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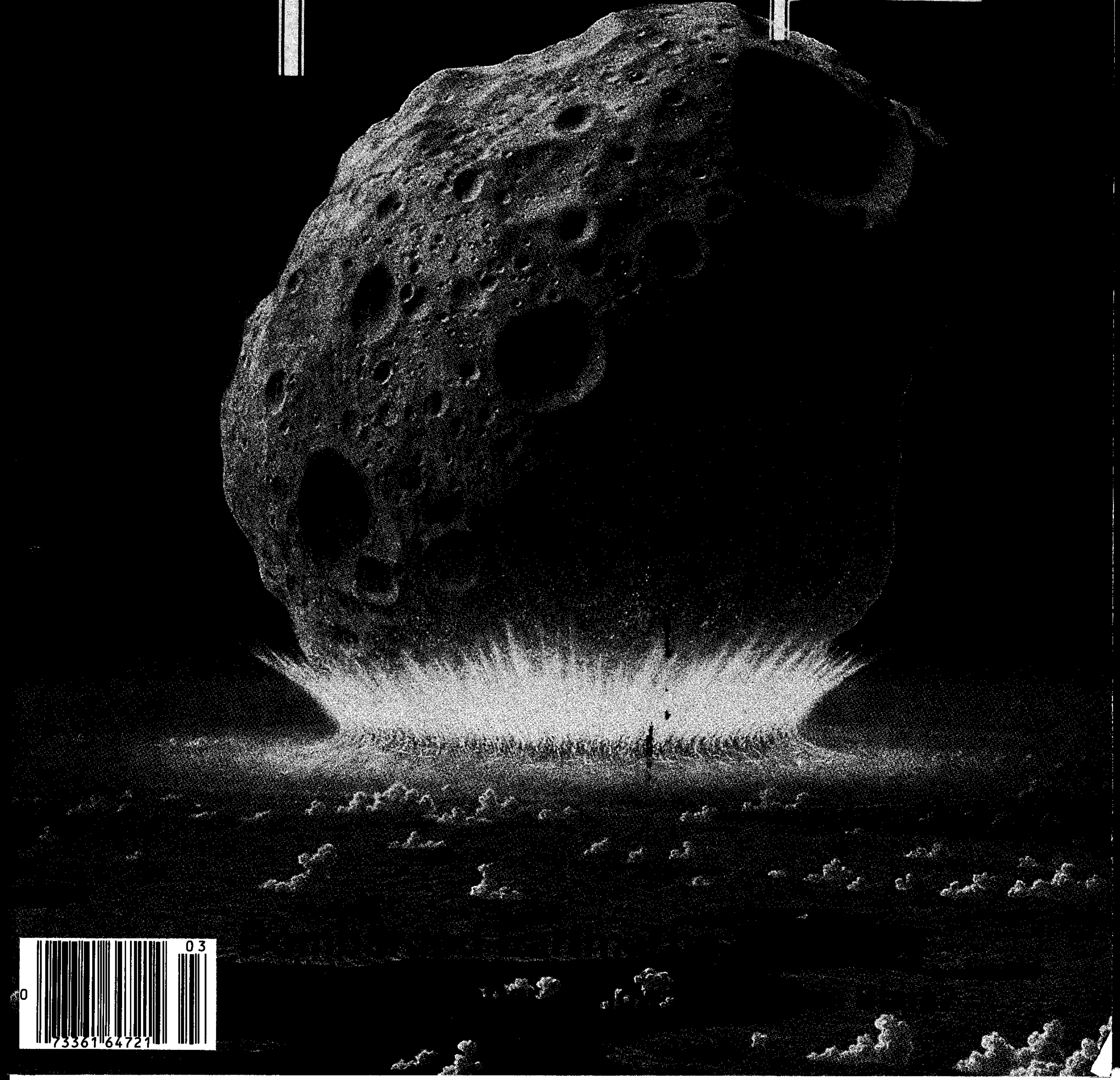

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Target Earth: It *Will* Happen

