COMET SHOEMAKER–LEVY 9

Dazzling demise of a comet

Clark R. Chapman

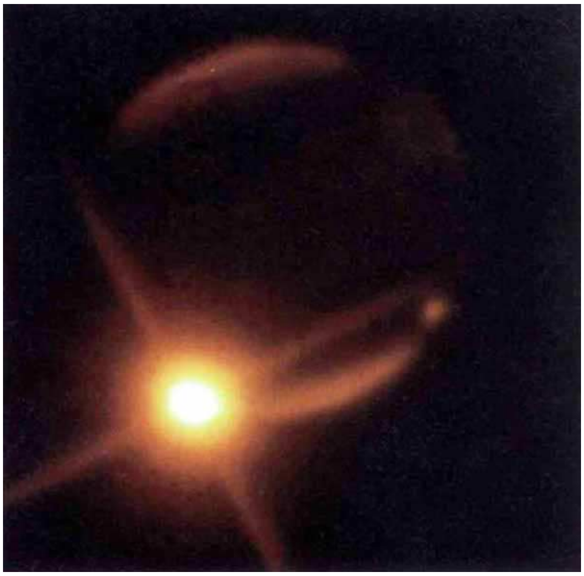
WHAT happens when a comet plunges into a planet? After a year of mounting speculation, last week we finally found out. Periodic comet Shoemaker–Levy 9, its 20-odd 'pearls' by then strung out over more than 300 million kilometres, has met its end; and its target, the gas giant Jupiter, ten times the radius of the Earth and more massive than the rest of the planets put together, bears the scars.

As the crash approached, comet researchers hesitated to predict more than a modest display — in Paul Weissman's phrase[1], a 'cosmic fizzle'. Perhaps they recalled the underwhelming reality of 'comet-of-the-century' Kohoutek in the early 1970s. But nature had something else in store for the worldwide, electronically connected network of astronomers who awaited the first impacts on Saturday evening, 16 July. The spectacular show during the subsequent week exceeded even the most optimistic predictions about the events' potential visibility from the Earth, nearly 800 million kilometres away. No one doubted that significant events would occur at the impact sites around Jupiter's limb, hidden from our sight. But the prominent visibility of high plumes, hotspots and enormous, long-lasting dark splotches on the face of Jupiter was wholly unexpected. What does it mean?

On the practical side, it has meant a revival of interest in amateur astronomy. Even the United States House of Representatives got into the act last week, adding language to NASA's authorization bill requiring the space agency to search for all the asteroids and comets that threaten the Earth. But the longer-term benefits to astronomy will come from years of analysis of the unprecedented wealth of information from this unique phenomenon.

As results continue to pour in over the Internet from all corners of the world it is difficult to synthesize all the observations. There seem to be contradictory implications from some of the different sets of data. But evidently none of the pre-crash models is entirely correct, which is not surprising for such an unprecedented event.

One of the most impressive and unexpected aspects of the comet impacts was the dramatic plumes that reached more than 2,000 km above Jupiter's cloud tops, clearly depicted in pictures by the Hubble Space Telescope. Some numerical modellers had tentatively hoped that one or two of the later impacts, which occurred much closer to the Earth-facing side of Jupiter, might manage to peek above Jupiter's limb before thinning into invisibility. Instead, the plumes either were propelled to higher altitudes or remained much more opaque (and hence capable of reflecting sunlight) than had been expected. Consequently, pictures of Jupiter taken through filters in deep methane absorption bands near 2 micrometres (where Jupiter is very dark) show dramatically bright flares shortly after impact. These are the plume tops that have ascended above Jupiter's atmosphere and catch the sunlight, undimmed by methane absorption. They remained bright at 2 μm for hours and days after the plumes fell back, persisting at altitudes where Jupiter's atmospheric pressure is only 2 thousandths the sea-level pressure on the Earth. Images taken at 10 μm (thermal infrared) show that the plumes were warm, and there is evidence that temperatures reached several thousand degrees.



The collision of fragment G, pictured 12 minutes after impact. The impact site of fragment A can still be seen dimly on the opposite limb. Image at 2.34 μm with CASPIR by Peter McGregor, using the ANU 2.3-m telescope at Siding Spring, Australia on 18 July.

