The evolution of comets in the Oort cloud and Kuiper belt

S. Alan Stern

Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 400, Boulder, Colorado 80302, USA

Comets are remnants from the time when the outer planets formed, ~4–4.5 billion years ago. They have been in storage since then in the Oort cloud and Kuiper belt—distant regions that are so cold and sparsely populated that it was long thought that comets approaching the Sun were pristine samples from the time of Solar System formation. It is now recognized, however, that a variety of subtle but important evolutionary mechanisms operate on comets during their long storage, so they can no longer be regarded as wholly pristine.

Comets are small bodies with characteristic sizes of 1 to 15 kilometres that orbit the Sun[1,2]. They are usually detected as they approach the Sun because their near-surface volatiles sublimate under the increasing insolation, in turn generating an extensive, highly visible gas-and-dust atmosphere, called the coma. Because of the small size of the solid nucleus of the coma, a comet's gravity is too weak to retain these constituents, so the coma expands to great distances and is lost to space. As first recognized decades ago[3,4], the cometary nucleus is the source of the escaping gas and dust that make up both the coma, and its extension, called the tail. Strong circumstantial evidence, based on the ease with which comets split and fragment, points to the inherent mechanical weakness of cometary nuclei[5]; in fact, many comets may essentially be strengthless, gravitationally bound 'piles of rubble'[6].

Comets consist of approximately equal proportions of nonvolatile solids (silicates, refractory organics) and volatile ices. Cometary ices are dominated by water ice[3], but CO_2 and CO are also present at significant levels (in extreme cases having combined abundances as high as ~15–20% that of the water ice[2]). Other volatiles, notably including H_2S, CH_3OH, H_2CO, NH_3, HCN, CH_4 and S_2, have also been detected in the atmospheres of comets. The presence of such a wide array of high-volatility species strongly suggest that comets (1) originated in the cool, outer regions of the Sun's protoplanetary nebula and (2) have ever since been stored only in cold conditions[2–4].

Most comets have very long-period orbits that extend from thousands to several tens of thousands of astronomical units (AU) from the Sun. This, and the related observation that the orbits of such comets are nearly isotropically oriented relative to the plane of

