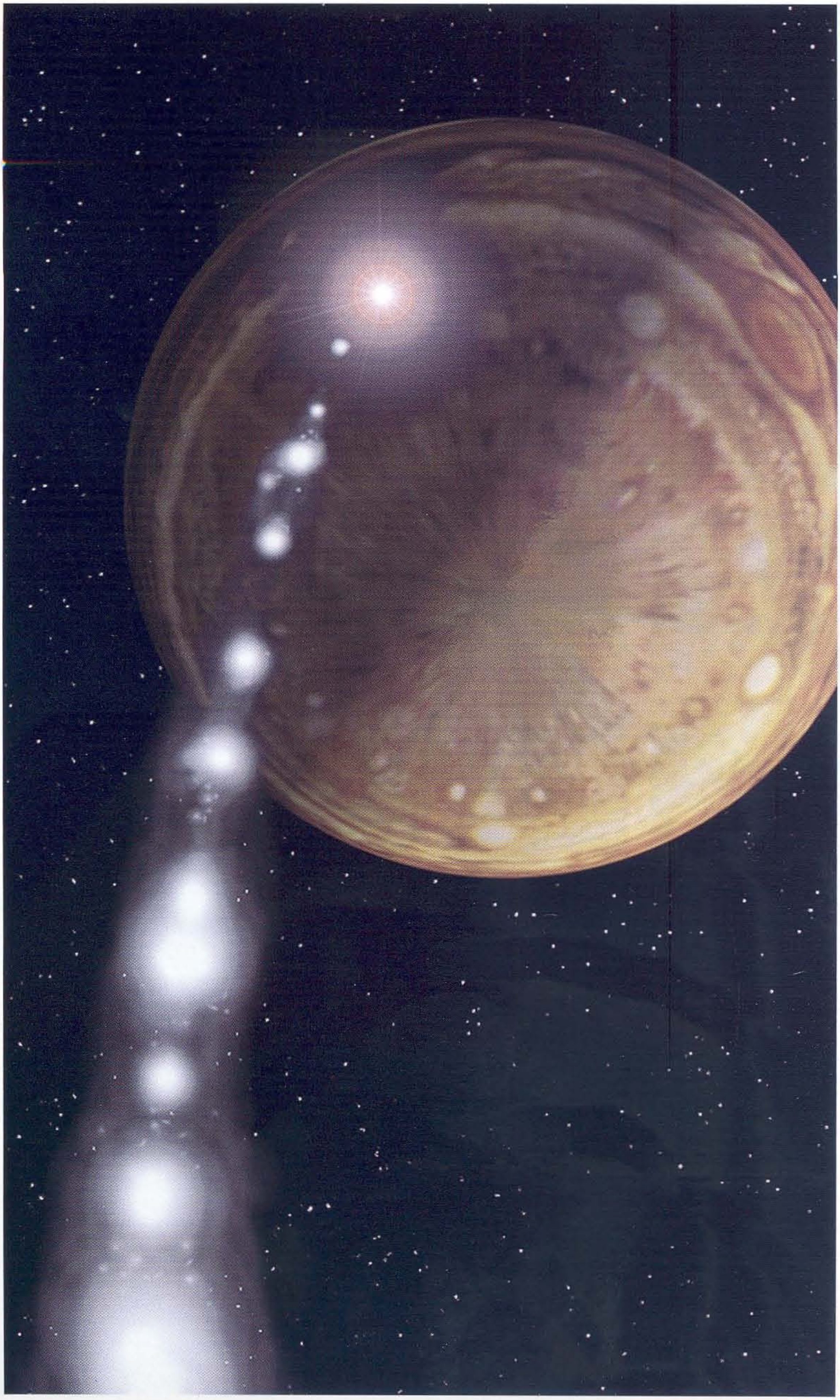


When a Body Hits a Body Comin' Through the Sky

by Douglas L. Smith

Its fate was sealed on July 8, 1992, when the star-crossed snowball passed within 1.6 Jupiter radii (113,000 kilometers) from the center of the massive planet and was literally torn apart.

Shoemaker-Levy 9's last moments, as they might appear to an observer over Jupiter's south pole. David Seal, a mission engineer on JPL's Cassini project, created this representation by wrapping Voyager data around a globe on which the impact point had been plotted. The image was generated using a computer-animation package designed by Caltech's James Blinn for the Voyagers' encounters with the outer planets, and off-the-shelf photo-editing software.

On or about July 21, 1994, a planetary hard-luck case named Periodic Comet Shoemaker-Levy 9 will perform the celestial equivalent of jumping off the Golden Gate Bridge, plunging headlong into Jupiter's atmosphere to a fiery finish. The comet had run afoul of the giant planet some time previously and been captured by Jove's gravitational field. A more fortunate prisoner might have taken up residence in a nice, regular orbit around Jupiter and started a new life as a minor moon, but this hapless hostage stumbled into a chaotic orbit, wandering footloose through the Jovian system.

In a sense, Shoemaker-Levy 9 is no more already. Its fate was sealed on July 8, 1992, when the star-crossed snowball passed within 1.6 Jupiter radii (113,000 kilometers) from the center of the massive planet and was literally torn apart. The strength of any body's gravitational attraction increases as one approaches the object, so Jupiter tugged harder at the comet's near side than at its far side. Within some distance—called the Roche limit—the difference between Jupiter's far-side pull and its near-side pull became stronger than the comet's own puny gravity. The tensile strength of the comet continued to hold it together a little while longer, but the stress soon overwhelmed the fragile comet, pulling it apart. Comets aren't put together very well—the differential acceleration that undid Shoemaker-Levy 9 was a mere 0.0016 meter per second squared. A snowball that loose would come apart in your hand. Truth to tell, it's not clear that this comet was really a snowball—the familiar periodic comets, such as Halley's, are best described as balls of dirty ice, but Shoemaker-Levy 9 could just as easily have been a ball of loose dirt and rock containing little or no ice. All we know for sure is that it was pretty shoddy construction, whatever it was made of.

