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# The Comet About to Smash into Jupiter

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Artist’s conception of the collision of Comet Shoemaker-Levy 9 with Jupiter, as seen from the Galileo spacecraft. At the time of the first impact, the comet fragments will be much farther apart than shown in this illustration. (Courtesy D.A. Seal/JPL)

For a period of about six days centered on July 19, 1994, fragments of Comet Shoemaker-Levy 9 are expected to collide with Jupiter, the solar system's largest planet. Now such event has ever before been available for study. The energy released by the larger fragments will be more than 10,000 times the energy released by a 100-megaton hydrogen bomb! Unfortunately for observers, the collisions will occur on the night side of Jupiter, the back side as seen from Earth. How did this comet fragment? And what do astronomers think will happen when it hits?

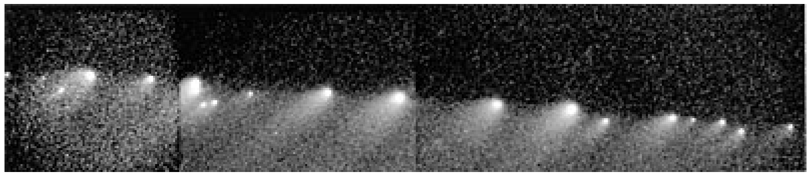


### What is Shoemaker-Levy 9?

Comet Shoemaker-Levy 9 was discovered photographically the husband and wife scientific team of Carolyn and Eugene Shoemaker and amateur astronomer David Levy on March 24, 1993, using the 0.46 meter (18-inch) Schmidt telescope at Palomar Observatory in Southern California. Its discovery was a serendipitous product of their continuing search for "near-Earth objects,'' those whose orbits bring them closer to the Sun than the, Earth's orbit and thus have some potential for collisions with Earth. The "9'' indicates that it was the ninth short-period comet (i.e., with a period, or the time it takes to orbit the Sun, less than 200 years) discovered by this team.

The appearance of the comet was reported as "most unusual": the object appeared as a "dense linear bar'' with a "fainter, wispy tail.'' The comet's brightness was reported as about magnitude 14, more than a thousand times too faint to be seen with the naked eye. Latter observations revealed that the "bar'' was made up of as many as 21 pieces "strung out like pearls on a string,'' according to one researcher.

Soon astronomers had enough observations of the comet's position to determine its orbit. Unlike most comets that orbit the Sun, Shoemaker-Levy 9 seemed also to be in orbit around Jupiter. One orbit, computer May 18, 1993 by Syuichi Nakano, showed that the comet passed close to Jupiter in July 1992, and would pass within 45,000 kilometers of the center of Jupiter in July, 1994. This distance is less than the radius of Jupiter. In other words, it appeared the comet would hit Jupiter.



This mosaic of images of Shoemaker-Levy 9, taken by the Hubble Space Telescope after it was repaired, shows some 20 of the fragments. (Courtesy H. Weaver/STScI)

