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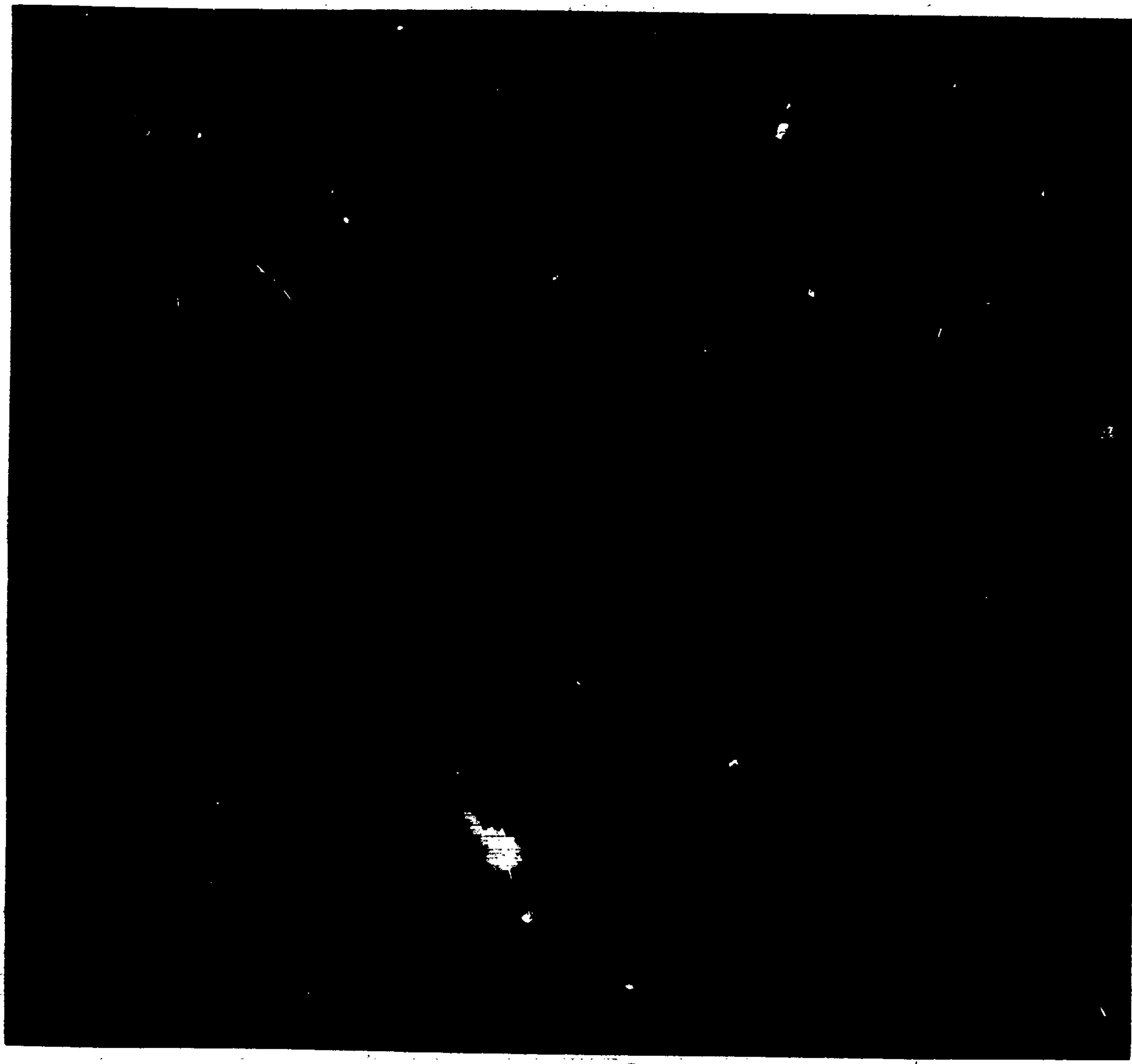
ABSTRACT

In July of 1994, fragments of Comet Shoemaker-Levy collided with Jupiter. This document has been provided to better inform students of the work that will be done by scientists and others involved in the study of this event. This document offers some background material on Jupiter, comets, what has and possibly will happen, and how scientists propose to take advantage of the impact events. The following sections are included: (1) What is A Comet?; (2) The Motion of Comets; (3) The Fragmentation of Comets; (4) The Discovery and Early Study of Shoemaker-Levy 9; (5) The Planet Jupiter; (6) The Final Orbit of Shoemaker-Levy 9; (7) The Collisions; (8) How Can These Impacts and Their Consequences Be Studied?; and (9) What Do Scientists Expect to Learn from All of This? (ZWH)

R. KAHN

Periodic Comet Shoemaker-Levy 9 Collides with Jupiter

Background Material for Science Teachers



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. No such event has ever before been available for study. The energy released by the larger fragments during impact 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, which also will be the back side as seen from Earth. The collisions can still be studied in many ways, nevertheless, by spacecraft more advantageously located, by light of the collisions reflected from Jupiter's satellites, and by the effects of the impacts upon the Jovian atmosphere. (The impact sites will rotate into view from Earth about 20 minutes after each collision.)

Stupendous as these collisions will be, they will occur on the far side of a body half a billion miles from Earth. There will be no display visible to the general public, not even a display as obvious as a faint terrestrial meteor. 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. 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 and magnetosphere to such a series of "insults."

This booklet offers some background material on Jupiter, comets, what has and possibly will happen, and how scientists propose to take advantage of the impact events.

Ray L. Newburn, Jr.

***Cover:* Comet Shoemaker-Levy 9 is expected to collide with Jupiter in July 1994. From this historic event, scientists hope to learn more about comets, Jupiter, and the physics of high velocity planetary impacts.**

1

What Is a Comet?

Comets are small, fragile, irregularly shaped bodies composed of a mixture of non-volatile grains and frozen gases. They usually follow highly elongated paths around the Sun. Most become visible, even in telescopes, only when they get near enough to the Sun for the Sun's radiation to start subliming the volatile gases, which in turn blow away small bits of the solid material. These materials expand into an enormous escaping atmosphere called the coma, which becomes far bigger than a planet, and they are forced back into long tails of dust and gas by radiation and charged particles flowing from the Sun. Comets are cold bodies, and we see them only because the gases in their comae and tails fluoresce in sunlight (somewhat akin to a fluorescent light) and because of sunlight reflected from the solids. Comets are regular members of the solar system family, gravitationally bound to the Sun. They are generally believed to be made of material, originally in the outer part of the solar system, that didn't get incorporated into the planets — leftover debris, if you will. It is the very fact that they are thought to be composed of such unchanged "primitive" material that makes them extremely interesting to scientists who wish to learn about conditions during the earliest period of the solar system.

Comets are very small in size relative to planets. Their average diameters usually range from 750 m or less to about 20 km. Recently, evidence has been found for much larger distant comets, perhaps having diameters of 300 km or more, but these sizes are still small compared to planets. Planets are usually more or less spherical in shape, usually bulging slightly at the equator. Comets are irregular in shape, with their longest dimension often twice the shortest. (See Appendix A, Table 3.) The best evidence suggests that comets are very fragile. Their tensile strength (the stress they can take without being pulled apart) appears to be only about 1,000 dynes/cm^2 (about 2 lb./ft.^{2}). You could take a big piece of cometary material and simply pull it in two with your bare hands, something like a poorly compacted snowball.

Comets, of course, must obey the same universal laws of motion as do all other bodies. Where the orbits of planets around the Sun are nearly circular, however, the orbits of comets are quite elongated. Nearly 100 known comets have periods (the time it takes them to make one complete trip around the Sun) five to seven Earth years in length. Their farthest point from the Sun (their aphelion) is near Jupiter's orbit, with the closest point (perihelion) being much nearer to Earth. A few comets like Halley have their aphelions beyond Neptune (which is six times as far from the Sun as Jupiter). Other comets come from much farther out yet, and it may take them thousands or even hundreds of thousands of years to make one complete orbit around the Sun. In all cases, if a comet approaches near to Jupiter, it is strongly attracted by the gravitational pull of that giant among planets, and its orbit is perturbed (changed), sometimes radically. This is part of what happened to Shoemaker-Levy 9. (See Sections 2 and 4 for more details.)

The nucleus of a comet, which is its solid, persisting part, has been called an icy conglomerate, a dirty snowball, and other colorful but even less accurate descriptions. Certainly a comet nucleus contains silicates akin to some ordinary Earth rocks in composition, probably mostly in very small grains and pieces. Perhaps the grains are "glued" together into larger pieces by the frozen gases. A nucleus appears to include complex carbon compounds and perhaps some free carbon, which make it very black in color. Most notably, at least when young, it contains many frozen gases, the most common being ordinary water. In the low pressure conditions of space, water sublimes, that is, it goes directly from solid to gas — just like dry ice does on Earth. Water probably makes up 75–80% of the volatile material in most comets. Other common ices are carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and formaldehyde (H_2CO). Volatiles and solids appear to be fairly well mixed throughout the nucleus of a new comet approaching the Sun for the first time. As a comet ages from many trips close to the Sun, there is evidence that it loses most of its ices, or at least those ices anywhere near the nucleus surface, and becomes just a very fragile old "rock" in appearance, indistinguishable at a distance from an asteroid.

A comet nucleus is small, so its gravitational pull is very weak. You could run and jump completely off of it (if you could get traction). The escape velocity is only about 1 m/s (compared to 11 km/s on Earth). As a result, the escaping gases and the small solid particles (dust) that they drag with them never fall back to the nucleus surface. Radiation pressure, the pressure of sunlight, forces the dust particles back into a dust tail in the direction opposite to the Sun. A comet's tail can be tens of millions of kilometers in length when seen in the reflected sunlight. The gas molecules are torn apart by solar ultraviolet light, often losing electrons and becoming electrically charged fragments or ions. The ions interact with the wind of charged particles flowing out from the Sun and are forced back into an ion tail, which again can extend for millions of kilometers in the direction opposite to the Sun. These ions can be seen as they fluoresce in sunlight.

Every comet then really has two tails, a dust tail and an ion tail. If the comet is faint, only one or neither tail may be detectable, and the comet may appear just as a fuzzy blob of light, even in a big telescope. The density of material in the coma and tails is very low, lower than the best vacuum that can be produced in most laboratories. In 1986 the Giotto spacecraft flew right through Comet Halley only a few hundred kilometers from the nucleus. Though the coma and tails of a comet may extend for tens of millions of kilometers and become easily visible to the naked eye in Earth's night sky, as Comet West's were in 1976, the entire phenomenon is the product of a tiny nucleus only a few kilometers across.

