the brightness estimates, is shown in Figure 1 of Kresák (1974a; see also Whipple, 1978a).

The secular trend of the brightness estimates is illustrated by Figure 1, with Vsekhsvyatskij's absolute magnitudes H (exponent 4, H_{10} in his notation) plotted against the year of perihelion passage T. All individual apparitions of comets with periods $P < 20$ years and perihelion distances $q < 1.5$ are included. For P/Encke ($q = 0.3$, open circles) the dashed curve is approximately fitted to the catalogized H-values. While the sample of 51 apparitions of the only 11 comets of $q < 1.0$ (large solid circles) may be affected by random fluctuations of small numbers, the addition of 118 apparitions of 32 other comets of $q < 1.5$ (solid dots) makes the data fairly representative. Only very few short-period comets of $q > 1.5$ were observed during the preceding century, so that their inclusion would make the sample rather inhomogeneous.

It is apparent at first glance that the data points exhibit a progressive displacement towards higher values of H. This refers not only to the lower boundary and the means - an effect to be expected from the improvement of the observing techniques - but also to the upper boundary. There are only two alternative explanations of this. Either the short-period comets are dying out rather rapidly as a family of objects, and after one or two centuries there will be no

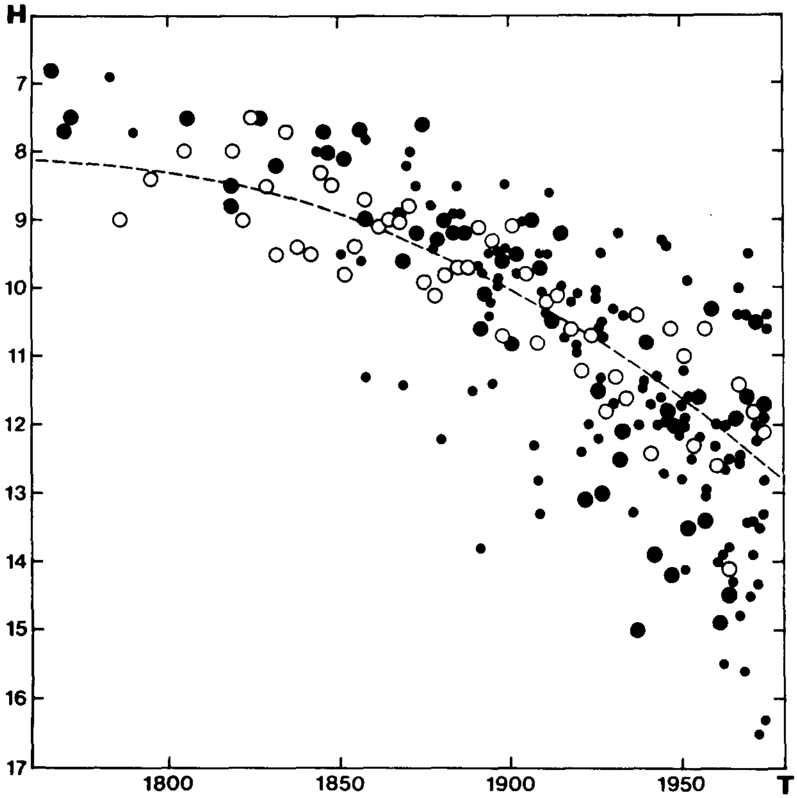

Figure 1. Vsekhsvyatskij's absolute magnitudes H for all individual apparitions of short-period comets of P < 20 years, q < 1.5 AU, as a function of the time of their perihelion passage T. Open circles, P/Encke; solid circles, all other objects of q < 1.0; solid dots, objects of 1.0 < q < 1.5.

detectable objects of this kind anymore; or the H-values are misrepresented by time-dependent instrumental effects. The former explanation appears highly unreasonable, the latter being evidently the correct one.

It is instructive that the interpolated curve for P/Encke, with a decline of more than 3 magn. during the last 100 years, deviates from the upper boundary of the populated area by only about 0.6 magn. per century. This is in fair agreement with the decrease determined from the maximum apparent brightness at different returns, which is less affected by instrumental effects because the comet is normally close to the naked-eye limit at maximum (Kresák, 1965). In his criticism of this conclusion, Sekanina (1969) defends a rapid brightness decrease accelerating from 2 magn. per century at the time of the comet's discovery to a present value of 4 magn. per century. At the same time, the failure of identifying any observations from the ancient and medieval Chinese records as pertaining to P/Encke (Ho Peng Yoke, 1962; Whipple and Hamid, 1972) implies that the secular fading must have been much less than 1 magn. per century over the past millennium or two. Whipple and Sekanina (1979) attribute this discordance to the effects associated with the precession of the comet's spin axis, leading to long-term changes of the regime of insolation, and thus to differences in the comet's activity over its heterogeneous surface and time. While this scenario is internally consistent, it can only solve the problem for this particular object and not for the comet statistics in general. Vsekhsvyatskij's (1981) mean fading rate for other short-period comets, 3 magn. per century, is even higher than the mean value of 2 magn. per century obtained from the same kind of data for P/Encke (Dobrovol'skij et al., 1983). The instrumental corrections for this comet are apparently less than the average, due to its higher apparent brightness. On the other hand, with the shortest period and smallest perihelion distance of all comets of $P < 20$ years, the time scale of fading of P/Encke should be 4 times shorter than the average. Thus there seems to be no escape from the paradox shown in Figure 1, unless substantial spurious trends in the absolute magnitudes are admitted.

Current efforts in better calibrated magnitude estimates of comets, and their unified annotated listing in International Comet Quarterly, lend promise of improvement in this respect. While this is obviously a long-term task, just the first processing and summarization demonstrates that many comets previously believed to fade rapidly, do not indeed exhibit significant changes since their discovery (Meisel and Morris, 1982). There are undoubtedly examples of a real progressive brightness drop over a limited time span, such as P/Faye in the second half of the 19th century. On the other hand, there are comets like P/D'Arrest which was at its last apparition 2 magn. brighter than at the time of discovery 20 revolutions ago, or P/Perrine-Mrkos whose variations are entirely erratic. For an overwhelming majority of short-period comets the total systematic reduction of absolute brightness since their discovery appears to be definitely within the noise of irregular fluctuations.

