The 200,000-Megaton Meeting

A shattered comet nears its cataclysmic end at Jupiter

By RON COWEN

At about 5 p.m. eastern daylight time on July 16, a chunk of icy material will slam into the back of Jupiter. Over the next 6 days, at least 20 more chunks, each packing a punch that may exceed 200,000 megatons of TNT, will take the same nosedive. With virtually every telescope on Earth focused on Jupiter, humans for the first time will watch what happens — albeit indirectly — when a comet strikes a planet.

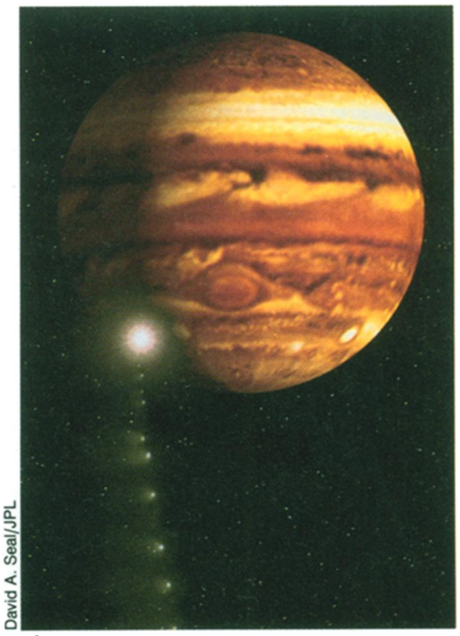
A little more than a year ago, few astronomers dreamed they would witness such an event. But in May 1993, Brian G. Marsden of the Smithsonian Astrophysical Observatory in Cambridge, Mass., calculated that a recently discovered comet, already shattered into 21 or more pieces by Jupiter's gravity, was homing in on the solar system's most massive planet. The trail of fragments, dubbed Shoemaker-Levy 9 for discoverers Eugene and Carolyn Shoemaker and David H. Levy, will crash into Jupiter's southern hemisphere.

Each fragment will hit the planet a few degrees behind its darkened limb, just out of view of Earth. Thus, ground-based and Earth-orbiting telescopes won't see the fragments as they enter Jupiter's atmosphere. Galileo, a craft en route to a 1995 rendezvous with Jupiter, will view most of the fireworks directly.

For ground-based observers, the fun will begin about 10 minutes later, when the sites of impact rotate into view. Astronomers may witness a variety of Jovian disturbances associated with the blasts. The repercussions may last for days, months, or even years.

Theorists have had a field day estimating the extent of the initial fireball that may accompany each collision, as well as the seismic and atmospheric waves that may later ripple across the planet. Water, hydrogen sulfide, and other chemicals thought to lie buried hundreds of kilometers beneath Jupiter's cloud tops may be kicked aloft and observed for the first time.

On the other hand, "it could all be a fizzle. We have theories, but we really don't know what's going to happen," says Mordecai-Mark Mac Low of the University of Chicago.



Artist's depiction of the comet fragments hitting Jupiter, as viewed by the Galileo spacecraft.

If some of the models do prove correct, they may help predict the destructive power of an asteroid or comet headed toward Earth. "Our model could tell us how big a rock our own atmosphere can protect us from," Mac Low adds.

"We'll make all these predictions and then we'll have this extraordinary event to test them out," says planetary scientist Lucy A. McFadden of the University of Maryland at College Park.

The bigger the fragment, the bigger the blast. For example, a 2-km-wide chunk would impart eight times as much kinetic energy as a fragment half its diameter. But scientists who make the predictions face a major problem: No one knows the size of any of the fragments. Only a flyby mission to the shattered comet could have revealed their dimensions.

At the distance Jupiter lies from Earth, the Hubble Space Telescope can only resolve objects more than about 300 km across — much bigger than the fragments, which measure no more than a few kilometers across. Even so, Hubble scientists had hoped the contrast between sunlight reflected from the icy fragments and sunlight scattered from the dusty shrouds that envelop each piece might be great enough to discern the size of the fragments. Alas, astronomers found no clear pinpoint of light inside the dust.

"There's no evidence that there even are nuclei inside [the dust]," says Harold A. Weaver of the Space Telescope Science Institute in Baltimore. "We simply can't tell whether each dust clump contains swarms of small objects a few hundred meters in diameter or a single, kilometer-size nucleus."

Weaver adds, however, that the most recent Hubble images reveal that some fragments continue to break up — evidence that icy, kilometer-size nuclei do exist. A swarm of smaller subunits probably wouldn't break up in the same way, he says. The Hubble images suggest that if each dust shroud does have a heart of ice, these frozen cores measure no more than 4 km across, Weaver says.