Because comet nuclei are so small, they are quite difficult to study from Earth. They always appear at most as a point of light in even the largest telescope, if not lost completely in the glare of the coma. A great deal was learned when the European Space Agency, the Soviet Union, and the Japanese sent spacecraft to fly by Comet Halley in 1986. For the first time, actual images of an active nucleus were obtained (see Figure 1) and the composition of the dust and gases flowing from it was directly measured. Early in the next century the Europeans plan to send a spacecraft called Rosetta to rendezvous with a comet and watch it closely for a long period of time. Even this sophisticated mission is not likely to tell scientists a great deal about the interior structure of comets, however. Therefore, the opportunity to reconstruct the events that occurred when Shoemaker-Levy 9 split and to study those that will occur when the fragments are destroyed in Jupiter's atmosphere is uniquely important (see Sections 4, 7, and 8).

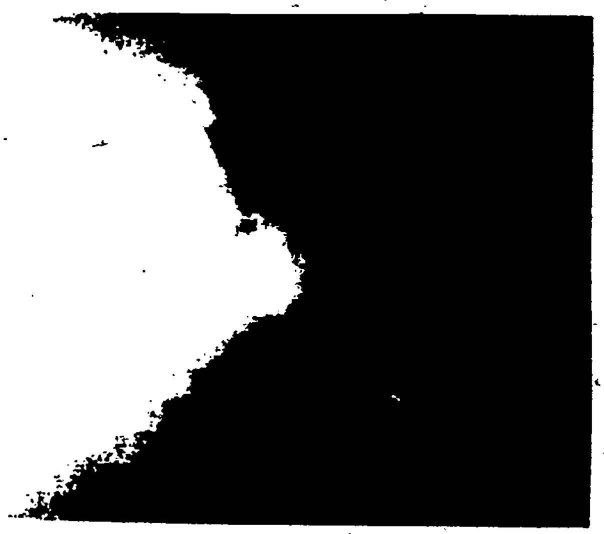


Figure 1. A composite image of the nucleus of Comet Halley from images taken by the Giotto spacecraft of the European Space Agency. (Courtesy of U. Keller, Max Planck Inst. for Aeronomy, Katlenburg-Lindau, Germany.)

2

The Motion of Comets

Comets necessarily obey the same physical laws as every other object. They move according to the basic laws of motion and of universal gravitation discovered by Newton in the 17th century (ignoring *very* small relativistic corrections). If one considers only two bodies — either the Sun and a planet, or the Sun and a comet — the smaller body appears to follow an elliptical path or orbit about the Sun, which is at one focus of the ellipse. The geometrical constants which fully define the shape of the ellipse are the semimajor axis *a* and the eccentricity *e* (see Figure 2). The semiminor axis *b* is related to those two quantities by the equation $b = a\sqrt{(1-e^2)}$. The focus is located a distance *ae* from the center of the ellipse. Three further constants are required if one wishes to describe the orientation of the ellipse in space relative to some coordinate system, and a fourth quantity is required if one wishes to define the location of a body in that elliptical orbit.

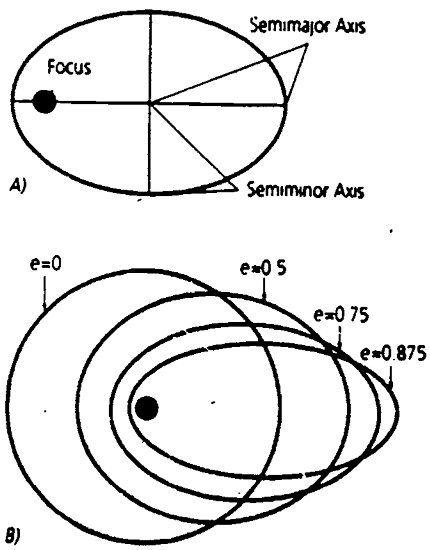


Figure 2. A) An ellipse with eccentricity = 0.75. B) A family of confocal ellipses (ellipses sharing the same focus) and having the same-length semimajor axis. (Prepared by R. L. Newburn, Jr.)

In Figure 2B several ellipses are drawn, all having the same semimajor axis but different eccentricities. Eccentricity is a mathematical measure of departure from circularity. A circle has zero eccentricity, and most of the planets have orbits which are nearly circles. Only Pluto and Mercury have eccentricities exceeding 0.1. Comets, however, have very large eccentricities, often approaching one, the value for a parabola. Such highly eccentric orbits are just as possible as circular orbits, as far as the laws of motion are concerned.

The solar system consists of the Sun, nine planets, numerous satellites and asteroids, comets, and various small debris. At any given time the motion of any solar system body is affected by the gravitational pulls of all of the others. The Sun's pull is the largest by far, unless one body approaches very closely to another, so orbit calculations usually are carried out as two-body calculations (the body in question and the Sun) with small perturbations (small added effects due to the pull of other bodies). In 1705 Halley noted in his original paper predicting the return of "his" comet that Jupiter undoubtedly had serious effects on the comet's motion, and he presumed Jupiter to be the cause of changes in the period (the time required for one complete revolution about the Sun) of the comet. (Comet Halley's period is usually stated to be 76 years, but in fact it has varied between 74.4 and 79.2 years during the past 2,000 years.) In that same paper Halley also became the first to note the very real possibility of the collision of comets with planets, but stated that he would leave the consequences of such a "contact" or "shock" to be discussed "by the Studious of Physical Matters."

In the case of Shoemaker-Levy 9 we have the perfect example both of large perturbations and their possible "consequences." The comet was fragmented and perturbed into an orbit where the pieces will hit Jupiter one period later. In general one must note that Jupiter's gravity (or that of other planets) is perfectly capable of changing the energy of a comet's orbit sufficiently to throw it clear out of the solar system (to give it escape velocity from the solar system) and has done so on numerous occasions. See Figure 3. This is exactly the same physical effect that permits using planets to change the orbital energy of a spacecraft in so-called "gravity-assist maneuvers" such as were used by the Voyager spacecraft to visit all the outer planets except Pluto.

One of Newton's laws of motion states that for every action there is an equal and opposite reaction. Comets expel dust and gas, usually from localized regions, on the sunward side of the nucleus. This action causes a reaction by the cometary nucleus, slightly speeding it up or slowing it down. Such effects are called "non-gravitational forces" and are simply rocket effects, as if someone had set up one or more rocket motors on the nucleus. In general both the size and shape of a comet's orbit are changed by the non-gravitational forces — not by much but by enough to totally confound all of the celestial mechanics experts of the 19th and early 20th centuries. Comet Halley arrived at its point closest to the Sun (perihelion) in 1910 more than three days late, according to the best predictions. Only after F. L. Whipple published his icy conglomerate model of a degassing nucleus in 1950 did it all begin to make sense. The predictions for the time of perihelion passage of Comet Halley in 1986, which took into account a crude model for the reaction forces, were off by less than five hours.

Much of modern physics is expressed in terms of conservation laws, laws about quantities which do not change for a given system. Conservation of energy is one of these laws, and it says that energy may change form, but it cannot be created or destroyed. Thus the energy of motion (kinetic energy) of Shoemaker-Levy 9 will be changed largely to thermal energy when the comet is halted by Jupiter's atmosphere and destroyed in the process. When one body moves about another in the vacuum of space, the total energy (kinetic energy plus potential energy) is conserved.

Another quantity that is conserved is called angular momentum. In the first paragraph of this section, it was stated that the geometric constants of an ellipse are its semimajor axis and eccentricity. The dynamical constants of a body moving about another are energy and angular momentum. The total (binding) energy is inversely proportional to the semimajor axis. If the energy goes to zero, the semimajor axis becomes infinite and the body escapes. The angular momentum is proportional both to the eccentricity and the energy in a more complicated way, but, for a given energy, the larger the angular momentum the more elongated the orbit.

The laws of motion do not require that bodies move in circles (or even ellipses for that matter), but if they have some binding energy, they must move in ellipses (not counting perturbations by other bodies), and it is then the angular momentum which determines how elongated is the ellipse. Comets simply are bodies which in general have more angular momentum per unit mass than do planets and therefore move in more elongated orbits. Sometimes the orbits are so elongated that, because we can observe only a small part of them, they cannot be distinguished from a parabola, which is an orbit with an eccentricity of exactly one. In very general terms, one can say that the energy determines the size of the orbit and the angular momentum the shape.

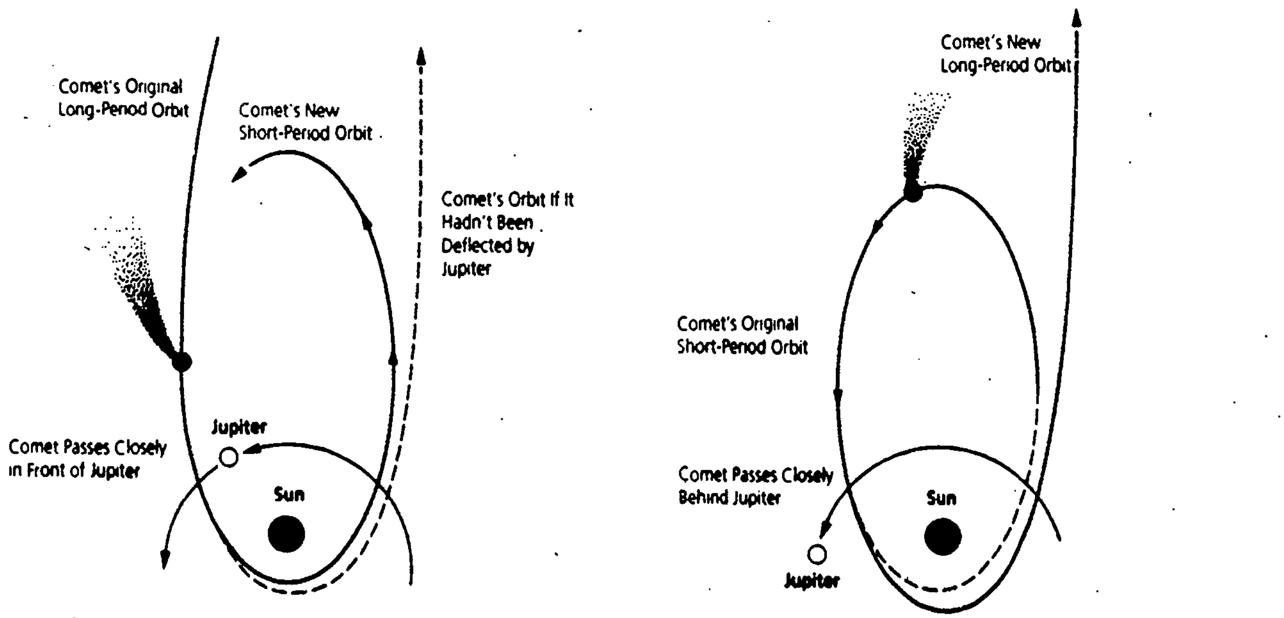


Figure 3. A) By passing closely in front of Jupiter, a long-period comet can lose enough orbital energy (gain enough binding energy) to be captured into a much shorter period orbit about the Sun. (Prepared by D. K. Yeomans.)