Before the crash, there had been much debate about the size of the comet fragments. Were they large fragments, several kilometres in diameter, from a tidally disrupted body initially nearly 10 km in size, as calculated by Z. Sekanina and his colleagues[2]? (That was a view that comet co-discoverer Eugene Shoemaker continued to maintain even after Harold Weaver, analysing Space Telescope photographs of the comet, changed from advocacy of large fragments to neutrality[3].) Was the original body much smaller, with individual fragments only half a kilometre across, or smaller, as calculated Jim Scotti and Jay Melosh[4]? Were the fragments actually rubble piles or swarms of much smaller components, as predicted by Stuart Weidenschilling[5], and modelled by Willy Benz and Erik Asphaug[6]? Or were the apparent fragments only ethereal wisps of dust, as some researchers privately began to fear after Hubble pictures last spring showed some of them to be vanishing like the Cheshire Cat?

A related question was how deep the comet pieces would plunge into Jupiter's atmosphere before exploding. If the fragments were large and cohesive, it was thought that they might dive more deeply, creating a buoyant fireball that would dredge up the water-rich lower-jovian atmosphere and spread it into the spectroscopically measurable stratosphere of Jupiter. Deep impacts might also induce seismic waves to spread through Jupiter's interior and re-emerge at the cloud surface, possibly with visible manifestations. Comet swarms, on the other hand, might yield upper-atmosphere meteor storms with no deep penetration.

It is widely assumed that last week's spectacular cosmic show means that the deep-plunging, large-fragment model is correct. But that is not necessarily so. For one thing, the penetration predictions varied more because of different assumptions in the physics involved than because of differences in the assumed size and nature of the projectiles. And the swarm proponents never ruled out the possibility that a meteor storm might be as impressive as, or more so than, single explosions.

Lest it be thought that all predictions were too pessimistic, consider large fragment K which struck on 19 July. It was first detected, at 2.3 μm, by Peter McGregor and Mark Allen at the Siding Spring Observatory in Australia. The fireball plume grew to be very bright. Yet they, and other observers in Australia, searched for and failed to detect any precursor brightening of Jupiter's satellite Europa. At the time, Europa was in sight of Earth and of the impact site, but hidden in Jupiter's shadow from any sunlight. Its shadowed, reflective, icy surface should have served as an excellent mirror for the expected brilliant meteor flash and the subsequent glowing fireball that would rush upwards from the explosion. Some researchers had predicted that this single opportunity for observing the reflection from an eclipsed moon of Jupiter would be

The succession of impacts leaves a glowing chain around Jupiter. The image here is taken in the 1.7-μm band of methane emission using MAGIC on the 3.5-m telescope at Calar Alto, Spain on 19 July.

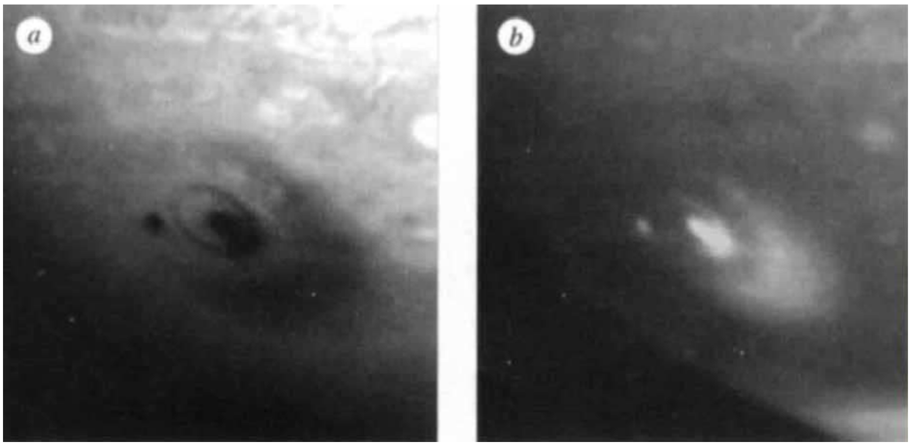
one of the most sensitive ways to detect an impact from Earth, even if everything else failed. But it turned out to be the other way round.