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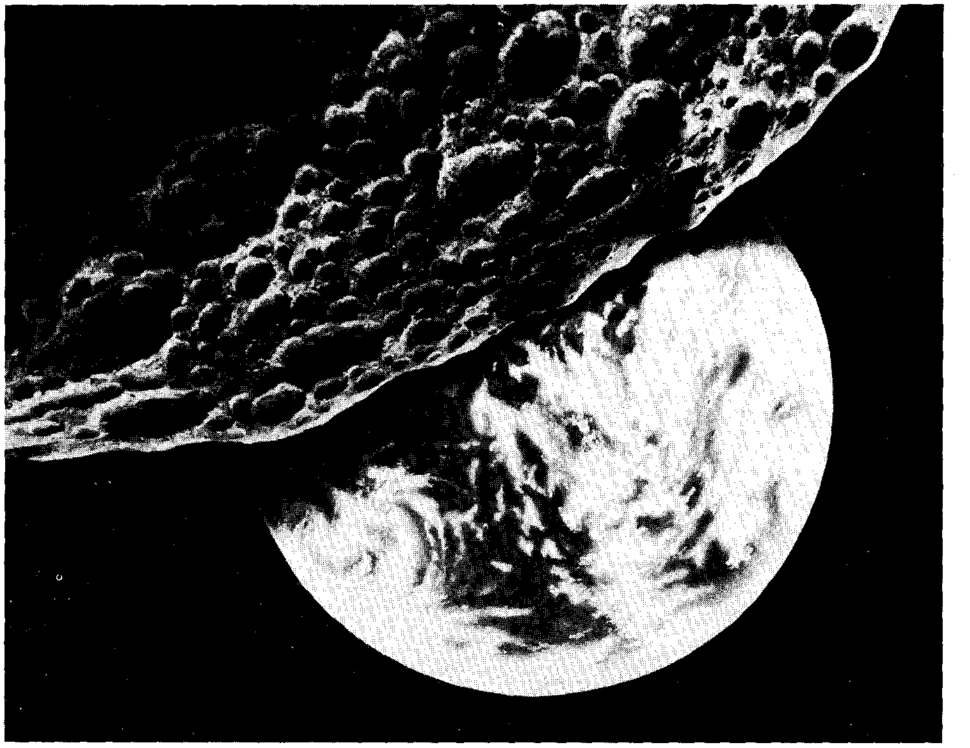


Astronomers have come to realize that comets and small asteroids occasionally collide with the inner planets. When they strike Earth, tremendous amounts of energy are unleashed that can threaten our fragile environment. Painting by Marilynn Flynn.

TAKE NOTE: the Earth is a target for cosmic impacts. We orbit the Sun within a sparse swarm of asteroids and comets, some of which will ultimately — and inescapably — collide with our planet. This seemingly simple fact lies at the heart of a profound revolution in thinking about the Earth, its history, and its relationship to the other planets. In fact, growing recognition of the role played by cosmic impacts in Earth history is changing some long-cherished ideas in both geology and biology, including how life evolves.

Consider, for example, the recent "near miss" of asteroid 1989 FC, which passed within 700,000 kilometers of Earth on March 22, 1989. This object is probably between 200 and 500 meters in diameter. Had it actually struck Earth, the impact would have delivered the energy equivalent of more than a million tons of exploding TNT and created a crater up to 7 km across (*S&T:* July, 1989, page 30).

Yet 1989 FC is just one of several thousand asteroids of this size or larger in Earth-approaching orbits. Although fewer than 80 of them have been discovered to date (see the table on page 264), the sampling statistics imply that many more fly past Earth undetected. In addition, several new comets are discovered each year, many of them potential impactors.

Astronomers have been aware for several decades of the significance of these Earth-approaching comets and asteroids. But very few geologists or biologists had thought much about them prior to the 1980 publication of a now-famous paper by Luis and Walter Alvarez and their collaborators. As explained on page 266, they proposed that the impact of a 10-km asteroid caused a widespread and devastating extinction of life 65 million years ago, at the end of the Cretaceous period of geologic history. Subsequent research has not only verified the Alvarezes' hypothesis but has also shown that other breaks in the evolutionary record may well have resulted from Earth's collisions with comets and asteroids.

At first, the notion that an asteroidal impact could so radically affect Earth history met strong resistance from geologists. Most objections were grounded in the then-standard dogma that all geologic

EVOLUTION

changes are gradual and result from the same processes we see today. Since no large impact or resulting worldwide dust cloud has been recorded in human history, the critics argued, it is "unscientific" to suggest such a cause for events 65 million years ago. At best, the impact hypothesis was to be a scenario of last resort, to be accepted only if more conventional ideas — such as massive volcanic eruptions — failed to explain the observed data.

