Figure 13.25 Gas Jets on Comet 67P. (a) This activity was photographed by the *Rosetta* spacecraft near perihelion. You can see a jet suddenly appearing; it was active for only a few minutes. (b) This spectacular photo, taken near perihelion, shows the active comet surrounded by multiple jets of gas and dust. (credit a, b: modification of work by ESA/Rosetta/MPS; credit c: modification of work by ESA/Rosetta/NAVCAM)

LINK TO LEARNING

The European Space Agency is continuing to make **interesting short videos (https://openstaxcollege.org/l/30ESAvideoros)** illustrating the challenges and results of the Rosetta and Philae missions. For example, watch "*Rosetta*'s Moment in the Sun" to see some of the images of the comet generating plumes of gas and dust and hear about some of the dangers an active comet poses for the spacecraft.

13.4 THE ORIGIN AND FATE OF COMETS AND RELATED OBJECTS

Learning Objectives

By the end of this section, you will be able to:

- Describe the traits of the centaur objects
- Chronicle the discovery and describe the composition of the Oort cloud
- Describe trans-Neptunian and Kuiper-belt objects
- Explain the proposed fate of comets that enter the inner solar system

The comets we notice when they come near Earth (especially the ones coming for the first time) are probably the most primitive objects we can study, preserved unchanged for billions of years in the deep freeze of the outer solar system. However, astronomers have discovered many other objects that orbit the Sun beyond the planets.

Centaurs

In the outer solar system, where most objects contain large amounts of water ice, the distinction between asteroids and comets breaks down. Astronomers initially still used the name "asteroids" for new objects discovered going around the Sun with orbits that carry them far beyond Jupiter. The first of these objects is Chiron, found in 1977 on a path that carries it from just inside the orbit of Saturn at its closest approach to the Sun out to almost the distance of Uranus (**Figure 13.26**). The diameter of Chiron is estimated to be about 200 kilometers, much larger than any known comet.

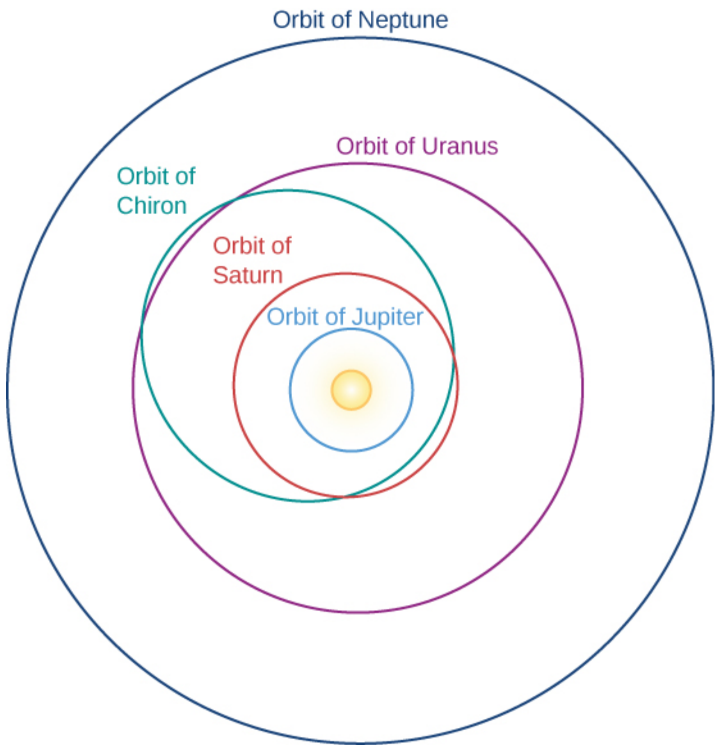


Figure 13.26 Chiron's Orbit. Chiron orbits the Sun every 50 years, with its closest approach being inside the orbit of Saturn and its farthest approach out to the orbit of Uranus.

In 1992, a still-more-distant object named Pholus was discovered with an orbit that takes it 33 AU from the Sun, beyond the orbit of Neptune. Pholus has the reddest surface of any object in the solar system, indicating a strange (and still unknown) surface composition. As more objects are discovered in these distant reaches, astronomers decided that they will be given the names of *centaurs* from classical mythology; this is because the centaurs were half human, half horse, and these new objects display some of the properties of both asteroids and comets.