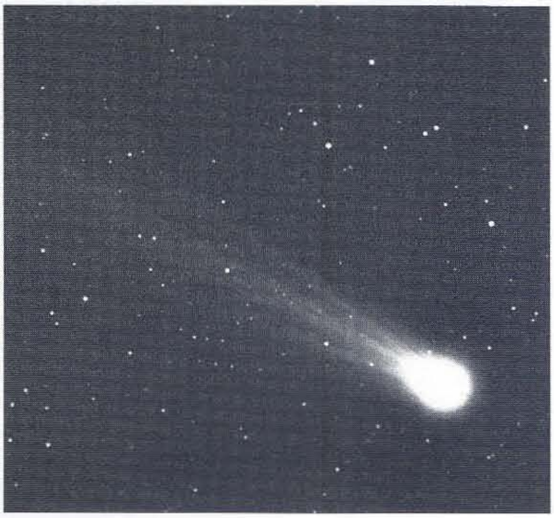
When discovered by Carolyn Shoemaker on March 24, 1993, the fragments of Shoemaker-Levy 9's dismembered body were already smeared out across some 160,000 kilometers—about one arc minute of sky as seen from Earth. (The photographic plate containing the comet was exposed by Carolyn and Eugene Shoemaker (BS '47, MS '48) and David Levy at Caltech's Palomar Observatory, using the 18-inch Schmidt telescope that the late Fritz Zwicky used for his pioneering cosmological studies.) The fragments—21 identifiable ones at last count—lie in a nearly perfect straight line, causing them to be widely likened to a string of pearls. Extending ahead and behind the fragments along essentially the same line are trails of rubble—particles ranging from perhaps the size of houses down to pebble-sized—that mark the abrupt edge of a vast sheet of diffuse material. The sheet is much thicker around the fragments. The ensemble looks rather like a stealth bomber seen from above and in front, with the thick part of the sheet being the cockpit. James Scotti of the University of Arizona has looked at the cockpit more closely and discovered that it's really a set of narrow, parallel tails, which he traced back to individual fragments.

By May, 1993, the object had been tracked long enough for scientists to begin calculating its current orbit. "Shoemaker-Levy 9 is only the

The "pearls" will plummet into the planet one by one, with all the slow-motion inevitability of a train going off the end of a dynamited bridge in an old Western.

Below: Shoemaker-Levy 9 as photographed by JPL astronomers Eleanor Helin, Ray Bambery, and Donald Hamilton on March 31, 1993, using Palomar Observatory's 60-inch telescope. The inset is a close-up of the comet's fractured nuclei. Colors are keyed to the comet's brightness, with white being the brightest and red, yellow, and green regions being progressively dimmer.

Right: What a "normal" comet looks like. This is Halley's comet, photographed by Helin on January 7, 1986, using Palomar's 18-inch Schmidt telescope. The comet has one nucleus, and a dust tail emanating from it.



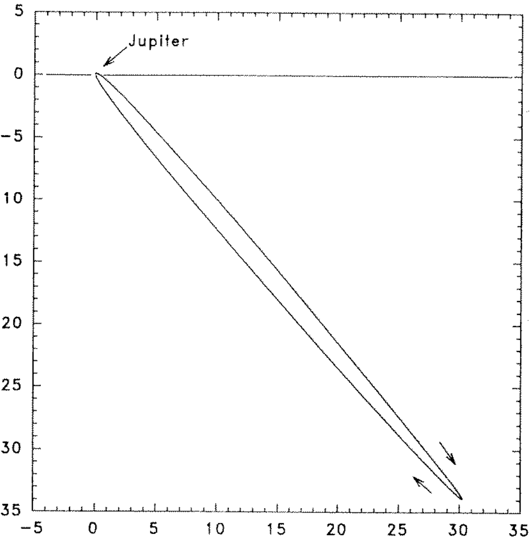
second or third known comet to orbit a planet, Jupiter in all cases, and the others weren't discovered until after escaping," notes Paul Chodas of JPL's Solar System Dynamics Group. (Caltech manages the Jet Propulsion Laboratory, better known as JPL, for NASA.) And Shoemaker-Levy 9 nearly got away, too—its current orbital eccentricity is 0.996, according to Chodas. With an orbital eccentricity of 1.0, the comet would have escaped—flung from Jupiter's clutches after half an orbit. "The sun is a very strong perturber of this comet's orbit," says Chodas. "In fact, the sun's influence is about equal to Jupiter's at the far extent of the orbit." Chodas and coworkers Donald Yeomans, head of the Solar System Dynamics Group, and Zdenek Sekanina, a senior research scientist at JPL, have studied the comet's orbit in detail. This orbit, whose major axis is tilted about 50 degrees to the south of Jupiter's own orbital plane and takes a shade over two years to complete, will pass within 37,000 kilometers of Jupiter's center next summer, according to independent calculations by Chodas and Yeomans and by Brian Marsden of the Minor Planet Center in Cambridge, Massachusetts. Unfortunately for Shoemaker-Levy 9, Jupiter's equatorial radius is 71,400 kilometers. The orbital geometry is such that the "pearls" will plummet into the planet one by one, with all the slow-motion inevitability of a train going off the end of a dynamited bridge in an old Western. It should take about five days for all 21 fragments to go over the brink. (The leading rubble trail will arrive earlier, and dust and small particles will continue to shower down on Jupiter for weeks afterwards.) The fragments will roll to their fate in single file, Chodas explains, because "the pieces of the comet that were closer to Jupiter at break-up have less orbital energy than the pieces that were farther out. The pieces in between, of course, have a continuum of orbital energies. The fragment closest to Jupiter at disruption remains closest to Jupiter throughout [its orbit], and impacts first. And the fragment farthest from Jupiter at disruption remains farthest throughout, and is the last to impact."

When it was first discovered that Shoemaker-Levy 9 and Jupiter were on a collision course, some preliminary calculations suggested that the impacts would generate fireballs bright enough to be visible from Earth in broad daylight. But don't bother rearranging your lawn chairs for the best view. Subsequent observations have shrunk the largest fragment's estimated size from 10 kilometers down to a few kilometers, causing the estimated energy release to shrink a hundredfold—the impact energy being proportional to the fragment's mass, which increases as the cube of its radius. Worse, better orbit calculations show that the impacts will occur on Jupiter's far side 10 degrees beyond the limb, invisible to Earth in any case. The incoming pieces will disappear behind Jupiter a tantalizing five minutes before they hit. Even though the impacts will occur over a five-day span, we won't see any of them, because the point where the comet's path intersects Jupiter's surface remains fixed in space as the planet spins. Like a machine filling milk bottles on a conveyor belt, the orbit will dispense blobs of comet into parcels of Jovian airspace that the planet's rotation will carry into our sight some two hours later.