The same observational effects apply to long-period comets as well, being only less pronounced because of their higher apparent brightness. Many of them would exceed the naked-eye limit, which would eliminate the instrumental effects entirely. Even so, it is possible to identify a definite spurious decrease of their mean photometric exponent with time (Table VIII in Kresák, 1974a), which is due to the extension of the observed orbital arcs by the use of larger telescopes. The widespread opinion that the brightness of short-period comets exhibits a steeper exponential dependence on heliocentric distance ($I \propto r^{-6}$) than that of long-period comets ($I \propto r^{-4}$) seems to result from the same instrumental effect.

As a statistical approach to elucidating the process of comet aging, Yabushita and Hasegawa (1981) use a correlation between the dynamical age, as represented by the binding energy $1/a$, and the physical age, as represented by the absolute magnitude H. Combining this correlation with the theoretical diffusion rate in $1/a$, they

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find that the mean number of 700 revolutions required for a capture of a new comet into an orbit of $P \sim 100$ years is accompanied by a mean brightness decrease of 1.6 magn. This is only equivalent to 0.002 magn. per revolution, or to 0.03 magn. per century for a typical comet of the Jupiter family. By taking in account only comets of $P > 30$ years, they essentially eliminate the systematic effect of the recurrence of discovery opportunities and the underestimates of the apparent brightness of short-period comets. Unfortunately, other selection effects remain involved. The demands on the duration and accuracy of astrometric observations are much more severe if a comet is to be classified as a new one; and the mean perihelion distance of new comets is larger. Both of these effects tend to increase the mean absolute brightness of new comets, but the former also makes them more numerous among the comets observed recently. This selection is reflected by the proportion of the two dynamical types of comets compared, strongly varying with time: it increases from 0.9 : 1 before 1900, through 2.9 : 1 between 1900 and 1950, to 7.5 : 1 after 1950! Now, these variations running along with the improvement of the detection techniques, tend to make the new comets absolutely fainter. As a result, there are two selection effects operating in the opposite sense, and it is difficult to believe that they cancel out exactly. Also, the perturbations in the perihelion distance make individual revolutions unequal in the decay rate, and a total extinction of a number of comets in the course of their dynamical evolution implies that the present population of comets of $P \sim 100$ years is composed of objects which were originally brighter than those constituting the present population of new comets. The problem involves so many poorly known parameters that this approach does not appear promising.

Another indirect source of information on the aging rates was pointed out by Hughes and Daniels (1982), who have found a significant difference in the absolute magnitude distribution functions of long- and short-period comets. Just like in the preceding case, there are two types of selection effects working in the opposite sense. For fainter objects the statistics of short-period comets are much more complete, because of the recurrence of discovery opportunities with their revolution periods. This effect tends to increase the slope of their distribution function, as compared with that of the long-period comets. At the same time, their much lower apparent brightness makes the instrumental effects more severe, and the absolute brightness of fainter objects becomes seriously underestimated. This effect tends to decrease the slope of their distribution function. And finally, the magnitude distribution of long-period comets is definitely far from exponential, with an abrupt cutoff near $H = 12$ magn., i.e., within the range characteristic for short-period comets (Kresák, 1978; Sekanina and Yeomans, 1984).

From all what was said it can be concluded that the time scale and irregularity of the systematic decrease of comet brightness, as well as the instrumental and selection effects involved, are such that the available photometric data cannot answer quantitatively the question of comet lifetimes.

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6. DIRECT EVIDENCE FROM OBSERVED CASES OF DISAPPEARANCE

The most straightforward way to determine the lifetimes of comets leads through specifying those cases where the death of the comet coincided with its observation. This is substantially easier for short-period comets, which can be repeatedly observed over decades to centuries. Failure of rediscovery at subsequent predicted returns would provide a good check of the comet's ultimate disappearance. As for the long-period comets, we have to restrict ourselves on circumstantial evidence gathered from a few weeks or months of observation around the perihelion.

At present we know 109 comets with revolution periods less than 20 years, and 18 between 20 and 200 years. Only 83 comets (76%) of the former group and 14 comets (78%) of the latter were observed at their last perihelion passage. Taken at the face value, these figures would imply the disappearance of 30 short-period comets, or a mean lifetime of 26 revolutions. However, a more detailed examination of all circumstances shows that in most cases the loss was due to other reasons than the death of the comet: mainly to changing observing geometry and inaccuracy of orbit determination (Kresák, 1981b). In fact, two thirds of the lost comets were discovered under especially favourable observing conditions which normally recur once or twice per century. For almost all of the lost comets there was either no favourable return since the last observation; or between the last observation and transition into an orbit of larger perihelion distance resulting in a considerable reduction of its apparent brightness; or between the last observation and the time when the ephemeris became entirely unreliable. To explain the failure of rediscovery, it even seems unnecessary to assume progressive fading. There are many cases of rediscovery of comets which were long held for hopelessly lost, the most recent examples being P/Denning-Fujikawa, P/Schwassmann-Wachmann 3, P/DuToit-Hartley, and P/Peters-Hartley. Sorting out all cases where the loss is readily explainable by other reasons, there remain only three or four comets for which a virtual disappearance can be inferred: P/Biela (in 1852), P/Brorsen (in 1879), P/Westphal (in 1913), and possibly P/Neujmin 2 (after 1927). The active lifetimes of comets expressed by the number of revolutions should increase approximately with the square root of the semilatus rectum of the orbit - a dependence which can be replaced with good approximation by one on the perihelion distance. Then, observations suggest lifetimes of about 300 $q^{1/2}$ revolutions for comets of $P < 20$ years, and about 100 $q^{1/2}$ revolutions for comets of $20 < P < 200$ years.