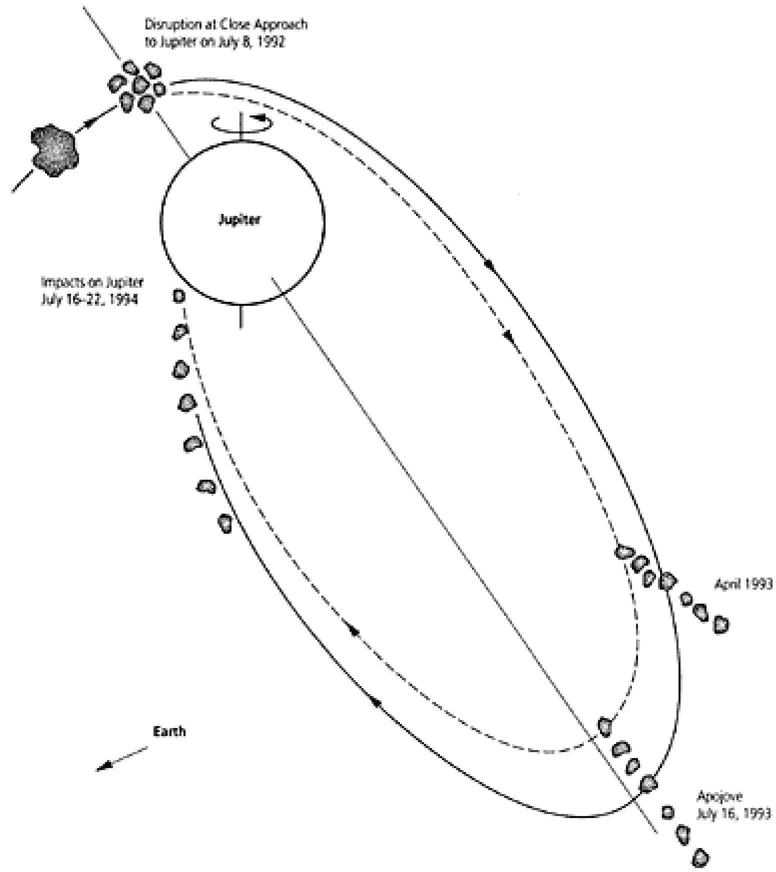
### What caused the comet to break apart?

Comets are small, irregularly shaped bodies composed of a mixture of tiny pieces of rock and frozen gases. Most become visible only when they get near enough to the Sun for the Sun's radiation to turn the ices directly to gas, and the gas, in turn, blows away bits of the solid material and forms the extended gas and dust tails we associate with comets. The best evidence suggests that comets are very fragile. You could take a big piece of cometary material and simply pull it in tow with your bare hands, something like a poorly compacted snowball. Some 25 comets have been observed to split over the past two centuries. A few disruptions have been obviously attributable to the tidal forces of Jupiter or the Sun, while other splittings have less obvious causes, for example, the rapid rotation of a nucleus weakened by the loss of gas and dust.

On July 7, 1992, Comet Shoemaker-Levy 9 passed only 25,000 kilometers (15,500 miles) above the clouds of Jupiter, according to the latest calculations. The differential pull of the planet's enormous gravitational force on the near and far sides of the comet fragmented it into 21 or more large pieces and an enormous amount of smaller debris. It had been in a rapidly changing orbit around Jupiter for some time before this, probably for at least several decades. It did not fragment during earlier approaches to Jupiter, however, because these were at much greater distances than that of 1992; the comet probably approached no closer than about nine million kilometers in the orbit prior to that of 1992.

It is unlikely that the exact circumstances of the breakup of Shoemaker-Levy 9 will ever be known with certainty. But one model suggests that the original comet cannot have been much smaller that 9 kilometers (6 miles) in diameter and that it probably was rotating quite rapidly (perhaps once every eight hours.) The breakup and subsequent collisions between the fragments were not completed until about two hours after closest approach to Jupiter. All of the large fragments were soon strung out in nearly a straight line that pointed at Jupiter, and they will remain so until colliding into the planet.

At discovery in March 1993, the train of fragments was about 50 arcseconds or 162,000 kilometers in length as projected on the sky. (A circle is divided into 360 degrees, each degree into 60 minutes, and each minute into 60 seconds. The word "arc'' is added to denote angular measure rather than time. For example, the diameter of the Moon is about 30 arcminutes.) This linear distance had increased by about 50 percent by the time the comet was lost in the glare of the Sun in July 1993. The spreading is caused mainly by the fact that the piece closest to Jupiter at breakup was some nine kilometers closer than the farthest piece ( the diameter of the comet) and therefore entered a faster orbit. The fragment nearest to Jupiter at breakup remains nearest to it and will be the first to impact. Astronomers predict that the train will reach an apparent length of some 1,286 arcseconds at the time the first of the fragments enters Jupiter's atmosphere. The true length of the train will be 4,900,000 kilometers, and it will require 5.5 days for all of the major fragments to impact.