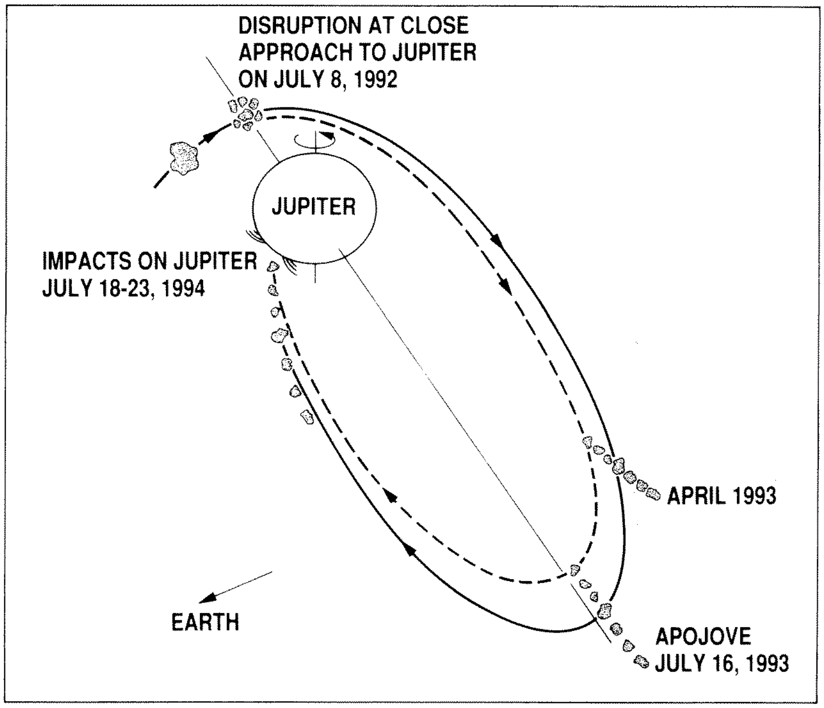
So is the entire episode a bust—the Comet Kohoutek of the '90s? (Remember Comet Kohoutek? Neither does anyone else.) Not exactly. JPL's spacecraft Galileo will be a mere 230 million kilometers from Jupiter, en route to a rendezvous on December 7, 1995. Galileo may be able to see just enough of Jupiter's night side so that the impacts will be on the planet's limb, giving us our only direct view of the crash site. Warns Chodas, "It is entirely possible that new orbit solutions for the comet will move the impact point back behind the limb as seen from Galileo. It's that close." The Hubble Space Telescope will have a look, too, but won't see anything any sooner than Earthbound observers. And it seems that every telescope on Earth will be watching as well.

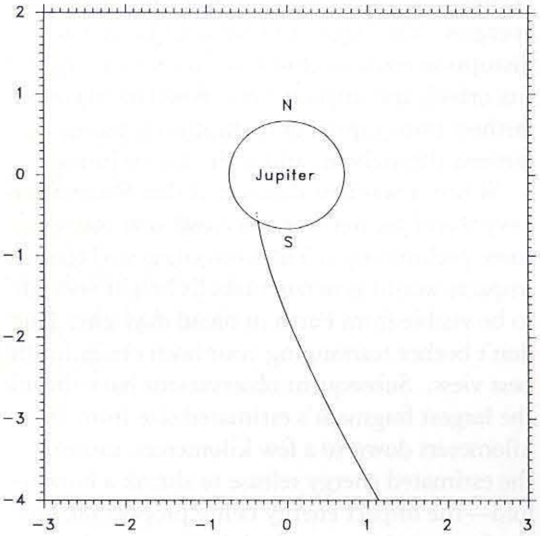
This is, after all, the first time we have ever gotten advance notice of such a collision, giving scientists the chance to follow the process from

Right: Shoemaker-Levy 9's current orbit, as it would appear from the sun on July 21, 1994. North is to the top, and the horizontal line at 0 is Jupiter's orbital plane; the axes are labeled in millions of kilometers. Jupiter is in the plane of the page, and the comet's orbit projects down and out from the page at an angle of about 40 degrees. The orbit isn't foreshortened, however—it really is that narrow!



Below: After the comet broke up, each fragment assumed its own orbit based on its point of origin. The fragments from the side farthest from Jupiter wound up in slightly larger orbits that take longer to complete, so the fragments from the comet's near side pull ahead and will hit Jupiter first. (The apojove is the point in the orbit farthest from Jupiter.)





Above: Shoemaker-Levy 9's trajectory as seen from Earth on July 21, 1994. The dotted portion is behind Jupiter, out of sight. The axes are labeled in units of 10,000 kilometers.

Right: Hubble's Wide-Field and Planetary Camera took this close-up on July 1, 1993. The individual points of brightness are believed to represent individual comet fragments. Although shrouded in dust, they have retained their identities in every image with sufficient resolution to discern them. Two systems for naming these putative fragments have been proposed—Sekanina, Chodas, and Yeomans call the one that will be first to hit (and which is just barely visible at the very top of this image) A, with the final one (not visible) being W. (The letters I and O aren't used.) Q is the brightest fragment, while P is a double. G, H, K, L, P, Q, R, and S are bright enough to show up as white spots.

beginning to end. Wrecks of this magnitude are rare—an object this size might hit Earth once every 10 to 100 million years, according to Professor of Planetary Science David Stevenson. Jupiter is a much bigger target, of course. It also has a hundredfold larger sphere of gravitational influence that can pluck slow-moving stragglers out of nearby orbits, and lives in a more cluttered region of the solar system. Even so, Jupiter probably runs into something this big only once every hundred years. And cometary suicides are of considerable interest, as it's now generally agreed that an asteroid slamming into Earth 65 million years ago did in the dinosaurs. The remains of Shoemaker-Levy 9 are considerably smaller bodies, but their impact energies may be comparable to the blow that wiped out Barney and his kin. That's because, gram for gram, an object hitting Jupiter packs 36 times the wallop that it would on Earth, due to Jupiter's stronger gravity.

When one of Shoemaker-Levy 9's main members hits, says Stevenson, "it will plunge through the upper atmosphere of Jupiter—the part above the clouds as seen from Earth—quite quickly, on a time scale of a second or two." Galileo may see a momentary flash like the one a meteor makes when it enters Earth's atmosphere, "due to the shock heating of the gas that passes the projectile, and also the heating and ablation of material on the surface of the body as it plunges through." The fragment will then tear through the opaque veil of clouds that forms Jupiter's visible surface, leaving no trace. But not for long.

