Shoemaker-Levy Dazzles, Bewilders

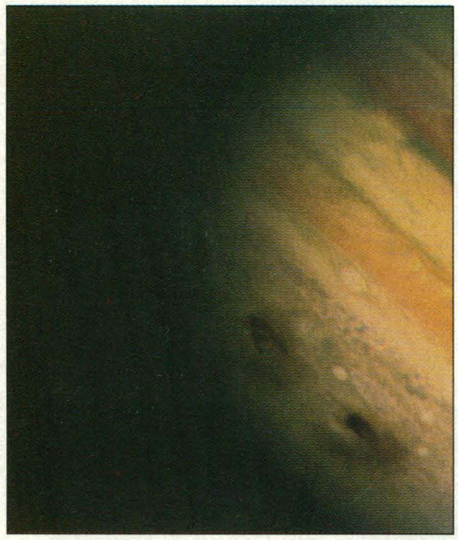
Astronomers' first opportunity to watch two solar system bodies collide produced the hoped-for fireworks, but relief has turned to puzzlement: Just what happened?

Observers poised at their telescopes for the collision between Jupiter and the first fragment of comet Shoemaker-Levy 9 were an anxious bunch. Getting ready for the start of the show on 16 July, they wondered whether there would be anything to see when bits of the disrupted comet dove into Jupiter's atmosphere at 200,000 kilometers per hour. No one knew how big the fragments were; estimates ranged from less than half a kilometer to almost ten times that size. And just days before the impacts began, some astronomers had warned that the 20 or so fragments might not even be solid; they might simply be loose swarms of fragments so small they could vanish without a trace. In the words of a headline in *Nature* that week, "The Big Fizzle is coming."

Guess again. The Shoemaker-Levy show, which went on for 6 days, looked almost as big and dazzling as the most optimistic predictions. "It's like seeing a supernova go off," exclaimed one astronomer who had flown at 12 kilometers over the South Pacific to get a view. "We're all running around like giddy kids," reported another at McDonald Observatory in Texas. A co-discoverer of the comet, Eugene Shoemaker of Lowell Observatory in Flagstaff, Arizona, pronounced himself well pleased with his namesake: "Nature has outdone herself; we're elated." To observers marveling over the first fireballs and dark bruises in Jupiter's atmosphere, it seemed clear that the comet's fragments must have been big, solid projectiles, plunging deep into the atmosphere. But as the week wore on and astronomers analyzed the impact sites, doubts set in.

By the time the curtain had come down on impact week, some researchers were arguing that the impact debris and scars didn't look as if they came from deeply penetrating wounds. And that has left astronomers struggling to explain how impacts that produced such dazzling displays for observers three quarters of a billion kilometers away could have failed to stir Jupiter itself to any great depth. Although planetary scientists had hoped that the impact effects might provide clues about Jupiter's interior—its internal structure and composition, for instance—such questions are on hold for the moment, as astronomers ponder what it was they saw.

At least they have data to ponder, which is something that seemed in doubt as the first fragment closed in on Jupiter. Most comet specialists had assumed that the 21 diffuse clouds of dust and debris seen in telescopes hid 21 solid fragments that would produce visible effects unless they were at the very small end of the size estimates. But 2 days before the first impact, comet specialist Paul Weissman of the Jet Propulsion Laboratory argued in a *Nature* News and Views article that the impacts would be a bust because each nucleus was no more than a loose swarm of small pieces, "like bees buzzing around a hive."



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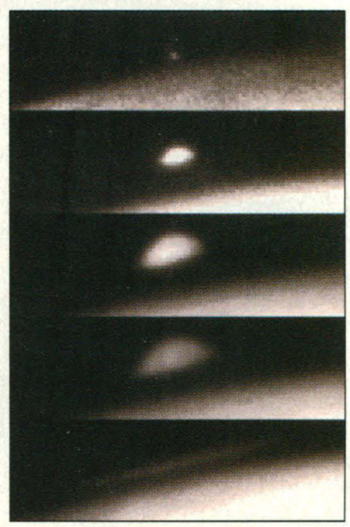

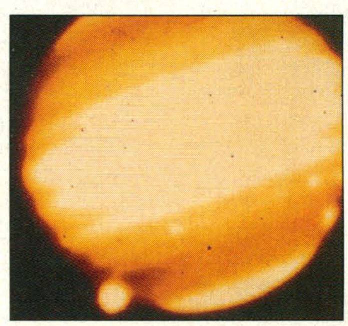

Assault on a giant. Jupiter's battering by a shattered comet yielded images of a high-altitude debris pall *(above)*, the evolving fireball plume from one impact *(right)*, and hotspots from a plume and from earlier impacts.