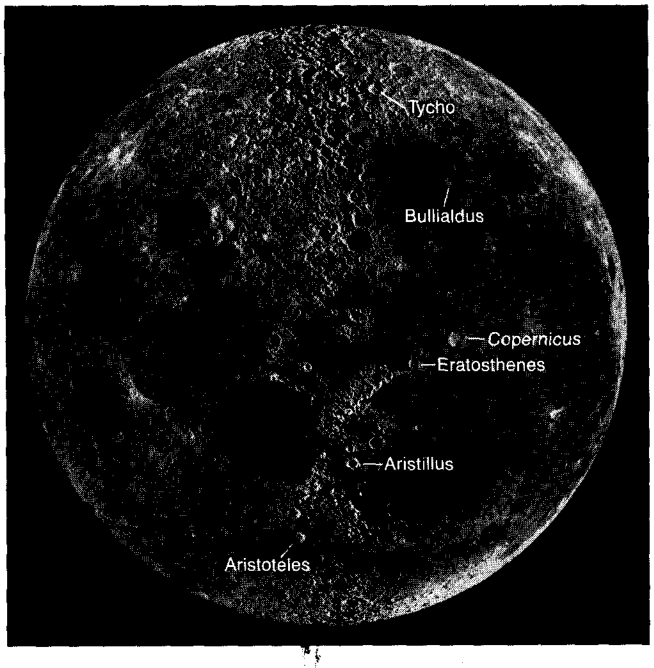
To an astronomer watching from the outside, these objections seem to be rooted in a false premise. Many researchers apparently assumed that collision-induced catastrophes are *ad hoc,* inherently unlikely events. In contrast, astronomers need only gaze upon the Moon's battered face to realize that cosmic impacts have occurred throughout solar system history. We would be surprised *not* to see some indication of their effects preserved in the Earth's geologic and biologic records.

With the benefit of hindsight, we can see that catastrophes such as the impact 65 million years ago must have happened throughout geologic history. As we will show, anyone with just a 6-inch telescope and some simple arithmetic can prove this conclusion for themselves.

THE MEASURE OF THE MOON

Consider the lunar craters. Because the Moon shares Earth's interplanetary niche, its impact history must be very similar to that of our own planet. Whatever the nature of the projectiles — whether comets, asteroids, or something else — they must have collided with the two bodies at similar rates. Thus we can use the Moon to estimate the frequency and magnitude of impacts on the Earth.

If you look at the Moon through a small telescope (or examine a photograph or map of it), you see a surface dominated by craters. In the light-colored highlands, craters are packed "shoulder to shoulder" — essentially saturating the landscape. Most of them were formed early in lunar



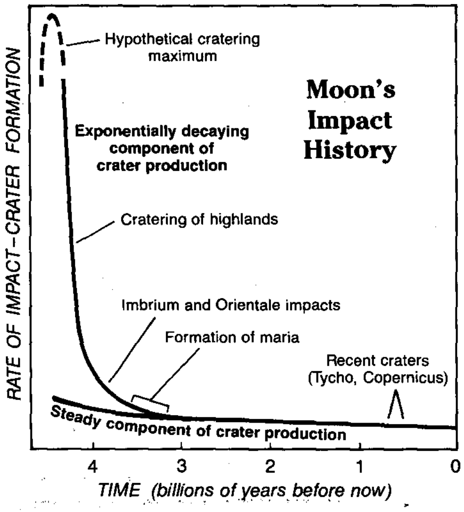
The dark lunar maria are volcanic outpourings that appeared after the most violent cratering on the Moon had ended. Even so, five craters with diameters exceeding 50 km have been blasted out of the maria since these vast plains were extruded some 3.5 billion years ago. Copernicus and the highland crater Tycho mark the sites of the two largest impacts in recent lunar history. Courtesy Lick Observatory.

history, when impact events were more frequent. This must be true because at present there are too few asteroids and comets coursing through the inner solar system to saturate the Moon's surface with craters over the 4.6-billion-year age of the solar system. Therefore, the lunar highlands tell us little about the current impact rates.

In contrast, the darker volcanic maria, which cover just 16 percent of the entire lunar surface, are plains that formed after the Moon's violent pummeling had subsided. They provide an excellent scorecard for measuring relatively recent lunar impact history.

Count the largest craters on the maria, those with diameters of 50 km or more. You will find Copernicus (93 km), Aristoteles (87 km), Bullialdus (61 km), Eratosthenes (58 km), and Aristillus (55 km) — a total of five large craters created since the emplacement of the maria's 6 million square kilometers of lava plains. A further examination yields 24 more mare craters with diameters from 25 to 50 km. From this tabulation, combined with the age of the maria (about 3.5 billion years, as derived from Apollo samples), you can estimate average impact rates in these size ranges for the entire Moon. It works out to about one new crater at least as big as Aristillus every 120 million years.