Thomas Ahrens (MS '58), professor of geophysics; Toshiko Takata, graduate student in planetary science; John O'Keefe, visiting associate in planetary science; and Glenn Orton (PhD '75), a Jovian atmosphere specialist at JPL, have run computer simulations of what happens next. The simulation consists of three parts. The first part uses a technique called smoothed-particle hydrodynamics—invented by Joseph Monaghan, of Monash University in Australia, to simulate galaxy formation and evolution—to follow the fragment's dissolution as it plunges into Jupiter's atmosphere. In the second step, the same technique is used to let the trail of gas heated by the fragment's passage expand and rise. And finally, the team has calculated the thermal radiation spectrum from the temperature and internal-energy distribution of the resulting plume, to discover what it might actually look like.

The computational key to smoothed-particle hydrodynamics is that it breaks up the object being studied into a large number of particles, in this case "atoms" of Jovian atmosphere one-tenth

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to ten kilometers in diameter, depending on their location. "Each particle behaves as if it has a set of springs around it that looks like a sea urchin," Ahrens explains. If you try to squeeze two particles together, the springs provide an opposing force that represents the properties of the object. If the object is compressible, the springs have a lot of give, but if the object isn't, the springs are stiff. The "technique is used to mimic the behavior of real materials with finite particles," says Ahrens. "The term 'smoothed particle' comes from the fact that these springs give the particles spatial extent, so that they're not point particles, but particles that are smeared over space. You can think of them as fuzz balls. When they're far apart they don't interact. When you get them close together, they start interacting, and if you really push them together hard they become quite stiff and impenetrable."

Even with this simplification, the technique isn't cheap computationally. It took Ahrens and company "hundreds of hours" of time on JPL's Cray Y-MP supercomputer to run the simulations. Says Ahrens, "At any particular point in the calculation, we were keeping track of more than 50,000 pieces of Jupiter—their pressures, their temperatures, their coordinates in three dimensions, and their velocities. It's hard to do that kind of three-dimensional calculation with other numerical methods." Other researchers have also modeled the impacts, but "most of the other calculational methods set up an imaginary grid, which is imbedded in the material, and they study the deformation of the grid." Such a grid is only a cross section, from which the three-dimensional behavior must be extrapolated.

The calculations assumed that the comet fragment being simulated entered Jupiter's atmosphere at 60 kilometers per second—the planet's escape velocity—at an angle of 40 degrees from the vertical. This angle came not from the comet's predicted impact point, which is about 40 degrees south latitude, nor from the 50-degree difference between the comet's and Jupiter's orbital planes, but from "the flight path angle of the comet on impact," Chodas explains. The comet's orbit is such an extremely flat ellipse—practically a straight line—that the comet will hook into a hairpin turn as it reaches Jupiter. It's this wrapping around, plus Jupiter's oblateness that far south, that determines the angle of entry.

Ahrens's group did two sets of calculations, for bodies two and ten kilometers in diameter. There's still considerable uncertainty about the fragments' actual size. The visible "string of pearls" is actually a set of comae—clouds of dust surrounding much smaller nuclei. Astronomers assume that the brightness of a coma is a proxy for the size of the solid nucleus within it. Depending on what other assumptions an observer makes, however, the largest fragment's estimated diameter ranges from less than a kilometer to nearly four and a half kilometers. Assuming the comet is solid ice, a two-kilometer chunk would have a mass of more than four billion metric tons. Of course, the fragments aren't all of equal size—there appear to be half a dozen relatively large pieces (including one possible doubleton), a dozen medium-sized ones, and an assortment of smaller debris. Notes Stevenson, "When you take something and break it, by hitting it with a hammer or whatever, most of the mass is in the biggest fragments. You don't get an enormous amount of stuff in fine fragments. That's true in the asteroid belt itself, and it's true—we think—of how objects fragment and coagulate as planets form. It's a very common characteristic."

Thus the two-kilometer calculation should be about right for an average chunk o' comet. In the computer, such a fragment took about 10 seconds to disintegrate after whooshing through the cloud deck, and reached a depth of perhaps 350 kilometers before breaking up completely. (Since Jupiter has no solid surface, all depths are relative to the so-called one-bar level—the altitude where Jupiter's atmospheric pressure equals that on Earth's surface. The one-bar level is beneath Jupiter's visible surface, which is formed by ammonia-ice clouds at pressures of a few tenths of a bar.) The simulated fragment, says Ahrens, "basically kept on going at 60 kilometers per second as pieces break off, until there's nothing left. And that's how we define the depth of penetration. The reason it didn't slow down very much is that we assumed in our calculations that the comet has no strength... a high-speed drop of ice." Ice's properties under such conditions are described by an "equation of state," some of whose parameters, such as compressibility, were measured by Ahrens and O'Keefe in the 1980s. "Everything else in the calculations is just the laws of physics—conservation of mass, momentum, and energy. The equation of state is really the only ground truth that we put into these calculations, both for cometary ice and Jupiter's, mostly hydrocarbon, atmosphere. But it's a very important ground truth."

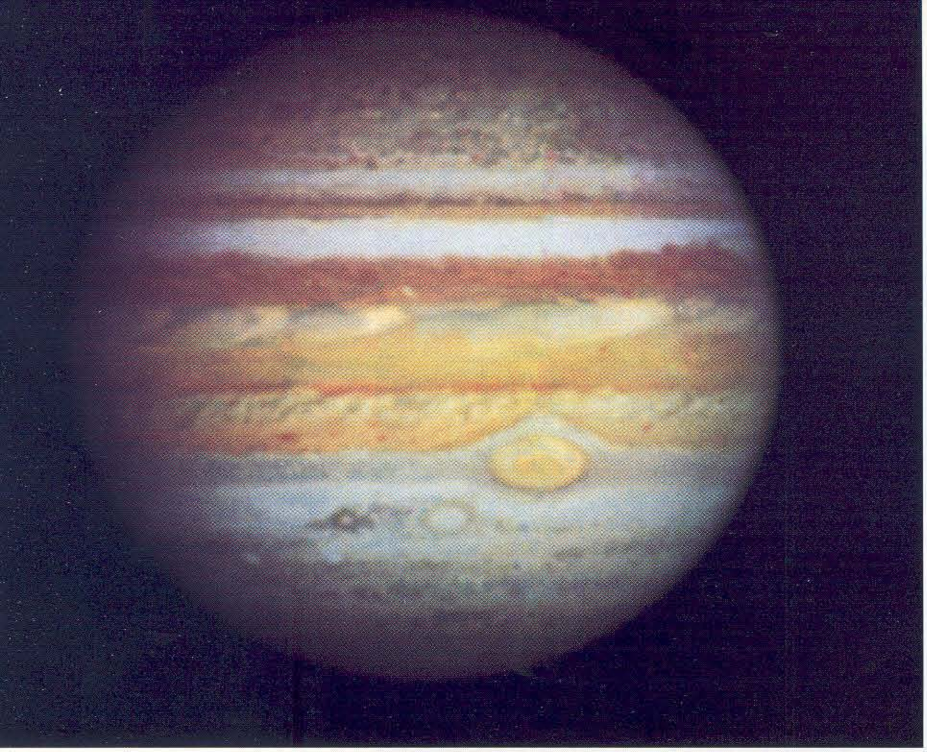
As the simulation continued, the hot gas expanded with the force of a hundred million megatons of TNT. (In contrast, the atomic bomb that leveled Hiroshima was equivalent to a mere 20 kilotons of TNT.)