An analysis of the observational records, orbital data and observing geometry of all 400 long-period comets discovered since 1840 (Kresák, 1984) helped to identify eight cases where the disappearance was apparently due to the final extinction of the comet (1859, 1897 III, 1903 I, 1926 III, 1954 II, 1954 XII, 1957 IX, and 1974 XV). One cannot be entirely sure with each individual case, but since there are additional cases of weaker evidence, the number of eight seems to be a fair estimate. There is a full agreement with the expectation that the rate of aging is proportional to the rate of change of the true anomaly, and that the lifetime varies with $q^{1/2}$. Comets approaching extinction are absolutely faint, lack in distinct nuclear condensation of the coma, and the ultimate brightness drop is much steeper than expected for a progressive removal of homogeneous spherical layers of volatiles. The mean active lifetime of long-period comets can be estimated at 20 $q^{1/2}$ revolutions. Unfortunately, most of the dying comets were observed too short to allow determination of their binding energies. Nevertheless, there is some indication that the mean lifetime (the number of revolutions) tends to increase with 1/a, i.e. with the dynamical age of the comet.

7. INDIRECT DYNAMICAL EVIDENCE

While the present review is concentrated on independent information on the physical aging of comets as a tool for improving the interpretation of the dynamical data, some constraints set by numerical modelling of their motions deserve mentioning. In the first place, it is the excess of nearly parabolic orbits ($1/a < 10^{-4}$) which has led to the concept of the Oort cloud (Oort, 1950).

The relevance of this phenomenon to the problem of comet aging is illustrated by Figure 2. The histogram pointing upwards shows the distribution of binding energies $E = 1/a$ of 111 best determined orbits of long-period comets (Marsden et al., 1978) before entering the planetary zone; that pointing downwards applies to the same comets after leaving it. The sharp peak at $0 < E < 10^{-4}$, formed by the

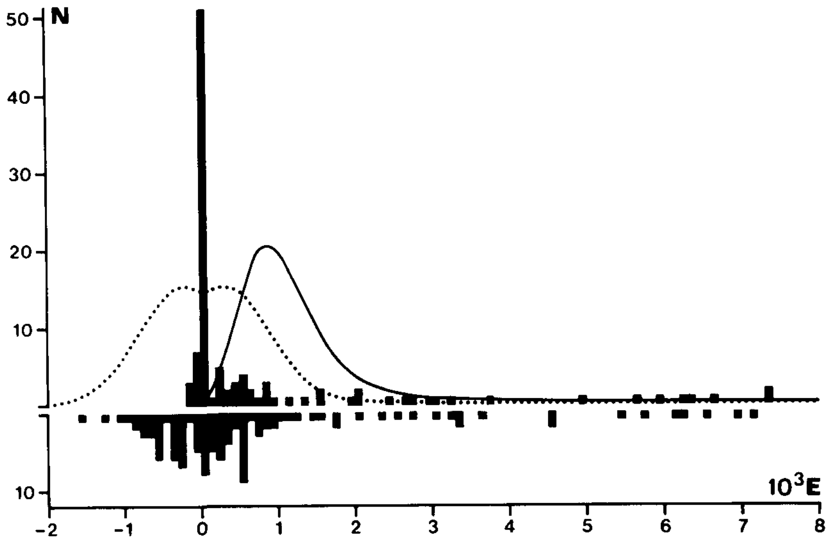

Figure 2. Distribution of the binding energies $E = 1/a$ of long-period comets before entering the planetary region (up), and after leaving it (down). For explanation of the curves see text.

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new comets, is smeared out completely just by the first passage between the planets. The dotted curve indicates the expected distribution immediately after the passage (Everhart, 1969), and the full curve that corrected for the probability of the next apparition falling into a limited time span (i.e., weighted by $E^{3/2}$). For a better discrimination, the curves are scaled by a factor of 10 with respect to the histograms.

While the lower histogram agrees very well with the dotted curve, there is a striking discrepancy between the upper histogram and the full curve. This implies that almost all of the new comets must have been observed at their only passage near the Sun, and will not return as observable objects anymore. Of course, this conclusion is tied with the assumption of a statistically steady influx of new comets, but we have no evidence contrary to it.

The nature of new comets still leaves some open questions. First, they do not display any apparent destructive changes during their apparitions, suspected to be the last ones. In view of their wide range of perihelion distances, one would expect that those with perihelia closer to the Sun will disappear more rapidly. But just on the contrary, the proportion of large-q orbits is appreciably higher among new comets than among the old ones. Second, energy perturbations which would become detectable in the statistics of comet orbits by smearing out the peak in the 1/a distribution, correspond to perihelion passages between Saturn and Uranus (Fernández, 1981), which seems too far for triggering the outgassing activity and aging of the nucleus. But in the random walk of their perihelia due to stellar perturbations, many of them should have evolved through this stage before the discovery apparition.

A simultaneous loss of the dynamical and physical signatures of new comets is indeed difficult to explain. Whipple (1977b) suggests that their fading away may be due to the removal of a primordial surface frosting of the nucleus, activated by a long exposure to the cosmic rays. The possibility of a rejuvenation process, effective on a time scale of 10^6 - 10^7 years (Kresák, 1977) lacks in the knowledge of an appropriate mechanism. The main problem with the new comets is that most of them seem to disappear exactly between their first and second passage near the Sun. Even if all the 8 extinct comets mentioned in Section 6 were new, this would be far from enough to explain the sharp peak in Figure 2.

Another implication of numerical modelling is that the statistics of dynamical evolutions remain at variance with observation when infinite physical lifetimes of comets are assumed. This fact was independently demonstrated by a number of authors. In general agreement with Dobrovol'skij's (1972) theoretical expectations, Fernández (1981) finds a good fit with the observed 1/a distribution of long-period comets for physical lifetimes L = 200 - 500 revolutions at $q < 1$, and a good fit with the proportion of new to old comets for L = 210 revolutions. However, his new/old ratio of 1:11 appears to be strongly underestimated, due to a much higher accuracy of the orbit determination required for the classification of a comet as a new one; for the best determined orbits (Marsden et al., 1978) the