The spacecraft Galileo is best situated to resolve questions about optical flashes. Its first tape-recorded images are due to be played back to Earth on about 15 August and will show the impacts directly. The camera is very sensitive, so it should have recorded both the meteor flashes and any subsequent fireballs for six of the events even if the phenomena were much fainter than expected. There are already indications from Galileo's photo-polarimeter–radiometer, which recorded two impacts, that the meteor flashes lasted longer than expected (about half a minute, at about 5 per cent of the total brightness of Jupiter), but that there were no fireballs. It may be back to the drawing board for the numerical modellers.

It appears, from preliminary spectroscopic data, that the fragments did not penetrate very deeply. The idea was to look for changes in very sensitive spectral lines, which might indicate contamination of Jupiter's stratosphere by material erupted from below. Evidently, little of Jupiter's presumed water-rich lower atmosphere was splashed up into the stratosphere. Most of the spectral changes can be explained by contamination from the dispersed comet itself. Yet other compounds such as hydrogen sulphide have been detected, which has never before been seen on Jupiter and which some researchers think is more likely to be derived from NH_4SH clouds below Jupiter's ammonia cloud deck than from the comet.

The size of the comet before it broke up must have been large. Whether the main fragments consisted of monolithic objects, or clusters of innumerable smaller objects, the total mass that struck Jupiter must have been enormous to generate such high plumes and extensive dark patches on Jupiter's cloudy surface. Indeed the effects are so large, even for the largest estimated sizes of the comet fragments, that it seems likely that our understanding of atmospheric impact physics will have to be revised to account for the amazing phenomena that have been seen — as well as for what has not been seen.

Somewhat overlooked in all the excitement about the first impact by fragment A, and some of the impressive subsequent ones, is the fact that several impactors, including B, F, U and V, really did fizzle. Although photographs of the comet earlier this year showed B to be as bright as A or C, there were only a couple of marginal reports of its impact plume, and it left only an insignificant black spot in Jupiter's atmosphere. Yet the Caltech Submillimetre Observatory seems to have detected hydrogen sulphide associated with B. Clearly, not all fragments of Shoemaker–Levy 9 were the same. One clue might be that some of the fizzled impactors had drifted off the main axis of the 'comet train' during the spring, like some of the fragments that prematurely vanished.



Aftermath of the G impact, as seen by the Wide Field Planetary Camera 2 on the Hubble Space Telescope shortly after impact. *a*, Taken with green light, *b*, taken with a methane filter. (H. Hammel, MIT/NASA HST.)

Unquestionably, the most dramatic evidence of the comet's demise is the belt of immense black patches left in Jupiter's high atmosphere. The larger ones are roughly the size of the largest spot on Jupiter — the Great Red Spot — and are much darker and more prominent than it in a small telescope. Even untrained observers using small, back-yard telescopes could easily watch the remnant of fragment G during the evenings following the impact. And most of the other fragments left black scars that were more visible than any of Jupiter's other usual spots. As these high atmospheric features are not grounded in the dynamics of Jupiter's lower atmosphere, like the Red Spot, it has been expected that the spots will fade and disappear over the days and weeks ahead. But they seem to be persisting. Because they are so black, and absorb so much sunlight, they could conceivably affect Jupiter's local atmospheric temperatures enough to generate longer-lived storms.

As some of the new black spots in Jupiter's southern latitudes are considerably larger than the whole planet Earth, sceptics about the potential effects of cometary impacts on Earth have fallen silent. News media and scientists alike started forgetting to add a caveat when they spoke of the link between the Chicxulub crater in Mexico and the extinction of dinosaurs 65 million years ago. Nothing about last week's impacts changes what is known about the incomplete fossil record of dinosaurs, but the Jupiter crash has certainly affected the way people feel about the role of impacts on our own planet. The black patches on Jupiter have converted planetary impact processes from the realm of theoretical possibilities and ancient geological history to a manifest, dynamic reality. □

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1. Weissman, P. R. *Nature* **370**, 94–95 (1994).
2. Sekanina, Z., Chodas, P. W. & Yeomans, D. K. *Astr. Astrophys.* (in the press).
3. Weaver, H. A. *IAU Circ.* No. 5947 (1994).
4. Scotti, J. V. & Melosh, H. J. *Nature* **365**, 733–735 (1993).
5. Weidenschilling, S. J. *Nature* **368**, 721–723 (1994).
6. Asphaug, E. & Benz, W. *Nature* **370**, 120–124 (1994).