The fragments of Shoemaker-Levy 9 move around Jupiter. This schematic is not drawn to scale. For example, the distance to apojove (the comet's farthest distance from Jupiter) is actually almost 1,200 times the distance from Jupiter at which it was disrupted, and the true representation would be a long narrow ellipse that looks almost like a straight line out and back. The length of the line should be 350 times the diameter of Jupiter and the disruption a tiny dot less than a quarter of the diameter above Jupiter. (Courtesy Z. Sekanina, P.W. Chodas, and D.K. Yeomans)


# The Comet About to Smash into Jupiter

### What will happen when the fragments hit Jupiter?

The impacts will be centered on June 19, 1994; the first is expected late at night on July 16, with an impact, on average, about every six hours. All the fragments will enter Jupiter's atmosphere at an angle of 42 degrees from the vertical and impact near a latitude of 44 degrees south, but on the back side of the planet as seen from Earth (about 10 degrees in longitude behind the edge of Jupiter, as seen from Earth). However, because Jupiter spins so rapidly (a day on Jupiter lasts only 9 hours 50 minutes), the sites will rotate into view from Earth within about 20 minutes of each impact.

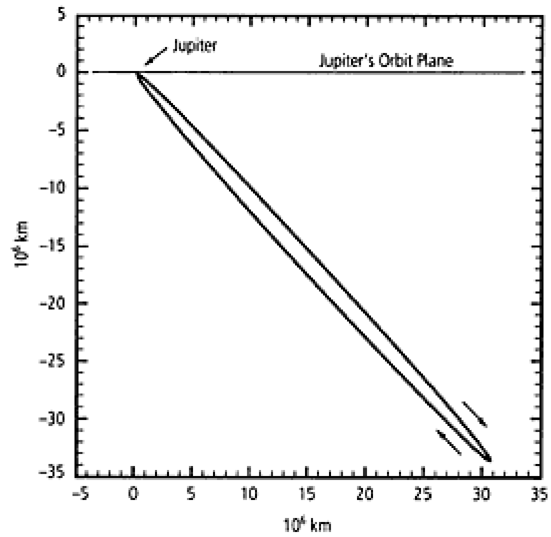
Exactly what will happen as the fragments enter the atmosphere of Jupiter is very uncertain, though there are many predictions. Any body moving through an atmosphere is slowed by atmospheric drag, by having to push the molecules of that atmosphere out of the way. The kinetic energy (energy of motion) lost by the body is given to the air molecules. They move a bit faster (become hotter) and in turn heat the moving body. The drag increases roughly as the square of the velocity. In any medium, a velocity is finally reached at which the atmospheric molecules can no longer move out of the way fast enough and they begin to pile up in front of the moving body. This is the speed of sound (Mach I -- 331.7 meters/second or 741 mph in air on Earth at sea level). A discontinuity in velocity and pressure is created which is called a shock wave. Comet Shoemaker-Levy 9 will enter Jupiter's atmosphere at about 60 kilometers per second. which would be about 180 times the speed of sound on Earth (Mach 180!) and is about 50 times the speed of sound even in Jupiter's very light, largely hydrogen atmosphere.

At high supersonic velocities (much greater than Mach 1) enough energy is transferred to an intruding body that it becomes incandescent and molecular bonds begin to break. The temperature may rise to 50,000 kelvin (90,000 degrees Fahrenheit.) or more for very large bodies such as the fragments of Shoemaker-Levy 9. The effect of increasing temperature, pressure and vibration on an intrinsically weak body is to crush it and cause it to flatten and spread. Meanwhile the atmosphere is also increasing in density as the comet penetrates to lower altitudes. All of these processes occur at an ever increasing rate. The net result is that the fragile Shoemaker-Levy 9 fragments will suffer almost immediate destruction. The only real question is whether each fragment will break into several pieces immediately after entry, and therefore exhibit multiple smaller explosions, or whether it will survive long enough to be crushed, flattened and obliterated in one grand explosion and terminal fireball.