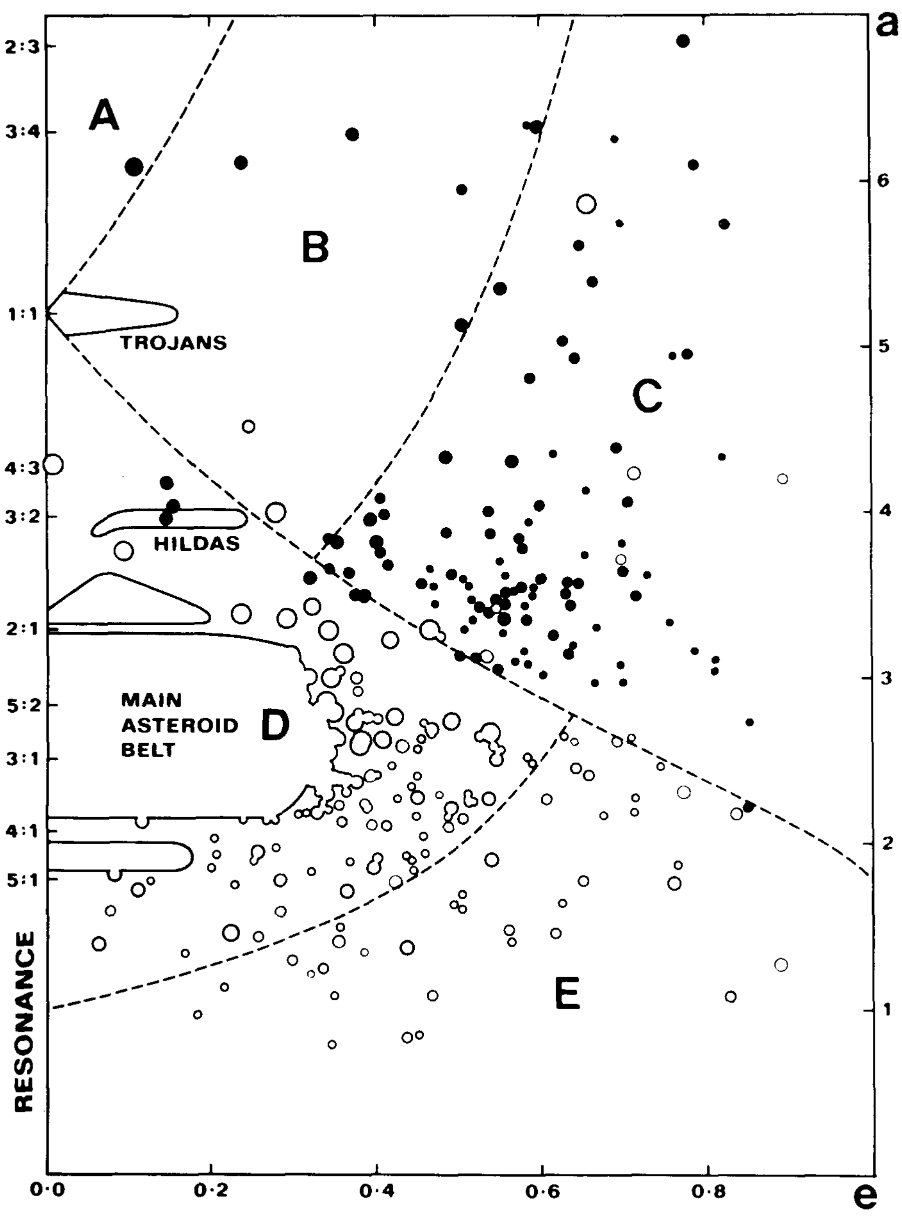

Figure 3. Short-period comets (solid circles) and asteroids (open circles) plotted in a diagram of semimajor axis vs. eccentricity. The increasing circle sizes distinguish tentatively the objects by size : diameter less than 1 km or a lost object, 1 to 3 km, 3 to 10 km, 10 to 30 km, > 30 km. A indicates the transjovian region, B Jupiter's domain of weak cometary activity, C Jupiter's domain of strong cometary activity, D the minor planet region, and E the Apollo region.

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proportion is nearly 1:1. Rickman and Vaghi (1976), simulating the evolution of short-period comets, assume L = 100 $q^{1/2}$ revolutions, but they point out that longer lifetimes would allow for more realistic replenishment rates from the region between Jupiter and Saturn. Weissman (1980) assumes much higher values of L = 600 to L = 28,000 for q = 1, depending on the albedo. Dividing the physical end states of long-period comets left in the solar system into random disruption and formation of an insulating crust, he finds disruption prevailing by a factor of four. He also finds the best combined fit of energy and perihelion distance distributions with 85% of comets subject to disruption and 15% immune to it. Hence, also in this case different interpretations exist, and the quantitative estimates of lifetimes cover a broad range.

8. THE FINAL EVOLUTIONARY STAGE

From a purely dynamical point of view, there are only two possible end fates of comets: catastrophic collision with some other object and hyperbolic ejection from the solar system, the latter being much more frequent. The physical evolution of comets, however, implies alternative possibilities: a total disintegration into meteoroids, dust and gas; a total loss of volatiles leaving one or more asteroid-like inactive nuclei; and a total coverage by a crust, after which the remnant can be reactivated again. Under very specific circumstances, the operation of nongravitational forces may also help the comet to settle in a stable orbit, e.g. in resonance with Jupiter. The principal distinction between a cometary orbit and an asteroidal orbit - the stability of motion - can thus get lost completely. This is also valid inversely, because destabilization of asteroids, in particular those librating around low-order resonance, is possible under special circumstances as well. By the degree of dynamical stability, the Amor and Apollo asteroids represent a transition between normal asteroids and short-period comets. It appears that both sources participate in maintaining the Amor-Apollo population, but there is little consensus about their relative contribution (Öpik, 1963; Whipple, 1967; Wetherill, 1979; Kresák, 1979 and 1981c; Degewij and Tedesco, 1982; Simonenko and Levin, 1983).