"Keep your fingers crossed," says Eugene M. Shoemaker, now retired from the U.S. Geological Survey in Flagstaff, Ariz. "Let's all hope that these things are as big as the Hubble Space Telescope observations permit them to be."

In fact, many researchers modeling the cometary collisions assume the fragments have a width of about 1 km. That's minuscule compared to Jupiter, some 140,00 km in diameter. Shoemaker likens the scale of the collisions to dust specks falling on a 6-foot-tall human. Slamming into Jupiter at 60 km per second — 50 times the speed of sound on the planet — each chunk will initially perturb only a tiny fraction of the planet. But over time the impacts may have a more global influence.

As each fragment begins its entry into Jupiter, it will flash like a shooting star. A 1-km icy chunk will tunnel 75 to 150 km beneath Jupiter's visible cloud tops in seconds, according to a model proposed by Mac Low and Kevin Zahnle of NASA's Ames Research Center in Mountain View, Calif. (Other models envision the frag-

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ments breaking apart even lower or just above the visible cloud tops.) As these fragments encounter denser and denser gas, they will flatten like pancakes and disintegrate, dumping energy equivalent to the explosion of 200,000 megatons of TNT, Mac Low and Zahnle calculate.

Mac Low says that some of the energy will create below the cloud tops sound waves equivalent to the seismic waves that would be generated on our planet if an earthquake struck 1 mile beneath San Francisco. The heat will hurl an expanding fireball of material – a mixture of hot cometary debris and buoyant, jazzed gases – back through the same tunnel created by the falling fragment. The expanding fireball will punch through the visible cloud tops within a minute of the initial collision and may be as wide as 100 km when it emerges. A rising plume of Jovian gas will follow the fireball a few minutes later.

The fireball will brighten Jupiter's moons by only a few percent above their average luminosity in full sunlight. It's therefore easiest to see the reflections when these satellites are darkened by Jupiter's shadow. According to the most recent predictions, one of the collisions will occur when an eclipse of the sun by Jupiter darkens its moon Europa, notes Paul Chodas of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, Calif. With the sun's illumination blocked, any sudden glimmer of light on Europa would probably represent a reflection of the fireworks on Jupiter, he says.

With luck, observers on Earth may glimpse the last vestiges of the fireballs directly. For a ground-based telescope to detect them, the fireballs must extend far enough above the cloud tops to creep over Jupiter's darkened limb and must remain opaque.

Because calculations now indicate that the impacts will occur closer to the limb of Jupiter than originally thought, "there's a small chance, but a real chance, that we'll actually see the fireball rise over the limb," says Mac Low. An infrared telescope will probably provide the best opportunity: Debris in the fireball may continue to glow in the infrared after it stops radiating in visible light.

Heidi B. Hammel of the Massachusetts Institute of Technology expects that other phenomena may prove more intriguing than the fireballs. The explosions, she says, might load Jupiter's stratosphere with huge amounts of excess material – cometary debris and gases exhumed from the lower depths. For the first time, clouds of water vapor and hydrogen sulfide that normally lie buried hundreds of kilometers below Jupiter's cloud tops may become visible.

A fountain of material carried aloft by each explosion could slowly settle in Jupiter's upper atmosphere, Hammel says. This would show up as an added smudge or extra cloud feature in visible-light images, she notes. Over weeks to months, tracking such clouds may help trace Jupiter's turbulent atmospheric motion.

Sound waves penetrating deep into Jupiter's liquid interior will refract upward and may reach the cloud tops during the first 2 hours after each impact. These waves are likely to form a pattern like ripples in a pond, moving at speeds of 10 to 20 km per second. Infrared telescopes may detect the waves as they alternately compress and expand atmospheric gases in their path.

Astronomers will search for a pattern in the ripples that may indicate whether the sound waves plumbed deep enough within Jupiter's interior to encounter the region where hydrogen gas becomes a liquid metal. In this region, thousands of kilometers beneath the cloud tops, enormous pressure strips hydrogen nuclei of their electrons; the charged particles then roam freely. This structural alteration endows the hydrogen with metallic properties. Sound waves that probe this layer before rising up to the visible Jovian surface may show a sudden, extra brightening in the ripples, revealing the nature of material buried within the planet.