B) By passing closely behind Jupiter, a short-period comet can gain enough orbital energy (lose enough binding energy) to become a long-period comet. (Prepared by D. K. Yeomans.)

3

The Fragmentation of Comets

Every body is held together by two forces, its self-gravitation and its internal strength due to molecular bonding. With no external forces on it (and no initial rotation) a liquid body would form a perfect sphere just from self-gravitation (and from very weak molecular forces — surface tension). Approaching another body, the sphere would begin to elongate toward that body. Finally, when the difference in gravitational force on the near side and far side of the former sphere exceeded the self-gravitation, the body would be torn apart. The distance from the larger body at which this disruption occurs is the so-called Roche limit, named for the man who first studied the problem. The differential gravitational effects of the Moon and the Sun are what raise the tides in Earth's oceans, and such forces are often referred to as tidal forces.

Solid bodies have intrinsic strength due to their molecular bonds. Aluminum wire may have a tensile strength of 2.4×10^9 dynes/cm^2 (5 million lb./ft.^{2}) and good steel wire a tensile strength 10 times larger still, which far exceeds the tidal force of anything short of a black hole. As stated in Section 1, comets have very low tensile strength, near 1×10^3 dynes/cm^2 (2 lb./ft.^{2}). They can be pulled apart very easily by tidal force (or any other substantial force, for that matter). Some 25 comets have been observed to split over the past two centuries. In other cases two or more comets have been discovered in nearly the same orbit, and calculations have indicated that they were once a single comet. A few of these cases have been obviously attributable to the tidal forces of Jupiter (Comet Brooks 2 and Comet Shoemaker-Levy 9) or the Sun (the Kreutz comet family), while other splittings have to be attributed to less obvious causes. For example, the loss of material from an active comet, which tends to occur from a few localized areas, is bound to weaken it. It may be that a rapidly rotating comet can be weakened to the point where the centrifugal force is sufficient to cause large pieces to break off.

The Kreutz family is the name given to many comets which closely approach the Sun from one direction in space. They always approach the Sun to within 3 million km or less, and some have actually hit the Sun. The family was named for Heinrich Kreutz who published extensive monographs on three of these comets and supported the idea that they had a common origin, perhaps in a giant comet observed in 372 B.C. Today the Kreutz family has eight definite, well-studied members; 16 probable members (that are listed as probable only because they didn't survive passage within 800,000 km of the Sun to permit further study); and three more possible members. Extensive work by Brian Marsden suggests that all of these may have resulted from the splitting of two comets around 1100 A.D., which in turn may have been the parts of the great comet of 372 B.C. Those Kreutz fragments which survive their encounters with the Sun are often found to have split yet again!

The classic Roche limit for a (fluid) body of density 1 g/cm^3 approaching Jupiter is about 119,000 km above the cloud tops of the planet. It is about 169,000 km for a body having a density of 0.5 g/cm^3. More complete modern theories making different assumptions result in a somewhat smaller limit. In 1886 Comet Brooks 2 came within 72,000 km of Jupiter's clouds and split into two pieces. In July 1992 Comet Shoemaker-Levy 9 came within about 25,000 km of Jupiter's clouds and fragmented into 21 or more large pieces and an enormous amount of smaller debris down to micron or submicron size. Details of this last event follow.

The Discovery and Early Study of Shoemaker-Levy 9

Comet Shoemaker-Levy 9 was discovered photographically by the husband and wife scientific team of Carolyn S. and Eugene M. Shoemaker and David H. Levy on March 24, 1993, using the 0.46-m (18-in.) Schmidt telescope at Palomar Observatory in California. Its discovery was a serendipitous product of their continuing search for "near-Earth objects," and the "9" indicates that it was the ninth short-period comet (period less than 200 years) discovered by this team. Near-Earth objects are bodies whose orbits come nearer to the Sun than that of Earth and hence have some potential for collisions with Earth. The appearance of the comet was reported as "most unusual"; the object appeared as "a dense, linear bar about 1 arc minute long" and had a "fainter, wispy 'tail.' " (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 an angular measure rather than time. The diameter of the Moon is near 30 arc minutes, for example, while the apparent diameter of Jupiter when closest to Earth is 50 arc seconds.) The comet's brightness was reported as about magnitude 14, more than a thousand times too faint to be seen with the naked eye.

The existence of this object was soon confirmed by James V. Scotti of the Spacewatch program at the University of Arizona, and the International Astronomical Union's Central Bureau for Astronomical Telegrams immediately issued "Circular No. 5725" reporting the discovery as a new comet, giving it the provisional designation of 1993e (the fifth comet discovered or recovered in 1993). Scotti reported at least five condensations in a "long, narrow train about 47 arc seconds in length and about 11 arc seconds in width," with dust trails extending 4.20 arc minutes to the east and 6.89 arc minutes to the west and tails extending about 1 arc minute from elements of the nuclear train. Bureau director Brian G. Marsden noted that the comet was some 4° from Jupiter and that its motion suggested that it could be near Jupiter's distance from the Sun.

By March 27 Marsden had enough positions to attempt to derive possible orbits. One elliptical solution gave a close approach to Jupiter in July 1992. Also on March 27, Jane Luu and David Jewitt took an image with the 2.2-m telescope on Mauna Kea in Hawaii that showed as many as 17 separate sub-nuclei "strung out like pearls on a string" 50 arc seconds long, and this was reported in Circular No. 5730 two days later. Figure 4 shows an early image taken by Scotti on March 30, 1993. This long exposure (440 seconds on a CCD detector) brings out the faint detail of the debris field, though it overexposes the individual nucleus fragments. Figure 5 is an image from the Hubble Space Telescope (HST), taken by Harold A. Weaver and collaborators on July 1, 1993 (before the HST repair mission), that clearly shows at least 15 individual fragments in one image frame of the train.

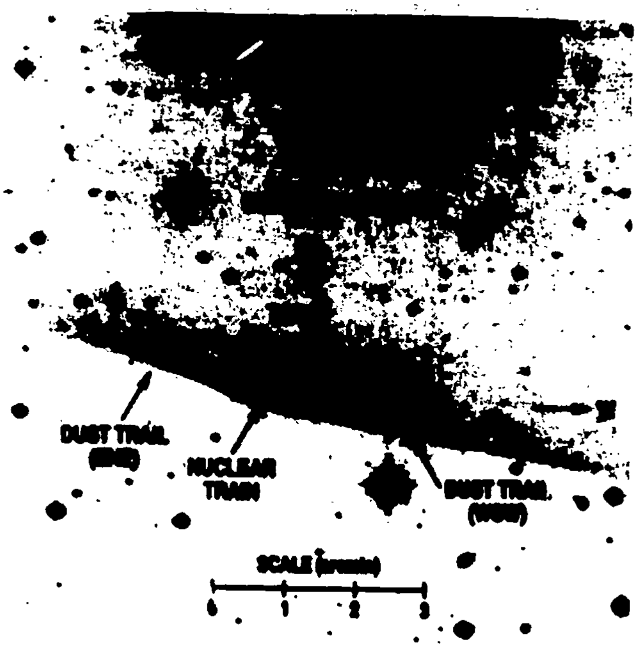


Figure 4. Image of Shoemaker-Levy 9 on March 30, 1993. Integration time 440 seconds with the 0.91-m Spacewatch telescope of the U. of Arizona Observatories on Kitt Peak, Arizona. (Courtesy of J. V. Scotti.)

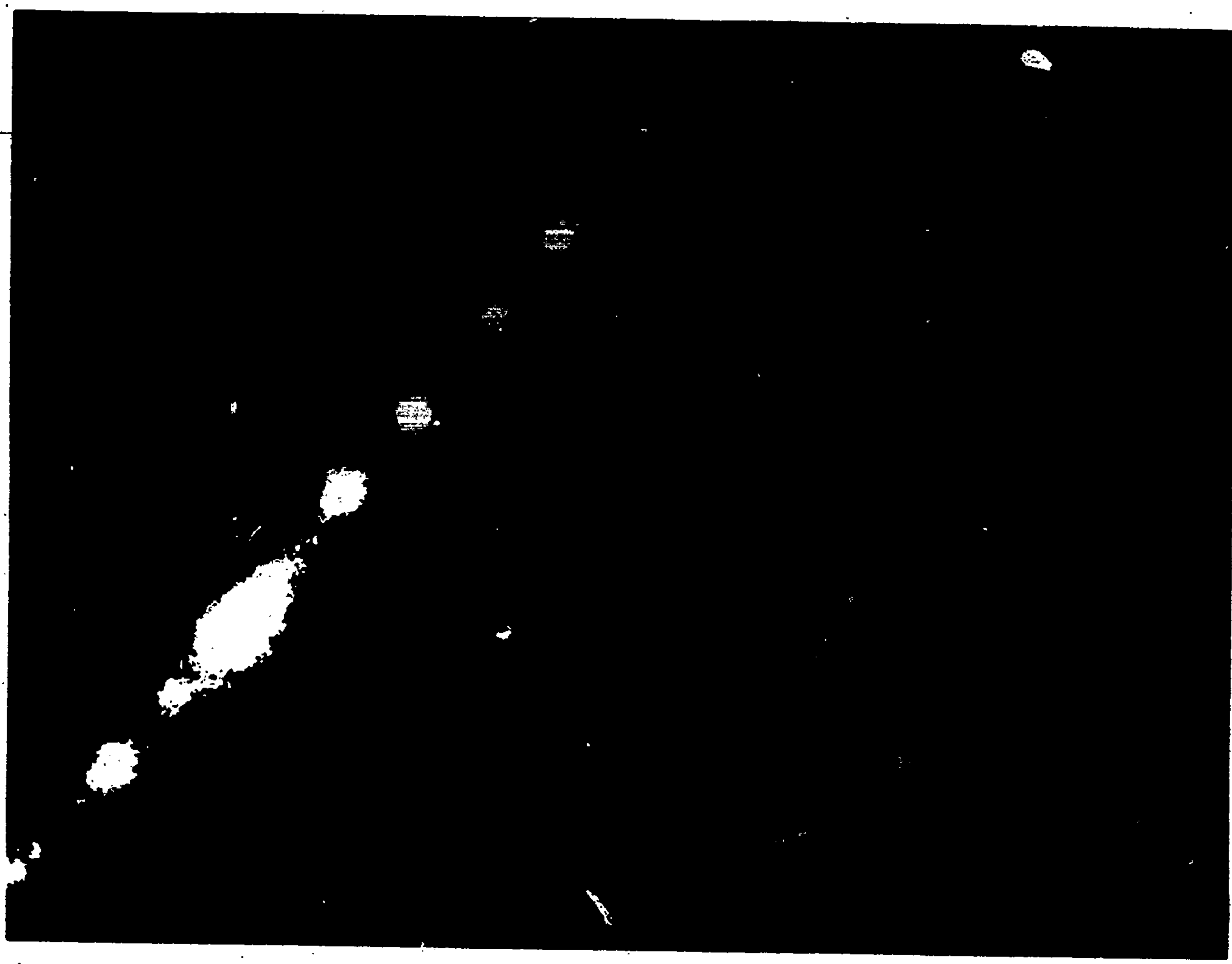


Figure 5. Image of Shoemaker-Levy 9 taken by the Hubble Space Telescope on July 1, 1993. (Courtesy of H. A. Weaver and collaborators.)