The lunar result can be extrapolated to our planet. Earth's surface area is 500 million square kilometers, about 80 times that of the lunar maria. Therefore, about *400 impacts* comparable to those that formed the five largest lunar mare craters must have taken place on Earth over the same time interval. Put another way, Earth endures one such event about every 10 million years.



Early in its history (and the Earth's), the Moon was bombarded by an incredibly violent shower of debris left over from the solar system's formation. More recently, however, impacts on the Earth and Moon have resulted from a "trickle" of comets and small asteroids.

Our atmosphere does little to slow down such large projectiles, so we will neglect this effect. More important is the fact that Earth's gravity "focuses" incoming projectiles, thus increasing the number and energy of impacts on Earth's surface relative to the Moon's. But we will ignore this effect as well, to keep the argument simple (and conservative).

A far greater number of smaller craters have been excavated from the lunar and terrestrial surfaces. We can count the craters in different size ranges on the lunar maria and thereby estimate the size distribution of the colliding objects. As noted, craters 25 to 50 km across are about five times more common than those 50 to 100 km across. A census of craters down to a few kilometers in diameter (the smallest ones easily discernible with amateur telescopes) tells us that the number of craters of a given size is roughly inversely proportional to the diameter squared. Thus, the time *between* impact events of a given size varies directly as the diameter squared. Put another way, projectiles 1 km across strike Earth about 100 times more often than those 10 km across.

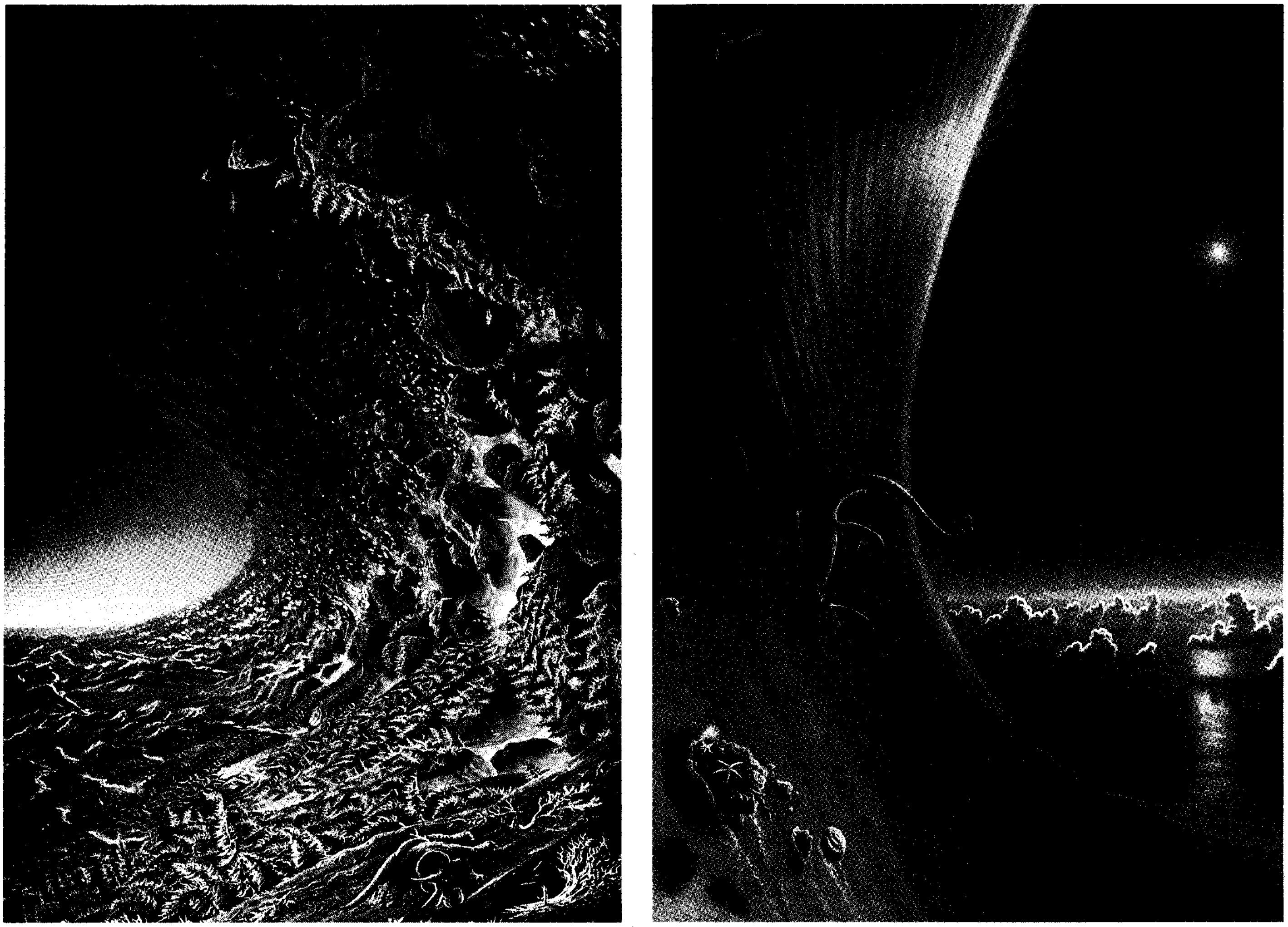
These cratering-frequency estimates are the average rates over the past 3.5 billion years. But how well do they represent the *current* impact rate, within the past few hundred million years, for example? One estimate can be obtained from Apollo data, which imply that two large craters — Copernicus on a mare plain and Tycho in the highlands — were gouged out of the lunar surface within the past billion years. The formation of two craters of this size over the Moon's entire Earth-facing hemisphere within 1 billion years is roughly consistent with five such craters appearing in the smaller area of the maria in 3.5 billion years. Thus, Copernicus and Tycho suggest that "recent" impact rates have not been very different from those over the past 3.5 billion years. Interplanetary impacts are a continuing process, not one confined to the early history of the solar system.