The simulated fragment punched a hole in the atmosphere—a thin, inverted cone like an upside-down wizard's hat that was perhaps 10 to 100 times less dense than the gas around it. The projectile's supersonic passage also piled up a tremendous shock wave—a sonic boom of deafening proportions, were anyone there to hear it. This and other processes converted roughly 60 percent of the fragment's kinetic energy into heat, most of which wound up in the atmosphere at depths between 125 and 225 kilometers. (The shock wave continued to propagate into Jupiter's interior, even after the fragment has vaporized.) The gas lining the hole was hot enough to emit a flash of white light—a continuation of the meteor streak Stevenson described, now diffused by the clouds overhead. "If you were in a position where you happen to be looking down the hole," says Ahrens, "which of course nobody will be, you'd see a very high-intensity source. If you were off to the side, you might see scattered light, like lightning in the clouds—you wouldn't actually see the lightning bolt, you'd see a glow." The nearby moons Io, Europa, and Ganymede may reflect a detectable bit of this glow to Earth.

As the simulation continued, the hot gas expanded with the force of a hundred million megatons of TNT. (In contrast, the atomic bomb that leveled Hiroshima was equivalent to a mere 20 kilotons of TNT.) Most of this explosion's oomph came from that sizzling 100-kilometer stretch where the bulk of the heating occurred. Says Ahrens, "It's not really a point-source explosion, it's more of a line source." This explosion created a balloon of hot, low-density gas analogous to the fireball from a nuclear blast. Most of the material from the fragment, now nothing but superheated hydrogen and steam, ended up in the balloon's skin. The fireball rose along the path of least resistance—the original entry wound—spewing out of a 200-kilometer-wide hole in the clouds as a plume containing some billion tons of gas. "That plume is really moving," Ahrens exclaims. "There's a lot of energy there! You wouldn't want to be in its way." The plume grew at a rate of perhaps 10 kilometers per second, exhausting its upward drive several minutes later some 3,000 kilometers above the cloud tops, creating an object that would easily be seen from Galileo.

The computer-generated plume gave off both infrared and visible light—its temperature was "on the order of 2,000 to 3,000 kelvins, which is hot, but not overwhelmingly hot," says Ahrens—but the brightest glow was in the infrared, in the 1–10 micron band. This glow radiated as much power—about 10^{24} ergs per second for several minutes—as the entire day side of Jupiter. In other words, this tiny plume—perhaps 700 kilometers wide at its top, compared to Jupiter's 143,000-kilometer equatorial diameter—packed a planet's worth of brightness. Furthermore, Jupiter's natural thermal radiation is in the 100 micron band, according to Ahrens, so the plume's light should be easy to distinguish. The glow began dimming immediately as the heat radiates off into space, but by the time the simulated impact point would roll into view from Earth some two hours later, the plume could still be 10 kelvins hotter than the surrounding atmosphere, a temperature difference readily detectable by terrestrial telescopes.

"It won't really be an impact," say Ahrens. "It'll be more like a soft catch, in the sense that there'll be great penetration, but not really any ejecta thrown out. If you had the same kind of



This photo of Jupiter was shot by Hubble's Wide-Field and Planetary Camera on May 28, 1991. The Great Red Spot is visible at lower right. To the left and below the Red Spot is one of three white ovals that were born about 1931. This white oval is roughly 7,000 kilometers wide, and may contain the same amount of kinetic energy as a two-kilometer-diameter comet fragment. Spots come in all sizes, including those too small to see in this image.

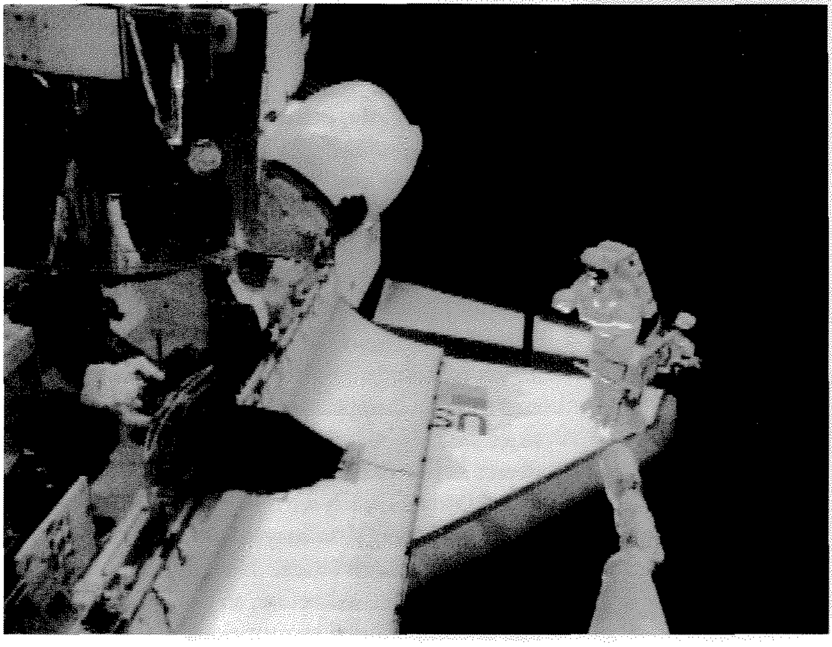
impact on Earth, it would be an erosive impact, meaning that there would be more material thrown off Earth than put on. The material would reach escape velocity." But Earth's escape velocity is a mere 11 kilometers per second to Jupiter's 60. And struggling free of Jupiter's dense, bottomless atmosphere would be like swimming up to the surface of a swimming pool filled with Jell-O.

