
The impact of Comet Shoemaker-Levy 9 (S-L 9) into Jupiter in July 1994 has helped us to reassess the degree of hazard from major impacts of asteroids and comets into the Earth. The public perception of the reality of the hazard was certainly increased by the comet crash, and Congress asked NASA to propose a specific program to implement the proposed Safeguard Survey [1]. But are there any objective changes in the technical evaluation of the hazard since the summaries, written prior to S-L 9, by Chapman and Morrison [2]; Morrison, Chapman and Slovic [3]; and by Toon et al. [4]?

Although the S-L 9 impacts were probably made by fragments each of order 1 km in diameter [5; also personal communication, M. MacLow, T. Ahrens, and M. Boslough] the individual energies were of order a million megatons (TNT equivalent) due to Jupiter's large escape velocity; hence, these events were energetically equivalent to larger and rarer impacts on the Earth. The post-impact dark spots that formed on Jupiter -- some considerably larger than the entire planet Earth -- suggest that if an analogous event happened on Earth, effects would be global in scale. The unparalleled visual prominence of the Jovian impact spots, which have not been seen previously in spite of nearly continuous observation of the planet over the past century, implies that impacts of this magnitude do not happen on Jupiter more often than once a century. However, there would be nothing inconsistent with the assumption that such impacts could hit Jupiter as often as every few of centuries.

As described in our review papers [1, 2], the Earth is struck, on average, every hundred thousand years by objects the nominal size of the S-L 9 fragments, but the mean interval for objects with the energy of the S-L 9 events is of order 1 m.y. Energetically, the S-L 9 impacts were of the scale that would be associated with severe short-term environmental effects on Earth, although not approaching the level of mass extinctions. Observations of the G fragment impact provide us with as good an empirical picture as we have of what could happen to us if the Earth experienced such a global catastrophe.

The Galileo spacecraft (NIMS [6], UVS, and PPR instruments [7]) measured the color temperatures of the brilliant, luminous phases of the G impact during the first seconds and minutes. Similar data for impacts H, L, and Q1, and by the Galileo camera [8] for the K, N, and W impacts provide a broader context for interpreting the G impact. A brilliant blue-white meteor or bolide flashed through Jupiter's skies for a few seconds. From Jupiter's cloud-tops, it would have appeared a hundred times brighter than the Sun. As the disintegrating fragment plunged beneath the clouds, the superheated atmosphere above formed a fireball ~10 km across. Over the next minute or two, the expanding bubble of gas grew hundreds of times in volume as it cooled and explosively erupted into space [6]. The Hubble Space Telescope's camera [9] captured what happened during the next 10 minutes, as the plume of gas -- including entrained material from the G fragment itself -- rose more than 3,000 km above Jupiter's cloud deck and then fell back across a region of Jupiter more than 20,000 km across. Re-impacting the top of Jupiter's stratosphere at roughly 10 km/s, the glowing secondary debris heated much of the impact region to more than 1,000 C [10]. Galileo's NIMS saw the heat beginning just 6 min. after impact [11], and, for ground-based observers the firestorm reached a crescendo 10 min. later as Jupiter's rotation carried the target region into direct view.

Temperatures cooled over the next few hours, leaving the stratospheric pall. Meanwhile, waves swept across the impact region, reverberating from the final demise of the comet fragment deep within Jupiter's atmosphere, far below the clouds [12]. Much of the dark stratospheric material was made of tiny, micrometer-sized aerosol particles [13]. Over the ensuing weeks and
months, upper atmospheric winds distorted the shape of the impact clouds, stretching them to merge with other impact bruises, forming a belt more than 100,000 km long. By late December 1994, as Jupiter emerged from solar conjunction, the impact belt remained visible and completely encircled Jupiter.

One might imagine that G's dark cloud would have shielded the surface below from the Sun, putting any local Jovians who had escaped the firestorm into a dark deep freeze. Actually, calculations [13] show that sunlight is dimmed only slightly beneath the black haze. Yet, on Earth, lowering surface temperatures by just 10% is the difference between summer and winter. More significant, according to R. West, would be stratospheric heating and resulting changes to upper atmospheric chemistry and winds.

It remains uncertain whether the dark impact aerosols were mostly derived from the comet or from Jupiter's atmosphere. Comets (and most asteroids) contain abundant carbonaceous materials. To whatever degree the disintegration and high-temperature processing of the comet yielded the dark spots on Jupiter, we might expect something similar if a comet struck Earth. However, if the aerosols were primarily high-temperature products of Jupiter's atmosphere -- e.g. from the methane that constitutes a fraction of a percent of Jupiter's atmosphere -- then the Earth's chemistry might yield different stratospheric aerosols, which could be less harmful...or more so.

So far, S-L 9 has not changed our estimates of how frequently comets and asteroids strike Earth, but the comet's tidal break-up highlights how little we know about the smaller bodies in the solar system. Shoemaker [14] recently suggested that many Earth-threatening comets might actually be fragments of precursor comets that pass too close to Jupiter and break up, like S-L 9. Such fragments would likely be sprayed throughout the inner solar system (S-L 9's dive back into Jupiter was a fluke). The more we learn about the nature and behavior of asteroids and comets, our perceptions about the impact hazard will surely evolve.