After the Crash

Puzzling over a comet's impact on Jupiter

By RON COWEN

In July, planetary scientists witnessed a once-in-a-lifetime event. Over 6 days, fragments of Comet Shoemaker-Levy 9 plowed into Jupiter, leaving behind a necklace of dark bruises. The Jovian fireworks kept electronic mail abuzz for weeks. But for most scientists, last month provided their first chance to compare observations face to face. For aficionados of the crash of '94, the annual meeting of the American Astronomical Society's Division for Planetary Sciences offered one big data dump.

How big were the fragments? How large a wallop did they pack? How deeply did they penetrate into Jupiter's atmosphere? Solving these related riddles will help reveal how much of the planet's hidden interior the collisions exposed. And from the meeting in Bethesda, Md., some common threads emerged.

The intensity and duration of light from each event offer important clues. Rather than producing a single burst, the larger fragments staged an extended light show: an initial flash as a chunk entered Jupiter's upper atmosphere, a glowing plume of debris shooting thousands of kilometers above the clouds, and the radiation generated when the plume crashed back down with a high-velocity splat.

Telescopes recorded these emissions at a variety of wavelengths, producing a characteristic set of light curves. Like arias in an opera, a light curve traces the progress of a protagonist — in this case a chunk of ice and rock — from fiery debut to untimely demise. "The Galileo light curves all look alike, which suggests that the impacting objects were all qualitatively similar," says Kevin Zahnle of NASA's Ames Research Center in Mountain View, Calif. The fragments "probably all have similar sizes and mass."

But just as different conductors may interpret the same musical score differently, astronomers can extract more than one interpretation from the peaks and valleys in these light curves.

Of all the instruments staring at Jupiter in July, only those on the Galileo spacecraft had a full view of the fireworks. Heading toward a 1995 rendezvous with Jupiter, the craft was in the right position to directly observe the collisions, which occurred on the back side of the planet just out of direct sight of ground-based and Earth-orbiting telescopes.

Hampered by a crippled main antenna, the craft won't finish transmitting its data until next month. In the meantime, scientists have begun to make sense of the information already received.

Galileo has already returned data on six of the impacts — G, H, K, N, Q1, and W. The craft will radio observations of the R fragment in a few weeks.

When Galileo first sighted the fireball from fragment G, believed to be the largest, it appeared to have a diameter of about 10 kilometers and a temperature of 7,500 kelvins. Five seconds later, the craft's near-infrared mapping spectrometer first saw the explosion, recording the rising fireball's expansion and cooling for 90 seconds, until it was thousands of kilometers across and only 400 kelvins.

Hubble comet team/NASA

Close-up of the G impact, taken by the Hubble Space Telescope, shows inner and outer rings of dark material that may trace gravity waves generated by the explosion.

In recording what seems to be an a expanding, cooling bubble of hot gas, Galileo has "characterized a comet impact directly for the first time in history," says Galileo project scientist Torrence V. Johnson of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, Calif.

For the K impact, one of the larger fragments, the craft's solid-state imaging camera saw a bright flash lasting about 5 seconds. Over the next 10 seconds, the light dimmed and then brightened again, fading away after another 30 seconds. For N, one of the smaller impacts, the camera recorded a similar pattern.

According to Michael J.S. Belton of Kitt Peak National Observatory in Tucson, the initial flashes probably reveal the fragments as they streaked through Jupiter's upper atmosphere and started to glow as meteors. As they tunneled through thicker atmosphere, the fragments heated material, which exploded in a fireball. Belton suggests that this produced the second, longer-lasting glow in visible light as well as the extended emission in the near infrared.

If his interpretation proves correct, it could help indicate how deeply the fragments plumbed Jupiter. According to Belton, the events viewed by Galileo's camera suggest the fragments didn't penetrate far. This, in turn, indicates that the chunks were not larger than 1 km in diameter.