In about a day, says Hammel, atmospheric waves, also known as inertia-gravity waves, may become visible. These also spread out from each impact site. The passing ripples should cause gas in Jupiter's upper atmosphere to bob up and down, notes Timothy E. Dowling of MIT. As the gas bobs up closer to the lower-density upper reaches of the atmosphere, it cools slightly; as it falls, it warms.

Infrared studies may detect the temperature changes, which could be as small as 0.1 to 0.5 kelvin, Hammel says. The NASA Infrared Telescope Facility and the U.K. Infrared Telescope, both atop Hawaii's Mauna Kea, will play a key role in such observations. In visible light, the Hubble Space Telescope and other instruments will search for an expanding white ring of material – ammonia ice that condenses out of the cloud tops as the ripples spread over the planet.

The speed of the ripples, if astronomers can detect them, could indicate the abundance of water in Jupiter's atmosphere, says Dowling. Water on Jupiter profoundly affects its atmospheric circulation but has only been found in small amounts – 1 molecule of water for every 1 million hydrogen atoms. However, a comparison with the abundance of oxygen

Fragment	Impact Time (EDT)		Regions from Which Jupiter Can Be Seen at Impact Time
A	July 16	3:46 p.m.	Africa (except West Africa), Middle East, Eastern Europe
B		10:42 p.m.	Eastern North America, Mexico, western South America
C	July 17	2:48 a.m.	New Zealand, Hawaii
D		7:10 a.m.	Australia, New Zealand, Japan
E		11:15 a.m.	India, Southern China, Southeast Asia, western Australia
F		8:11 p.m.	South America
G	July 18	3:33 a.m.	New Zealand, Hawaii
H		3:31 p.m.	Africa (except West Africa), Middle East, Eastern Europe
K	July 19	6:22 a.m.	Australia, New Zealand
L		6:17 p.m.	Brazil, West Africa, Spain
N	July 20	6:06 a.m.	Australia, New Zealand
P2		10:55 a.m.	India, southern China, Southeast Asia, western Australia
Q1		4:06 p.m.	Africa (except West Africa),
Q2		3:39 p.m.	Middle East, Eastern Europe
R	July 21	1:38 a.m.	Hawaii, west coast of North America
S		11:28 a.m.	India, southern China, Southeast Asia, western Australia
T		2:35 p.m.	Africa (except West Africa), Middle East, Eastern Europe
U		5:52 p.m.	Brazil, West Africa, Spain
V		11:39 p.m.	Western United States, Mexico
W	July 22	4:21 a.m.	New Zealand, Hawaii, eastern Australia

Note: Predictions are accurate to within 30 minutes.

Chodas/JPL

Chart shows predicted impact times for the known fragments of Comet Shoemaker-Levy 9 and the regions on Earth from which astronomers have the best chance of observing the immediate aftermath of each impact.

and hydrogen in the sun suggests that the planet contains 1,000 times as much water as that detected.

Where's the rest of it?

Scientists believe that Jupiter harbors most of its water in clouds that lie 100 km below the visible disk, but they haven't had proof. The atmospheric waves that Shoemaker-Levy 9 may generate could change that. As water vapor rises slightly in Jupiter's atmosphere, some of it cools and condenses into ice crystals, releasing heat in the process. The rising heat, like the blanket of warm air that sits above Earth's tropics, creates a stabilizing layer for the atmospheric waves traveling in the water cloud. The heat confines and channels the waves like sound waves in an organ pipe.

Andrew P. Ingersoll and Hiroo Kanamori of the California Institute of Technology in Pasadena and Dowling calculate that if Jupiter's water supply is 1,000 times greater than detected, then some of the atmospheric waves should travel at a speed of 130 meters per second. They describe their work in the June 1 GEOPHYSICAL RESEARCH LETTERS.

While the comet may create disturbances in Jupiter's atmosphere that last for days or weeks, it might also add one feature to the planet that will take several years to form. In about a decade, dust generated by the breakup of the comet and by further fragmentation of the chunks may form a faint ring around the planet (SN: 10/30/93, p.287). When the Galileo craft arrives near Jupiter in 1995, it might find evidence of a budding dust ring. Such a ring, only the second one known around Jupiter, could last for more than 1,000 years.

To fully understand Shoemaker-Levy 9's effects on Jupiter, astronomers already are training a global network of telescopes on the planet. An archive of such observations before impact will be critical for revealing postimpact changes.

After next week, the comet will no longer exist, but a fantastic adventure in studying the hidden nature of the solar system's largest planet will have begun. Says Dowling: "Something like this has simply never happened before." □

Eying the impacts from Earth and space

Telescopes in the Southern Hemisphere have the best chance of capturing any reflected flashes from Shoemaker-Levy 9. That's because Jupiter is visible for 4 to 5 hours a night there and about 2 to 3 hours in the north.

