PERSPECTIVES: PLANETARY SCIENCE

The Death of a Comet and the Birth of Our Solar System

Hermann Boehnhardt

The comet C/1999S4 LINEAR appeared first in images of the Lincoln Lab Near Earth Asteroid sky survey on 27 September 1999. It was a little more faint than its famous cousins, comets Hale-Bopp and Hyakutake, but bright enough to be seen with the naked eye in the Northern Hemisphere during summer 2000.

Unexpectedly, comet LINEAR passed away just 10 months after its discovery, only a few days before reaching the closest distance to the Sun. After some outbursts and the release of a few smaller fragments during June and early July 2000, the comet nucleus (the dirty snowball of ice and dust in the center of the coma and the origin of the phenomenon called a comet) split into several larger pieces about 100 m in diameter and millions of tons of icy junk, boulders, and dust on 21 and 22 July 2000. The debris faded away during the next 2 weeks, and, by mid August 2000, comet LINEAR was considered "dead."

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Comet LINEAR provided only a brief opportunity for observations from Earth. However, the fatal nucleus breakup at the end of its life left some unforgettable and important messages, pieces of the scientific puzzle of how our solar system was born. Six papers in this issue describe the key results from this event.

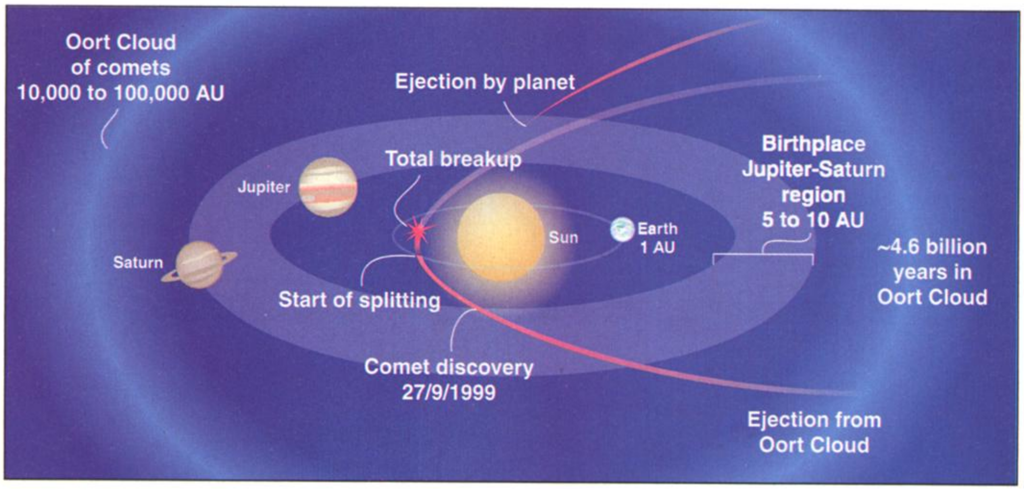
Comets are believed to be remnants from the birth of our planetary system, which evolved together with the Sun from a collapsing cloud of dust and gas some 4.6 billion years ago. This formation scenario predicts that the birthplace of comets was in the outer part of the disk surrounding the collapsing core in the center—the early Sun. Comets are therefore believed to originate from the region of the major planets Jupiter, Saturn, Uranus, and Neptune. At that distance, temperatures were low (200 K at Jupiter's and 30 K at Neptune's distance), allowing icy grains (mostly water and carbon monoxide ices) to survive in the primordial planetary disk and become the ingredients of cometary nuclei.

The planetary system in our solar system formed in three phases (*1*). First, agglomeration and gentle collision led to the growth of stones, rocks, boulders, and mountain-sized bodies (called planetesimals) from dust. This was followed by the runaway growth of planet-sized bodies through heavy collisions of planetesimals. Finally, the disk was cleaned up through gas dispersion, accretion and gravitational scattering of planetesimals by planets, and destructive collisions of the planetesimals, boulders, and rocks followed by the removal of the produced dust by radiation pressure from the Sun.

In this picture of the early solar system, comets play the role of the planetesimals in the region of the major planets. Comets that were scattered inward contributed to the heavy bombardment in the early history of the inner planets. These comets may have brought the ocean water and prebiotic organic material to Earth. Comets that were scattered outward during disk cleanup were either lost to interstellar space or "stored" in a reservoir of icy bodies at the edge of the solar system, the Oort Cloud of comets. From there, some comets are occasionally injected back into the inner solar system by gravitational interaction with neighboring stars and molecular clouds of the Milky Way. While they reside in the Oort Cloud, they are deeply frozen and their physicochemical nature remains essentially unaltered. Only the upper surface layers may change as a result of exposure to high-energy radiation (space weathering).

During its short apparition, comet C/1999S4 LINEAR illuminated some aspects of its origin and evolution. It also provides very interesting information and constraints on the formation of the solar system and the environmental conditions in the primordial planetary disk around the Sun.

Comet LINEAR formed in the inner part of the outer dust disk of the solar system [Mumma *et al.*, p. 1334 (*2*)], most likely in the Jupiter-Saturn region. The dust in this region was hot enough to cause the escape of carbon-rich molecules from the grains before they got buried in the interior of the building blocks of the nucleus. The possible depletion of carbon-rich material in Jupiter-region comets may require a critical review of the scenario of delivery of prebiotic organics to the young Earth.



The fate of comet LINEAR. The comet was likely born in the Jupiter-Saturn region in the early days of the solar system. It was ejected into the Oort Cloud, where it resided until it was recently ejected into the inner solar system. The comet broke up close to its nearest approach to the Sun, offering an opportunity for researchers to study its breakup in detail. The drawing is not to scale. Distances are given in astronomical units (AU), the distance between Earth and the Sun.