The recent series of discoveries of peculiar asteroids moving in comet-like orbits opened an unexpected development of this problem. Not long ago the dividing line between comets and Amor-Apollo asteroids appeared rather sharp. For example, in the semimajor axis/eccentricity diagram there was practically no overlap, except for the asteroid 944 Hidalgo situated deep within the comet region, and the librating asteroids whose stability is controlled by the resonance rather than by the size and shape of the orbit. The a/e diagram, depicted in its 1978 shape in Kresák (1979b) and Degewij and Tedesco (1982) is presented in its updated version in Figure 3. One can clearly recognize a number of new asteroids occupying the comet region, in particular 5025 P-L (Van Houten et al., 1984), 1983 SA, 1982 YA, 1984 BC and 1983 XF. All of them are faint objects complying in every respect with our expectation of extinct comet nuclei.

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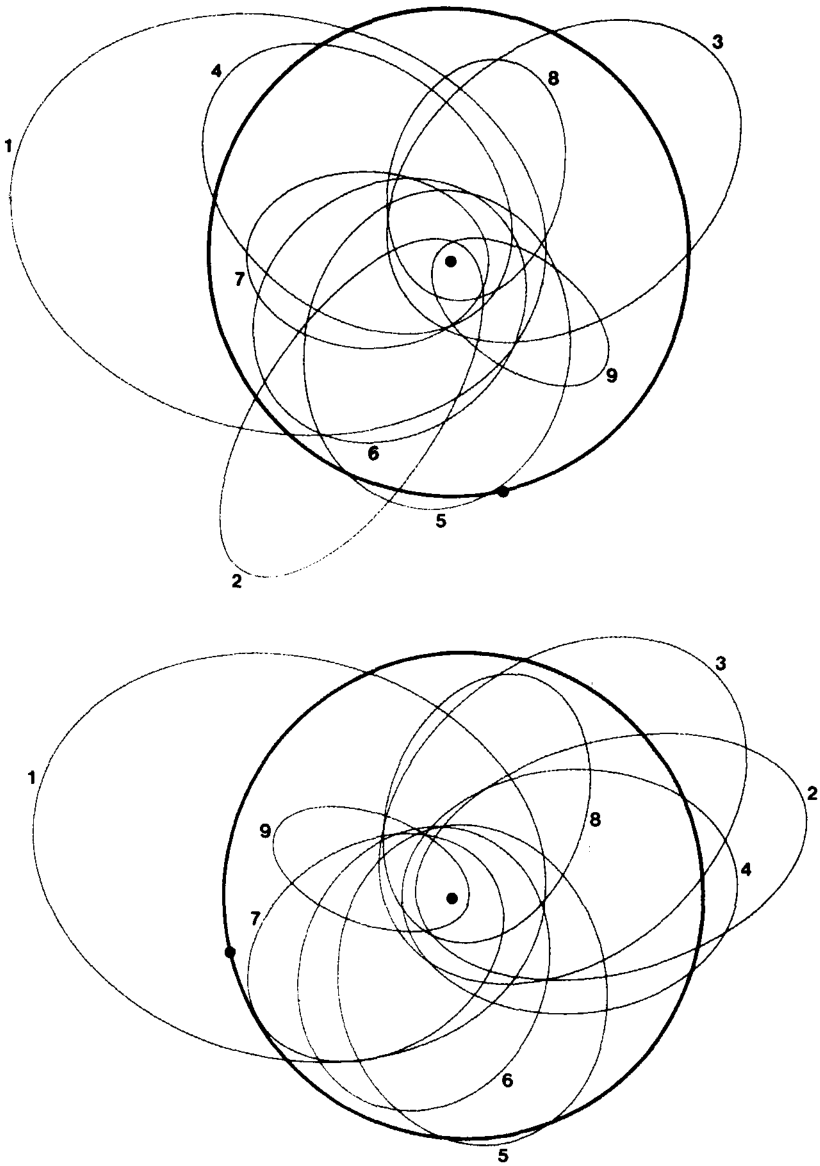

Figure 4. Above, most comet-like asteroid orbits : 1 = 944 Hidalgo, 2 = 5025 P-L, 3 = 1983 SA, 4 = 1982 YA, 5 = 1984 BC, 6 = 1983 XF, 7 = 1983 LC, 8 = 1983 VA, 9 = 2212 Hephaistos. Below, similar comet orbits : 1 = P/Wild 1, 2 = P/Denning-Fujikawa, 3 = P/Swift-Gehrels, 4 = P/Finlay, 5 = P/Kopff, 6 = P/Tempel 1, 7 = P/Blanpain, 8 = P/Grigg-Skjellerup, 9 = P/Encke. The two pictures are rotated by 90^{o} with respect to one another, as indicated by the dots marking the Sun and the perihelion of Jupiter's orbit (the thick, low-eccentricity ellipse). Vernal equinox is down for the asteroids and to the left for the comets.

The long-term integrations of these objects, as performed by Benest et al. (1985) and Hahn and Rickman (1985) are entirely consistent with their cometary origin.

The orbits of nine asteroids which are most comet-like are plotted in the upper half of Figure 4; the lower half shows a selection of nine comet orbits which are most similar to them. The two pictures are rotated by 90^0 with respect to one another to bear out the similarity more clearly; it must be stressed that there are no individually associated pairs of close orbits, as one could infer for Nos 1 (944 Hidalgo and P/Wild 1) or 3 (1983 SA and P/Swift-Gehrels) after the rotation. Another comet-like asteroid is 1939 TN, but this may well be an active comet. The absence of a coma may be simply due to its large perihelion distance (3.4 AU) and brightness near the plate limit of the four existing photographic observations. An entirely exceptional object is 2060 Chiron (Kowal, 1979; Oikawa and Everhart, 1979) revolving between Saturn and Uranus. The asteroid of smallest known perihelion distance, 1983 TB, identified as the parent body of the Geminid meteor stream (Whipple, 1983b; Williams et al., 1985), demonstrates that even inactive objects with aphelia in the inner zone of the asteroid belt may be indistinguishable from active comets as to the production of meteor showers and the observable properties of their members (Jacchia et al., 1967). Transition from the objects of Figure 4 to typical Amor and Apollo asteroids is represented by 6433 P-L, 1979 VA, and others.