In IAU Circular No. 5744, dated April 3, 1993, Marsden used positions covering a period of 17 days (including two prediscovery positions from March 15) and was able to report that no orbit of very long period (near parabolic) was possible. The orbit had to be an ellipse of rather small eccentricity relative to the Sun and relatively short period. Since it was not at all obvious where the center of mass of this new comet lay, most observers were just reporting the position of what appeared to be the center of the train. This made an accurate orbit (or orbits) difficult to determine. Marsden suggested that a very close approach to Jupiter in 1992 continued to be a distinct possibility, and the orbit he chose to publish was one with the comet "at least temporarily" i: orbit around Jupiter.

By May 22 Marsden had almost 200 positions of the center of the train. In Circular No. 5800 he reported on an orbit computed May 18 by Syuichi Nakano that showed the comet approaching within 120,000 km of Jupiter on July 8, 1992, and approaching again, this time within 45,000 km of the center of Jupiter, on July 25, 1994. Marsden noted that this distance was less than the radius of Jupiter. In other words, the comet, or at least parts of it, could very well hit Jupiter.

By October 18, 1993, Paul W. Chodas and Donald K. Yeomans were able to report at the annual American Astronomical Society's Division of Planetary Sciences meeting that the probability of impact for the major fragments of Shoemaker-Levy 9 was greater than 99%. The fragments apparently would hit over a period of several days, centered on July 21.2, on the night side of Jupiter at latitude 44° S and longitude 35° past the midnight meridian, according to available observations. This unfortunately is also the back side of Jupiter as viewed from Earth. The 1992 approach to Jupiter that disrupted the comet was calculated to have been at a distance of 113,000 km from the planet's center and only 42,000 km above its cloud tops. Furthermore, they found that the comet 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.

After recovery of the comet on December 9, following the period during which it was too near to the Sun in the sky to observe, Chodas and Yeomans found that the probability was greater than 99.99% that all the large fragments will hit Jupiter. The encounter period is now centered on July 19.5, and orbits for individual fragments are uncertain by about 0.03 days (1 σ). The impact site has moved closer to the limb of Jupiter, now near 75° from the midnight meridian and only a few degrees beyond the dark limb as seen from Earth, but all pieces still impact on the back side. The 1992 approach that split the comet is now calculated to have occurred on July 7.84 and only 25,000 km (15,500 mi.) above the clouds. These data now cover a much longer time base and are based upon calculations for individual fragments. They are unlikely to change significantly in the future. The comet probably approached Jupiter no nearer than about 9 million km in the orbit prior to that of 1992.

In a comprehensive paper prepared for *The Astronomical Journal*, Zdenek Sekanina, Chodas, and Yeomans report on the details of the breakup of Shoemaker-Levy 9 as calculated from the positions, motions, and brightness of the fragments and debris. They used data from Jewitt, Luu, and Chen taken in Hawaii, Scotti in Arizona, and Weaver's Hubble Space Telescope (HST) observing team. For example, the 11 brightest fragments as measured with the HST, visual (V) magnitude 23.7–24.8 or about 15 million times too faint to be seen by the naked eye, had the brightness one would expect from spheres 4.3 down to 2.5 km in diameter, assuming a normal cometary reflectivity for the fragments (about 4%). Of course the fragments are not spheres, since tidal disruption tends to occur in planes perpendicular to the direction of the object causing the disruption (Jupiter) and since comets generally are not spherical to begin with. Nevertheless, adding up the sizes of these 11 fragments, the other fragments not precisely measured, and all of the debris making up the trails and tails, suggests that the original comet must have been at least 9 km in average diameter, and it could have been somewhat larger. This was a good-sized comet, about the same size as Comet Halley.

When comets split, the pieces do not go flying apart at a high velocity, each to immediately go into its own independent orbit. The escape velocity from a non-rotating spherical comet 5 km in radius with a density of 0.5 g/cm^3 (half that of water) is 2.65 m/s (6.5 mph). If suddenly freed of gravity and molecular bonds, a particle at the equator of that 10-km body, assuming a rotation period of 12 hours, would depart with a velocity of only 0.72 m/s (1.6 mph) relative to the center of the comet. Some comets appear to rotate more rapidly than once per half day, while many, such as Halley, rotate more slowly. In any case the centrifugal force on unattached pieces of material lying on the surface of a rotating comet is not normally sufficient to overcome the gravity holding them there. Pieces do not fly off of the nucleus "spontaneously." Even when the tidal forces overcome self-gravity the pieces separate slowly, and they continue to interact gravitationally. More important, the pieces bang into one another, changing their velocities and perhaps fragmenting further.

In the case of Shoemaker-Levy 9, Sekanina, Chodas, and Yeomans estimate that although fragmentation probably began before closest approach to Jupiter, dynamic independence of the pieces didn't occur until almost two hours after closest approach. For a period of at least two–three hours, collisions dominated the dynamics of all but the largest pieces, with each small grain suffering some 10 collisions per second and the bigger pieces being subjected to many times this number of low velocity impacts by the small particles. All of this converted the original rotational velocities of the bits and pieces of 0–2 mph into a random "equilibrium" velocity distribution, with some smaller pieces having velocities several times their original velocity. Once the pieces stopped hitting one another, each continued to move in its own independent orbit determined mainly by the gravity of Jupiter and the Sun. The pressure of light from the Sun also had a significant effect upon the smallest particles, creating a broad dust tail just as happens in a normal comet. There has been no evidence of the presence of gases from Shoemaker-Levy 9, either direct spectroscopic evidence or motion of the dust particles that cannot otherwise be explained. This is not to say that there are no gases, only that there is no evidence for them. The only direct evidence we have that Shoemaker-Levy 9 is really a comet and not an asteroid is the fact that it broke up so easily! Asteroids are not thought to be so fragile.

It is unlikely that the exact circumstances of the breakup of Shoemaker-Levy 9 will ever be known with certainty. However, the physical model needed to reproduce the train (of individual large fragments), the trails (of debris on either side of the train), and the tails (of very small particles in the anti-Sun direction) in many images like those shown in Figures 4 and 5 does set limits on the separation time, sizes, and velocities of the pieces and particles making up each element. The model of Sekanina, Chodas, and Yeomans, the most complete at this writing, suggests that the original comet cannot have been much smaller than 9 km in mean diameter, that it probably was rotating quite rapidly (perhaps once in eight hours), and that the breakup, as defined by dynamical independence from collisions and limited mutual gravitational effects, was not completed until about two hours after the closest approach to Jupiter. The comet nucleus was probably not very spherical or the debris trails on either side of the train of nucleus fragments would be nearly equal in length, which they are not. After the collisions ceased, the motion of the largest fragments was dominated by Jupiter, with those fragments closest to Jupiter at breakup remaining closest and therefore moving with a shorter period in accordance with basic mechanics. The fragment that started nearest to Jupiter will be the first to return to Jupiter and hit the planet.

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 with the planet (see Figure 6). H. J. Melosh and P. Schenk have offered the intriguing suggestion that linear chains of craters observed on Jupiter's satellites Ganymede and Callisto are the product of impacts by earlier comets fragmented by Jupiter.

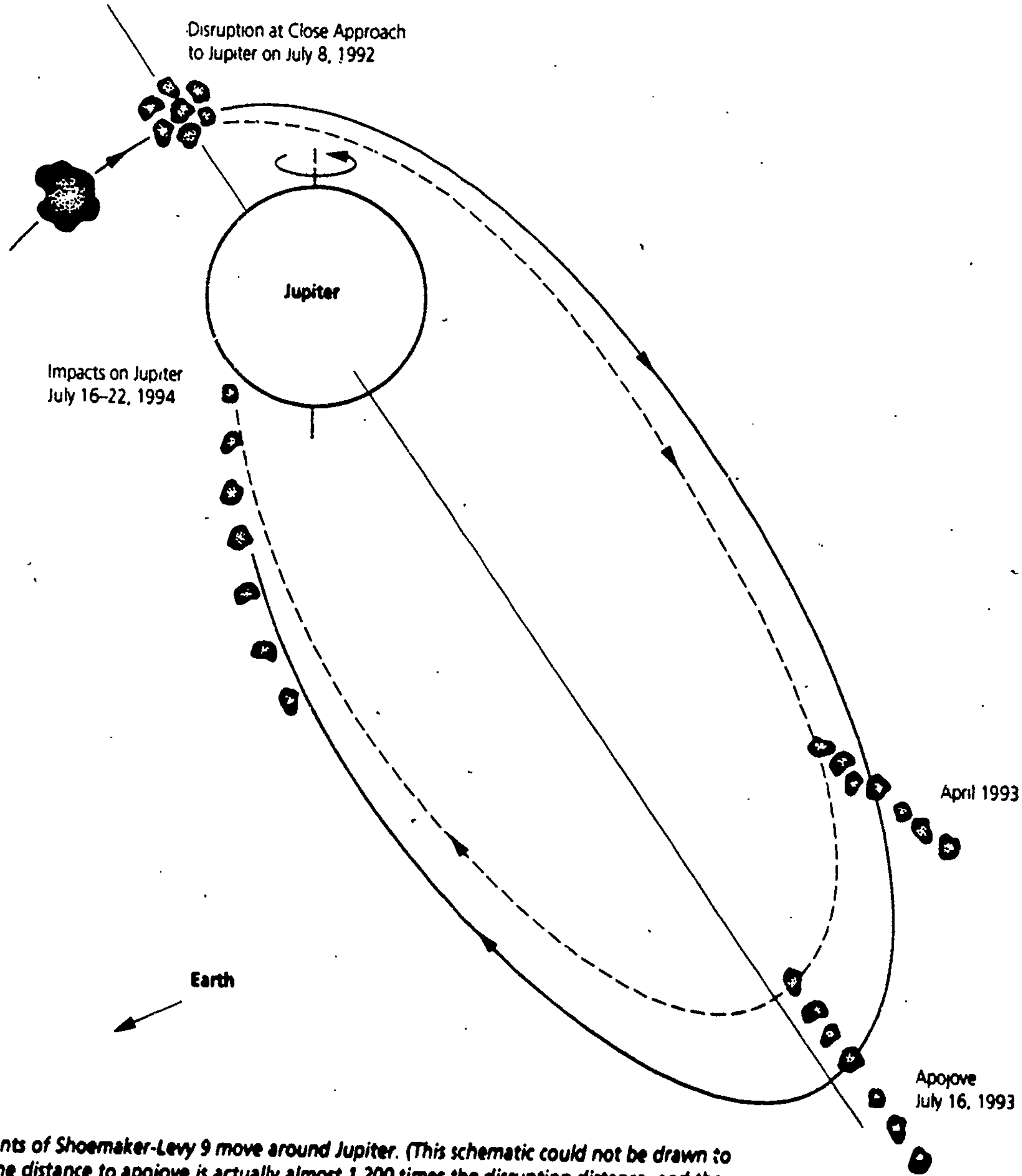


Figure 6. The fragments of Shoemaker-Levy 9 move around Jupiter. (This schematic could not be drawn to scale. For example, the distance to apojove is actually almost 1,200 times the disruption distance, and the true representation would be a long narrow ellipse, e > 0.99, that looks almost like a straight 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.) Prepared by Z. Sekanina, P. W. Chodas, and D. K. Yeomans.)