Beyond the orbit of Neptune lies a cold, dark realm populated by objects called simply trans-Neptunian objects (TNOs). The first discovered, and best known, of these TNOs is the dwarf planet Pluto. We discussed Pluto and the New Horizons spacecraft encounter with it in **Rings, Moons, and Pluto**. The second TNO was discovered in 1992, and now more than a thousand are known, most of them smaller than Pluto.

The largest ones after Pluto—named Eris, Makemake, and Haumea—are also classed as dwarf planets. Except for their small size, dwarf planets have many properties in common with the larger planets. Pluto has five moons, and two moons have been discovered orbiting Haumea and one each circling Eris and Makemake.

The Kuiper Belt and the Oort Cloud

TNOs are a part of what is called the **Kuiper belt**, a large area of space beyond Neptune that is also the source of many comets. Astronomers study the Kuiper belt in two ways. New, more powerful telescopes allow us to discover many of the larger members of the Kuiper belt directly. We can also measure the composition of comets that come from the Kuiper belt. More than a thousand Kuiper belt objects have been discovered, and astronomers estimate that there are more than 100,000 with diameters large than 100 kilometers, in a disk extending out to about 50 AU from the Sun.

The short-period comets are thought to originate in the Kuiper belt, where small gravitational perturbations from Neptune can gradually shift their orbits until they can penetrate the inner solar system. The long-period comets, however, come from a much more distant reservoir of icy objects, called the Oort cloud.

Careful studies of the orbits of long-period comets revealed that they come initially from very great distances. By following their orbits backward, we can calculate that the *aphelia* (points farthest from the Sun) of newly discovered comets typically have values near 50,000 AU (more than a thousand times farther than Pluto). This clustering of aphelion distances was first noted by Dutch astronomer Jan Oort, who, in 1950, proposed an idea for the origin of those comets that is still accepted today (**Figure 13.27**).

Figure 13.27 Jan Oort (1900–1992). Jan Oort first suggested that there might be a reservoir of frozen chunks, potential comet nuclei, at the edge of the region of the Sun's gravitational influence. (credit: The Leiden Observatory)

It is possible to calculate that a star's gravitational *sphere of influence*—the distance within which it can exert sufficient gravitation to hold onto orbiting objects—is about one third of its distance to the nearest other stars. Stars in the vicinity of the Sun are spaced in such a way that the Sun's sphere of influence extends a little beyond 50,000 AU, or about 1 light-year. At such great distances, however, objects in orbit about the Sun can be perturbed by the gravity of passing stars. Some of the perturbed objects can then take on orbits that bring them much closer to the Sun (while others might be lost to the solar system forever).

Oort suggested, therefore, that the new comets we were seeing were examples of objects orbiting the Sun near the edge of its sphere of influence, whose orbits had been disturbed by nearby stars, eventually bringing them close to the Sun where we can see them. The reservoir of ancient icy objects from which such comets are derived is now called the **Oort cloud**.

Astronomers estimate that there are about a trillion (10^{12}) comets in the Oort cloud. In addition, we estimate that about 10 times this number of icy objects could be orbiting the Sun in the volume of space between the Kuiper belt (which is gravitationally linked to Neptune) and the Oort cloud. These objects remain undiscovered because they are too faint to be seen directly and their orbits are too stable to permit any of them to be deflected inward close to the Sun. The total number of icy or cometary objects in the outer reaches of our solar system could thus be on the order of 10 trillion (10^{13}), a very large number indeed.

What is the mass represented by 10^{13} comets? We can make an estimate if we assume something about comet sizes and masses. Let us suppose that the nucleus of Comet Halley is typical. Its observed volume is about 600 km^3. If the primary constituent is water ice with a density of about 1 g/cm^3, then the total mass of Halley's nucleus must be about 6×10^{14} kilograms. This is about one ten billionth (10^{-10}) of the mass of Earth.

If our estimate is reasonable and there are 10^{13} comets with this mass out there, their total mass would be equal to about 1000 Earths—comparable to the mass of all the planets put together. Therefore, icy, cometary material could be the most important constituent of the solar system after the Sun itself.

EXAMPLE 13.1

Mass of the Oort Cloud Comets

Suppose the Oort cloud contains 10^{12} comets with an average diameter of 10 km each. Let's estimate the mass of the total Oort cloud.