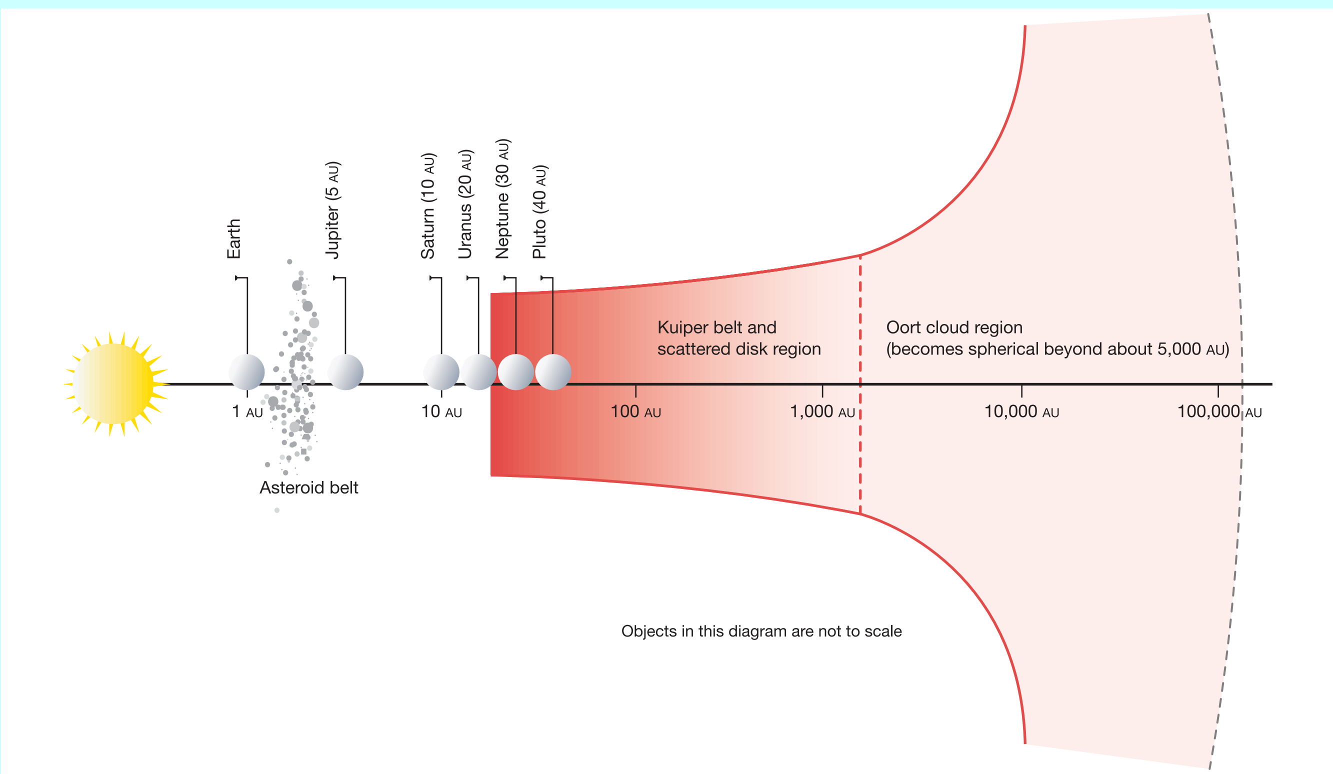

Figure 1 Diagram showing the Kuiper belt and Oort cloud to scale with our planetary system. The huge scale of the Oort cloud can be appreciated by the fact that the nearest star is located only about three times farther from the Sun than the edge of the Oort cloud (that is, $\sim 3 \times 10^5$ AU from the Sun).

the Solar System, caused Oort to conclude in 1950 that such comets must be derived from an essentially spherical reservoir surrounding the Sun at these very great distances[8]. This reservoir is now known as the Oort cloud. Modern estimates[9] place the number of Oort cloud comets in the range 10^{11} to perhaps 5×10^{12}, corresponding to a total Oort cloud mass of order 1 $M_\oplus$ (where $M_\oplus$ is the mass of the Earth) to perhaps 50 $M_\oplus$ (depending also upon the presently ill-determined typical masses of cometary nuclei). Models of Solar System and Oort cloud formation[10,11] have repeatedly shown that the formation of an Oort cloud is a natural by-product of the clearing and ejection of debris from the giant planets' region some ~3.5–4.5 Gyr ago. (See Table 1.)

Not all comets, however, have the highly extended orbits indicative of an extremely distant, spheroidal reservoir. On the contrary, many comets are observed to be on much more tightly bound orbits that are either trapped among the planets, or never stray to the Oort cloud[12]. Unlike the isotropically distributed orbits of the Oort cloud comets, these shorter-period comets predominantly display shallow, prograde orbital inclinations relative to the plane of the Solar System.

In the late 1980s and early 1990s, these facts were used to infer that a second, as yet undiscovered cometary reservoir must exist. This second reservoir must be far more compact (lying primarily within a few hundred AU) and more disk-like (typical orbital inclinations of <30°) than the huge, spherical Oort cloud[13]. The existence of such a disk of material beyond the planets had been suggested by various workers, most famously Kuiper[14]. Kuiper's hypothesis was that a debris field of remnant, small bodies might naturally be expected beyond the last of the giant planets, representing a region where planetary formation had not gone to completion. By the early 1990s it became possible for groundbased techniques to detect moderate-sized bodies in this region directly, which is now known as the Kuiper belt[15].

Comets are the oldest and coldest, the most accessible, and the most nearly pristine samples of the outer solar nebula available for study[2]. Of course, it was known even 20 years ago that comets are modified by early, internal radiogenic heating[7] and insolation-driven evolution after dislodgement from their storage regions[16]. It was long thought that comets were essentially held in perfect stasis during their long storage in the remote, cold dynamical storage reservoirs known as the Oort cloud and the Kuiper belt. In recent years, however, a broad array of processes have been discovered that could describe the evolution of comets while they are in cold storage. Owing to our lack of knowledge of the thermophysical and structural details of cometary surfaces, which can only be definitively explored through *in situ* orbiter/lander and sample return missions, it is not yet clear which of these evolutionary processes dominate. Nonetheless, there is a growing appreciation that comets do evolve during storage in the Oort cloud and the Kuiper belt in a variety of potentially important ways.

Processes affecting comets during dynamical storage

The longstanding big-picture view of cometary evolution has been that the cryogenic conditions and highly dilute nature of the Oort cloud and the Kuiper belt suggest conditions of stasis. This, along with evidence that comets themselves are samples of the planetesimal population from which the planets were built, suggested long ago[17] that comets represent wholly pristine samples from the formation epoch of the planets. Chiefly for these reasons, comets remain on the top priority list of planetary science mission targets[18]. Nonetheless, a variety of thermal, collisional, radiation, and interstellar medium (ISM) processes affect comets during their long storage in the Oort cloud and Kuiper belt. These processes complicate the interpretation of cometary observations and suggest that *in situ* sample analysis and sample return missions will reveal a substantially modified surface layer on comets. I will now describe each of the various effects that cause comets to evolve while in dynamical storage far from the Sun.