5

The Planet Jupiter

Jupiter is the largest of the nine planets, more than 10 times the diameter of Earth and more than 300 times its mass. In fact the mass of Jupiter is almost 2.5 times that of all the other planets combined. Being composed largely of the light elements hydrogen and helium, its mean density is only 1.314 times that of water. The mean density of Earth is 5.245 times that of water. The pull of gravity on Jupiter at the top of the clouds at the equato. is 2.4 times as great as gravity's pull at the surface of Earth at the equator. The bulk of Jupiter rotates once in $9^h\ 55.5^m$, although the period determined by watching cloud features differs by up to five minutes due to intrinsic cloud motions.

The visible "surface" of Jupiter is a deck of clouds of ammonia crystals, the tops of which occur at a level where the pressure is about half that at Earth's surface. The bulk of the atmosphere is made up of 89% molecular hydrogen (H_2) and 11% helium (He). There are small amounts of gaseous ammonia (NH_3), methane (CH_4), water (H_2O), ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO), hydrogen cyanide (HCN), and even more exotic compounds such as phosphine (PH_3) and germane (GeH_4). At levels below the deck of ammonia clouds there are believed to be ammonium hydrosulfide (NH_4SH) clouds and water crystal (H_2O) clouds, followed by clouds of liquid water. The visible clouds of Jupiter are very colorful. The cause of these colors is not yet known. "Contamination" by various polymers of sulfur (S_3, S_4, S_5, and S_8), which are yellow, red, and brown, has been suggested as a possible cause of the riot of color, but in fact sulfur has not yet been detected spectroscopically, and there are many other candidates as the source of the coloring.

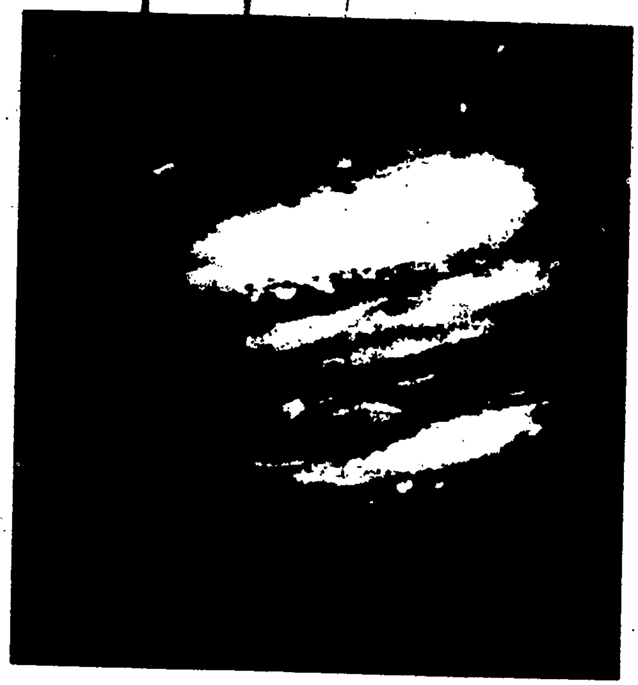


Figure 7. An image of Jupiter taken by the Voyager 1 spacecraft in 1979.

The meteorology of Jupiter is very complex and not well understood. Even in small telescopes, a series of parallel light bands called zones and darker bands called belts is quite obvious. The polar regions of the planet are dark. (See Figure 7.) Also present are light and dark ovals, the most famous of these being "the Great Red Spot." The Great Red Spot is larger than Earth, and although its color has brightened and faded, the spot has persisted for at least 162.5 years, the earliest definite drawing of it being Schwabe's of Sept. 5, 1831. (There is less positive evidence that Hooke observed it as early as 1664.) It is thought that the brighter zones are cloud-covered regions of upward moving atmosphere, while the belts are the regions of descending gases, the circulation driven by interior heat. The spots are thought to be large-scale vortices, much larger and far more permanent than any terrestrial weather system.

The interior of Jupiter is totally unlike that of Earth. Earth has a solid crust "floating" on a denser mantle that is fluid on top and solid beneath, underlain by a fluid outer core that extends out to about half of Earth's radius and a solid inner core of about 1,220-km radius. The core is probably 75%

iron, with the remainder nickel, perhaps silicon, and many different metals in small amounts. Jupiter on the other hand may well be fluid throughout, although it could have a "small" solid core (say up to 15 times the mass of Earth!) of heavier elements such as iron and silicon extending out to perhaps 15% of its radius. The bulk of Jupiter is fluid hydrogen in two forms or phases, liquid molecular hydrogen on top and liquid metallic hydrogen below; the latter phase exists where the pressure is high enough, say 3–4 million atmospheres. There could be a small layer of liquid helium below the hydrogen, separated out gravitationally, and there is clearly some helium mixed in with the hydrogen. The hydrogen is convecting heat (transporting heat by mass motion) from the interior, and that heat is easily detected by infrared measurements, since Jupiter radiates twice as much heat as it receives from the Sun. The heat is generated largely by gravitational contraction and perhaps by gravitational separation of helium and other heavier elements from hydrogen, in other words, by the conversion of gravitational potential energy to thermal energy. The moving metallic hydrogen in the interior is believed to be the source of Jupiter's strong magnetic field.

Jupiter's magnetic field is much stronger than that of Earth. It is tipped about 11° to Jupiter's axis of rotation, similar to Earth's, but it is also offset from the center of Jupiter by about 10,000 km (6,200 mi.). The magnetosphere of charged particles which it affects extends from 3.5 million to 7 million km in the direction toward the Sun, depending upon solar wind conditions, and at least 10 times that far in the anti-Sun direction. The plasma trapped in this rotating, wobbling magnetosphere emits radio frequency radiation measurable from Earth at wavelengths from 1 m or less to as much as 30 km. The shorter waves are more or less continuously emitted, while at longer wavelengths the radiation is quite sporadic. Scientists will carefully monitor the Jovian magnetosphere to note the effect of the intrusion of large amounts of cometary dust into the Jovian magnetosphere.

The two Voyager spacecraft discovered that Jupiter has faint dust rings extending out to about 53,000 km above the atmosphere. The brightest ring is the outermost, having only about 800-km width. Next inside comes a fainter ring about 5,000 km wide, while very tenuous dust extends down to the atmosphere. Again, the effects of the intrusion of the dust from Shoemaker-Levy 9 will be interesting to see, though not easy to study from the ground.

The innermost of the four large satellites of Jupiter, Io, has numerous large volcanos that emit sulfur and sulfur dioxide. Most of the material emitted falls back onto the surface, but a small part of it escapes the satellite. In space this material is rapidly dissociated (broken into its atomic constituents) and ionized (stripped of one or more electrons). Once it becomes charged, the material is trapped by Jupiter's magnetic field and forms a torus (donut-shape) completely around Jupiter in Io's orbit. Accompanying the volcanic sulfur and oxygen are many sodium ions (and perhaps some of the sulfur and oxygen as well) that have been sputtered (knocked off the surface) from Io by high energy electrons in Jupiter's magnetosphere. The torus also contains protons (ionized hydrogen) and electrons. It will be fascinating to see what the effects are when large amounts of fine particulates collide with the torus.

Altogether, Jupiter has 16 known satellites. The two innermost, Metis and Adrastea, are tiny bodies, having radii near 20 and 10 km respectively, that interact strongly with the rings and in fact may be the source of the rings. That is, the rings may be debris from impacts on the satellites. Amalthea and Thebe are still small, having mean radii of 86.2 and about 50 km, respectively, but they are close to Jupiter and may serve as useful reflectors of light from some of the impacts. The Galilean satellites (the four moons discovered by Galileo in 1610), Io, Europa, Ganymede, and Callisto, range in radius from 1,565 km (Europa) to 2,634 km (Ganymede). (Earth's Moon has a radius of 1,738 km.) They lie at distances of 421,700 km (Io) to 1,883,000 km (Callisto) from Jupiter. These objects will serve as the primary reflectors of light from the impacts for those attempting to indirectly observe the actual impacts. The outer eight satellites are all tiny (less than 100-km radius) and at large distances (greater than 11 million km) from Jupiter. They are expected to play no role in impact studies.

6

The Final Orbit of Shoemaker-Levy 9

The motion of Comet Shoemaker-Levy 9 can technically be described as chaotic, which means that calculations based upon the input of comet positions having very tiny differences (small input errors) causes large differences in the results of calculations of the subsequent motion and the apparent prior motion. Large perturbations caused by successive close approaches to Jupiter have resulted in each orbit being different in size, shape, and orientation. The orbits have not been the simple result of a small body in orbit around a large one but rather the product of a "tug of war" between Jupiter and the Sun, a classic "three-body problem." Near to Jupiter the planet's gravity has dominated the motion, but far from Jupiter the Sun is more important. On July 16, 1993, at apojove (the point farthest from Jupiter) in the current orbit, Shoemaker-Levy 9 was almost 1,200 times as far from Jupiter as at the time of breakup, a distance of 50 million km, equal to a third of the distance of Earth from the Sun. The comet has been in a closed orbit around Jupiter for many decades, but that orbit is far from stable. Figure 8 by Chodas shows what this orbit will look like as viewed from the Sun at the time of impact. It is tipped (inclined) 53° to Jupiter's equator as measured at apojove and is bent about 20° more near to Jupiter. (A three-body orbit rarely lies in one plane like the simple two-body orbit.)