The infrared welt shouldn't be the only phenomenon visible from Earth. Says Professor of Planetary Science Andrew Ingersoll, four billion tons of water "could cover a band of Jovian latitude 10 degrees wide with a layer of ice crystals one micron thick. And that's enough to make an opaque layer. But in addition to the mass of the comet, you can dredge up a lot of water vapor and stuff from Jupiter's deep atmosphere." The layer would probably be white. "Most of the things that you condense from a comet, like water, are white crystals. The colors on Jupiter are caused by more complex reactions that take some time." How much water is deep within Jupiter is one thing scientists hope to learn from this event, but it will be a difficult number to extract from the observations—you have to subtract the water contributed to the plume by the comet, whose size and composition is uncertain. "That's the reason for doing all this modeling."

When you toss a rock in a pond, you see a splash, followed by spreading ripples. The comet's splash will be out of sight from Earth, but Timothy Dowling (PhD '89) at MIT, his graduate students Joseph Harrington, Raymond LeBeau, and undergrad Kari Backes have concluded that we may see the ripples. The ripples would extend vertically through the stratosphere, which is clear, and the troposphere, where the visible cloud surface lies. These waves wouldn't be visible directly, but as a subtle temperature difference—about half a kelvin—between a wave's peak and its trough. Such temperature changes may be observable in the stratosphere's thermal-infrared emissions, showing up as parcels of gas that register as hotter or colder than their surroundings. But the ripples should be easiest to see in the cloud layer, where disrupted condensation patterns may alter the clouds' reflectivity, and thus their appearance. "The wave temperatures we're predicting are going to be hard to detect at best," Harrington warns. "We do have over 20 nuclei, each with a different detonation depth and energy, so maybe a few will make waves big enough to see. Needless to say, this has never happened before, so predictions are full of compounded assumptions."

The speed at which the ripples spread through the narrow cloud layer will depend on the temperature difference between the tops and the bottoms of the clouds, and on their thermodynamic properties. This, in turn, will allow scientists to derive the radius of deformation, a parameter that describes how the atmosphere's density increases with depth. Ingersoll is skeptical that the waves will actually be visible, but "if we can see 'em, it will provide information about the thermal structure down in the clouds. And that's something we'd love to know. All our models of the Red Spot and the long-lived ovals depend on this parameter. In fact, that temperature structure is the big unknown that prevents us from doing a definitive model of the dynamics of the atmosphere. We argue about what that structure is, and construct models where we vary that structure, but it would sure be nice to measure it."

Since Jupiter is not only a fluid planet but a rapidly spinning one, the gas displaced by the comet's splash will get a twist from the planet's rotation and become a whirlpool. If a vortex forms, it will almost certainly linger long enough for Jupiter's rotation to bring it into Earth's field of view, says Ingersoll. Its size will depend on the atmosphere's density structure, which is determined by that radius of deformation that Ingersoll hopes to derive, but it could be 1,000 kilometers in diameter. (A feature this size would be below the atmospheric distortion limit for ground-based telescopes, but could be seen by the Hubble, which orbits above Earth's atmosphere.) "Then what happens is not so clear, because of the shear zones on Jupiter—the alternating jet streams. Vortices with the wrong spin



You may close now, Doctor. The white panel at upper left is the back end of the new Wide-Field and Planetary Camera, which has just been installed in the Hubble Space Telescope. Payload Commander Story Musgrave balances the old camera on the edge of the cargo bay, while Mission Specialist Jeffrey Hoffman rides the shuttle *Endeavour's* robot arm.

Since there could be as many as 21 such vortices, we may be treated to the sight of them playing Pac-Man with one another, eventually forming one or more semipermanent bruises on Jupiter's face.

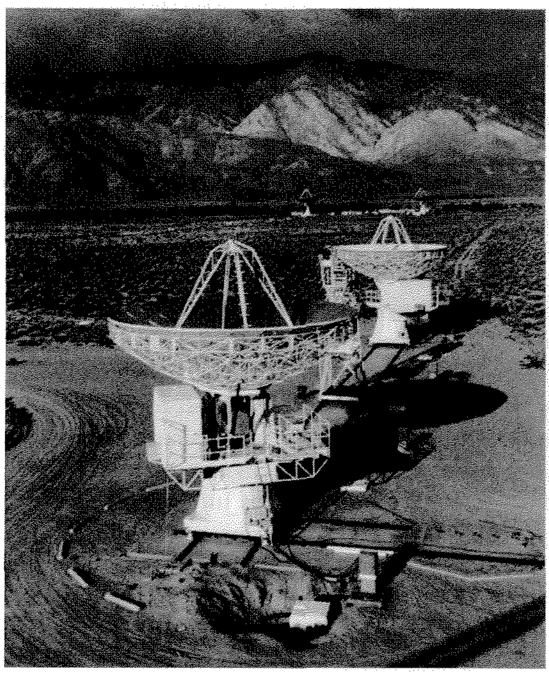
for the shear zone they're in get ripped apart very quickly. If they have the right spin, then they tend to roll like ball bearings and can last as long as the Red Spot, in principle, although they tend to get swallowed up by each other. They merge." And since there could be as many as 21 such vortices, we may be treated to the sight of them playing Pac-Man with one another, eventually forming one or more semipermanent bruises on Jupiter's face. After all, four billion tons hitting at 60 kilometers per second has got to hurt!

Such blemishes are common features on Jupiter. In addition to the Great Red Spot, which has graced the planet in one form or another since at least 1665, when Giovanni Cassini saw it, Jupiter boasts hundreds of smaller ovals that live for months or years before merging or disappearing in Jove's roiling atmosphere. Smaller is a relative term here, as the ovals range from 700 to 7,000 kilometers in diameter, the latter being about one-third the diameter of the Great Red Spot. (By comparison, Earth is slightly less than 13,000 kilometers in diameter.) According to Ingersoll, assuming that these twisters run from the top to the bottom of the cloud layer like a knot in a plank, then one of the larger white ovals has approximately as much kinetic energy as a two-kilometer comet fragment, while the Great Red Spot has about as much as a five-kilometer piece. "That doesn't mean that you can convert all the energy of the comet into a steady, standing vortex. That's too much to ask. It could be like one of those champion divers who just slips into the water without making a ripple."

