Impact consensus emerges

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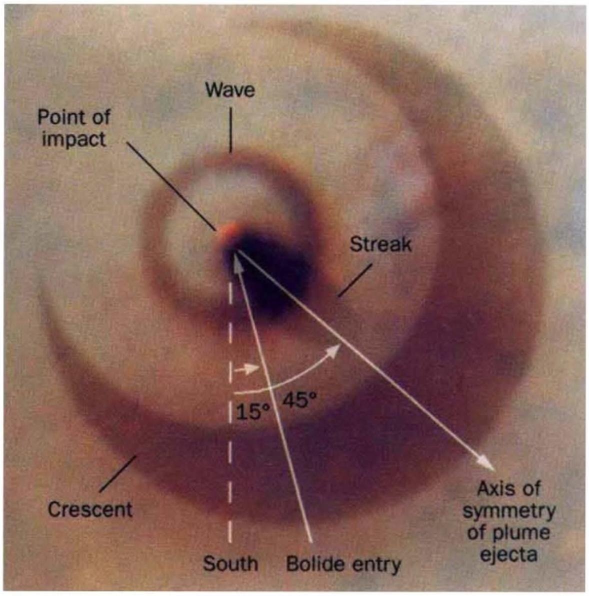
WHAT happened during the first hour after each fragment of comet P/Shoemaker–Levy 9 struck Jupiter in July 1994? A meeting last month on the comet impact* revealed a surprising convergence of opinion regarding observations that had everyone baffled just months ago. General agreement was reached about the nature of the various flashes seen during each impact, the explanation for the shapes and orientations of the dark spots observed at each impact site, and the size of the largest fragment. The meeting was a remarkable scientific show; it required a year of work by hundreds of talented scientists — and of course the collision of a comet with a major planet.

From a comparison of observers' notes during one of several subworkshops, a unified picture emerged for the light curve of a hypothetical impact as viewed from the Earth. First seen was a faint glow that slowly increased in brightness on a timescale of tens of seconds, believed to be due to a large number of small meteors in the coma surrounding each fragment. The meteor shower was followed by a very sharp increase in brightness as the main part of the fragment entered the jovian atmosphere. This bolide phase lasted less than ten seconds and was directly observed by the Galileo spacecraft, which was 1.5 AU away from Jupiter at the time. During the impact of fragment W, the bolide was detected by the Hubble Space Telescope (HST), presumably in reflection off dust in the coma. A few tens of seconds later, a fireball exploded up the 'chimney' created in the atmosphere by the bolide. The fireball was initially hot enough to be self-luminous at optical wavelengths and was detected by the HST. Later, this plume was visible via reflected sunlight as it emerged from Jupiter's shadow.

The 'main event', which was so very prominent in the infrared, peaked ten minutes after impact. This was the 'splash' caused by the 'fallback' of the plume onto the jovian atmosphere. Some of this fallback 'bounced', and a second peak in thermal emission was seen during a second splash ten minutes after the main event. Modelling of the emission from the bounces neatly illustrates a 10-minute periodicity (Drake Deming, NASA Goddard Space Flight Center).

The most notable consequence of the impacts was the dark features that resulted from the fallback of the plume onto the atmosphere. This dark material has come to be known technically as the 'brown stuff'. Extending to the southeast (in a jovigraphic sense) from each of the impact sites was a very dark 'streak', lying on the axis of symmetry of a much larger but lighter coloured crescent. (The 'wave' seen by the HST to be moving radially away from several of the impact sites will be discussed below.) It was perplexing that the axis of symmetry of the streak and crescent was twisted 45° east of south, whereas the chimney that shot out the plume was orientated 15° east of south, and the Coriolis deflection during the 10-minute ballistic flight of the ejecta was only an additional 10°. Kevin Zahnle (NASA Ames Research Center) and Gene Shoemaker (US Geological Survey) argued convincingly that the remaining 20° of rotation is the result of a Coriolis deflection during 30 minutes of horizontal flow as the plume ejecta bounced across the jovian atmosphere. Unfortunately, the nature of the ubiquitous brown stuff remains obscure. Among the candidates are grains of silicates from the impacting body coated with poly-HCN. The latter substance mixed with water readily produces amino acids, the building blocks of life (Clifford Matthews, Univ. Illinois).



The geometry of the impact site of a major fragment of Comet Shoemaker–Levy 9. The difference between the angle of bolide entry and the axis of symmetry of the plume ejecta is due to Coriolis deflection during a 10-minute ballistic flight followed by a 30-minute horizontal flow.

The most complete picture of the impacts arises if the diameters of the largest fragments were only 0.7 km. There are several arguments in favour of this interpretation: the dimmer-than-expected fireballs, the lack of seismic waves, the lack of atmospheric disturbances at millimetre and centimetre wavelengths, the lack of chemistry consistent with dredged-up water, the estimated total mass of dust, and the meagre evidence for impacts due to small, previously unknown fragments (Mordecai Mark MacLow, Univ. Chicago). The sub-kilometre diameter is consistent with tidal disruption models of the parent body, which point to a comet with a diameter of only 1.5 km and a density of 0.5 g cm^{-2} (E. Asphaug and W. Benz/J. C. Solem *Nature* **370**, 120–122/349–351; 1994). In addition, one can explain the almost constant plume heights (3,000 ± 500 km) from impacts of fragments of quite different mass only if the largest fragments did not penetrate far into the troposphere (Zahnle).

There are still a few who would prefer the largest fragments of Comet Shoemaker–Levy 9 to have been 2 km in diameter rather than less than a kilometre. David Crawford (Sandia Labs) asserts that comparisons of his hydrodynamic models with observation favour the larger size. Andy Ingersoll (California Inst. Technol.) concludes that the wave detected by HST moving away from the impact sites at 450 m s^{-1} can be explained as the result of a tropospheric gravity wave that travels horizontally through the water vapour layer in the jovian atmosphere (A. P. Ingersoll and H. Kanamori, *Nature* **374**, 706–708; 1995). A small dip in stratospheric temperature occurs as the wave passes by, which causes the 'brown stuff' to condense and then evaporate. Ingersoll's wave requires fragment sizes consistent with Crawford's estimates in order to deposit at least 10^{27} erg deep in the troposphere.

Finally, although there were several comments during the meeting that it would be nice to have a second comet hit Jupiter to firm up the observations, another impact is not likely to happen any time soon. Gene Shoemaker estimates that, on average, a 1.5-km-diameter comet is captured and tidally disrupted by Jupiter and strikes the planet once every 2,000 years. He added that for the impacts to happen as they did — after the repair of HST, when the Galileo spacecraft was suitably placed, during the era of very efficient infrared detectors, and while the United States government is still investing in basic research — was a miracle indeed.

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