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The Risk to Civilization From Extraterrestrial Objects and Implications of the Shoemaker-Levy 9 Comet Crash*)

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Extraterrestrial Objects
Shoemaker-Levy 9 Comet
Impact

The role of impact cratering in shaping the face of our planet Earth has been hardly taken serious until recent decades. The possibility that some rare crater-shaped features might be of exogenic rather than endogenic (e.g., volcanic) origin was entertained by some individuals a century ago, but it was not until the dawn of the Space Age when the impending investigation by spacecraft of the Earth's Moon focussed renewed attention on the hypothesis that the Moon's craters were caused by impact and that such terrestrial features as Meteor Crater in Arizona were also of impact origin. To a few astronomers, this hypothesis seemed natural. After all, meteorites had been recognized since the beginning of the 19th century to be of extraterrestrial origin. And, later, asteroids – the first of which were discovered contemporaneously with the beginning of meteoritics as a science – were linked to meteorites. After the discovery of the first Earth-crossing asteroid in the 1930's, a few astronomers realized that impacts with Earth, and other planets, were inevitable – and that the impacts could be of horrendous magnitude.

Nevertheless, until the several Mariner and Voyager spacecraft of the 1960's and 1970's returned images of the pock-marked surfaces of Mars, Mercury, and the moons of Jupiter, even the planetary science community (not to mention the broader communities of geologists, scientists in general, and the lay public) failed to appreciate the full significance of bombardment by cosmic projectiles. Since then, the Moon rocks returned by the Apollo astronauts provided an absolute chronology for the lunar bombardment; together with an ever-increasing number of terrestrial impact structures (now approaching 200) that have been found and dated, the lunar cratering record provided proof of the general frequency with which the Earth is struck by projectiles of various kinetic energies. Meanwhile, modest telescopic search programs, aided by modern instrumentation, have discovered hundreds of Earth-approaching asteroids and comets. From determinations of their orbital trajectories and the dynamical processes that shape them, independent estimates of the frequency of bombardment grew increasingly accurate and robust, and they agree with data on lunar and terrestrial crater ages to better than a factor of two.

No longer is the question, how often is the Earth struck by objects 1 km or 10 or more km in diameter, but simply when and where will the next one strike ... and what precise range of physical and environmental consequences may be expected. Thus, the hypothesis a decade-and-a-half ago by ALVAREZ et al. that the mass extinction at the end of the Cretaceous was caused by the impact of a cosmic projectile seems, in retrospect, to be the wholly natural application to Earth of a prime conclusion from the first two decades of planetary exploration by spacecraft. The Earth must have been struck at least several times since the beginning of the Cambrian by objects 10 to 20 km in diameter and at least once by an even larger object.

Although much of the geological community, and paleontologists in particular, reacted with skepticism to suggestions that the major geological epochs were brought about by giant cosmic impacts, the burden is really on the skeptics to answer this question: "If the great mass extinctions aren't the evidence of these colossal impacts, then where is the evidence, for surely such impacts happened?" And there is another question: "What other possible terrestrial catastrophe, or cumulative processes, could possibly equal the destructive magnitude of an impact with energies of a thousand million megatons of TNT?" One clear fact about the asteroid and comet population is that objects of unlimited size (tens or even hundreds of kilometers in diameter) exist and have a statistical probability of impacting our planet. All known terrestrial processes, however, are bounded.

Studies of the Chicxulub crater have revealed abundant evidence for enormous geological effects in the sector of our planet struck by the K/T boundary impactor. And, of course, the global distribution of iridium-enriched materials at the boundary provides evidence of global effects. However, it is not the geology, but the ecosystem of our planet – the thin bodies of water we know as oceans and

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the tenuous atmospheric gases held by gravity chiefly in the lowest kilometers above the surface of Earth – that should be most affected by a giant impact. Being so rarified and so capable of contamination by an impact, which after all is dominantly manifested by the ejecta that is shot away from the forming crater, the atmosphere and oceans of our planet are dramatically more susceptible to disruption than is the bulky body of our planet studied by geologists. For example, even the very limited injection of materials into the stratosphere by small, explosive volcanoes like Mt. Pinatubo have readily measurable effects (through dimming of sunlight) on the global climate. Asteroids and comets can inject many orders of magnitude more contaminants into the atmosphere.