Thermal processes. Because of the Oort cloud's immense cross-section, it has been recognized since the 1950s that passing stars regularly penetrate it; this process has long been known to be fundamental to the diffusion and dynamical randomization of orbital inclinations in the Cloud[8,11,19]. In the late 1980s, it was also recognized that such encounters also have consequences for the heating of comets there[20].

Importantly, rare parsec-range and closer encounters with highly luminous O and supergiant stars ($L_\star \approx 3$–$6 \times 10^5 L_\odot$, where L is the luminosity of a star or the Sun, depending on the subscript) as far away as 5 pc were found to be capable of heating the entire Oort cloud well above its ambient 5–6 K temperature, to temperatures capable of removing the most volatile ices from surface layers. For example, there is a unit chance that in the past 4.5 Gyr a 'nearby' (5 pc distant) O star has heated the Oort cloud to 16 K, thereby removing species like condensed neon and molecular oxygen. (Owing to the far greater proximity of the Sun to the Kuiper belt than the Oort cloud, however, such highly luminous stars do not much affect the 30–60 K ambient temperature of Kuiper belt comets, raising them only ~1 K.)

Although supernovae explosions are far briefer (~0.1 yr) than O-star passages (~3×10^4 yr), supernovae are so much more luminous ($L_\star \approx 10^9 L_\odot$) than even the brightest O stars, that they can heat the Oort cloud from far larger distances. Using modern supernova rates and luminosity estimates, it has been estimated[20] that ~30 supernovae heating events close enough (<20 pc) to heat the surfaces of Oort cloud objects to 30 K have occurred in the past 4 Gyr; this in turn depletes the abundances of condensed, near-surface argon, CO, N_2 and CH_4. Furthermore, models indicate there is a unit chance that the Oort cloud should have experienced one supernova heating event to 50 K over the past 4 Gyr, and there is a 50% probability that a supernova heating event occurred to warm all cometary surfaces to 60 K, at which temperature other important species like formaldehyde will be depleted. This effect probably masks some primordial signatures in the surface (but not the deep interior) compositions of Oort cloud and Kuiper belt comets.

Given a heating timescale, the depth of penetration of the thermal wave resulting from a stellar or supernova encounter can be estimated from the diffusion equation, based on the thermal properties of the surface material, the orientation of the cometary rotation pole, and the duration of the heat pulse. The major uncertainty in this calculation is the thermal diffusivity of cometary

Table 1 **The primary cometary reservoirs of the Solar System**

	Kuiper belt	Oort cloud
Shape	Disk-like	Spheroidal
Distance range	30–1,000 AU	1×10^3–1×10^5 AU
Comet population	~5–10 × 10^9	1×10^{11}–5×10^{12}
Estimated mass (including smaller debris)	~0.1 $M_\oplus$	1–50 $M_\oplus$
Ambient surface temperatures	30–60 K	5–6 K
Origin	Largely *in situ*	Ejected material from the Kuiper belt and outer-planets zone
Return mechanism from the reservoir	Dynamical chaos due to planetary perturbations and collisions	Perturbations due to passing stars, galactic tides and molecular clouds

surfaces, which—owing to the lack of returned comet samples and orbital/lander missions—has never been directly measured. By adopting a range of surface diffusivities consistent with ice-conductivity measurements relevant to cometary materials[21,22], it was found that the thermal wave of a typical, O-star encounter could plausibly penetrate to depths of 5–50 m into comets. Supernovae encounters, while generating a more severe thermal pulse, are much briefer. Therefore their intense but shorter thermal pulses have been estimated to propagate only 0.1–2 m into cometary surfaces[20]. The primary effect of these heating events is preferentially to remove supervolatiles like O_2, N_2, He, Ne, CO, CH_4 and Ar from cometary surface layers. However, these heating events may also be related to both high cometary ice spin-temperature results[2,23] and the depletion of argon recently reported in some comets by observers using the FUSE spacecraft[24].