Weissman and some others believe comets are merely clumps of millions of house-sized "dirty snowballs." Ordinarily, these comet bits are held together by little more than their own feeble gravity. So when Shoemaker-Levy made its fatal pass just above the cloud tops of Jupiter 2 years ago, Weissman argued, the planet's powerful gravity pulled the comet apart into puny pieces, loosely gathered in 21 swarms. In the days and hours before impact, argued Weissman, astronomer Terrence Rettig of the University of Notre Dame, and others, Jupiter's gravity would stretch those swarms into elongated streams. The streams would pepper the planet "like machine gun bullets lacing into a moving target," burning up in the upper atmosphere as meteors do rather than plunging deep into the planet and exploding to produce a visible fireball.

Most researchers still held out for solid bodies, arguing that even if Weissman were right about the comet's makeup, the swarms would have reassembled themselves over the 2 years since the cometary breakup. And the first impacts seemed to bring a dramatic vindication for the majority. Fragment A, which looked modest-sized in telescopes, sent a plume more than 1000 kilometers above the planet. A day later, the plume from fragment G rose to several thousand kilometers and left a "black eye" of debris 25,000 kilometers across. By midweek, researchers who had simulated the effects of impacters of various sizes in computer models were in agreement: The plume heights and brightnesses and debris fallout patterns implied that the largest fragments were solid bodies 2 to 3 kilometers in diameter. "Everything we calculated is very close to what was observed," said Thomas Ahrens of the California Institute of Technology, one of the modelers.

Later in the week, however, observations and theory began to diverge as astronomers wrestled with the question of how deep the cometary fragments had penetrated into Jupiter's atmosphere. The models had predicted that hefty ice balls, like those favored by the "solid impacter" group, would plunge through Jupiter's uppermost clouds, made of ammonia, and on into the atmosphere's little-known deeper reaches, finally

The Comet Explodes by E-Mail

While comet Shoemaker-Levy mounted its fireworks display at Jupiter, another kind of tour de force was under way on a computer in the astronomy department at the University of Maryland. An Internet "exploder"—a system capable of multiplying any incoming electronic mail message hundreds of times and automatically sending the copies to a predetermined mailing list—had linked hundreds of observers in an unprecedented on-line community. "The exploder was one of the greatest things that ever happened to observational astronomy," says planetary scientist Paul Weissman of the Jet Propulsion Laboratory (JPL).

Weissman, like other planetary scientists, was thrilled with the free, fast exchange of data about an ongoing event in space. "The whole world is wired," says Roger Yelle of the University of Arizona. "The free flow of information is amazing....I was involved in the Voyager missions [to the outer planets], but I've never seen data flowing back and forth at this rate."

Full participation in the Voyager flybys of the 1980s and in earlier spacecraft encounters, after all, was generally limited to a coterie of scientists. Teams operating each Voyager instrument met daily at JPL in Pasadena, California, to review the latest data and decide what would be released that day to the rest of the planetary science community and the public. For Shoemaker-Levy, that kind of centralization was out of the question. There was no mission control, no project scientist—just hundreds (if not thousands) of astronomers aiming different instruments at Jupiter from around the world.

The flow of information was sure to be freer than during earlier events in planetary science, but it also threatened to be slower—because of the lack of coordination. So last January, astronomers planning to observe the impacts set up the exploder, which ultimately linked about 250 observing groups and theorists. One result was that during impact week, theorists could start puzzling over startling observations almost immediately. For example, when David Rabinowitz and Harold Butner of the Carnegie Institution of Washington, observing from Chile, saw Jupiter's satellite Io redden for 7 minutes during the impact of fragment B, they sent a message to the exploder. In minutes to hours, depending on network traffic, the exploder had dispatched the puzzling news from Chile to everyone else on the mailing list.