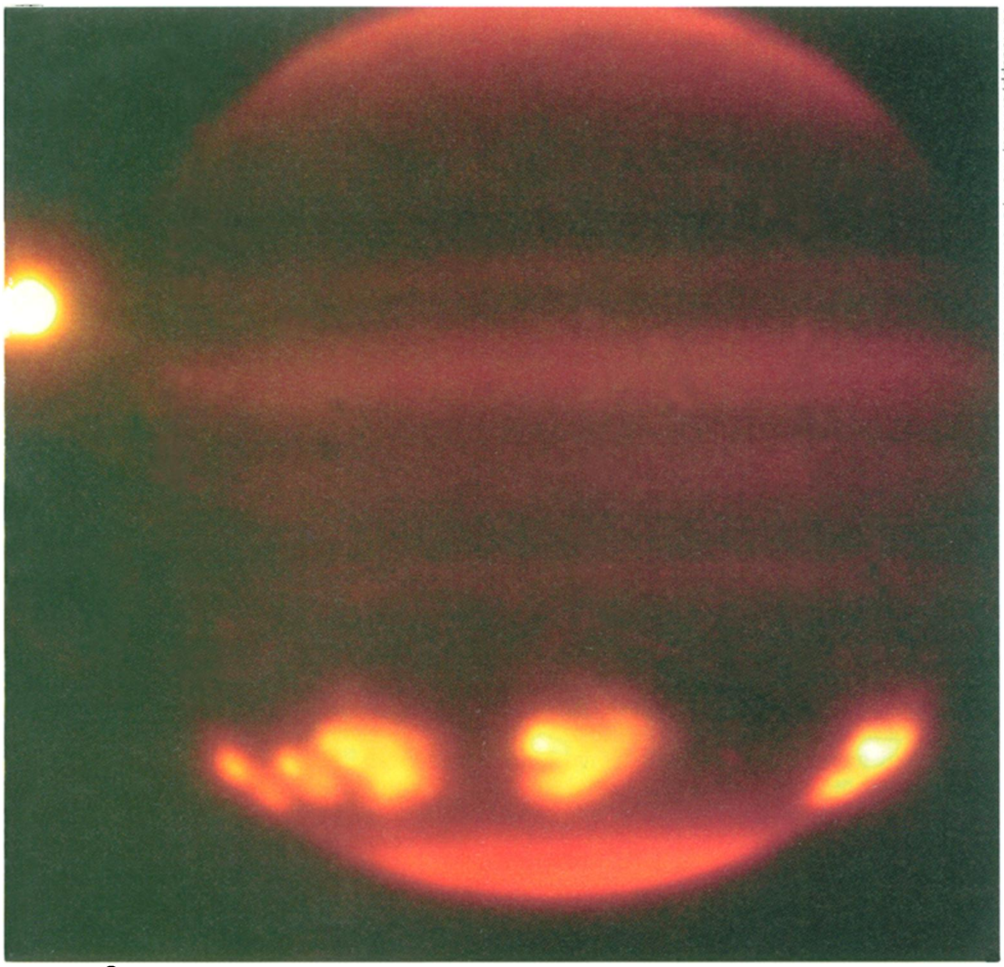
Had the fragments plowed deeper, into thicker layers of atmosphere, Galileo's camera would have recorded several blank frames until the fireball reemerged above these light-absorbing regions, Belton says.

But this early in the analysis, researchers have other interpretations of the findings. "There's only weak evidence that Galileo saw meteor flashes," says Michael F. A'Hearn of the University of Maryland at College Park.

Even if Galileo did miss the meteor flashes, notes A'Hearn, the craft still captured much of the light emissions, since the exploding fragments radiated most of their energy during the fireball phase. However, he adds, the meteor flash provides a key point in time — signaling when a fragment first entered the Jovian atmosphere. By knowing the elapsed time between a fragment's entry and the time when ground-based telescopes first glimpsed a plume of material above Jupiter's limb, researchers hope to calculate the energy delivered by the impact.

If the craft did record some flashes, it may not have captured the most spectacular part of this light show, speculates Terry Z. Martin of JPL. To detect the hot meteor and the cooler fireball, Martin and his colleagues used Galileo to observe both phenomena in the near infrared.