Solution

We can start by assuming that typical comets are about the size of Comets Halley and Borrelly, with a diameter of 10 km and a density appropriate to water ice, which is about 1 g/cm^3 or 1000 kg/m^3. We know that density = mass/volume, the volume of a sphere, $V = \frac{4}{3}\pi R^3$, and the radius, $R = \frac{1}{2}D$.

Therefore, for each comet,

$$\begin{aligned} \text{mass} &= \text{density} \times \text{volume} \\ &= \text{density} \times \frac{4}{3}\pi\left(\frac{1}{2}D\right)^3 \end{aligned}$$

Given that 10 km = 10^4 m, each comet's mass is

$$\begin{aligned} \text{mass} &= 1000\ \text{kg/m}^3 \times \frac{4}{3} \times 3.14 \times \frac{1}{8} \times \left(10^4\right)^3\ \text{m}^3 \\ &\approx 10^{15}\ \text{kg} \\ &= 10^{12}\ \text{tons} \end{aligned}$$

To calculate the total mass of the cloud, we multiply this typical mass for one comet by the number of comets:

$$\begin{aligned} \text{total mass} &= 10^{15}\ \text{kg/comet} \times 10^{12}\ \text{comets} \\ &= 10^{27}\ \text{kg} \end{aligned}$$

Check Your Learning

How does the total mass we calculated above compare to the mass of Jupiter? To the mass of the Sun? (Give a numerical answer.)

Answer:

The mass of Jupiter is about 1.9 × 10^{27} kg. The mass of the Oort cloud calculated above is 10^{27} kg. So the cloud would contain about half a Jupiter of mass. The mass of the Sun is 2 × 10^{30} kg. This means the Oort cloud would be

$$\frac{10^{27}\ \text{kg}}{\left(2 \times 10^{30}\ \text{kg}\right)} = 0.0005 \times \text{the mass of the Sun}$$

Early Evolution of the Planetary System

Comets from the Oort cloud help us sample material that formed very far from the Sun, whereas the short-period comets from the Kuiper belt sample materials that were planetesimals in the solar nebula disk but did not form planets. Studies of the Kuiper belt also are influencing our understanding of the early evolution of our planetary system.

The objects in the Oort cloud and the Kuiper belt have different histories, and they may therefore have different compositions. Astronomers are therefore very interested in comparing detailed measurements of the comets derived from these two source regions. Most of the bright comets that have been studied in the past (such as Hyakutake and Hale-Bopp) are Oort cloud comets, but P67 and several other comets targeted for spacecraft measurements in the next decade are Jupiter-family comets from the Kuiper belt (see **Table 13.2**).

The Kuiper belt is made up of ice-and rock planetesimals, a remnant of the building blocks of the planets. Since it is gravitationally linked to Neptune, it can help us understand the formation and history of the solar system. As the giant planets formed, their gravity profoundly influenced the orbits of Kuiper belt objects. Computer simulations of the early evolution of the planetary system suggest that the gravitational interactions between the giant planets and the remaining planetesimals caused the orbit of Jupiter to drift inward, whereas the orbits of Saturn, Uranus, and Neptune all expanded, carrying the Kuiper belt with them.

Another hypotheses involves a fifth giant planet that was expelled from the solar system entirely as the planetary orbits shifted. Neptune's retrograde (backward-orbiting) moon Triton (which is nearly as large as Pluto) may have been a Kuiper belt object captured by Neptune during the period of shifting orbits. It clearly seems that the Kuiper belt may carry important clues to the way our solar system reached its present planetary configuration.

MAKING CONNECTIONS

Comet Hunting as a Hobby

When amateur astronomer David Levy (**Figure 13.28**), the co-discoverer of Comet Shoemaker-Levy 9, found his first comet, he had already spent 928 fruitless hours searching through the dark night sky. But the discovery of the first comet only whetted his appetite. Since then, he has found 8 others on his own and 13 more working with others. Despite this impressive record, he ranks only third in the record books for number of comet discoveries. But David hopes to break the record someday.

All around the world, dedicated amateur observers spend countless nights scanning the sky for new comets. Astronomy is one of the very few fields of science where amateurs can still make a meaningful contribution, and the discovery of a comet is one of the most exciting ways they can establish their place in astronomical history. Don Machholz, a California amateur (and comet hunter) who has been making a study of comet discoveries, reported that between 1975 and 1995, 38% of all comets discovered were found by amateurs. Those 20 years yielded 67 comets for amateurs, or almost 4 per year. That might sound pretty encouraging to new comet hunters, until they learn that the average number of hours the typical amateur spent searching for a comet before finding one was about 420. Clearly, this is not an activity for impatient personalities.