Collisional processes. The enormous volume of the Oort cloud dilutes the spatial density of comets to very low levels (the mean separation between comets in the Oort cloud is of the order of 50–500 million km). This, combined with the very low orbital velocities in the Oort cloud (of the order of 0.2 km s^{-1}), naturally suggests an almost collisionless environment. Collision-rate estimates for bodies in the Oort cloud[25] have confirmed this, indicating that (1) Oort cloud comets must be ancient and (2) the fraction of a typical Oort cloud comet's surface that is expected to be covered by craters caused by collisions with other objects during the 4.5-Gyr storage in the Oort cloud is of order 1% or less, depending on assumptions regarding the Cloud's spatial density. Nonetheless, although collisions in the Oort cloud itself are rare and apparently of little effect, recent work indicates that collisions probably greatly affected the surfaces and interiors of many of these bodies during their ejection from the planetary region to the Oort cloud[26].

The collisional history of the Kuiper belt is different[27,28]. Kuiper belt comets are widely thought to have originated essentially *in situ* in the Kuiper belt. However, owing to the higher orbital speeds (typically 4 km s^{-1}) and space density of kilometre-sized bodies (higher than in the Oort cloud by a factor of 2×10^5), collision rates in the KB exceed those in the Oort cloud by a factor of the order of 10^6. Importantly, Kuiper belt collisions happen at such high speeds that they are highly erosional, causing Kuiper belt comets to lose surface material over time. In fact, the time-averaged rate of erosion in the Kuiper belt is so high that almost all kilometre-scale and smaller Kuiper belt bodies are now thought to be fragments 'chipped' off larger Kuiper belt objects in the last 10–20% of the age of the Solar System. Hence, most comets derived from the Kuiper belt are expected to exhibit low surface exposure ages, and are therefore not expected to exhibit many craters.

These results, now obtained by many independent groups[27,28], represent both a significant shift in our view of cometary bodies, and a great difference between Kuiper belt and Oort cloud comets. Whereas Oort cloud comets are still expected to be (damaged) relics of the formation era, most Kuiper belt comets must be young. Furthermore, owing to collisions, the interior mechanical properties and structure of both Oort cloud and Kuiper belt comets are unlikely to reflect their gentle accretional environment, having been significantly modified by the effects of collisions thereafter.

Interactions with the interstellar medium. The first study of the interaction between comets and the ISM was made three decades ago[29,30], when it was suggested that ISM gas would slowly accrete onto cometary surfaces, forming an accretion crust that might amount to a layer 10–100 μm thick over 4.5 Gyr. However, these studies ignored the role of high-velocity ISM grain impacts on cometary surfaces.

Later, when the competition between ISM grain-driven erosion and ISM gas-driven accretion was first modelled[31], it was found that grain-driven erosion on icy surfaces is about 1,000 times more efficient than gas accretion, causing comets to lose (rather than gain) material as a result of ISM interactions. The primary reason for this is that while gas sticking is inefficient (typical sticking ratios being a few per cent), high-velocity grain impacts (at typical ISM–comet relative velocities of 10–30 km s^{-1}) are very efficient at micro-cratering (causing far more material to be lost from the cometary surface than the imported mass of the impacting grain). Similar results were obtained in studying the source of dust generated in β Pictoris-type stellar disks[32].

Owing primarily to the strong density gradients between the cloud and intercloud phases of the interstellar medium, it was subsequently found[33] that ISM interactions vary severely in time. Indeed, it was found that the majority of the surface erosion comes during the occasional passage of the Solar System through galactic, giant molecular clouds (GMCs). It is estimated that about 5–10 such erosion events have occurred since the formation of the Oort cloud, which may in total have caused comets in the Oort cloud to have lost about 1–20 m of surface material since the formation of the Oort cloud[2].

Comets in the Kuiper belt will also suffer from this erosion because they cannot be protected by the heliosphere (ISM pressure during GMC passage compresses the heliosphere down to a size perhaps as small as 5 AU). However, given the much younger ages of cometary surfaces in the Kuiper belt (owing to collisions), the number of expected GMC erosion events likely to have occurred on these bodies is only about one, and could plausibly be zero. Therefore, it is uncertain whether the surfaces of present-day Kuiper belt comets may, or may not, have experienced a significant ISM-driven surface erosion.