An important point is that the number of known asteroidal objects moving in cometary orbits is already about 1/10 of the active comets, as far as objects with aphelia inside the orbit of Saturn are concerned. Except for the big Hidalgo (diameter 28.6 km according to Bowell et al., 1979), their diameters range between 0.5 km and 6.0 km (median 1.8 km) if albedo of S-type asteroids is assumed, and are twice as large for C-type albedo. This is about the same as the size estimates for larger short-period comets. Since the observational coverage must be much more complete for active objects of comparable size, it seems that the number of extinct comets revolving within the orbit of Saturn is at least the same as that of the active ones and possibly even greater.

On the other hand, there is not a single known asteroid moving in an orbit similar to those of over 600 known comets with aphelia beyond Saturn. It is true that in the ecliptical zone, where searches for small solar system objects are most effective, short-period comets would spend more time and move at lower angular velocities, which makes their detection easier. But even so the discrepancy is much too large. It suggests that the end fates of long- and short-period comets and, hence, their structure and physical evolutions are different.

9. CONCLUSIONS

From the various possible approaches to determining the lifetimes of comets, those based on the mass loss rates are limited by our lack of knowledge of the exact sizes of cometary nuclei; and those based

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on the progressive fading are biased by instrumental and selection effects involved in the determination of the absolute brightness of comets. Indirect methods still give controversial or ambiguous results. Direct observational evidence on the disappearance of some comets, when properly corrected for all interfering effects, seems to be most reliable, yielding estimates of mean lifetimes with an uncertainty presumably within a factor of two.

The main feature of the lifetimes, as expressed by the number of revolutions for which the comet remains active, is their broad dispersion. The physical survival is strongly correlated with the revolution period, and thereby with the dynamical age of the comet, as documented by the following table. For the first entry the period refers to the original orbit, i.e. to the osculating orbit before entering the planetary region.

Revolution period	Mean lifetime
years	revolutions
$> 10^6$	mostly 1
$200 - 10^6$	$20\ q^{1/2}$
$20 - 200$	$100\ q^{1/2}$
< 20	$300\ q^{1/2}$

There is little doubt about an additional considerable dispersion within individual dynamical types; but in general, the number of revolutions for which the comet remains active tends to increase with the number of revolutions required for entering the respective type of orbit. The only feasible explanation of this interrelation is a substantial difference between individual comets just at the time when they enter the inner region of the solar system and become active for the first time. During the number of revolutions required for capturing the comet into a short-period orbit, selection by size and structure becomes effective. If all comets come from the Oort cloud, those which are not abnormally resistive disintegrate long before reaching the short-period stage, unless they are ejected by accelerating perturbations.

After a new comet has passed for the first time near the Sun, its activity may become substantially reduced by the loss of a super-active frosting (Whipple, 1977b). During the subsequent returns the comet would purge its renewing insulating crust (Whipple, 1978b). At this evolutionary stage, the activity is kept at a slowly decreasing level, corresponding approximately to a progressive removal of surface layers to the same depth per revolution. Normally, the comet would become destroyed after a few tens of revolutions. This process may be accompanied by splitting of the nucleus which would occur, on the average, about twice during the comet's active lifetime. However, only exceptionally the secondary fragments are large enough to reduce substantially the survival time of the primary component. The progressive disintegration of the parent object of the Kreutz group of comets by solar tides is possibly one of such exceptions.

Towards the end of the comet's lifetime, the relative mass loss and the absolute brightness drop would strongly accelerate, giving rise to an abrupt decrease of the number of active comets at $H > 12$ (Kresák, 1978; Sekanina and Yeomans, 1984). As evidenced by the observed absence of asteroidal objects moving in long-period orbits, all or almost all long-period comets disintegrate completely at the end of their active lifetime. They may also evolve into objects of Halley type ($P \sim 100$ years), provided that they are able to survive physically $\sim 100\ q^{1/2}$ revolutions. The latter figure is rather uncertain due to the very limited statistical sample available.

The situation is different for short-period comets of the Jupiter family ($P < 20$ years), typical lifetimes of which amount to $\sim 300\ q^{1/2}$ revolutions. A definite disproportion between their mass loss rates and photometric size estimates indicates the presence of a shielding crust of non-volatile low-albedo materials. Temporary activation of isolated surface areas (in rare cases possibly due to impacts of small satellites - Whipple, 1983a and 1984) makes them more apt to sudden brightness bursts, which can reduce their lifetimes even more drastically than the splitting (Kresák, 1974b). It appears that the conversion factor between absolute brightness and mass (Equation 2) is substantially higher for short-period comets than for the long-period ones.

The reason for this difference between long- and short-period comets is puzzling, the more that there are no observable systematic differences in their radiation mechanism (Donn, 1977). One possible explanation is that their birthplaces are different, which would allow for their different internal constitution. The short-period comets may come, at least predominantly, from the inner condensation of the Oort cloud, as hypothesized by Whipple (1972), Hills (1981), and Fernández and Ip (1983). This inner condensation would provide an adequate source of replenishment not only for the short-lived family of short-period comets, but also for the outer envelope of the Oort cloud, stripped away during encounters with the giant molecular clouds (Van den Bergh, 1982; Bailey, 1983). In fact, if the latter process is also going on, the original source would be essentially the same. But even in this case, or in the case of absence of the inner condensation, the two types of comets differ substantially by their dynamical history. The comets of the Jupiter family would have to make a number of revolutions with perihelia not far from the orbit of Jupiter, within Everhart's (1973) capture zone, before their perihelion is changed into aphelion. This interlude could affect their subsequent physical evolution and survival time, whether by changing their surface structure or by removal of the less resistive objects, before they become detectable. The IRAS data files may already contain some information on such objects.

The decelerated physical evolution of short-period comets would allow at least some of them to leave extinct asteroid-like nuclei.

It remains open whether such objects still include some supply of volatiles under their surface crusts, which would make possible a later re-activation, say, by a non-destructive collision. Otherwise their dynamical lifetimes would be limited mainly by accelerating encounters with Jupiter.