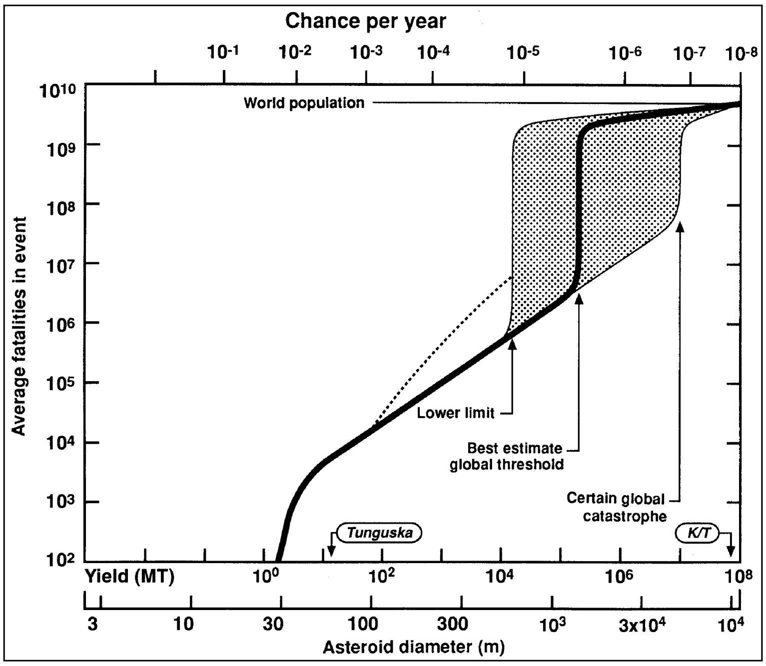
Since life depends on stability of the environment, such enormous disruptions of the environment by impacts should have been expected to be most prominently revealed by the preserved fossil record of life on the surface of the Earth. Yet old ideas and prejudices are difficult to overcome, and even now – long after many independent proofs of the ALVAREZ et al. hypothesis have been amassed, at least so far as the K/T event is concerned – there remains much skepticism in some quarters that mass extinctions are caused by these inevitable giant impacts.

Development of the physical theory of chaotic dynamics, combined with the exceptional calculating power of modern computers, has led to a much more thorough understanding of the orbits of the asteroids and comets through the history of the solar system. It has been recently realized (P. MICHEL, P. FARINELLA & Ch. FORESCHLÉ, 1996, Nature 380, 689–691) that the asteroid 433 Eros, target of the Near Earth Asteroid Rendezvous (NEAR) mission spacecraft launched in early 1996, has approximately a 50 % chance of colliding with Earth during the next 100 million years or so. One of the largest of the Earth-approaching asteroids, Eros could produce an explosion more than an order-of-magnitude more powerful than the K/T boundary extinctor. There may be as many as 2000 smaller asteroids already in Earth-crossing orbits that nevertheless are large enough so that an impact by any one of them would cause a global agricultural disaster (although not a mass extinction) and would thereby threaten the lives of most people now living.