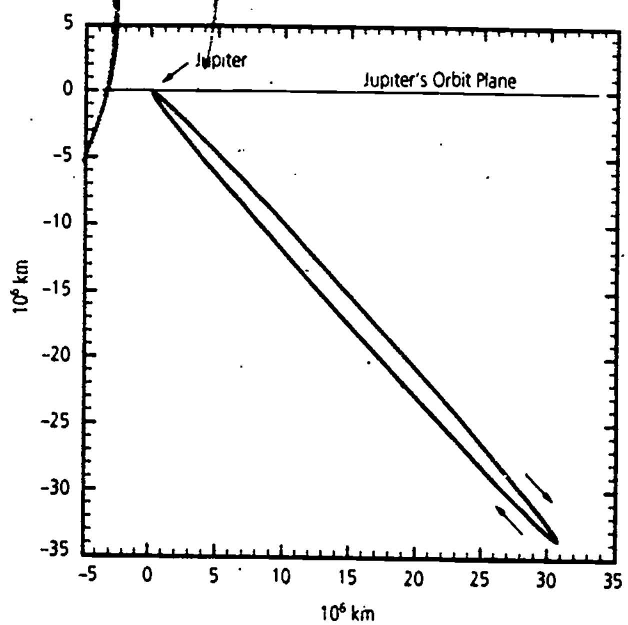


Figure 8. Jovicentric orbit of Shoemaker-Levy 9 as viewed from the Sun on July 21, 1994. (Prepared by P. W. Chodas.)

During this final orbit, after breakup in July 1992, Shoemaker-Levy 9 was followed carefully from discovery in March 1993 until the time the comet's angular distance from the Sun became too small to permit observations. The last useful astrometric (positional) observations reported before the fragments were lost in the glare of the Sun were made on July 11. The comet was recovered (found again after almost five months without observations) by Scotti and Tom Gehrels on December 9, with the comet rising above the horizon a bit more than three hours before the Sun in the morning sky. (The comet is so faint that it cannot be observed in twilight or too low on the horizon.) The quality of the predictions for the time of impact of the individual fragments on Jupiter will depend upon the number of high-quality astrometric observations of each comet fragment made between December 1993 and the time of impact. A week before the impacts the times should be known at least to ±10 minutes (with 50% confidence), improving to perhaps ±5 minutes a half day before impact.

At a fall planetary astronomy meeting (DPS) Jewitt, Luu, and Chen exhibited an image showing 21 distinct fragments in the Shoemaker-Levy 9 nucleus train. At discovery in March, this train was about 50 arc seconds or 162,000 km in length as projected on the sky. This angular distance had increased by about 40% (and the true linear distance by about 50%, since Jupiter was then farther from Earth) by the time the comet was lost in the glare of the Sun in July. The spreading is caused mainly by the fact that the piece closest to Jupiter at breakup was some 9 km closer than the farthest piece (the diameter of the comet) and therefore entered a faster orbit. The orbits are all so elongated that from Earth they appear to be nearly a straight line with the fragments strung out along it. The fragment nearest to Jupiter at breakup remains nearest to it and will be the first to impact. At this writing, Chodas and Yeomans predict that the train will reach an apparent length of some 1,286 arc seconds at the time the first of the fragments enters Jupiter's atmosphere. The true length of the train will be 4,900,000 km at that time, and it will require 5.5 days for all of the major fragments to impact.

The new data taken following solar conjunction (the closest apparent approach to the Sun as projected against the sky) more than doubled the length of time since discovery for which cometary positions were available. With this new data, it appears that the impacts will be centered on about July 19.5, a day and a half earlier than the first predictions. The approach to Jupiter that shattered the comet appears to have been even closer than first thought, about 96,000 km from the planet's center and only 25,000 km above the clouds. The revised orbit has also moved the impact points closer to the visible hemisphere, but unfortunately still on the back side as seen from Earth. The brightest fragment, of which there is some indication that it itself is fragmented, will impact on about July 20.78 and contains about 10% of the total mass of the comet. The other 20 observed fragments contain more than 80% of the mass. The remaining mass is contained in all of the dust and small pieces in the train, the trails, and the tails. Most of this mass also will hit Jupiter over a period of several months beginning about July 10, but it probably will cause few or no detectable effects.

Meanwhile, the dust trails of small debris will continue to spread, as will the major fragments. The east–northeast trail is expected to reach a maximum apparent length of some 70 arc minutes in late June of 1994 and then decrease again in apparent length with the tip turning around into a "V" shape. The west–southwest trail may reach a length of almost 100 arc minutes before impacts begin. Only the larger trail material will actually impact Jupiter. The earliest dust will begin to hit about July 10, and impacts will continue into October. The smaller dust will be moved into the tail by solar radiation pressure and will miss the planet completely.

If upon further study it is found that the pieces of Shoemaker-Levy 9 have continued to fragment, then predicting impact times will be much more difficult and the predictions less reliable. Such continued fragmentation of pieces already badly fractured is very possible, but fragmentation in the last day or two, when it is most likely to occur, will have no significant effect on the predicted *times* of impact. The pieces typically separate with a velocity of less than a meter per second. There are 86,400 seconds in a day, so even pieces separating at a full meter per second would be only 86.4 km apart after one day. Moving jointly at a velocity which reaches 60 km/s at impact, the pieces would hit within a few seconds of each other. The effect of further splitting upon the impact phenomena would be far greater and is discussed in the next section.

Figure 9 by David Seal shows the final segment of the comet fragment's trajectories. They will impact near a latitude of 44° S and a longitude 70° past the midnight meridian, still 10° beyond the limb of Jupiter as seen from Earth, impacting the atmosphere at an angle of about 42° from vertical.

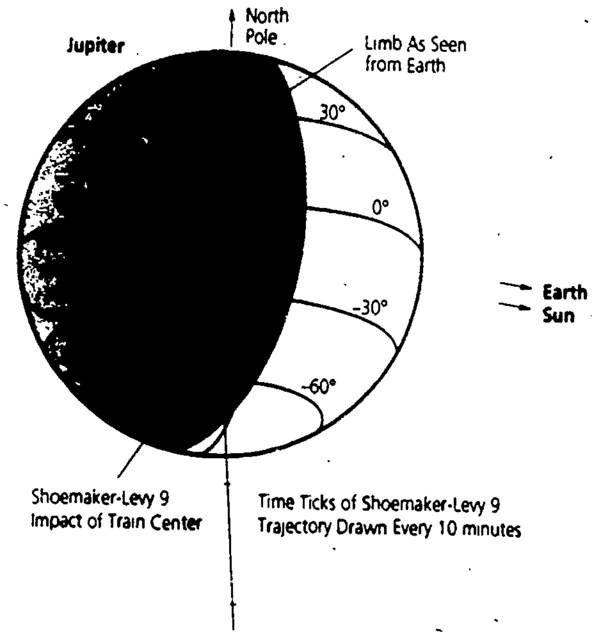


Figure 9. The impact site of the fragments of Comet Shoemaker-Levy 9 on Jupiter. (Prepared by D. Seal.)

Observing conditions from Earth will not be ideal at the time of the impacts, since there will be only about two hours of good observing time for large telescopes at any given site after the sky gets good and dark and before Jupiter comes too close to the horizon to observe. At least it will be summer in the northern hemisphere, and there will be a better chance for good weather where many observatories are located. With 21 pieces hitting over a 5.5-day period, there will be an impact on average about every 6 hours, so any given site should have about one chance in three of observing at the actual time of an impact each night. Since the impacts will be on the back side of Jupiter, light from the impacts can only be observed by reflection from Jupiter's moons or perhaps from the rings or the dust comae of the comet fragments. Those attempting observations of the effects of the impacts on Jupiter can begin about 20 minutes after the impacts, when the impact area rotates into view from Earth.

7

The Collisions

Exactly what will happen as the fragments of Shoemaker-Levy 9 enter the atmosphere of Jupiter is very uncertain, though there are many predictions. If the process were better understood, it would be less interesting. Certainly scientists have never observed anything like this event. There seems to be complete agreement only that the major fragments will hit Jupiter and that these collisions will occur on the back side of Jupiter as seen from Earth.

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 lost by the body is given to the air molecules. They move a bit faster (become hotter) and in turn heat the moving body by conduction. This frictional process turns energy of mass motion (kinetic energy) into thermal energy (molecular motion). 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 1 — 331.7 m/s 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 km/s, 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 surface of the solid body becomes a liquid and then a gas. The gas atoms begin to lose electrons and become ions. This mixture of ions and electrons is called a plasma. The plasma absorbs radio waves and is responsible for the communication blackouts that occur when a spacecraft such as the Space Shuttle reenters Earth's atmosphere. The atmospheric molecules are also dissociated and ionized and contribute to the plasma. At higher temperatures, energy transfer by radiation becomes more important than conduction. Ultimately the temperatures of the plasma and the surface of the intruding body are determined largely by the radiation balance. The temperature may rise to 50,000 K (90,000° F) or more for very large bodies such as the fragments of Shoemaker-Levy 9 entering Jupiter's atmosphere at 60 km/s. The loss of material as gas from the impacting body is called thermal ablation. The early manned spacecraft (Mercury, Gemini, and Apollo) had "ablative heat shields" made of a material having low heat conductivity (through to the spacecraft) and a high vaporization temperature (strong molecular bonds). As this material was lost, as designed, it carried away much of the orbital energy of the spacecraft reentering Earth's atmosphere.

There are other forms of ablation besides thermal ablation, the most important being loss of solid material in pieces. In a comet, fragile to begin with and further weakened and/or fractured by thermal shock and by melting, such spallation of chips or chunks of material has to be expected. Turbulence in the flow of material streaming from the front of the shock wave can be expected to strip anything that is loose away from the comet and send it streaming back into the wake. 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 (mostly exponentially).

On Earth a sizable iron meteoroid or even some relatively low velocity stony meteoroids can survive all of this and impact the surface, where we collect them for study and exhibition. (Small bodies traveling in space are called meteoroids. The visible phenomena which occur as a meteoroid enters the atmosphere is called a meteor. Surviving solid fragments are called meteorites. There is no sharp size distinction between meteoroids and asteroids. Normally, if the body has been detected telescopically before entering the atmosphere, it has been called an asteroid.) Many meteoroids suffer what is called a "terminal explosion" when crushed while still many kilometers above the ground. This is what happened in Tunguska, Siberia, in 1908. There a body with a mass of some 10^9 kg (2.2 billion lb.) and probably 90 to 190 m in diameter entered Earth's atmosphere at a low angle with a velocity of less than 15 km/s. It exploded at an altitude of perhaps 5–10 km. This explosion, equivalent to 10–20 megatons of TNT, combined with the shock wave generated by the body's passage through the atmosphere immediately before disruption, leveled some 2,200 km^2 of Siberian forest. The Tunguska body had a tensile strength of some 2×10^8 dynes/cm^2, more than 100,000 times the strength of Shoemaker-Levy 9, but no surviving solid fragments of it (meteorites) have ever been found. The fragile Shoemaker-Levy 9 fragments entering an atmosphere of virtually infinite depth at a much higher velocity will suffer almost immediate destruction. The only real question is whether each fragment may 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.