Paul Chodas and his JPL colleagues Donald Yeomans and Zdenek Sekanina calculate that one of the collisions, on July 19, will occur just as Jupiter's moon Europa undergoes an eclipse. The most optimistic picture has the fireball from this impact illuminating Europa so brightly that observers in Australia and New Zealand may need only a backyard telescope to see this 1-minute event.

Observers should also keep their eye on Io, says Peter J.T. Leonard of the University of Maryland at College Park. Because of the moon's large size and proximity to Jupiter, astronomers should monitor this Jovian satellite each time it's in eclipse between July 15 and July 22.

While calculations indicate that none of the kilometer-size fragments will hit while Io is in eclipse, smaller pieces — roughly the size of a football field — may be spread throughout the train of Shoemaker-Levy 9 fragments, suggests Leonard. "When you break a cookie, you get some crumbs as well as bigger pieces," he says. Leonard estimates that the meteoric flash from one of these 100-meter "crumbs" may brighten Io in eclipse from complete invisibility to a level an amateur astronomer could see with a 12-inch telescope.

The most favorable sites for viewing the reflected fireballs include Africa, New Zealand, Australia, and Hawaii (see chart, p.27), Chodas says. Some astronomers will fly from one site to another, since no one place offers a vantage point for all 21 known fragments. On average, observers at any one Southern Hemisphere site may see the immediate aftermath of four or five hits, while a northern observer might detect only one or two.

Spectroscopy of the plumes — analyzing the intensity of specific wavelengths of light emitted by particular molecules and atoms — could reveal the comet's composition and the temperature of the fireballs. But if the explosions occur beneath Jupiter's visible cloud tops, there may be too little light to do such measurements.

When the impact sites rotate into view, some of Earth's largest telescopes will have the best chance of imaging the crash zones and making infrared temperature measurements. Amateur astronomers, however, will have difficulty detecting postimpact changes in the planet's cloud structure. "Unless you already know exactly what Jupiter looks like right before the impact, you're not going to notice any changes," says theorist Mordecai-Mark Mac Low.

Spectroscopic measurements may reveal chemical changes in Jupiter's upper atmosphere, including atoms and molecules dredged up by the fireballs. The cometary impacts may also introduce molecules never before found on Jupiter.

The Galileo spacecraft will have the best vantage point of any telescope in the solar system. Poised at about 246 million kilometers from the planet — less than one-third the distance from Earth to Jupiter — Galileo will look directly at the impacts with its high-resolution visible-light camera. Other instruments on the craft may track the entry of the comet fragments and the resulting fireballs at wavelengths ranging from the ultraviolet to the infrared.

Because Galileo's main antenna remains jammed, the craft can transmit to Earth only a few percent of the data it will store on its tape recorder. The slower transmission rate of its low-gain antenna and the limited time available on NASA's network of ground-based receivers means the craft will take weeks to months to return the collision data.

Complicating matters further, the craft received its commands to observe the impacts several weeks ago, when the collision times were known only within a window of about 40 minutes. To compensate for the uncertainty, the craft may begin observations 30 minutes before the time of each expected impact and continue for 30 minutes afterward.

"This is the most godawful experiment design problem I've ever run into," says Torrence Johnson of JPL.

Although the Voyager 2 spacecraft has an even better viewing angle than Galileo, the aging craft is now at the edge of the solar system, about 6.1 billion km from Jupiter. NASA scientists have calculated that it's not worth the effort to try to turn Voyager's camera back on. But the craft's detectors may gather radio and ultraviolet data from the impacts.

Ulysses, a spacecraft designed to study the poles of the sun, will lie about 378 million km from Jupiter next week. Ulysses doesn't carry a camera, but it can use its radio receivers to detect heat from the fireballs — once they rise above the radio noise of Jupiter's ionosphere.

Two Earth-orbiting missions devoted to ultraviolet work will study the aftermath of the collisions. Both the venerable International Ultraviolet Explorer satellite, now in its 17th year of operation, and the Extreme Ultraviolet Explorer craft, launched in 1992, will take spectra of the plumes of material carried aloft by the Jovian explosions.

While the Earth-orbiting Hubble Space Telescope won't see the impacts, it will track the fragments until about 6 hours before they hit Jupiter. And for hours to days after each crash, Hubble and ground-based telescopes will look for atmospheric ripples and seismic waves triggered by the explosions.

— R. Cowen