The comet nucleus had "planetesimal" size [Weaver *et al.*, p. 1329 (*3*), Mäkinen *et al.*, p. 1326 (*4*)]. Its building blocks—the subnuclei after breakup—had smaller, but still similar dimensions, thus confirming the

The author is at the European Southern Observatory, VLT Observatory Cerro Paranal, Alonso de Cordova 3107, Santiago, Vitacura, Chile. E-mail: hboehnha@eso.org

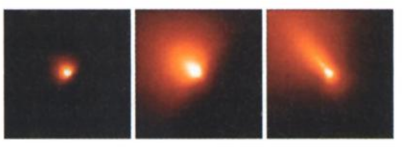
CHRONOLOGY OF COMET C/1999 S4 (LINEAR)

Date (UT)	Event	Reference
27 September 1999	Discovery announcement and suggestion that the comet may reach naked-eye visibility during mid-summer 2000	(*11*)
December 1999	Leveling off of dust production suggests that the comet may be substantially fainter than originally predicted ("Kohoutek-like" behavior)	(*12*)
5 April 2000 to 10 May 2000	Comet is within 20° of the Sun, so poorly placed for observations	
2 June, 6 June, 16 June, 5 July, 18 July 2000	Large temporal outbursts; the nucleus may be shedding large material at these times, suggesting the progressive chunks of nature of the comet's fragmentation	(*2–6*)
7 July 2000	Fragment observed near the nucleus	(*3*)
4 to 24 July 2000	Large depletions measured for C_2, CO, CH_3OH, CH_4, C_2H_6 and C_2H_2	(*2, 5, 6*)
14 July 2000	Chandra detection of x-ray line emissions, probably produced by charge exchange between cometary neutrals and solar wind ions	(*13*)
21 to 24 July 2000	Peaks in dust and gas production after major fragmentation event	(*3–6*)
22 July 2000	Comet's closest approach to Earth at 0.37 AU	
≥24 July 2000	Rapid decrease in gas production as dust grains released during the fragmentation completely lose their icy coatings	(4, *5*)
26 July 2000	Comet's closest approach to the Sun at 0.77 AU	
27 July 2000	Central condensation of light disappears, suggesting completed disruption of the nucleus	(*14*)
5 August 2000	HST detection of ≥14 fragments	(*3*)
7 August 2000	VLT detection of ≤16 fragments	(*3*)
14 August 2000	Fragments no longer visible	(*3*)

presence of 100-m-diameter planetesimals in the formation region of the comet. The internal structure of the nucleus kept the memory of its birth from planetesimal-sized bodies. Within 2 weeks of breakup, these pieces either dissolved into even smaller boulders and rocks or lost all volatile material and became inactive (dead comets).

The chemistry of the building blocks of the nucleus was very uniform [Bockelée-Morvan *et al.*, p. 1339 (*5*)]. This may thus also apply to their formation region between Jupiter and Saturn in the protoplanetary disk. The orbit and the activity evolution during the approach to the Sun classify LINEAR as a dynamically new comet from the Oort Cloud, possibly on one of its first visits to the Sun [Farnham *et al.*, p. 1348 (*6*)].

Nucleus splitting is a frequent phenomenon among comets—more than 30 cases are known—and it shows a variety of faces. The breakup of comet LINEAR ended in the complete dissolution of the nucleus, whereas the splitting of comet 73P/Schwassmann-Wachmann 3 (*7*) produced a few long-lived fragments that behave and survive as independent nuclei. Nucleus disintegration is part of the evolution scenario for comets causing either a fatal death of the object or the birth of "new" daughter comets.



A temperamental comet. These images from the Hubble telescope show a brief, violent outburst when comet LINEAR blew off a piece of its crust. The resulting mist of dust reflected sunlight, thus temporarily increasing the comet's brightness. The last picture shows the ejected chunk of material floating away along the comet's tail.

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Cometary nuclei are very fragile. However, the physics and conditions for the nucleus splitting of comets remain unclear (*8*), and only one case is really understood. Comet D/1993F2 Shoemaker-Levy 9 (*9*) broke up in July 1992 because of tidal forces when the nucleus passed Jupiter at a close distance in its orbit around the planet. The fragments exploded in Jupiter's atmosphere about 2 years later (*10*).

Cometary nuclei are among the most pristine objects that we can observe in our solar system. They preserve information on the physicochemical conditions prevailing at the time when our planetary system was formed. It is for this reason that NASA and ESA are planning to target a fleet of spacecraft for visits at a number of comets over the next 12 years.

The series will start in summer 2001, when DEEP SPACE 1 will fly by at comet 19P/Borrelly. The STARDUST mission, among others, aims to return in 2006 samples of dust grains from the fly-by at comet 81P/Wild 2 in 2004. The CONTOUR spacecraft will visit three different comets between 2003 and 2008, including 2P/Encke, 6P/d'Arrest and 73P/Schwassmann-Wachmann 3, the latter a split comet with three surviving fragments that may allow material from the interior of the nucleus to be explored at the newly exposed surface. DEEP IMPACT will probe the nucleus and subsurface layers of comet 9P/Tempel 1 through the impact of a 500-kg copper bullet. The crater and debris excavated by the impact are expected to display fresh and unaltered material from inside the nucleus. Finally, in 2012 to 2013, the ROSETTA mission will for the first time bring a spacecraft with a comprehensive set of scientific experiments in orbit around a cometary nucleus (46P/Wirtanen) and drop a lander for the in situ analysis of cometary material.

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