What do comet hunters do if they think they have found a new comet? First, they must check the object's location in an atlas of the sky to make sure it really is a comet. Since the first sighting of a comet usually occurs when it is still far from the Sun and before it sports a significant tail, it will look like only a small, fuzzy patch. And through most amateur telescopes, so will nebulae (clouds of cosmic gas and dust) and galaxies (distant groupings of stars). Next, they must check that they have not come across a comet that is already known, in which case, they will only get a pat on the back instead of fame and glory. Then they must re-observe or re-image it sometime later to see whether its motion in the sky is appropriate for comets.

Often, comet hunters who think they have made a discovery get another comet hunter elsewhere in the country to confirm it. If everything checks out, the place they contact is the Central Bureau for Astronomical Telegrams at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts (http://www.cbat.eps.harvard.edu/). If the discovery is confirmed, the bureau will send the news out to astronomers and observatories around the world. One of the unique rewards of comet hunting is that the discoverer's name becomes associated with the new comet—a bit of cosmic fame that few hobbies can match.

Figure 13.28 David Levy. Amateur astronomer David Levy ranks third in the world for comet discoveries. (credit: Andrew Fraknoi)

The Fate of Comets

Any comet we see today will have spent nearly its entire existence in the Oort cloud or the Kuiper belt at a temperature near absolute zero. But once a comet enters the inner solar system, its previously uneventful life history begins to accelerate. It may, of course, survive its initial passage near the Sun and return to the cold reaches of space where it spent the previous 4.5 billion years. At the other extreme, it may collide with the Sun or come so close that it is destroyed on its first perihelion passage (several such collisions have been observed with space telescopes that monitor the Sun). Sometimes, however, the new comet does not come that close to the Sun but instead interacts with one or more of the planets.

LINK TO LEARNING

SOHO (the Solar and Heliospheric Observatory) has an **excellent collection of videos of comets (https://openstaxcollege.org/l/30SOHOcomvid)** that come near the Sun. At this site, comet ISON approaches the Sun and is believed to be destroyed in its passage.

A comet that comes within the gravitational influence of a planet has three possible fates. It can (1) impact the planet, ending the story at once; (2) speed up and be ejected, leaving the solar system forever; or (3) be perturbed into an orbit with a shorter period. In the last case, its fate is sealed. Each time it approaches the Sun, it loses part of its material and also has a significant chance of collision with a planet. Once the comet is in this kind of short-period orbit, its lifetime starts being measured in thousands, not billions, of years.

A few comets end their lives catastrophically by breaking apart (sometimes for no apparent reason) (**Figure 13.29**). Especially spectacular was the fate of the faint Comet Shoemaker-Levy 9, which broke into about 20 pieces when it passed close to Jupiter in July 1992. The fragments of Shoemaker-Levy were actually captured into a very elongated, two-year orbit around Jupiter, more than doubling the number of known jovian moons. This was only a temporary enrichment of Jupiter's family, however, because in July 1994, all the comet fragments crashed unto Jupiter, releasing energy equivalent to millions of megatons of TNT.