Something else that's apparently too much to ask is to be able to look down the eye of the hurricane and get a direct glimpse of the atmosphere beneath the clouds. The vortex will probably be filled with clouds of its own—the water vapor and whatever other warm gases get dredged up from below will condense out in the colder stratosphere. The vortex will be a high-pressure region, or anticyclone, says Ingersoll, because it was produced by hot, expanding gas. The Great Red Spot and the white ovals are also anticyclones, and their cloud-filled centers give them their color.

So, although lawn-chair astronomers will be disappointed, the planetary-science community is mobilizing for the show. Jupiter will be in the evening sky, and at Palomar's latitude, will set around 10:30 p.m. Pacific Daylight Time. Ground-based observers will get the best view of the infrared and microwave regions of the spectrum. Aloft, the Hubble Space Telescope's replacement Wide-Field and Planetary Camera will see Jupiter unblurred by Earth's distorting atmosphere—assuming the space shuttle's service call was as successful as it appears to have been. WFPC2, designed and built by a Caltech/JPL collaboration, has optics to compensate for Hubble's misground mirror. Ground controllers will need "several weeks" after the repair mission to restart the telescope's instruments and check out the new optics, according to Professor of Planetary Science James Westphal, a member of the collaboration.

JPL's Glenn Orton is organizing part of a worldwide network of infrared astronomers who will keep Jupiter under 24-hour watch during



Two of the three radiotelescopes that make up the Owens Valley Radio Observatory's millimeter-wave array.

the impacts, and a less frenetic eye on it before and afterwards. The infrared is a good place to look for a number of phenomena. The ripples predicted by Dowling and Harrington might show up in several ways. The thermal-infrared differences between the waves and troughs should be visible at wavelengths greater than 16 microns (millionths of a meter), with different wavelengths corresponding to different pressures and thus altitudes. The waves could also be visible in the troposphere above the clouds as perturbations in the 13-micron radiation emitted by colliding hydrogen molecules, says Orton. And although Jupiter's cloud layers are very reflective, they're normally hard to see at certain wavelengths between 1 and 4 microns in the near infrared, because the methane and hydrogen gas above them strongly absorbs those wavelengths. "Thus, the 'background' clouds are barely detectable [at those wavelengths]," says Orton. "However, the deposition of sufficient amounts of reflecting particles in the upper atmosphere will produce a bright spot with respect to the rest of the planet... There may also be perturbations of deep cloud properties, as observable through Jupiter's best atmospheric window at 5 microns." Hydrogen (Jupiter's stratosphere and troposphere are more than 90 percent hydrogen) and methane don't absorb at 5 microns, allowing the clouds below to be seen. Infrared astronomers can also detect water directly, as well as enhanced amounts of ammonia from the lower atmosphere. If the impact is sufficiently penetrating, it might even launch detectable amounts of "H_2S or other trace constituents such as SiH_4 or AsH_3 from the *very* deep atmosphere." The mixing ratios of stratospheric hydrocarbons may be disrupted as well. All of the above are detectable between 5 and 14 microns, according to Orton.

Palomar's 200-inch Hale telescope will also dedicate 11 or 12 evenings to watching Jupiter, says Keith Matthews (BS '62), a member of the professional staff in physics. "We can actually see Jupiter in the afternoon in the infrared, but you do have to worry about the sun's glare." The Hale will be outfitted with two instruments, the Cornell Spectrocam 10, an imaging spectrometer that covers the 10–20 micron range, and a Matthews-built imager that sees in the 1–5 micron range.

Professor of Planetary Science Duane Muhleman and Tony Phillips, research fellow in astronomy, will be using Caltech's Owens Valley Radio Observatory to follow the action in the microwave band. They will be mapping Jupiter's emissions at 3 millimeters. "There is so much [gaseous] ammonia in Jupiter that nearly all the radiation from below is absorbed between 1 millimeter and 10 centimeters," forming an opaque surface at those wavelengths, says Muhleman. "If the ammonia weren't there, we could see deep in, but we only see down to one bar. When the comet explodes at about 10 bars' pressure, it will make a great disturbance in the ammonia gas." The gas molecules will re-emit some radiation at 3 millimeters, with the intensity of the emission proportional to their temperature. The impact could register as a cold region, marking where upwelling ammonia has been cooled to a temperature below the background temperature emitted at the altitude where the gas originally was. (Ammonia thrown too high freezes, and ammonia ice doesn't absorb these wavelengths.) Alternatively, the impact might show up as a hot spot if the ammonia ionizes or decomposes, revealing warmer radiation sources below. Either way, the temperature distribution will reveal the size of the explosion, and help elucidate its physics. "We will be checking the theorists' calculations," says Muhleman, "and looking for things nobody predicted. Because you never see what's predicted—it's always something else." Muhleman's team will also be using the Very Large Array in Socorro, New Mexico to look at the 6-centimeter band, another handy wavelength for ammonia, in cooperation with Arie Grossman (MS '87, PhD '90), now at the University of Maryland.

JPL's Galileo, Ulysses, and Voyagers will also attend from their vantage points in space. Ulysses doesn't carry a camera, but all four spacecraft will listen for radio signals. During the fragment's last few hours of life, it will traverse the inner reaches of Jupiter's magnetosphere—the region of space dominated by the planet's magnetic field—where lurk belts of intense radiation similar to, but thousands of times stronger than, Earth's Van Allen belts. Both sets of belts contain high-energy protons and electrons trapped and accelerated by the planet's magnetic field. Interactions between the fragment and these particles should generate radio waves at frequencies below and in the AM radio band, as well as electrostatic waves. These waves could be detectable by an assortment of instruments on board the various spacecraft. "There's so much energy involved that it doesn't take a very high degree of conversion efficiency to see an effect," says Torrence Johnson (PhD '70), Galileo's project scientist.