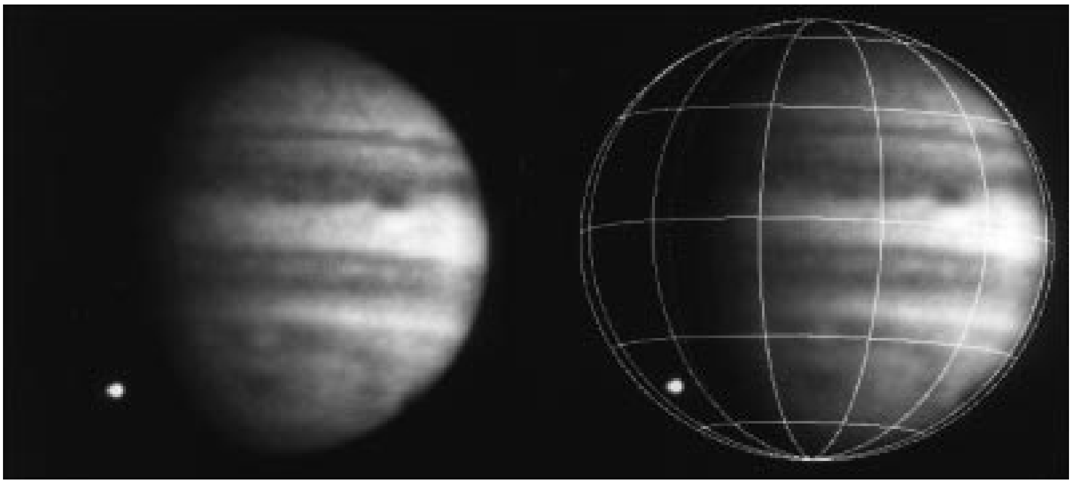
It is one of these smaller objects that inevitably will strike in the next few hundred thousand years and, accordingly, has one chance in a few thousand of striking during the next century. While such a chance is very small, the consequences of such an impact would be so enormous – killing much of the world's population and perhaps threatening the survival of modern civilization – that it is worth evaluating. The cosmic threat to the life of an individual is greater than that from many other hazards that people and governments take very seriously, for example the chance of dying in an air crash due to terrorism. Perhaps even more relevant, the possibility that civilization itself might be at stake has a qualitative difference from all other horrors the human species has encountered. Even plagues and World Wars have affected only some peoples and some nations, so that other nations remained intact and thus were able to help rebuild the decimated nations. A global ecological catastrophe might leave no nation capable of providing a nucleus for rebuilding civilization, even though the human species would survive.

While it is easy to argue that the hazard from the heavens is a significant one, I do not want to give the impression that I view it as the most important one for nations to deal with. There is an exceedingly small probability that such an impact will actually happen in the foreseeable future, whereas the dangers of nuclear proliferation, genocide, and pandemic disease are manifestly with us right now. Many other problems, including natural disasters like earthquakes and floods, can be mitigated much more effectively and certainly by the expenditure of public funds than is true for the impact hazard. On the other hand, given that modern technology probably could be developed to identify nearly all of the hazardous objects – including long-period comets – and could be employed, in most cases, to deflect any hazardous body that might be found, it is important that policy-makers and the public be aware of this very real, if unlikely, threat.

In July 1994, only half a year before the Vienna symposium "Apocalypse Now?", an exceptionally poignant event took place in the solar system that vividly demonstrated the continuing existence – not merely historical record – of impact cratering as a major process in the solar system. About two years earlier, a modest comet in temporary orbit around Jupiter came close enough to that giant planet so that it was tidally disrupted into debris, which soon coalesced into about 20 separate fragments. The enhanced surface area of the disrupted comet debris



Text-Fig. 1.
The average number of fatalities expected worldwide in an impact of an asteroid onto the Earth is shown for a range of asteroid diameters between 30 meters and 10 kilometers. Additional scales show the equivalent explosive yield in megatons (MT) and the chance of such an impact event happening during any one year. The nearly vertical part of the curve near 1.5 km diameter represents the transition from regional to global scale catastrophic consequences; the shaded area indicates the range of uncertainties in estimating this threshold prior to the S-L 9 event (the diagram is adapted from CHAPMAN & MORRISON, 1994). The sobering lesson of S-L 9 probably reduces the upper limit of the threshold ("certain global catastrophe") to 10^6 MT or less.



Text-Fig. 2.

The final fragment of Comet Shoemaker-Levy 9 (fragment "W") streaks down through Jupiter's nightside troposphere as a brilliant bolide; it begins to explode with energy equivalent to several thousand megatons of TNT.

The lefthand image was taken by the camera on the Galileo spacecraft; the righthand image is the same but has a longitude-latitude grid superimposed. Although this image records the final second of part of S-L 9 as a comet, the band of black spots created by all the fragments (some of the smaller spots are visible on Jupiter's disk immediately to the right of the impact flash) remained visible for six months and the spectroscopic signature of the impact ejecta plumes may last for many years.

made it bright enough to be discovered by the observing team of Eugene and Carolyn SHOEMAKER and David LEVY, who were engaged in their routine observing program at Mt. Palomar (California) searching for Earth-approaching asteroids and comets and other interesting small bodies in the solar system. The early discovery of the broken comet, and predictions that it would crash into Jupiter, gave astronomers unparalleled advance opportunity to prepare a world-wide observing campaign to observe a transient astronomical event.