Astronomer Zdenek Sekanina, of the Jet Propulsion Laboratory in Pasadena, California, calculates that about 93 percent of the mass of a $10^{13}$-kilogram fragment, still moving at almost 60 kilometers per second, remains one second before the terminal explosion. During that last second, the energy of perhaps 10,000 100-megaton bombs is released. Much of the cometary material will be heated to many tens of thousands of degrees, vaporized, and ionized along with a substantial amount of Jupiter's surrounding atmosphere. The resulting fireball should balloon upward, even fountaining clear out of the atmosphere, before falling back and spreading out into Jupiter's atmosphere, imitating in a non-nuclear fashion some of the atmospheric hydrogen bomb tests of the 1950s.

One of the more difficult questions to answer is just bow bright these explosions will be. Sekanina calculates that a $10^{13}$--kilogram fragment, a reasonable value for the largest piece, will reach an apparent visual magnitude of -10 during the terminal explosion. This is 1,000 times Jupiter's normal brilliance and only 10 times fainter than the full Moon! However, Sekanina calculates that the explosions will occur above the clouds. There is much controversy as to exactly how deep into the atmosphere the fragments will penetrate before exploding, with other astronomers arguing that the fragments will explode beneath the visible clouds.

The brightness of explosions occurring below the clouds would be attenuated by a factor of at least 10,000, making them most difficult to observe.




Jupiter-centered final orbit of Shoemaker-Levy 9 as viewed from the Sun. (Courtesy P.W. Chodas)

The fireball created by the terminal explosion will spew vaporized comet material to very high altitudes as it expands and balloons upward. It may carry with it atmospheric gases that are normally to be found only far below Jupiter's visible clouds. Hence the impacts may give astronomers opportunity to detect gases which have been hitherto hidden from view. As the gaseous fireball rises and expands it will cool, with some of the gases it contains condensing into liquid droplets or small solid particles. If a sufficiently large number of particles form, then the clouds they produce may be visible from Earth-based telescopes after the impact regions rotate onto the visible side of the planet. These clouds may provide the clearest indication of the impact locations after each event.

Large regular fluctuations of atmospheric temperature and pressure will be created by the shock front of each entering fragment and travel outward from the impact sites, somewhat analogous to the ripples created when a pebble is tossed into a pond. These may be observable near layers of existing clouds in the same way that regular cloud patterns are seen on the leeward side of the mountains. Jupiter's atmosphere will be sequentially raised and lowered. creating a pattern of alternating cloudy areas where ammonia gas freezes into particles (the same way that water condenses into cloud droplets in our own atmosphere) and clear areas where the ice particles warm up and evaporate back into the gas phase.

Whether or not these "wave'' clouds appear, the ripples spreading from the impact sites will produce a wave structure in the temperature at a given level that may be observable in infrared (or thermal) maps. In addition there should be compression waves, alternate compression and rarefaction in the atmospheric pressure, which could reflect and refract within the deeper atmosphere, much as seismic waves reflect and refract due to density changes inside Earth.

The phenomena directly associated with each impact from entry trail to rising fireball will last perhaps three minutes. The fallback of ejecta over a radius of a few thousand kilometers will last for about three hours. Seismic waves from each impact might be detectable for a day, and atmospheric waves for several days. Vortices and atmospheric hazes could conceivably persist for weeks. New material injected into the Jovian ring system might be detectable for years. Changes in the magnetosphere (Jupiter's magnetic field is much stronger than that of Earth and affects an area of space tens of millions of kilometers from the planet) and/or the Io torus (particles ejected from Io's volcanoes are ionized and trapped by Jupiter's magnetic field into a donut-shaped torus completely circling the planet) caused by the sudden influx of large amounts of cometary dust might also persist for some weeks or months. There is the potential to keep planetary observers busy for a long time!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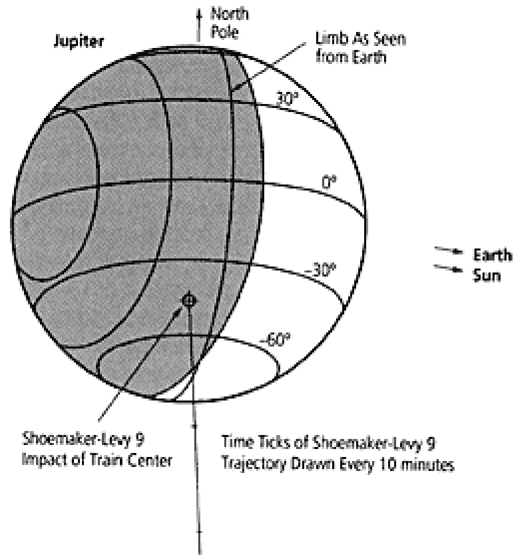
### What observations are astronomers planning?