Of the paparazzi spacecraft, Voyager 2 has the best viewing angle, being on Jupiter's night side and south of the ecliptic plane. Unfortunately, Voyager 2 is also 6.3 billion kilometers away, heading in the general direction of Proxima Centauri after having taken a close look at Neptune in August 1989. The spacecraft's cameras were turned off soon after, as no one thought there was anything more to see for the next several thousand years. The camera software was then deleted from onboard and ground computers in order to streamline spacecraft operations and save money, according to Voyager Project Manager George Textor. Re-creating that software and making the other modifications needed to turn the cameras back on would take considerable effort and expense at a time of very tight budgets, and it isn't going to happen. However, the spacecraft's ultraviolet spectrometer is still running, and will be watching Jupiter.

"It's like a sports photographer with a manual frame advance taking a bunch of pictures at a game, and hoping to catch someone scoring in one of them."

Thus Galileo will have the only working camera with a direct view—albeit in profile—of the comet's last moments, assuming the point of impact doesn't move beyond the horizon as orbital calculations improve. The spacecraft will take several dozen pictures bracketing the predicted impact times of the brightest fragments. The exact moment of each fragment's impact won't be known until an hour or two beforehand, and command sequences, including camera instructions, will have to be finalized well in advance. (In fact, the flight team is going to start writing them in March.) Remarks Johnson, "It's like a sports photographer with a manual frame advance taking a bunch of pictures at a game, and hoping to catch someone scoring in one of them. I've tried to do this at my daughter's soccer games, and it's tough." At its fastest speed, Galileo can take one picture every $2\frac{1}{3}$ seconds. The second-fastest speed is one every eight seconds.

Because Galileo's main antenna is stuck, the pictures will go on a tape recorder for playback to Earth over the much smaller low-gain antenna. But each image contains 5,000,000 data bits, according to Project Manager William O'Neil, and playing back just one at the low-gain antenna rate of 10 bits per second would take "nearly a week of near-continuous downloading." The Galileo project has requested three months of near-continuous tracking time on the Deep Space Network, which NASA uses to communicate with all its spacecraft, in order to download the equivalent of seven to ten full-frame images. In fact, most of each image will be blackness, as Jupiter will fill only about one-eighth of the frame at that range. So the flight team plans to play back just the Jupiter-containing portions of the images, which is relatively easy because Jupiter's exact position in each frame will be known in advance. And since tracking time will be limited, the engineers want to transmit to Earth only those frames containing impacts. Enter Galileo's Near-Infrared Mapping Spectrometer (NIMS) and Photopolarimeter Radiometer (PPR), which take data much faster than the camera. Jupiter will barely fill a single pixel in NIMS and cover a mere one-sixth of the PPR field of view, but if any of the impacts are as bright as Jupiter's day side, as advertised, the flare-up(s) will be obvious. So by looking at the NIMS and PPR data (which are encoded in much smaller numbers of bits) first, the flight team will know which frames to play back. The PPR has a 0.25 to 0.5 second time resolution, adds Orton, who is a co-investigator on the instrument, so if the fragment's meteoric career is bright enough, it may be resolvable into a time sequence.

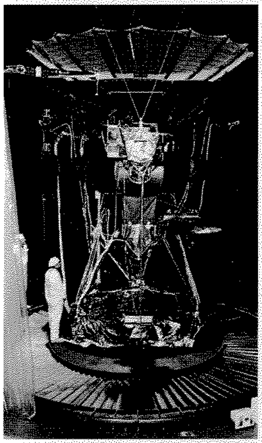
At Galileo's range, one camera pixel will cover a square of Jovian real estate 2500 kilometers on a side, comparable to a medium-quality telescopic image from Earth. A plume would just about fill a single pixel from top to bottom, so there's no chance of resolving detail. But Galileo's camera should be sensitive enough to see the lightning-in-the-clouds glow predicted by Ahrens, as well as the above-cloud flash (if the frame-advance timing is lucky) and the plume. The spacecraft will see Jupiter in three-quarter view with a dark limb, says Johnson, and the impact will look like "a bright star right on the limb. We'll measure how bright it is, and see how the brightness changes with time. This will tell us about the physics of the impact—how deep it went, which will tell us the size of the comet." Galileo might also see a glint from material spattered high enough above the planet's night side to catch the sun.

Galileo could also use its ultraviolet spectrometer to look at the ring of plasma surrounding Io, Jupiter's volcanic moon. The volcanoes spew sulfur dioxide, which Jupiter's magnetosphere promptly ionizes to create the ring. These sulfur and oxygen ions glow brightly in the ultraviolet, so a comet-induced change in the magnetosphere could noticeably affect the plasma glow.

Combining all these observations will enable theorists to practice forensic planetology and work out the details of the comet fragments' lemming-like demise. Remarks Johnson, "Comet impacts are a very-big-ticket item right now in the theory of the evolution of planetary atmospheres—it's a way to blow off layers of atmosphere—but all these theories depend on whether we have the right fairy story about the physics of impacts."

Jupiter and its comet disappeared behind the sun late in July. But on December 9, the University of Arizona's Scotti and T. Gehrels found it again "under difficult conditions in the dawn." And JPL's Yeomans is coordinating a campaign of observations to hone the orbit estimates and reduce the uncertainties in the impact-time predictions. Says Chodas, "Right now, the uncertainties are a fair fraction of a day, and we're trying to get them down to minutes, which is a challenging problem. We're five AU from Jupiter, so our angular observations are not that accurate. [An AU, or Astronomical Unit, is the average distance from Earth to the sun—150 million kilometers.] We're seeing this on a single orbit, so we don't have the benefit of a long data arc to fit an orbit through. And finally, what do you measure? We were measuring the center of the train of fragments, and that's a very ill-defined point. But observers are now measuring the positions of individual fragments. That, of course, is 21 times more work for us. So it's a formidable problem." And ultimately, as Ingersoll says, "We are very much at the mercy of the size of the comet. You can't just go out and measure the size, because comets are surrounded by little clouds of dust, and you might be measuring the size of the dust cloud. And the dust cloud is so low-density that having a great big dust cloud doesn't mean very much."

What with uncertainties in the fragments' orbits, compositions, diameters, and masses, everything is still very much up in the air. We won't know what's going to happen when Shoemaker-Levy 9 buys the farm until it happens. But whatever happens in the wake of the dear departed's passage, it's a wake that a lot of scientists are planning to attend. □



Left: Galileo being tested at JPL.

Below: Io, Jupiter's volcanic moon, as seen from Voyager 1. A volcanic plume rising some 300 kilometers above the Ionian surface is clearly visible in profile on the moon's limb. Galileo should see Shoemaker-Levy 9's impacts from a similar perspective, although unfortunately not in such detail.