HOW MANY MEGATONS?

Theory, laboratory simulations, and test explosions in the field have allowed researchers to estimate the consequences of an asteroid or comet's collision with the Earth. The incoming projectile strikes at tens of kilometers per second and is largely vaporized upon impact. Blasting a 100-km-wide crater involves the excavation of several times 10^{15} tons of rock, which requires the energy equivalent of exploding more than 10 trillion tons (10 million megatons) of TNT. If just 1 percent of the excavated mass reaches the upper atmosphere — an amount supported by calculations — the entire Earth will soon be covered with a layer of fine dust several centimeters thick. During the months that the dust remains airborne, the surface below is plunged into total and impenetrable darkness.

The energy to form a 5-km crater is still several million megatons, and the resulting dust cloud will be equally opaque though not as long lived.

How does the putative impact 65 mil-



Don Davis' paintings suggest the consequences of a 10-km-wide asteroid striking the Earth 65 million years ago. Regardless of whether the object struck land *(left)* or ocean *(right)*, a huge fraction of Earth's inhabitants were wiped out by the cataclysmic consequences.

lion years ago compare with these estimates of crater-forming events? Unfortunately, the site of the impact has not yet been found. (The crater most likely formed on the seafloor and may already have been subducted and destroyed by plate-tectonic motion.) But based on the excess of iridium in the clay layer laid down worldwide at the end of the Cretaceous period, the impacting asteroid must have been about 10 km across — big enough to produce a crater between 100 and 150 km in diameter. A crater of this size, created 65 million years ago, roughly fits our estimate of one new crater in the 50- to 100-km range every 10 million years, since larger impacts should be correspondingly rarer.

The devastating event at the close of the Cretaceous is just one of a series of catastrophic impacts that must have occurred, on average, at intervals of tens of millions of years. Such events cannot be avoided. This conclusion follows simply from the observed lunar cratering record. Therefore, it would be the height of folly to try to reconstruct the geologic (and biologic) history of the Earth *without* taking such impacts into account.

So how could geologists have neglected impact catastrophes for the past century? In part, the answer lies in the conservative nature of science. We are justifiably cautious about overturning the accumulated wisdom of the past. Until the middle of the present century, no craters on the Earth could be reliably shown to have resulted from infalling asteroids or comets. Many geologists even disputed the impact origin of lunar craters. Another problem is the narrowness of vision of scientists, who are immersed in their specialities. Before the recent blossoming of comparative planetology, thanks to spacecraft missions to the planets, not many Earth scientists had considered the implications of the lunar craters.