Scientists have differed in their computations of the depths to which fragments of given mass will penetrate Jupiter's atmosphere before being completely destroyed. If a "terminal explosion" occurs above the clouds, which are thought to lie at a pressure level of about 0.5 bar or roughly 0.5 Earth atmosphere (see Section 5), then the explosion will be very bright and easily observable by means of light reflected from Jupiter's satellites. Using ablation coefficients derived from observation of many terrestrial fireballs, Sekanina predicts that the explosions indeed will occur above the clouds. Mordecai-Mark Mac Low and Kevin Zahnle have made calculations using an astrophysical hydrodynamic code (ZEUS) on a supercomputer. They assume a fluid body as a reasonable approximation to a comet, since comets have so little strength, and they predict that the terminal explosions will occur near the 10-bar level, well below the clouds. Others have suggested still deeper penetration, but most calculations indicate that survival to extreme depths is most unlikely. The central questions then appear to be whether terrestrial experience with lesser events can be extrapolated to events of such magnitude and whether all the essential physics has been included in the supercomputer calculations. We can only wait and observe what really happens, letting nature teach us which predictions were correct.

O.K. So an explosion occurs at some depth. What does that do? What happens next? Sekanina calculates that about 93% of the mass of a 10^{13}-kg fragment remains one second before the terminal explosion and the velocity is still almost 60 km/s. 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. Once again, the total energy release here will be many thousands of times that of any hydrogen bomb ever tested, but the energy will be deposited initially into a much greater volume of Jupiter's atmosphere, so the energy density will not be so high as in a bomb, and, of course, there will be no gamma rays or neutrons (nuclear radiation or particles) flying about. The energy of these impacts will be beyond any prior experience. The details of what actually occurs will be determined by the observations in July 1994, if the observations are successful.

If differential gravitation (tidal forces) should further fragment a piece of the comet, say an hour or two before impact, the pieces can be expected to hit within a second of each other. In one second a point at 44° latitude on Jupiter will rotate 9 km (5.6 mi.), however, so the pieces would enter the atmosphere some distance apart. Smaller pieces will explode at higher altitudes but not so spectacularly. If smaller pieces do explode above the clouds, they may be more "visible" than larger pieces exploding below the clouds. It is also possible that implanting somewhat less energy density over a wider volume of atmosphere might create a more visible change in Jupiter's atmosphere. Sekanina notes that pieces smaller than about 1.3-km mean radius should not be further fragmented by tidal forces unless they were already weakened by earlier events.

One of the more difficult questions to answer is just how bright these events will be. Terrestrial fireballs have typically exhibited perhaps 1% luminous efficiency. In other words about 1% of the total kinetic energy has been converted to visible light. The greater magnitude of the Jupiter impacts may result in more energy appearing as light, but let's assume the 1% efficiency. Then Sekanina calculates that a 10^{13}-kg 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! Sekanina, of course, calculates that the explosions will occur *above* the clouds. And, remember that, unfortunately, these impacts will occur on Jupiter's back side as seen from Earth. There will be no immediate visible effect on the appearance of Jupiter. The light of the explosion may be seen reflected from the Galilean satellites of Jupiter, if they are properly placed at the times of impacts. Ganymede, for example, might brighten as much as six times, while Io could brighten to 35 times its normal brilliance for a second before fading slowly, if the explosions occur above the clouds. This would certainly be visible in an amateur telescope and could conceivably be visible to the naked eye at a dark mountain site as a tiny flash next to Jupiter at the location of the normally invisible satellite. Emphasis on "tiny"! The brightness of explosions occurring below the clouds will be attenuated by a factor of at least 10,000, making them most difficult to observe. 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 most recent predictions are that at least some of the impacts will occur very close to the planetary limb, the edge of the planet's disk as seen from Earth. That edge still has 11° to rotate before it comes into sunlight. This means that the tops of some of the plumes associated with the rising fireballs may be just visible, although with a maximum predicted height of 3,000 km (0.8 arc second as projected on the sky) they will be just "peeking" over the limb. The newly repaired Hubble Space Telescope (HST), with its high resolution and low scattered light, may offer the best chance to see such plumes. By the time they reach their maximum altitude the plumes will be transparent (optically thin) and not nearly so bright as they were near the clouds. Some means of blocking out the bright light from Jupiter itself may be required in order to observe anything. A number of observers plan to look for evidence of plumes and to attempt to measure their size and brightness.

It also is difficult to predict the effects of the impacts on Jupiter's atmosphere. Robert West points out that a substantial amount of material will be deposited even in the stratosphere of Jupiter, the part of the atmosphere above the visible clouds where solar heating stabilizes the atmosphere against convection (vertical motion). Part of this material will come directly from small cometary grains, which vaporize during entry and recondense just as do meteoritic grains in the terrestrial atmosphere. Part will come from volatiles (ammonia, water, hydrogen sulfide, etc.) welling up from the deeper atmosphere as a part of the hot buoyant fireballs created at the time of the large impact events. Many millimeter-sized or larger pieces from the original breakup will also impact at various times for months and over the entire globe of Jupiter. There is relatively little mass in these smaller pieces, but it might be sufficient to create a haze in the stratosphere.

James Friedson notes that the fireball created by the terminal explosion will expand and balloon upward and perhaps spew vaporized comet material and Jupiter's entrained atmospheric gas to very high altitudes. The fireball 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 an 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.

After the particles condense, they will grow in size by colliding and sticking together to form larger particles, eventually becoming sufficiently large to "rain" out of the visible part of the atmosphere. The length of time spent by the cloud particles at altitudes where they can be seen will depend principally on their average size; relatively large particles would be visible only for a few hours after an impact, while small particles could remain visible for several months. Unfortunately, it is very difficult to predict what the number and average size of the particles will be. A cloud of particles suspended in the atmosphere for many days may significantly affect the temperature in its vicinity by changing the amount of sunlight that is absorbed in the area. Such a temperature change could be observed from Earth by searching for changes in the level of Jupiter's emitted infrared light.

Glenn Orton notes that large regular fluctuations of atmospheric temperature and pressure will be created by the shock front of each entering fragment, somewhat analogous to the ripples created when a pebble is tossed into a pond, and will travel outward from the impact sites. These may be observable near layers of condensed clouds in the same way that regular cloud patterns are seen on the leeward side of 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. If such waves are detected, measurement of their wavelength and speed will allow scientists to determine certain important physical properties of Jupiter's deep atmospheric structure that are very difficult to measure in any other way.

Whether or not "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 images. In addition there should be compression waves, alternate compression and rarefaction in the atmospheric pressure, which could reflect from and refract within the deeper atmosphere, much as seismic waves reflect and refract due to density changes inside Earth. Orton suggests that these waves might be detected "breaking up" in the shallow atmosphere on the opposite side of the planet from the impacts. Others suggest the possibility of measuring the small temperature fluctuations wherever the waves surface, but this requires the ability to map fluctuations in Jupiter's visible atmosphere of a few millikelvin (a few thousandths of a degree). Detection of any of these waves will require a very fine infrared array detector (a thermal infrared camera).

Between the water and other condensable gases (volatiles) brought with the comet fragments and those exhumed by the rising fireballs, it is fairly certain that a cloud of condensed material will form at the location of the impacts themselves, at high altitudes where such gases seldom, if ever, exist in the usual course of things. It may be difficult to differentiate between the color or brightness of these condensates and any bright material below them in spectra at most visible wavelengths. However, at wavelengths where gaseous methane and hydrogen absorb sunlight, a distinction can easily be made between particles higher and lower in the atmosphere, because the higher particles will reflect sunlight better. Much of the light is absorbed before reaching the lower particles. Observing these clouds in gaseous absorption bands will then tell us how high they lie in the atmosphere, and observations over a period of time will indicate how fast high-altitude winds are pushing them. The speed with which these clouds disappear will be a measure of particle sizes in the clouds, since large particles settle out much faster than small ones, hours as compared to days or months.

Orton also notes that in the presence of a natural wind shear (a region with winds having different speeds and/or directions) such as exists commonly across the face of Jupiter, a long-lived cyclonic feature can be created which is actually quite stable. It may gain stability by being fed energy from the wind shear, in much the same way that the Great Red Spot and other Jovian vortices are thought to be stabilized. Such creation of new, large, fixed "storm" systems is somewhat controversial, but this is a most intriguing possibility!

8

How Can These Impacts and Their Consequences Be Studied?

Space-Based

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 advantages of perfect "seeing" (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 km away from the planet, less than a third the distance of Earth from Jupiter at that time. All of the impacts will occur directly in the field of view of its high resolution camera and 20°–25° of Jovian longitude from the limb. Images of Jupiter will be 60 picture elements (pixels) across, although the impact site will still be smaller than the resolution of the camera. Several instruments besides the camera have potential use, including an ultraviolet spectrometer, a near infrared mapping spectrometer, and a photopolarimeter radiometer. This last suite of instruments could acquire light curves (plots of intensity versus time) of the entry and fireball at many wavelengths from ultraviolet to thermal infrared (from wavelengths much shorter than visible light to much longer).

Using Galileo to make these observations will be challenging. The amount of data the spacecraft can transmit back to Earth is limited by the capability of its low-gain antenna and the time available on the receiving antennas of the National Aeronautics and Space Administration's (NASA's) Deep Space Network here on Earth. The "commands" that tell the spacecraft what to do must be sent up several weeks before the fact and before the impact times are known to better than about 20 minutes with 95% certainty. A later command that simply triggers the entire command sequence may be possible. A lot of data frames can be stored in the Galileo tape recorder, but only about 5% of them can be transmitted back to Earth, so the trick will be to decide which 5% of the data are likely to include the impacts and to 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 Ulysses spacecraft was designed for solar study and used a gravity assist from 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 km 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 receiver of radio frequency signals from 1 to 1000 kHz (kilohertz, or kilocycles in older terminology) called URAP (Unified Radio and Plasma wave experiment). URAP 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 (its last object of study back in 1989 after visiting Jupiter in 1979, Saturn in 1981, and Uranus in 1986) and is about 6.4 billion km 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 been 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 acquire ultraviolet light curves (brightness versus time) of the impact phenomena. The possibility of using one or two other instruments is being considered, though useful results from them seem less likely.

A new small spacecraft called Clementine was launched on January 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. The impact sites will still be just over the limb, and Clementine's resolution will be only a few picture elements on Jupiter. Since the spacecraft will be in cruise mode at the time, on its way to Geographos and not terribly busy, it seems probable that attempts will be made to observe "blips" of light on the limb of Jupiter, from the entering fragments or the fireballs or perhaps light scattered from cometary material (coma) that has not yet entered the atmosphere. Useful light curves could result.

Ground-Based

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. Small portable telescopes can fill in gaps in existing observatory locations for some purposes. Imaging, photometry, spectroscopy, and radiometry will certainly be carried out using a multitude of detectors. Many of these attempts will fail, but some should succeed.

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 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 clear 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.