Many large telescopes will be available on Earth with which to observe the phenomena associated with the Shoemaker-Levy 9 impacts on Jupiter in visible, infrared, and radio wavelengths. Apart from the obvious difficulty that the impacts will occur on the back side of Jupiter as seen from Earth, the biggest problem is that Jupiter in July can only be observed usefully for about two hours per night from any given northern hemisphere site. Earlier the sky is still too bright and later the planet is too close to the horizon. Therefore, to keep Jupiter under continuous surveillance would require a dozen observatories equally spaced in longitude around the globe. A dozen observatories is feasible, but equal spacing is not. There will be gaps in the coverage, notably in the Pacific Ocean, where Mauna Kea, Hawaii, is the only astronomical bastion. In the southern hemisphere Jupiter can be observed for longer periods of time for example, at 30 degrees south latitude it will be visible for five hours. but only Australia and Chile offer major observing facilities and it will be mid-winter there.

There are at least four spacecraft -- *Galileo*, *Ulysses*, *Voyager 2*, and *Clementine* -- with some potential to observe the Jovian impacts from different vantage points than that of Earth. There is also the *Hubble Space Telescope* (*HST*) in orbit around Earth, which will view the event with essentially the same geometry as any Earth-based telescope. *HST*. however, has the advantage of' no atmospheric turbulence, very low scattered light, ultraviolet sensitivity, and the ability to observe much more than two hours each day. *HST* is scheduled to devote considerable time to the observation of Shoemaker-Levy 9 before as well as during the impacts.

The *Galileo* spacecraft has the best vantage point from which to observe the impacts. It is on its way to Jupiter and will be only 246 million kilometers away from the planet, less than a third the distance of Earth from Jupiter at the time. All of the impacts will occur directly in the field of view of its high resolution camera. In addition, instruments that study infrared and ultraviolet light will most likely be used.

Using *Galileo* to make observations will be challenging however. The amount of data the spacecraft can transmit back to Earth is limited by the capability of its low-gain antenna (the spacecraft's high-gain antenna, which could have transmitted large amounts of data in short periods of time, failed after launch and the time available on the receiving antennas of NASA's Deep Space Network here on Earth. A lot of data frames can be stored in the *Galileo* tape recorder, but only about 5 percent of them can be transmitted back to Earth. so the trick will be to decide which 5 percent of the data are most likely to include the impacts and have the greatest scientific value, without being able to look at any of them first! After the fact, the impact times should be known quite accurately. This knowledge can help to make the decisions about which data to return to Earth.




The impact site of the fragments of Comet Shoemaker-Levy 9 on Jupiter. (Courtesy D. Seal)

The *Ulysses* spacecraft was designed for solar study and used a "gravity assist'' for flying close to Jupiter to change its inclination (the tilt of its path relative to the plane of the planets) so it can fly over the poles of the Sun. In July 1994 it will be about 378 million kilometers south of the plane of the planets (the ecliptic) and able to "look'' over the south pole of Jupiter directly at the impact sites. Unfortunately, *Ulysses* has no camera as a part of its instrument complement. It does have an extremely sensitive radio receiver that may be able to detect thermal radiation from the impact fireballs once they rise sufficiently high above interference from the Jovian ionosphere (upper atmosphere) and to measure a precise time history of their rapid cooling.