A few, of course, were ahead of their time. Foremost among these is Ralph Baldwin, who wrote eloquently of the possible role of impact cratering in Earth history in his classic 1949 book *The Face of the Moon*. Subsequently, Eugene Shoemaker (U. S. Geological Survey) probed the interrelated questions of the numbers and orbits of comets and asteroids, the cratering record of the Moon, and the search for ancient impact craters on the Earth. Other planetary scientists were aware of the significance of large impacts on the Earth as well, but for most researchers in other fields the concept was new and unfamiliar when introduced by the Alvarezes' paper in 1980.

The cataclysm at the end of the Cretaceous wiped out most life on Earth. Most families of marine animals were terminated, and widespread extinctions of land plants and animals also occurred. Several dozen species of dinosaurs, including terrestrial, aquatic, and flying creatures, became extinct. So did many species of mammals, though some (our ancestors) managed to survive. We can suppose that even within a species that survived, the vast majority of its individuals were killed.

Another mass extinction 250 million years ago, which ended the Permian era and which may also have been impact-triggered, was even more devastating. Impacts may be natural and inevitable, but they have come uncomfortably close to sterilizing our planet on a number of occasions.

On the Moon, the multi-million megaton impact of a comet or asteroid does little harm. The blow generates large moonquakes, a crater is formed, and ejecta are scattered over much of the Moon's face. From a planetary perspective, this is not a big deal. On the Earth, however, the environmental consequences of the same impact are much greater. Life on our planet is confined to the thin layer of ocean and atmosphere. A large impact can actually blow away part of the atmosphere, and if it takes place in the ocean, it causes huge tsunamis. Chemical reactions catalyzed by the projectile's passage through the atmosphere generate global acid rain. Widespread fires burn up much of the biomass, adding soot to the dust injected by the impact itself.

The atmosphere and ocean thus amplify the ecological damage of an impact and spread its effects around the planet. For these reasons even a geologically modest cratering event can have disastrous effects on Earth's biologic communities. Their eradication, in turn, provides opportunities for the evolution of new species from among the survivors, leading to biologic diversification. Without impact-generated mass extinctions, there might be much less opportunity for evolutionary development of life on our planet.

WAITING FOR THE BIG ONE

So far we have discussed impact events in a fairly narrow range, with energies of several million to several tens of millions of megatons. These energies correspond to impacts by objects with diameters of a few kilometers. What about the effects of both smaller and larger impacts?

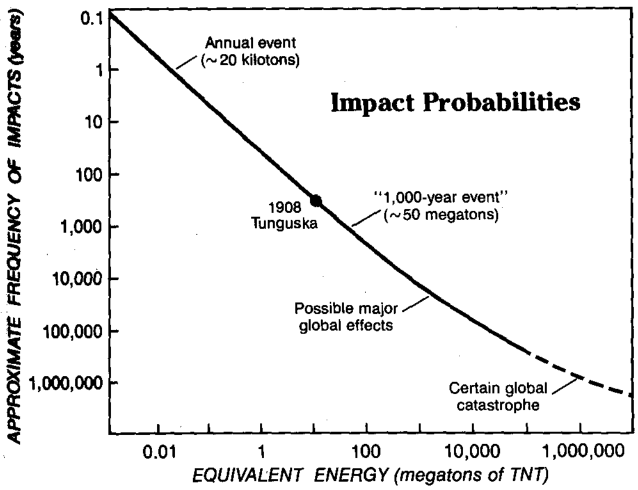
The energy of an impact by a 1-km asteroid is tens of thousands of megatons. An explosion of this size, while causing terrible damage regionally, would probably not trigger a mass extinction. It might, however, generate sufficient atmospheric dust to reduce temperatures globally, damage crops, and lead to starvation and a worldwide breakdown of the fragile human institutions of economy, government, and civilization.

The largest craters on the lunar maria, such as Copernicus, are the work of asteroids or comets with diameters of about 10 km. If the average interval