Measuring the light curve of the entering fragments and the post-explosion fireball can be done only by measuring the light reflected from something else, one of Jupiter's satellites or perhaps the dust coma accompanying the fragment. That dust coma could still be fairly dense out to distances of 10,000 km or more around each fragment. Moving at 60 km/s, it will be almost three minutes before all of the dust also impacts Jupiter. Proper interpretation of such observations will be difficult, however, because the area of the "reflector," the coma dust particles, will be changing as the observations are made. Another complication is the brightness of Jupiter itself, which will have to be masked to the greatest extent possible. Observations in visible light reflected from the satellites will be relatively straightforward and can be done with small telescopes and simple photometers or imaging devices. This equipment is small enough that it can be transported to appropriate sites.

Spectroscopy of the entry phenomena via reflected light from one of the Galilean satellites could be used to determine the composition of the comet and the physical conditions in the fireball, if the terminal explosions occur above Jupiter's clouds. If the explosion occurs below the clouds, there will be too little light to do useful spectroscopy with even the largest telescopes.

The impact zone on Jupiter will rotate into sight from Earth about 20 minutes after each impact, though quite foreshortened as initially viewed. Extensive studies of the zone and the area around it can be made at that time. Such studies surely will include imaging, infrared temperature measurements, and spectroscopy using many of the largest telescopes on Earth. These studies will continue for some weeks, if there is any evidence of changes in Jupiter's atmosphere and cloud structure as a result of the impacts.

For example, astronomers will use spectrometers to look for evidence of chemical changes in Jupiter's atmosphere. Some of the species observed might be those only present in the deep atmosphere and carried up by the fireball (if the explosion occurs deep enough). Others will be the result of changes to the chemistry of the upper atmosphere, taking place because of the energy deposited there by the impacts or because of the additional particulates.

The faint rings of Jupiter, mentioned in Section 5, can be usefully observed from the ground at infrared wavelengths. Shoemaker-Levy 9 debris might bring in new ring material by hitting the two small satellites embedded in the rings (Metis and Adrastea). The rings surely will be monitored for some time using infrared imaging array detectors, which are sensitive to wavelengths more than eight times as long as red visible light.

In Section 5, note was made of the Jovian magnetosphere, which makes its presence known at radio wavelengths, and the Io torus of various ions and atoms, which can be mapped spectroscopically. Either or both of these could be affected sufficiently by the intruding dust from Shoemaker-Levy 9 to be detectably changed. Radio telescopes will surely monitor the former and optical telescopes the latter for weeks or months looking for changes. Jupiter's intense electromagnetic environment is responsible for massive auroral emission near the planet's poles and less intense phenomena across the face of the planet. These may also be disrupted by the collisions and/or the dust "invasion," making auroral monitoring a useful observing technique.

In summary, 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 and/or the Io torus might also persist for some weeks or months. There is the potential to keep planetary observers busy for a long time!

9

What Do Scientists Expect to Learn from All of This?

To give a simple and succinct answer to the title of this section, scientists hope to learn more about comets, more about Jupiter, and more about the physics of high velocity impacts into a planetary atmosphere. Something has already been learned about comets from the behavior of Shoemaker-Levy 9 during its breakup, as discussed in Section 4. Bits and pieces of what everyone hopes will be learned have been noted in Sections 5 through 8. A more complete summary follows.

If the fragments explode above the clouds, there should be enough light reflected from various Jovian satellites to take spectra of the explosions. Since the atmosphere of Jupiter contains very few heavier elements to contaminate the spectra, they could give a great deal of information about the composition of cometary solids. If the fragments explode below the clouds, then spectroscopy must wait until the impact sites rotate into view from Earth. By that time everything will have cooled a great deal, and the cometary component will have been diluted by mixing with the Jovian atmosphere, making such study difficult. In that case the Jovian material itself may prove of interest, with spectroscopic study giving new knowledge of Jupiter's deeper atmospheric composition.

It seems somewhat more certain that new knowledge of Jupiter's atmosphere will be obtained, even if predictions differ as to exactly what that new knowledge will be. There is nearly unanimous agreement that the impacts *will* cause observable changes in Jupiter, at least locally at the impact sites. These may include changes in the visible appearance of the clouds, locally or more widely, measurable temperature fluctuations, again locally or more widely, composition changes caused by material brought up from below the clouds (if the fragments penetrate that deeply), and/or chemical reactions brought about by the thermal pulse and the introduction of cometary material. Any dynamic processes such as these will give a new and better understanding of the structure of Jupiter's atmosphere, perhaps of its motion as well as its static structure.

If sufficient material impacts Jupiter's rings or especially the ring satellites, then there should be local brightening caused by the increase in reflecting area due to the introduction of new material. These new ring particles will each take up their own orbits around Jupiter, gradually spreading out and causing local brightening followed by slow fading into the general ring background. Careful mapping of that brightening and fading will reveal a great deal about the structure and dynamics of the rings. Many believe that impacts on those small inner satellites are the source of the rings, the reason for their existence. Enhancement of the rings from Shoemaker-Levy 9 impacts would be strong confirmation of this idea. Similarly, the interaction of cometary dust with the magnetosphere and with the Io torus will be quite informative, if the dust density proves sufficient to cause observable effects. Radio telescopes will be active in the magnetospheric studies, along with optical spectroscopy of the ions and atoms in the torus.

Last, but far from least, the physics of the impact phenomena themselves, determined from the reflected light curves and from spectra, will be most instructive. Note the inability of scientists to agree on the level of Jupiter's atmosphere at which the terminal explosion will occur. (A few even believe that there will be no terminal explosion or that it will occur so deep in that atmosphere as to be completely unobservable.) Entry phenomena on this scale cannot be reproduced, even by nuclear fusion explosions, and have never before been observed. Better knowledge of the phenomena may allow scientists to predict more accurately just how serious could be the results of future impacts of various-sized bodies on Earth, as well as to determine their effects in the past as registered by the fossil record.

Appendix A
Comparative Tables

*Table 1. Energy comparisons.**

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

**1 BTU = 252 (small) calories = 1,055 J = 2.93×10^{-4} kWh.*

*Table 2. Power comparisons.**

Power Producer	Power, MW	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 Shoemaker-Levy 9, final second	$\sim 9 \times 10^{15}$	6,700,000,000,000
Sun	3.8×10^{20}	280,000,000,000,000,000

**1 horsepower = 745.7 W = 7.457×10^{-4} MW.*

*Table 3. Size comparisons.**

Object	Radius, km	Volume, km³
Jupiter	71,350 (Equatorial) 67,310 (Polar)	1.4×10^{15}
Earth	6,378 (Equatorial) 6,357 (Polar)	1.1×10^{12}
Comet Shoemaker-Levy 9	4.5 (Equivalent sphere)	382
Comet Halley	$7.65 \times 3.60 \times 3.61$	365

**1 mi. = 1.609 km*

Table 4. Brightness comparisons.

Object	Magnitude V_0 (V Magnitude at Opposition)	Relative Brightness
Largest fragment of Shoemaker-Levy 9 during last second	~ –10	1,000
Jupiter	–2.5	1
Ganymede	4.6	1/692
Io	5.0	1/1,000
Largest fragment of Shoemaker-Levy 9 as viewed today	23.7	1/30,000,000,000

Appendix B

The K-T Event

Sixty-five million years ago about 70% of all species then living on Earth disappeared within a very short period. The disappearances included the last of the great dinosaurs. Paleontologists speculated and theorized for many years about what could have caused this "mass extinction," known as the K-T event (Cretaceous-Tertiary Mass Extinction event). Then in 1980 Alvarez, Alvarez, Asaro, and Michel reported their discovery that the peculiar sedimentary clay layer that was laid down at the time of the extinction showed an enormous amount of the rare element iridium. First seen in the layer near Gubbio, Italy, the same enhancement was soon discovered to be worldwide in that one particular 1-cm (0.4-in.) layer, both on land and at sea. The Alvarez team suggested that the enhancement was the product of a huge asteroid impact.

On Earth most of the iridium and a number of other rare elements such as platinum, osmium, ruthenium, rhodium, and palladium are believed to have been carried down into Earth's core, along with much of the iron, when Earth was largely molten. Primitive "chondritic" meteorites (and presumably their asteroidal parents) still have the primordial solar system abundances of these elements. A chondritic asteroid 10 km (6 mi.) in diameter would contain enough iridium to account for the worldwide clay layer enhancement. This enhancement appears to hold for the other elements mentioned as well.

Since the original discovery many other pieces of evidence have come to light that strongly support the impact theory. The high temperatures generated by the impact would have caused enormous fires, and indeed soot is found in the boundary clays. A physically altered form of the mineral quartz that can only be formed by the very high pressures associated with impacts has been found in the K-T layer.

Geologists who preferred other explanations for the K-T event said, "show us the crater." In 1990 a cosmochemist named Alan Hildebrand became aware of geophysical data taken 10 years earlier by geophysicists looking for oil in the Yucatán region of Mexico. There a 180-km (112-mi.) diameter ring structure called "Chicxulub" seemed to fit what would be expected from a 65-million-year-old impact, and further studies have largely served to confirm its impact origin. The Chicxulub crater has been age dated (by the ^{40}Ar/^{39}Ar method) at 65 million years! Such an impact would cause enormous tidal waves, and evidence of just such waves at about that time has been found all around the Gulf of Mexico. Similarly, glassy debris of appropriate age called tektites (and their decomposition products), which are produced by large impacts, have been found all around the Gulf.

One can never prove that an asteroid impact "killed the dinosaurs." Many species of dinosaurs (and smaller flora and fauna) had in fact died out over the millions of years preceding the K-T event. The impact of a 10-km asteroid would most certainly have been an enormous insult to life on Earth. Locally there would have been enormous shock wave heating and fires, a tremendous earthquake, hurricane winds, and trillions of tons of debris thrown everywhere. It would have created months of darkness and cooler temperatures globally. There would have been concentrated nitric acid rains worldwide. Sulfuric acid aerosols may have cooled Earth for years. Life certainly could not have been easy for those species which did survive. Fortunately such impacts occur only about once every hundred million years.

This booklet is the product of many scientists, all of whom have cooperated enthusiastically to bring their best information about this exciting event to a wider audience. They have contributed paragraphs, words, diagrams, slides, and preprints as well as their critiques to this document, which attempts to present an event that no one is quite sure how to describe. Sincere thanks go to Mike A'Hearn, Paul Chodas, Gil Clark, Janet Edberg, Steve Edberg, Jim Friedson, Mo Geller, Martha Hanner, Cliff Heindl, David Levy, Mordecai-Mark Mac Low, Al Metzger, Marcia Neugebauer, Glenn Orton, Elizabeth Roettger, Jim Scotti, David Seal, Zdenek Sekanina, Anita Sohus, Harold Weaver, Paul Weissman, Bob West, and Don Yeomans — and to those who might have been omitted. The choice of material and the faults and flaws in the document obviously remain the responsibility of the author alone.

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