However, meteors streaking through Earth's atmosphere emit much of their



K. Hodapp, J. Hora, K. Jim, D. Jewitt/Univ. Hawaii

***C**rash sites on Jupiter, as seen in the near infrared by the University of Hawaii's 2.2-meter telescope about 75 minutes after fragment R struck the planet. The R impact site is the third spot from the left; the bright object at upper left is Jupiter's moon Io.*

light at shorter, bluer wavelengths. By looking only at longer wavelengths, "we may not have seen the whole ball of wax," Martin says.

The upper reaches of Jupiter's clouds appear to consist of three distinct layers (SN: 7/30/94, p.69). Visible clouds of ammonia lie at the top. Beneath this may be a layer of ammonium hydrosulfide. The deepest layer is thought to contain water. How deep did the fragments go? Belton suggests the Shoemaker-Levy 9 fragments didn't reach the water clouds, which would have absorbed visible light. But, he cautions, the verdict isn't in yet.

Indeed, others argue that the fragments may have plowed into the thicker atmosphere, which smothered the deeper parts of the explosions.

"We only saw what was happening above the cloud tops; we don't really know what was going on below," says Clark R. Chapman of the Planetary Science Institute in Tucson.

Several telescopes on Earth also recorded intriguing near-infrared light curves. Using the 5-meter telescope at Palomar Observatory near Escondido, Calif., a team led by Philip D. Nicholson of Cornell University noticed several curious features about the R impact.

Its light curve shows three separate rises and dips, he reports. First came an abrupt flash of about 10 seconds. After a 1-minute gap, a signal three times as bright appeared and lasted for about 30 seconds. Finally, 5 minutes after the initial flash, the telescope recorded another rise in light intensity that took 5 minutes to peak and didn't fade completely for half an hour. Before dying out, this signal exhibited two small "bumps" — brief surges in brightness.

Observing the same fragment with the 10-meter Keck Telescope atop Hawaii's Mauna Kea, Imke de Pater of the University of California, Berkeley, and her colleagues saw a similar pattern. And researchers who observed the Q1 and L impacts from Spain's Canary Islands reported several rises and dips in the visible light emissions.

Nicholson conjectures that the initial flash seen from Palomar Mountain, like the flashes detected by Galileo, represent the R fragment streaking into Jupiter's upper atmosphere. But how could a telescope on Earth have detected an event on the back side of Jupiter? (It took about 10 minutes for the impact sites to rotate into view from Earth.)

Nicholson suggests two possibilities. The telescope may have detected the streak in reflection, from light scattering off dust deposited in Jupiter's atmosphere by the cometary fragments. Alternatively, the meteor flash may have begun high enough in Jupiter's atmosphere — some 250 km above the visible cloud tops — for it to be visible above Jupiter's darkened limb.

The second rise in intensity, he suggests, occurred when a plume of hot material generated in the explosion shot up through the Jovian atmosphere. Data from the Hubble Space Telescope indicate that this plume, and many others, rose about 3,500 km above the cloud tops.

Nicholson believes that the third and longest rise represents the violent shock generated when the giant plume crashed back into the atmosphere. Forming a dark spot the diameter of Earth, the falling plume apparently heated the atmosphere around it to some 500 kelvins, creating an infrared glow. He suggests that the two "bumps" represent material from the falling plume that bounced back up once or twice before settling into the atmosphere.

This scenario agrees with a model proposed by Mordecai-Mark Mac Low of the University of Chicago and NASA's Zahnle, in which fragments no larger than 1 km in diameter explode relatively high in Jupiter's atmosphere.

This model gains support from the presence — and absence — of specific molecules in the Jovian atmosphere soon after the fragments struck. In August, Gordon Bjoraker of NASA's Goddard Space Flight Center in Greenbelt, Md., reported that he and his colleagues, using data from the Kuiper Airborne Observatory, had detected emissions from water vapor just after the fireballs from the G and K impacts became visible. Using the same observatory, Ann L. Sprague of the University of Arizona in Tucson and her coworkers found water vapor a few minutes after the R and W impacts.