EARTH-CROSSING ASTEROIDS

Number	*Name or designation*	*Year of discovery*	*Radius (km)*	*Semimajor axis (a.u.)*	*Period (years)*	*Eccentricity*	*Inclination (°)*
1862	Apollo	1932	0.7	1.471	1.78	0.56	6
2101	Adonis	1936	0.5?	1.875	2.57	0.76	1
	Hermes	1937	0.5?	1.639	2.10	0.62	6
2201	Oljato	1947	1.5?	2.173	3.20	0.71	3
1685	Toro	1948	2.4	1.367	1.60	0.44	9
1863	Antinous	1948	1.5	2.260	3.40	0.61	18
1566	Icarus	1949	0.7	1.078	1.12	0.83	23
	1950 DA	1950	1.5	1.683	2.18	0.50	12
1620	Geographos	1951	1.0	1.245	1.39	0.34	13
	1954 XA	1954	0.3	0.777	0.68	0.34	4
4183	1959 LM	1959	1.5	1.981	2.79	0.64	7
	5025 P-L	1960	?	4.201	8.61	0.90	6
	6344 P-L	1960	0.1	2.576	4.13	0.64	5
	6743 P-L	1960	0.5	1.620	2.06	0.49	7
1864	Daedalus	1971	1.7	1.461	1.77	0.62	22
1865	Cerberus	1971	1?	1.080	1.12	0.47	16
1866	Sisyphus	1972	5	1.894	2.61	0.54	41
1981	Midas	1973	1.0?	1.776	2.37	0.65	40
	1973 NA	1973	3	2.427	3.78	0.64	68
	1974 MA	1974	3?	1.775	2.36	0.76	38
2102	Tantalus	1975	1.5	1.290	1.46	0.30	64
2062	Aten	1976	0.5	0.966	0.95	0.18	19
2329	Orthos	1976	1.5	2.405	3.73	0.66	24
2340	Hathor	1976	0.1	0.844	0.78	0.45	6
2063	Bacchus	1977	0.5?	1.078	1.12	0.35	9
2135	Aristaeus	1977	0.5	1.600	2.02	0.50	23
2100	Ra-Shalom	1978	1.7	0.832	0.76	0.44	16
2212	Hephaistos	1978	4.4	2.165	3.18	0.84	12
	1978 CA	1978	1.0	1.125	1.19	0.21	26
4015	1979 VA	1979	1.6	2.641	4.29	0.62	3
	1979 XB	1979	0.3	2.262	3.40	0.71	25
3360	1981 VA	1981	1	2.458	3.86	0.74	22
3103	1982 BB	1982	2	1.407	1.67	0.35	21
3361	Orpheus	1982	0.3	1.209	1.33	0.32	3
3757	1982 XB	1982	0.2	1.836	2.49	0.45	4
	1982 DB	1982	0.5	1.489	1.82	0.36	1
4197	1982 TA	1982	2?	2.297	3.48	0.77	12
3200	Phaethon	1983	3	1.271	1.43	0.89	22
	1983 LC	1983	0.5?	2.632	4.27	0.71	2
	1983 TF2	1983	0.5	2.439	3.81	0.74	15
	1983 VA	1983	1.5	2.611	4.22	0.69	16
3362	Khufu	1984	0.5	0.990	0.98	0.47	10
3671	Dionysius	1984	1	2.198	3.26	0.54	14
	1984 KB	1984	2	2.216	3.30	0.76	5
3752	Camillo	1985	?	1.414	1.68	0.30	56
3554	Amun	1986	?	0.974	0.96	0.28	23
3753	1986 TD	1986	?	0.998	1.00	0.51	20
3838	1986 WA	1986	?	1.505	1.85	0.70	29
4034	1986 PA	1986	?	1.060	1.09	0.44	11
	1986 JK	1986	?	2.802	4.69	0.68	2
	1987 KF	1987	?	1.836	2.49	0.68	12
	1987 OA	1987	?	1.497	1.83	0.60	9
4257	1987 QA	1987	?	1.647	2.11	0.47	41
	1987 SB	1987	?	2.204	3.27	0.66	3
	1987 SY	1987	?	1.442	1.73	0.59	6
	1988 EG	1988	?	1.269	1.43	0.50	3
	1988 TA	1988	?	1.541	1.91	0.48	3
	1988 VP4	1988	?	2.263	3.40	0.65	12
	1988 XB	1988	?	1.467	1.78	0.48	3
4179	1989 AC	1989	?	2.509	3.97	0.64	0
	1989 AZ	1989	?	1.646	2.11	0.47	12
	1989 DA	1989	?	2.162	3.18	0.54	6
	1989 FB	1989	?	1.042	1.06	0.25	14
	1989 FC	1989	0.2	1.023	1.03	0.36	5
	1989 JA	1989	?	1.770	2.36	0.48	15
	1989 PB	1989	0.6	1.063	1.10	0.48	9
	1989 QF	1989	?	1.151	1.24	0.41	4
	1989 UP	1989	?	1.861	2.54	0.47	4
	1989 UQ	1989	?	0.915	0.88	0.27	1
	1989 UR	1989	?	1.077	1.12	0.35	10
	1989 VA	1989	?	0.729	0.62	0.59	28
	1989 VB	1989	?	1.850	2.52	0.46	2

This table, compiled by Roger W. Sinnott, is based on data from the *Minor Planet Circulars*, IAU *Circulars*, and Eleanor F. Helin (Jet Propulsion Laboratory).