REFERENCES

Bailey, M.E.: 1983, Mon. Not. R. Astron. Soc. 204, pp. 603-633.
Benest, D., Bien, R. and Rickman, H.: 1985, this volume.
Bowell, E., Gehrels, T. and Zellner, B.: 1979, in T. Gehrels (ed.), Asteroids, Univ. Arizona, Tucson, pp. 1108-1129.
Carusi, A., Kresák, L., Perozzi, E. and Valsecchi, G.B.: 1984, IAU Circ. No. 3940, and this volume.
Degewij, J. and Tedesco, E.F.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 665-695.
Delsemme, A.H.: 1976, Lecture Notes in Phys. 48, pp. 314-318.
Delsemme, A.H.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 85-130.
Delsemme, A.H. and Rudd, D.A.: 1973, Astron. Astrophys. 28, pp. 1-6.
Dobrovol'skij, O.V.: 1972, IAU Symp. 45, pp. 352-355.
Dobrovol'skij, O.V., Ibadinov, Kh.I., Aliev, S. and Gerasimenko, S. I.: 1983, Dokl. Akad. Nauk Tadzh. SSR 26, pp. 25-29.
Donn, B.A.: 1977, in A.H. Delsemme (ed.), Comets, Asteroids, Meteorites, Univ. Toledo, Ohio, pp. 15-23.
Everhart, E.: 1969, Astron. J. 74, pp. 735-750.
Everhart, E.: 1973, Astron. J. 78, pp. 329-337.
Feldman, P.D.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 461-479.
Fernández, J.A.: 1980, Mon. Not. R. Astron. Soc. 192, pp. 481-491.
Fernández, J.A.: 1981, Astron. Astrophys. 96, pp. 26-35
Fernández, J.A. and Ip, W.-H.: 1983, Icarus 54, pp. 377-387.
Finson, M.L. and Probstein, R.F.: 1968, Astrophys. J. 154, pp. 327-380.
Hahn, G. and Rickman, H.: 1985, Icarus, in press.
Harwit, M.: 1967, in J.L. Weinberg (ed.), The Zodiacal Light and the Interplanetary Medium, NASA, Washington, pp. 307-313.
Hills, J.G.: 1981, Astron. J. 86, pp. 1730-1740.
Ho Peng Yoke : 1962, Vistas in Astron. 5, pp. 127-225.
Hughes, D.W. and Daniels, P.A.: 1982, Mon. Not. R. Astron. Soc. 198, pp. 573-582.
Jacchia, L.G., Verniani, F. and Briggs, R.E.: 1967, Smithson. Contr. Astrophys. 10, pp. 1-139.
Kamoun, P.G., Campbell, D.B., Ostro, S.J., Pettengill, G.H. and Shapiro, I.I.: 1982a, Science 216, pp. 293-295.
Kamoun, P.G., Pettengill, G.H. and Shapiro, I.I.: 1982b, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 288-296.
Kowal, C.T.: 1979, in T. Gehrels (ed.), Asteroids, Univ. Arizona, Tucson, pp. 436-439.
Kresák, L.: 1965, Bull. Astron. Inst. Czechosl. 16, pp. 348-355.

Kresák, L.: 1973, Bull. Astron. Inst. Czechosl. 24, pp. 264-283.
Kresák, L.: 1974a, Bull. Astron. Inst. Czechosl. 25, pp. 87-112.
Kresák, L.: 1974b, Bull. Astron. Inst. Czechosl. 25, pp. 293-304.
Kresák, L.: 1977, in A.H. Delsemme (ed.), Comets, Asteroids, Meteorites, Univ. Toledo, Ohio, pp. 93-97.
Kresák, L.: 1978, Bull. Astron. Inst. Czechosl. 29, pp. 114-125 and 135-149.
Kresák, L.: 1979a, IAU Symp. 90, pp. 211-222.
Kresák, L.: 1979b, in T. Gehrels (ed.), Asteroids, Univ. Arizona, Tucson, pp. 289-309.
Kresák, L.: 1981a, Bull. Astron. Inst. Czechosl. 32, pp. 19-40.
Kresák, L.: 1981b, Bull. Astron. Inst. Czechosl. 32, pp. 321-339.
Kresák, L.: 1981c, Adv. Space Res. 1, pp. 85-90.
Kresák, L.: 1982a, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 56-82.
Kresák, L.: 1982b, Bull. Astron. Inst. Czechosl. 33, pp. 150-160.
Kresák, L.: 1984, Bull. Astron. Inst. Czechosl. 35, pp. 129-150.
Lindblad, B.A.: 1985, this volume.
Marsden, B.G., Sekanina, Z. and Everhart, E.: 1978, Astron. J. 83, pp. 64-71.
McIntosh, B.A. and Hajduk, A.: 1983, Mon. Not. R. Astron. Soc. 205, pp. 931-943.
Meisel, D.D. and Morris, C.S.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 413-432.
Ney, E.P.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 323-340.
Oikawa, S. and Everhart, E.: 1979, Astron. J. 84, pp. 134-139.
Oort, J.H.: 1950, Bull. Astron. Inst. Netherl. 11, pp. 91-110.
Öpik, E.J.: 1963, Adv. Astron. Astrophys. 2, pp. 219-262.
Öpik, E.J.: 1973, Astrophys. Space Sci. 21, pp. 307-398.
Rickman, H. and Vaghi, S.: 1976, Astron. Astrophys. 51, pp. 327-342.
Roemer, E.: 1966, Mém. Soc. R. Sci. Liège 12/1, pp. 23-28.
Sekanina, Z.: 1969, Astrometriya i Astrofizika 4, pp. 54-76.
Sekanina, Z.: 1982, in L.L. Wilkening (ed.), Comets, Univ. Arizona, Tucson, pp. 251-287.
Sekanina, Z. and Yeomans, D.K.: 1984, Astron. J. 89, pp. 154-161.
Shul'man, L.M.: 1972, IAU Symp. 45, pp. 271-282.
Simonenko, A.N. and Levin, B.Yu.: 1983, Highlights of Astronomy 6, pp. 391-398.
Stefanik, R.P.: 1966, Mém. Soc. R. Sci. Liège 12/1, pp. 29-32.
Svoreň, J.: 1979, Contr. Astron. Obs. Skalnaté Pleso 8, pp. 105-140.
Van den Bergh, S.: 1982, J. Astron. Soc. Canada 76, pp. 303-308.
Van Flandern, T.C.: 1981, Icarus 47, pp. 480-486.
Van Houten, C.J., Herget, P. and Marsden, B.G.: 1984, Icarus 59, pp. 1-19.
Vsekhsvyatskij, S.K.: 1958, Fizicheskie Kharakteristiki Komet, Gos. izd. fiz.-mat. literatury, Moskva, 575 pp.
Vsekhsvyatskij, S.K.: 1966, Fizicheskie Kharakteristiki Komet 1954-1960 gg, Nauka, Moskva, 88 pp.
Vsekhsvyatskij, S.K.: 1967, Komety 1961-1965 gg, Nauka, Moskva, 86 pp.

