PERSPECTIVES: PLANETARY SCIENCE

Where Have All the Comets Gone?

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Beyond the orbit of the most distant planets, the Oort cloud has long been known as the source of the comets that reach the inner solar system. But the distribution of the dynamically evolved, "captured" comets from the Oort cloud has been difficult to explain. In particular, there is a severe deficit in the number of comets observed in short-period orbits like that of comet Halley.

On page 2212 of this issue, Levison *et al.* (*1*) investigate this so-called "fading problem" by combining two models: a detailed model of the dynamical evolution of comets from the Oort cloud to intermediate and short-period orbits, and a statistical model that describes the likelihood that current astronomical surveys would discover these comets or their inert "asteroidal" remnants. This refined model still predicts two orders of magnitude more comets in short-period "Halley-type" orbits (periods of revolution $P < 200$ years) than are observed.

The modern picture for the origin of comets was first developed in detail by Oort (*2*). He proposed that the planetary system is surrounded by an enormous swarm of comets, with randomly distributed orbits that extend almost halfway to the nearest star. Oort's model was spherically symmetrical, with the Sun at the center, and contained about 2×10^{11} comets with diameters greater than a few kilometers. In this model, the cometary space density varied roughly as $r^{-3/2}$, where r is the distance from the Sun. More recent models (*3–5*) indicate a greater degree of central condensation, with most of the mass in a hypothetical dense inner core at $r \approx 10^3$ to 10^4 astronomical units (AU), where 1 AU is the mean distance of Earth from the Sun.
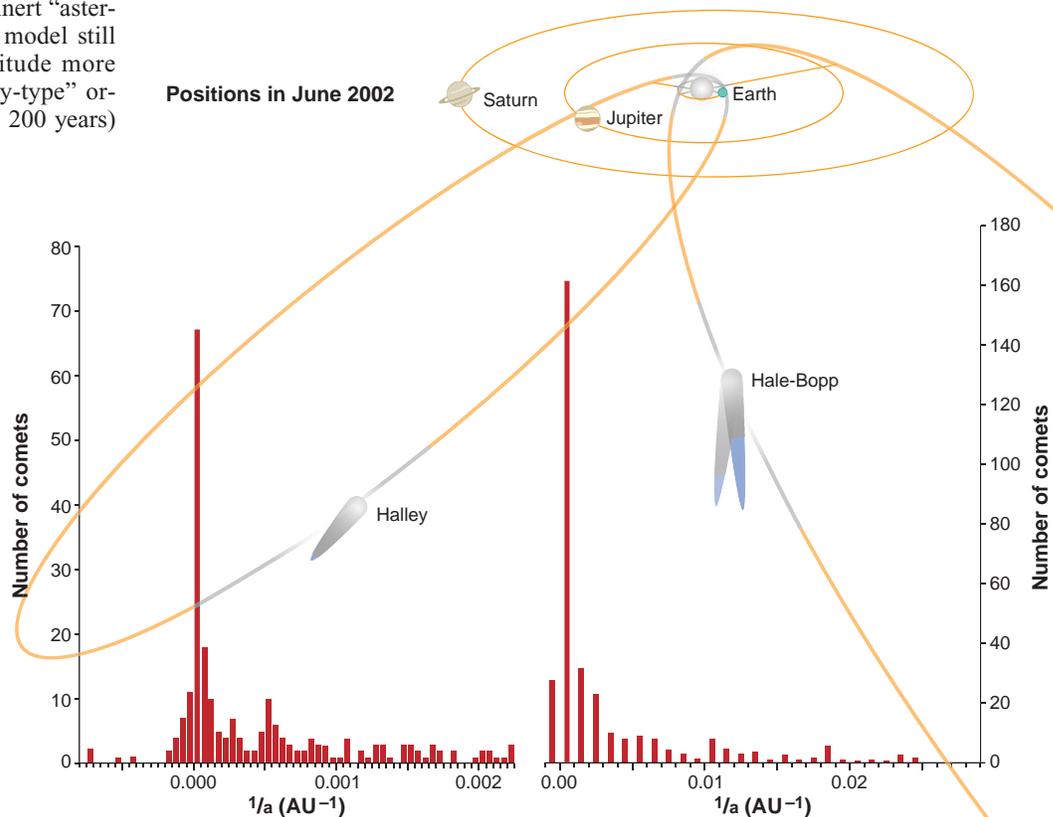
This picture for the home of comets has stood the test of time remarkably well. However, the inability to predict accurately the observed flux of nearly isotropic intermediate and short-period comets shows that much in the cometary world remains obscure. It is timely that the fading problem (*6–13*) should be reassessed in light of new observations and theoretical understanding.

This is not the first time that our understanding of comets has proved incomplete. For years, it was known that the distribution of perihelion directions of long-period comets was nonuniform (*14–17*) and that the Oort cloud must be affected by the differential tidal gravitational force

of the Galaxy (*18*). Yet it was not until the early 1980s that Oort's picture, in which random stellar perturbations feed new long-period comets into the inner solar system, was overturned. The old order was replaced by one in which perturbations by the Galactic disc were dominant (*19–21*), with stellar and occasional molecular cloud perturbations producing occasional enhancements in the comet flux—so-called comet showers—on time scales of 100 to 1000 million years.