The *Voyager 2* spacecraft is now far beyond Neptune and is about 6.4 billion kilometers from the Sun. It can look directly back at the dark side of Jupiter, but the whole of Jupiter is now only two picture elements in diameter as seen by its high resolution camera, if that instrument were to be used. In fact the camera has shut down for several years, and the engineers who knew how to control it have new jobs or are retired. It would be very expensive to take the camera "out of mothballs'' and probably of limited scientific value. *Voyager* does have an ultraviolet spectrometer which is still taking data, and it will probably be used to observe the impact.

A new small spacecraft called *Clementine* was launched on Jan. 25 of this year, intended to orbit the Moon and then proceed on to study the asteroid Geographos. *Clementine* has good imaging capabilities, but its viewpoint will not be much different from Earth's. Still. it seems probable that attempts will be made to observe "blips'' of light on the edge of Jupiter from the entering fragments or subsequent fireballs.

Stupendous as these collisions will be, they will occur on the far side of a planet half a million miles from Earth. There will be no display visible to the general public. Amateur astronomers may note a few seconds of brightening of the inner satellites of Jupiter during the impacts, and they might observe minor changes in the Jovian cloud structure during the days following the impacts. In the best of cases, these events will be spectacles for the mind to imagine and big telescopes to observe, not a free fireworks display. The real value of this most unusual event will come from scientific studies of the comet's composition. of the impact phenomena themselves, and of the response of a planetary atmosphere to such a series of "insults.''

Atmospheric phenomena on this scale cannot be reproduced, even by nuclear fusion explosions, and have never before been observed. Sixty-five million years ago the Earth was struck by a large asteroid or comet, an event which may have hastened the extinction of the dinosaurs. Better knowledge of the effects of Comet Shoemaker-Levy 9 on Jupiter may allow scientists to predict more accurately just how serious could be the results of future impacts of various-sized bodies on Earth.

### Energy Comparisons & Power Comparisons

## Energy Comparisons

| Event | Energy in Joules | Energy Relative |
|---|---|---|
| Two 3,500-lb. cars colliding head-on at 55 mph | $9.6 \times 10^{5}$ | 1 |
| Explosion of 1 U.S. ton of TNT | $4.2 \times 10^{9}$ | 4,271 |
| Explosion of a 20-megaton fusion bomb | $8.4 \times 10^{16}$ | 87,500,000,000 |
| Total U.S. annual electric power production, 1990 | $1 \times 10^{19}$ | 10,400,000,000,000 |
| Energy released in last second of $10^{13}$-kg fragment of Comet Shoemaker-Levy 9 | $9 \times 10^{21}$ | 9,375,000,000,000,000 |
| Total energy released by $10^{13}$-kg fragment of Comet Shoemaker-Levy 9 | $1.8 \times 10^{22}$ | 18,750,000,000,000,000 |
| Total sunlight on Jupiter for one day | $6.6 \times 10^{22}$ | 68,750,000,000,000,000 |

*+ Note: 1 BTU = 252 (small) calories = 1,055 Joules = 2.93 X $10^{4}$ kWh.*

## Power Comparisons

| Power Producer | Power in Megawatts | Power Relative |
|---|---|---|
| Hoover Dam | 1,345 | 1 |
| Grand Coulee Dam, final plant | 9,700 | 7.2 |
| Annual average, sum of all U.S. power plants | 320,000 | 238 |
| Average, impact of $10^{13}$-kg fragment of Comet Shoemaker-Levy 9, final second | $9 \times 10^{15}$ | 6,700,000,000,000 |
| Sun | $3.8 \times 10^{20}$ | 280,000,000,000,000,000 |

*+ Note: 1 horsepower = 745.7 W = 7.457 X $10^{4}$ Megawatts (MW)*