Radiation processes. This area subdivides naturally into two subcategories: photon bombardment and charged particle bombardment[34]. Considering photon bombardment first, interstellar and solar ultraviolet (that is, $h\nu > 3$ eV) photons have copious fluxes in the Oort cloud and Kuiper belt, providing the energy necessary to break bonds and initiate substantial chemical change in cometary

Table 2 **Cometary evolution mechanisms in the Kuiper belt and Oort cloud**

	Primary effects	Maximum modification depth	Primary temporal style	Notes
Heating by supernovae	Loss of supervolatiles	Metres	Stochastic	Less important in the Kuiper belt
Heating by passing stars	Loss of supervolatiles	Tens of metres	Stochastic	Less important in the Kuiper belt
Collisions	Cratering, regolith evolution and overturning, and structural/thermophysical evolution	Tens of metres	Stochastic	Not important in the Oort cloud
Ultravidet damage	Chemical reactions, polymerization, surface albedo and colour changes	Tens of micrometres	Continuous	More effective in the Kuiper belt
Cosmic ray damage	Chemical reactions, sputtering devolatalization, polymerization, surface albedo, colour and microstructure changes	Metres	Continuous	–
Sputtering erosion by ISM gas	Regolith removal and selective loss of volatiles	Tens of micrometres	Continuous	More effective in the Kuiper belt
Mechanical erosion by ISM grains	Regolith removal and erasure of other evolutionary effects	Metres	Stochastic	–

surfaces. Ultraviolet photosputtering is capable of eroding away the uppermost few micrometres of icy surfaces[35]. But more importantly, in a classic series of laboratory experiments and theoretical studies, M. Greenberg showed that ultraviolet photons would produce significant alteration of the composition, colour, and volatility of the upper several to few tens of micrometres of cometary surfaces[36]. Others[37,38] confirmed and extended these results, showing that ultraviolet photons promote surface darkening (to albedos of only a few per cent) and devolitalization that becomes progressively more severe with dosage, and therefore age. Because of their much closer proximity to the Sun, Kuiper belt comets experience a much ($\sim 10^5$ times) higher ultraviolet and solar cosmic ray (SCR) surface dose, greatly increasing the total deposited charged-particle energy incident on the surfaces of these bodies, relative to Oort cloud comets, but their ~10 times lower average surface age somewhat mitigates this effect.

Now consider energetic charged particles. The fluence of charged particles in the Oort cloud is dominated by Galactic Cosmic Rays (GCRs) with keV-to-MeV energies. Like ultraviolet photons, charged particle radiation is capable of both sputtering surfaces and breaking bonds, thereby inducing chemical reactions and consequently reordering the surface ice matrix[39]. The irreversible radiation-driven conversion of the original, water-dominated ice matrix to a more complex 'crust' inevitably leads to the darkening of the surface, via the formation of long-chain hydrocarbons[36,37]. If cometary surfaces have bulk densities of $1\,\mathrm{g\,cm^{-3}}$ or less, then the cosmic ray damage layer may reach several metres in depth[40]. The GCR dose onto Kuiper belt comets is expected to be much reduced, relative to Oort cloud comets, because of the shielding effects of the heliosphere out to ~100 AU.

The chemical and structural changes in cometary surfaces produced by radiation processes may be responsible for some instances of cometary activity at large distances (5–15 AU) during the approach of new comets to perihelion[16]. Indeed, this may explain the greater tendency for Oort cloud comets to erupt at large heliocentric distances on their first approach to the Sun[16]. Interestingly, sputtering by cosmic rays, solar wind, or perhaps even hot ISM gas may also be responsible for generating the particles that, after acceleration, explain the long-mysterious anomalous cosmic rays (ACRs)[41].

Towards a new perspective

As a result of the discovery of evolutionary processes acting in the Oort cloud and the Kuiper belt, comets—though still the most pristine bodies known—have been modified in several important ways since their birth. It also now seems inevitable that most comets from the Kuiper belt, although they are constructed of ancient material, cannot themselves be ancient—instead they must be 'recently' created chips off larger Kuiper belt objects, formed in violent ($\mathrm{km\,s^{-1}}$ class) impacts, rather than the gentle environment required for cometary accretion in the early solar nebula. (See Table 2.)

Beyond deepening our knowledge of comets and their storage reservoirs, these effects also indicate a fascinating link between long-term cometary surface evolution and the Sun's 4.6-Gyr passage through the ISM and the Galaxy. Moreover, it now appears that the surfaces, surface ages, and deep interior mechanical properties of comets derived from the Kuiper belt and Oort cloud could be different from one another, at least before their modification by intense activity associated with heating due to passages into the warm inner Solar System.

The realization that comets do slowly evolve during their long storage in remote dynamical reservoirs provides insight and context to more confidently evaluate the results of astronomical and space mission observations of comets. It also strongly argues for relatively deep (metres scale or deeper) subsurface sampling of comets, if pristine samples of ancient material are to someday be had. □

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Correspondence and requests for materials should be addressed to S.A.S. (astern@swri.edu).