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Vsekhsvyatskij, S.K.: 1979, Fizicheskie Kharakteristiki Komet 1971-1975 gg, Naukova dumka, Kiev, 116 pp.
Vsekhsvyatskij, S.K.: 1981, Problemy Kosm. Fiziki 16, pp. 20-25.
Vsekhsvyatskij, S.K. and Il'chishina, N.I.: 1974, Fizicheskie Kharakteristiki komet 1965-1970 gg, Nauka, Moskva, 112 pp.
Weissman, P.R.: 1980, Astron. Astrophys. 85, pp. 191-196.
Wetherill, G.W.: 1979, Icarus 37, pp. 96-112.
Whipple, F.L.: 1964, Astron. J. 69, pp. 152-155.
Whipple, F.L.: 1967, in J.L. Weinberg (ed.), The Zodiacal Light and the Interplanetary Medium, NASA, Washington, pp. 409-426.
Whipple, F.L.: 1972, IAU Symp. 45, pp. 401-408.
Whipple, F.L.: 1977a, Icarus 30, pp. 736-746.
Whipple, F.L.: 1977b, in A.H. Delsemme (ed.), Comets, Asteroids, Meteorites, Univ. Toledo, Ohio, pp. 25-35.
Whipple, F.L.: 1978a, in J.A.M. McDonnell (ed.), Cosmic Dust, Wiley, Chichester, pp. 1-73.
Whipple, F.L.: 1978b, Moon and Planets 18, pp. 343-359.
Whipple, F.L.: 1983a, Highlights of Astronomy 6, pp. 323-331.
Whipple, F.L.: 1983b, IAU Circ. No. 3881.
Whipple, F.L.: 1984, Icarus, in press.
Whipple, F.L. and Douglas-Hamilton, D.H.: 1966, Mém. Soc. Roy. Sci. Liège 12/1, pp. 469-480.
Whipple, F.L. and Hamid, S.E.: 1972, IAU Symp. 45, pp. 152-154.
Whipple, F.L. and Sekanina, Z.: 1979, Astron. J. 84, pp. 1894-1909.
Williams, I.P., Fox, K.A. and Hunt, J.: 1985, this volume.
Yabushita, S. and Haségawa, I.: 1981, Mon. Not. R. Astron. Soc. 195, pp. 361-370.

DISCUSSION

B. Lokanadham : How the complete disintegration of some comets could be explained ?

L. Kresák : Unless the nucleus is differentiated with depth, the only processes which can prevent a complete disintegration are removal of the perihelion far from the Sun or formation of an insulating crust. Otherwise the nucleus would grow smaller, until no sizable object remains. The total disappearance of P/Biela and P/Brorsen, and the absence of asteroidal objects moving in long-period high-eccentricity orbits, hardly admit an alternative end fate for a majority of comets.

P. Weissman : I believe that these lifetimes you state are too short and they are influenced by a variety of physical and observational effects. For new comets from the Oort cloud it is obvious that they are anomalously bright due to a surface layer of more volatile ices which sublimate away on the first return. This is clear from the 1/a vs. q scatter diagram, where only new comets are found beyond about 3 AU, the point at which water ice sublimation becomes negligible. This step decrease in brightness occurs only on the first return and only slow fading occurs afterward. Our thermal calculations show that for a 1 km nucleus with perihelion of 1 AU the

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lifetime is about 1000 returns against sublimation. In reality, the governing process on the lifetime of comets is more likely the build-up of nonvolatile crusts on the nucleus, or random disruption, each of which gives much shorter lifetimes, but not as short as you state. Also, the thermal modeling indicates the sublimation or crust build-up processes have a $q^{0.7}$ dependence (the exponent increasing sharply beyond 2 - 3 AU), not $q^{0.5}$. Random disruption does not appear to be strongly correlated with perihelion distance. I do agree that comets appear to have variable "survivability" as some sort of intrinsic quality, the more survivable comets being the ones which evolve to short-period orbits.

L. Kresák : For the mean lifetime of 1000 returns, the probability of having just a single observational record of extinction of a long-period comet would be about 1:8. In fact, there are about five cases where this seems to be proven beyond any shadow of doubt, and about ten additional cases of various degree of confidence. From this point of view, a mean lifetime much longer than 20 returns appears inconsistent with observational evidence. But I agree that the most survivable objects, in particular some short-period comets, can remain active for 1000 revolutions or more. Observational evidence also casts doubts on the assumption that the new comets from the Oort cloud simply become much fainter for the subsequent returns. In that case we would have an abundance of absolutely faint, dynamically old long-period comets. However, what we observe is just the opposite: a definite lack of long-period comets of $H > 12$ magn. The lifetime dependence on $q^{0.5}$ is the simplest way to take in account the integrated insolation, without considering its efficiency for the destruction processes. More sophisticated thermal models may yield different and variable values of the exponent, but I think we know too little about the crusting and purging processes, phase transition effects etc. to be sure which is correct. The q-distribution of comet disappearances is fully consistent with the exponent of 0.5, but it would not contradict to that of 0.7 either. The difference is simply too small, within ± 10% for one half of the known comets, and for statistical mean lifetime estimates it is practically irrelevant. Similarly, the neglect of the reduced irradiation efficiency at larger solar distances cannot affect the results appreciably, because one half of these comets have $q < 1$ AU, and thus receive more than 50% of the total irradiation at $r < 2$ AU. The main source of uncertainty is definitely the limited size of the sample of known comets, and the limited time span covered by the observations.