Bjoraker now calculates that his team detected enough vapor after the G and K impacts to form a solid sphere of ice 400 meters in diameter — assuming that the fireballs heated the vapor to 1,000 kelvins.

Bjoraker notes that combined with other data, the amount of water observed could provide an important clue to how deep the fragments penetrated. The abundance of water and the relative lack of methane, he says, indicate that the chunks did not reach the proposed water clouds. At this level, he says, roughly equal amounts of both molecules would exist.

Zahnle cites another reason for arguing that the explosions occurred relatively high in Jupiter's atmosphere. Above the proposed water cloud layer, he says, carbon has a higher abundance than oxygen. Below the water clouds, the opposite holds true. The explosions deposited large amounts of sulfur in Jupiter's upper atmosphere, and this element will form different compounds depending upon the relative abundance of carbon and oxygen.

If more carbon than oxygen were dredged up, sulfur would combine with carbon to form carbon disulfide. If oxygen were more prevalent, sulfur dioxide would form. Hubble spectra show a clear signature of carbon disulfide, suggesting, says Zahnle, that the fragments did not breach the water cloud layer.

But with knowledge about Jupiter's chemistry limited, other theorists disagree. Given the size of the plumes and the dark spots on Jupiter, "it's hard to understand why these fragments wouldn't have penetrated to deeper layers," says Thomas J. Ahrens of the California Institute of Technology in Pasadena.

After analyzing an entirely different phenomenon, Andrew P. Ingersoll, also of Caltech, concurs. Though he initially believed the fragments exploded higher in Jupiter's atmosphere, he now suggests that some plunged into the proposed layer of water clouds.

"I'm totally changing my tune," he says.

Ingersoll cites Hubble images of dark rings moving outward, like ripples on a pond, from several crash sites. Initially, astronomers found indications of rings around only the G impact, but further analysis reveals ripples at four others.

In July, after estimating that a sharply defined ring around the G impact had a velocity of 800 meters per second, Ingersoll proposed that Hubble had detected a sound wave — a sonic boom — generated by the explosion of the fragment (SN: 7/30/94, p.68). He suggested that the sound wave originated in Jupiter's tropopause, a region just below the stratosphere and above the visible cloud tops.

But at the planetary meeting, Ingersoll reported that a more accurate measurement shows the ring traveling at about 450 meters per second — too slow for a sound wave. Ingersoll now says this ring represents a gravity wave — atmospheric ripples that cause the debris from the impact to bob up and down.

The gravity waves, he adds, move too fast to have originated in the stratosphere, where Hubble detected them. He proposes that they arose from the water cloud layer, indicating that the G fragment penetrated to this depth.

In contrast to Ingersoll's latest scenario, Joseph Harrington and Timothy E. Dowling of the Massachusetts Institute of Technology maintain that a gravity wave at the speed measured would lie higher up, in the stratosphere.

What gives these ripples their dusky hue, and why are Jupiter's bruises so dark? By assuming the ripples and the bruises have the same composition, Robert A. West of JPL has shed light on this mystery.

Hubble saw the ripples as dark rings because some material deposited in Jupiter's stratosphere fortuitously acted as a visual tracer. This material condensed as a dark solid around colder ripples yet remained as a relatively transparent gas around adjacent, warmer ones. The bruises and the ripples also exhibited another unusual behavior: Hubble observations showed that they remained dark at wavelengths ranging from the ultraviolet to the near infrared.

According to West, these constraints limit the dark material to a handful of compounds. Organic compounds rich in sulfur and nitrogen offer one possibility. In addition, such carbon-based materials as graphite, which could give a dark coat to ice or silicate particles delivered to Jupiter by Shoemaker-Levy 9, might explain the coloring of the bruises.

Researchers aim to resolve many questions by next May, when they will gather at a special meeting of the International Astronomical Union in Baltimore. But if puzzles still remain, scientists may not have to wait long to solve them.

Next December, a Galileo probe will parachute into Jupiter's atmosphere. Unlike the comet fragments of last July, the probe will carry a mass spectrometer and other sensitive detectors designed to study the planet's gaseous interior. The crash of '94 may be just a prelude for the Jovian exploration of '95. □