Similarly, Jupiter-family comets (those with low-inclination "direct" orbits and $P < 20$ years) were long believed to originate primarily as a result of the action of Jupiter on long-period comets. This belief persisted even though far too many Jupiter-family comets were observed relative to predictions (*22, 23*). This problem has been resolved by introducing into models new sources for Jupiter-family comets: either a dense inner core of the Oort cloud (*3, 4, 24, 25*), necessary in any case to explain the outer Oort cloud's dynamical survival for the age of the solar

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The fading problem. The frequency distribution of the semimajor axes, $1/a$, for 330 long-period and new comets (*38*), superposed on a plot of the inner solar system and the orbits of comets Halley and Hale-Bopp provided by D. J. Asher. The $1/a$ distribution is shown on two scales (left, bin width 50×10^{-6} AU^{-1}; right, bin width 10^{-3} AU^{-1}). The whole of the first histogram to the right of $1/a = 0$ is contained in the first two positive bins of the second plot. The similar shape of the two plots shows that the fading problem is not solely an issue for dynamically new comets. Without fading, apart from the Oort cloud spike, the $1/a$ distribution would be nearly flat. Note the existence of a few puzzling cases of comets with originally slightly hyperbolic orbits; these are usually explained as a result of outgassing or poor orbit determination.

system, or the newly discovered Edgeworth-Kuiper belt (26–30).

The fading problem, however, has been a persistent thorn in the flesh of the Oort theory. The Oort cloud explains why most long-period comets have such extremely long periods, with orbits stretching in some cases more than halfway to the nearest star (see the figure). But close examination shows that the frequency distribution of $1/a$ values (where a is half the length of the elliptical orbit) has too few comets at large $1/a$. Astronomers have therefore introduced an arbitrary "fading" function that links the physical and dynamical evolution of cometary nuclei. It has been suggested that 95% of comets that are initially favorably perturbed, so as to return to the inner planetary system, are never seen (11–13).

Comets are expected to decay (if only because of observed mass loss), but there is no direct evidence that new comets from the Oort cloud disappear in such large numbers. On the contrary, the repeated return of comet Halley suggests that kilometer-sized cometary nuclei may survive for hundreds or perhaps thousands of revolutions before finally disintegrating.

Herein lies the problem: If comets fade, then they must do so largely out of sight and probably at large heliocentric distances. If comets do not decay, however, then there should be many more intermediate-period comets than observed, and far more Halley-type comets. Previous estimates (31–36) have now been independently confirmed by the new, comprehensive computer-based model of Levison et al., who argue that the majority of comets must physically disrupt.

This important result raises the question: Where does the mass go? An alternative possibility, not favored by Levison et al., is that long-period comets become inert (that is, they lose the capacity to undergo outgassing) and hence evolve into low-albedo objects resembling asteroids, virtually invisible against the blackness of space. These potentially hazardous objects—the astronomical equivalent of black cats in coal cellars—have important implications for programs aiming to identify the next kilometer-size impactor before it identifies us.

Another alternative is that Oort cloud comets may easily break up into essentially unobservable smaller bodies after just a few perihelion passages. The Sun-grazing Kreutz family may be a prototype. These comets have orbital periods of hundreds of years, yet they appear to have undergone a hierarchy of fragmentation events during at least the past two millennia. There are at least half a dozen Sun-grazing families,

each potentially containing tens of thousands of comets and subcometary fragments with diameters from 10 to 100 m. Astronomers using data from the Solar and Heliospheric Observatory (SOHO) satellite have detected nearly 500 such comets in less than 7 years, with new objects reported on an almost daily basis.

With the recognition that the Kreutz group is not unique and the observation of other examples of split comets, a few of them disappearing before our eyes, an important cometary end-state may have been identified. This, however, also raises the specter of a cometary risk to civilization, as a result of encounters with possibly dense cometary meteoroid streams containing fragments of a size that could produce catastrophic events on Earth.

A third possibility is that Oort cloud comets decay into nothing more substantial than dust. The rapid disintegration of a kilometer-sized cometary nucleus into its component dust and ice grains is perhaps a seriously counterintuitive result, especially as most comets run into nothing harder than the solar wind. However, a few comets have been observed to disintegrate for no apparent reason. If comets decay rapidly to dust, then the dense meteoroid trails should be detectable—for example, as meteor showers, through impacts on spacecraft, or possibly via thermal infrared emission analogous to the dust trails discovered with the Infrared Astronomical Satellite (IRAS) (37).

Perhaps, as with previous questions concerning the origin of comets, astronomers are collectively missing a trick. A fundamental, though not essential, tenet of the Oort theory is that the observed cometary flux is in a steady state, with the numbers of short-period and other comets in balance with the observed near-parabolic flux from the Oort cloud and other reservoirs. Could the steady-state assumption be mistaken? This would put us in the uncomfortable position of living at a special epoch, perhaps within a few million years of the start of a comet shower (6, 9), with all sorts of attendant repercussions; but while such models may show promise, none completely resolves the fading problem (33, 36).

If comets indeed disrupt, whether to unobservable small bodies or to dust, Levison et al. (1) make the interesting point that perhaps this behavior truly distinguishes the nearly isotropic Halley-type short-period comets from those of the Jupiter family, which in their model originate from the Edgeworth-Kuiper belt rather than the Oort cloud. In this case, the different fading behavior of the two classes of comet would provide the first hard

evidence for a real physical difference between the "inner" and "outer" comets, perhaps the result of different origins and thermal and collisional histories.

At present, comets remain a puzzle: They have to be both strong and weak, and there seems to be a substantial missing mass. Does this provide a clue to the origin of cometary material?

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