For every large object in space that may someday strike Earth, there exist many smaller ones. This plot shows the likelihood that our planet will be hit by a member of the current population of Earth-crossing asteroids and comets. Also noted are the impacts' energy equivalents, in tons of exploding TNT, and the likely consequences for Earth.

between such impacts on Earth is tens of millions of years, the corresponding interval between impacts due to 1-km projectiles must be hundreds of thousands of years. In other words *every year* the odds are one in some hundred thousand of having a civilization-threatening impact.

Impacts from larger projectiles would be less frequent but more damaging. For example, the same size distribution extrapolated to larger sizes suggests that a billion-megaton event should take place once every few hundred million years. But we are not sure that projectiles this large (with diameters of 30 to 40 km) are likely to collide with the Earth at all. For instance, there are no craters on the lunar maria corresponding to this size. It may be that billion-megaton events cannot occur because none of the Earth-approaching asteroids and comets are large enough to cause them.

The situation must have been different in the past, however. The lunar mare lavas themselves fill a group of impact basins 500 to 1,000 km across, all formed about 4 billion years ago. These huge basins came about from bombardment by projectiles at least 50 km in diameter. Even more basins of comparable size must have been formed on the Earth during that period. Impacts of this magnitude are capable of throwing off large fractions of the atmosphere and boiling the oceans. If terrestrial life existed at that time (we have no fossil evidence indicating one way or the other), its survival must have been a close call. Or maybe it *was* obliterated, and new life formed again from scratch — perhaps several times.

Planetary scientists have extended these simple crater-counting techniques from the Moon to the other planets, and we now recognize impact cratering to be an important process throughout the solar system. We are also beginning to tally directly the numbers of potential impactors — Earth-approaching comets and asteroids — though this work remains in its infancy. Only in the past year or two, however, have scientists from other disciplines begun to assess the implications of this knowledge for the history of the Earth.

Some still remain unconvinced. In the June, 1989, *National Geographic,* Rick Gore notes, "Many scientists refuse to accept that such catastrophes have caused the great dyings. 'We don't need an impact,' I have heard over and over from paleontologists. 'We can explain mass extinctions with earthly causes.'" Perhaps these paleontologists have never raised their eyes to look at the Moon.

The lunar impact record is incontrovertible, and its extrapolation to our own planet is straightforward. The Earth exists in a cosmic shooting gallery, and impact-induced catastrophes have been a part of its natural history for billions of years. In the future, astronomers, geoscientists, ecologists, and biologists will have to work together to understand how such events have influenced the evolution of our planet and its life. ◆

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The Tunguska Event

The scene is Siberia, in the great taiga forests below the Arctic Circle; the date is June 30, 1908. There is no warning at 7:30 on this sunny morning when suddenly a column of fire descends from the east. A fireball as bright as the Sun speeds silently toward the desolate wilderness.

The fireball explodes suddenly in a 10-megaton airburst about 6 km above the ground; seconds later the shock wave strikes. The Siberian forest is flattened for thousands of square miles, the trees stripped of branches and leaves and left scattered like matchsticks all pointing away from the blast. There are no fatalities, since the nearest witness is a lone trader at a post about 110 km away.

This scenario may sound like science fiction or the beginning of some apocalyptic novel of nuclear war. Unfortunately, the explanation is more prosaic and more frightening. The explosion near the Podkamennaya Tunguska River in 1908 was caused by the collision of a fragment of cosmic debris with the Earth's atmosphere (*S&T:* January, 1984, page 18).

The most frightening aspect of the Tunguska event is that the colliding object was probably a piece of ice and rock no bigger than about 100 meters in diameter. Despite decades of searching, astronomers have never spotted an object this small in space. Yet many tens of thousands of them must exist.

Trees near the Podkamennaya Tunguska River in Siberia still looked devastated nearly 20 years after being flattened by the airborne explosion of a chunk of interplanetary debris in 1908. The Tunguska event was the most violent impact of the 20th century. Courtesy Novosti Press Agency.