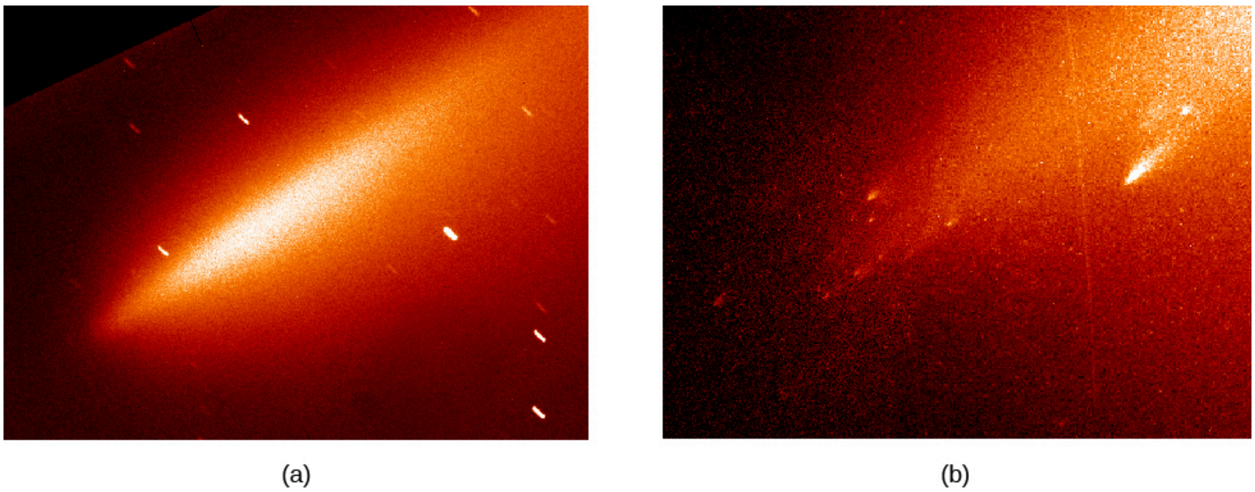
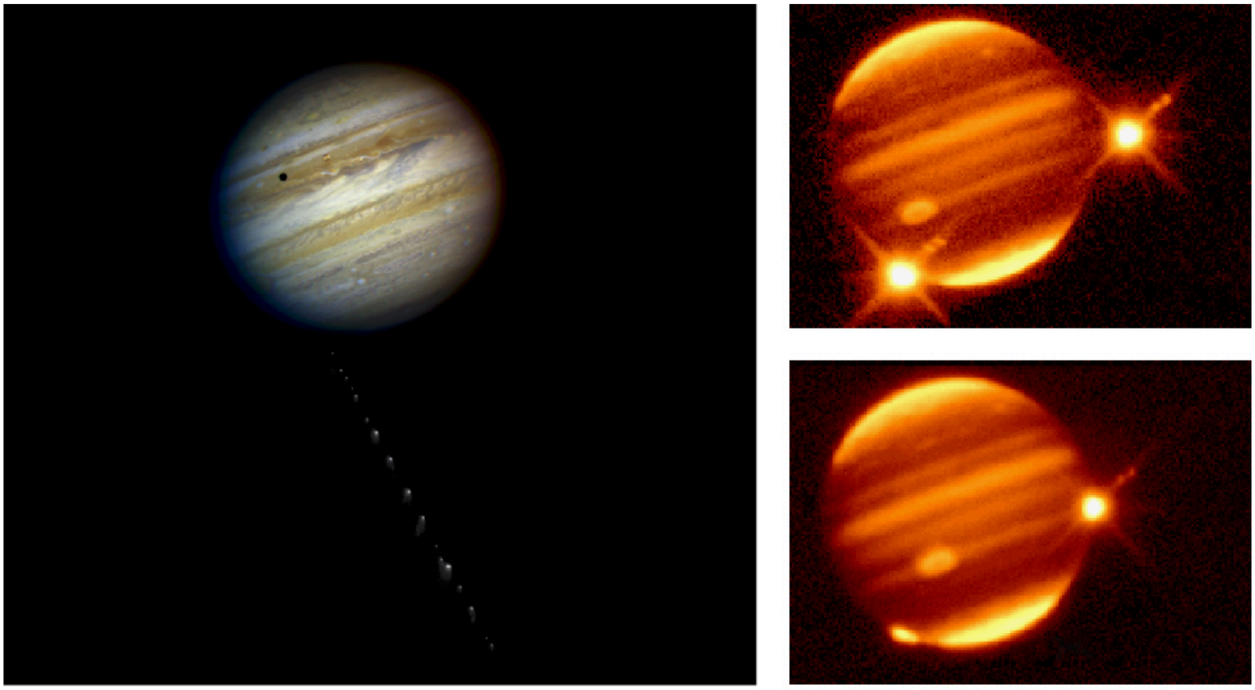


Figure 13.29 Breakup of Comet LINEAR. (a) A ground-based view with much less detail and (b) a much more detailed photo with the Hubble Space Telescope, showing the multiple fragments of the nucleus of Comet LINEAR. The comet disintegrated in July 2000 for no apparent reason. (Note in the left view, the fragments all blend their light together, and can't be distinguished. The short diagonal white lines are stars that move in the image, which is keeping track of the moving comet.) (credit a: modification of work by the University of Hawaii; credit b: modification of work by NASA, Harold Weaver (the Johns Hopkins University), and the HST Comet LINEAR Investigation Team)

As each cometary fragment streaked into the jovian atmosphere at a speed of 60 kilometers per second, it disintegrated and exploded, producing a hot fireball that carried the comet dust as well as atmospheric gases to high altitudes. These fireballs were clearly visible in profile, with the actual point of impact just beyond the jovian horizon as viewed from Earth (**Figure 13.30**). As each explosive plume fell back into Jupiter, a region of the upper atmosphere larger than Earth was heated to incandescence and glowed brilliantly for about 15 minutes, a glow we could detect with infrared-sensitive telescopes.