Similarly, astronomers preparing to make observations could modify their plans depending on what others had seen. Astronomers waiting for sunset in Arizona, for example, were privy to what their colleagues had just seen from a tiny island in the Indian Ocean, including information on when the impacts were occurring and which filters and exposures worked best. Even images from the latest observations became available within hours over the network. Much of the information also found its way onto a Shoemaker-Levy electronic bulletin board at the University of Maryland that was open to the entire astronomy community.

These systems not only provided more information faster, says Weissman; often, the information was better than what usually accompanies such events. "It's not the rumors you usually have. It portends better coordination." Still, a few theorists trying to make sense of the stream of messages sounded a little wistful for times when the pace was more deliberate. "It's like trying to drink from a fire hose," says Donald Yeomans of JPL. "There's too much to digest before the next message comes in." But Yeomans, who like all scientists prefers a data glut to a shortage, adds: "It's fun."

–R.A.K.

exploding at depths of 100 kilometers and more. Planetary scientists had predicted a cloud layer of ammonium hydrosulfide beneath the ammonia clouds and water clouds beneath that. Stirred up by the deep explosions, these compounds would surely appear in the visible impact scars, they thought.

And, just as predicted, the first compound reported by spectroscopists monitoring the darkened impact sites through the Hubble Space Telescope was ammonia, presumably from the uppermost cloud layer. Then sulfur turned up, possibly from the comet's "dirt" or the middle cloud deck. But clear signs of water never showed up during impact week, sowing seeds of doubt about the penetrating power of Shoemaker-Levy's fragments.

Those doubts grew on the day of the last impact, when planetary meteorologist Andrew Ingersoll of Caltech, who had assumed the explosions were deep, jumped ship. At the daily press conference, Ingersoll showed a diagram of a fragment plunging through the water clouds and said, "I don't believe it anymore. I think the comet did not go through the water cloud." What had changed his mind was two dark rings that the Hubble Space Telescope had caught spreading from the site of the G fragment impact.

To judge by the expansion speeds of the two rings, the larger and more energetic of them was in the Jovian stratosphere, above all the clouds, while the weaker one was deeper, within the clouds. Ingersoll assumed the rings were waves of some sort, made visible as their changing pressure triggered chemical changes in the atmosphere. The evidence that the strongest wave was spreading above the cloud deck convinced him that the fragment itself must have exploded above the clouds, leaving just enough residual energy to stir up the ammonia layer.

These signs of shallow penetration left the comet watchers with a puzzle: How could fragments potent enough to produce the dazzling fireballs have failed to make it very far into the atmosphere? One possibility is that the fragments were swarms after all. Swarms, as Weissman had pointed out, would be stopped much higher in the atmosphere than would solid fragments of the same mass; their unexpectedly showy deaths, he now argues, might be a sign that they had not spread out quite as far as he had assumed. Alternatively, Shoemaker and others suggest, weak but coherent fragments might have started to break up under Jupiter's gravity during their final hours, blunting their penetrating power without detracting from the display.

Then there's the possibility that the comet and its fragments were solid but small, at the low end of the size estimates made before the impact (*Science*, 1 July, p. 31). Mordecai-Mark MacLow of the University of Chicago, for one, argues that it doesn't necessarily take a big comet chunk to make a big fireball. A half-kilometer ice ball might not make it to the water clouds, he says, but it would be able to put more of its energy into a display visible from Earth. "My models showed these huge [plume] clouds even for half-kilometer objects," he says.

MacLow's proposal will likely prove controversial, like other efforts to make sense of the impacts. But a little discord might have been expected. Hundreds of observers were watching an event unprecedented in planetary science, exploiting every wavelength from radio through visible to ultraviolet and sharing observations in real time (see box). The impacts themselves were actually taking place just out of view, on Jupiter's backside. And some of the most revealing data have yet to come in, such as observations from the Galileo spacecraft, which had a direct view of the impacts. Eventually, however, planetary scientists expect to sort out the confusion—and secure a unique scientific legacy from the dying comet.

–Richard A. Kerr