During a week-long period, the comet fragments plunged at 60 km/sec into the southerly latitudes of Jupiter, just around Jupiter's horizon as observed from Earth. Fortunately, the Galileo spacecraft, enroute to its 1996/7 orbital tour of Jupiter, was off to the side and had a direct view of the impact sites. Moreover, the resulting explosions were so enormous that they erupted into direct view from Earth-based observatories (including Hubble Space Telescope), as well.

Two years later, as I write this manuscript, much of the Shoemaker-Levy 9 (S-L 9) impact data remain to be reduced and evaluated – the mass of data is simply so enormous that much remains to be done. However, some essential results are becoming clear, and they have a profound message for us here on Earth that go far beyond the obvious confirmation that asteroids and comets really do crash into planets.

There is now nearly unanimous agreement among researchers, who have considered the matter from many different aspects, that even the largest of the individual comet fragments that struck Jupiter were less than 1 km in diameter, and probably only a few hundred meters in diameter. Given such sizes and their 60 km/sec velocities (compared with 20 km/sec for a typical Earth-impactor), the largest S-L 9 impacts carried roughly the same kinetic energy as would a 1.5 km diameter asteroid striking the Earth, which is just the size that my collaborator David MORRISON and I (Clark R. CHAPMAN & David MORRISON, 1994: Impacts on the Earth by asteroids and comets: assessing the hazard, Nature 367, 33–40) have estimated as the likely threshold size for a civilization-threatening ecological disaster. As is well known, the famous "black spots" left in Jupiter's stratosphere by the impacts of several of these largest fragments (e.g., those given the designations G, L, and K) had dimensions comparable to that of the whole planet Earth. Instead of being spread out on Jupiter's broad face, the analogous impacts on Earth would have wrapped a pall of stratospheric haze around the entire globe.

On Jupiter, the black material gradually dispersed – first longitudinally and then latitudinally – over successive months. However, even as I write this account two years after the impacts, prominent evidence of the impacts remains in Jupiter's atmosphere. Whereas the visible blackening has faded to near the threshold of visibility, the spectroscopic signatures of certain gaseous species may even be still increasing! In the Earth's atmosphere, of course, there would be no lateral room for the material to spread into, so the duration would be longer – perhaps a couple of years – before the atmospheric aerosols eventually fell and precipitated out. While fully quantitative calculations have not been finalized, it is likely that the diminution of sunlight by a dark haze layer like that observed on Jupiter would have lowered temperatures globally on Earth sufficient to create havoc to the agricultural industry worldwide. Thus, in summary, we have now actually observed an impact and its consequences (on Jupiter) which, on Earth, would have been the most momentous catastrophe in human civilization.

Such impacts do not occur regularly on Jupiter. Jupiter has been well observed by telescopic observers for at least a century, and monitored often during the four centuries since the invention of the telescope, that the lack of similar black spots in the observational records suggests that there has been no equivalent cometary impacts for at least a century or more. By virtue of the Earth's size and other factors, our planet is struck less than one-thousandth as often as Jupiter is. Nevertheless, given the massive atmospheric modification documented on Jupiter by very small comet fragments, it is clear that the "danger from the skies" on Earth is at least as great as that estimated by MORRISON and myself in our aforementioned 1994 paper.

Not only the geological community but also the public at large must eventually come to terms with the fact that the Earth orbits the Sun in a dangerous interplanetary environment. Reservoirs of the fragments inevitably left over from the accretionary birth of the planets remain well populated. There are numerous large bodies in the asteroid belt, in the Jovian Trojan clouds, in the Kuiper Belt, and in the Oort Cloud – and perhaps in other locations, as well. Although the cratering rate is now much reduced from that during the epoch prior to 3.8 billion years ago when extraterrestrial impacts must have truly dominated the geology of planetary crusts, it remains a potent force for shaping the biosphere of our planet, and its clues are prominent enough to be studied by geologists.

Amid all of the other concerns of modern society to which the geological community can contribute (finding sources of energy and raw materials, protecting against natural hazards like earthquakes), the cosmic impact hazard is one that should not be overlooked. Indeed the proximate location of the Ries impact crater and the widespread occurrence of tektites not far from Vienna is adequate evidence that impact cratering could, literally, “hit home”.

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