(a) (b)

Figure 13.30 Comet Impact on Jupiter. (a) The “string” of white objects are fragments of Comet Shoemaker-Levy 9 approaching Jupiter. (b) The first fragment of the comet impacts Jupiter, with the point of contact on the bottom left side in this image. On the right is Jupiter’s moon, Io. The equally bright spot in the top image is the comet fragment flaring to maximum brightness. The bottom image, taken about 20 minutes later, shows the lingering flare from the impact. The Great Red Spot is visible near the center of Jupiter. These infrared images were taken with a German-Spanish telescope on Calar Alto in southern Spain. (credit a: modification of work by ESA; credit b: modification of work by Tom Herbst, Max-Planck-Institut fuer Astronomie, Heidelberg, Doug Hamilton, Max-Planck-Institut fuer Kernphysik, Heidelberg, Hermann Boehnhardt, Universitaets-Sternewarte, Muenchen, and Jose Luis Ortiz Moreno, Instituto de Astrofisica de Andalucia, Granada)

After this event, dark clouds of debris settled into the stratosphere of Jupiter, producing long-lived “bruises” (each still larger than Earth) that could be easily seen through even small telescopes (**Figure 13.31**). Millions of people all over the world peered at Jupiter through telescopes or followed the event via television or online. Another impact feature was seen on Jupiter in summer 2009, indicating that the 1994 events were by no means unique. Seeing these large, impact explosions on Jupiter helps us to appreciate the disaster that would happen to our planet if we were hit by a comet or asteroid.

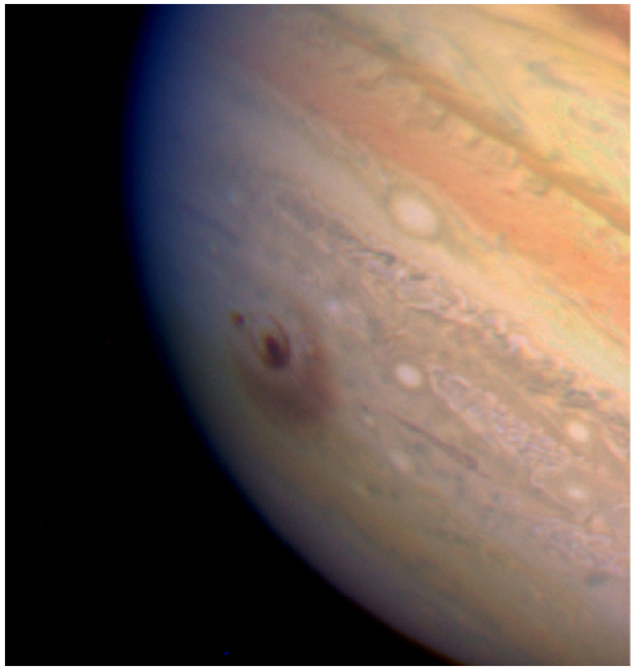


Figure 13.31 Impact Dust Cloud on Jupiter. These features result from the impact of Comet Shoemaker-Levy 9 with Jupiter, seen with the Hubble Space Telescope 105 minutes after the impact that produced the dark rings (the compact back dot came from another fragment). The inner edge of the diffuse, outer ring is about the same size as Earth. Later, the winds on Jupiter blended these features into a broad spot that remained visible for more than a month. (credit: modification of work by H. Hammel, MIT, and NASA/ESA)

For comets that do not meet so dramatic an end, measurements of the amount of gas and dust in their atmospheres permit us to estimate the total losses during one orbit. Typical loss rates are up to a million tons per day from an active comet near the Sun, adding up to some tens of millions of tons per orbit. At that rate, a typical comet will be gone after a few thousand orbits. This will probably be the fate of Comet Halley in the long run.

LINK TO LEARNING

This **History Channel video (https://openstaxcollege.org/l/30hischanUNIV)** shows a short discussion and animation from the TV documentary series *Universe*, showing the collision of Comet Shoemaker-Levy 9 with Jupiter.