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When the Irresistible Force Meets the Immovable Object

The results of such encounters are plainly visible on the surfaces of the moon, Mars, and the earth

by Eugene Shoemaker

A solid object moving at speeds of many kilometers per second or faster creates a truly irresistible force if it strikes another solid object. Such fast-moving objects abound in the inner part of the solar system, and they occasionally collide with the solid surfaces of the terrestrial planets and the moon. Most of these cosmic projectiles are so small that, when they collide with a planet, the planet may for most purposes be considered immovable. A complex series of events take place, however, in the near vicinity of the impact point. A shock, which decelerates the projectile, is propagated back to the projectile from the impact interface, and another shock is propagated out into the planetary target where it sets a small region within the target in motion. Rarefaction waves, reflected from the free surfaces of the projectile and target behind the shocks, deflect the moving, shocked material so that it flows away from the target in a diverging spray, leaving a cavity in the target. Thus, the answer to the old paradox about what happens when an irresistible force meets an immovable object is: *It will make a crater.*

High-speed impact cratering is a process that geologists, with a few exceptions, have almost entirely ignored. Other scientists who ought to be concerned about it, such as astronomers, have generally ignored it too. So it has only been in the last few years that the significance of impact phenomena in the evolution of solid planetary surfaces has come to be appreciated.

Normally we are not conscious of the relatively big pieces of solid debris in the vicinity of the earth except on those occasions when there is a near-miss. One of the best documented near-misses was discovered by the late Walter F. Baade of Caltech on a photographic plate taken in 1949 with the 48-inch Schmidt camera at the Palomar Observatory; he found a long streak on the plate that represented an object moving very rapidly near the earth. Subsequent exposures permitted a calculation of its orbit which showed that this body, usually called an asteroid (although we have good reason, I think, for calling these objects something else), not only comes close to earth but crosses the orbit of Venus and Mercury and passes close to the sun. Because of its close approach to the sun it was named Icarus.

Icarus is only one of a family of more than 15 telescopically observed objects that cross the orbit of the earth (i.e., their perihelion distance, the nearest point in their orbit of the sun, is less than the average distance of the earth from the sun). Some of them have been observed to pass much closer than Icarus, which came within eight million miles of the earth at the time of its discovery. In 1937, Rheinmuth at Heidelberg discovered a very near object, later called Hermes, which passed within less than half a million miles of the earth, a little less than twice the average distance to the moon.

If the earth is pictured as a bullseye on a target with a radius of half a million miles, the frequency with which it is hit by things like Hermes can be calculated by a simple probability argument. It turns out that this frequency, from the geological viewpoint, is rather high. If there is a population of objects like Hermes in space near the earth, with more or less randomly distributed orbits, then the earth ought to be hit by objects as large as Hermes at a rate of about once every 100,000 years. This is a minimum estimate of the rate because we don't know what other telescopically resolvable objects may have gone whizzing by that we didn't see. We have discovered only a small fraction of them, and most of the discoveries have been accidental.

An object has to be of substantial size to be telescopically observable even in a fairly close passage by the earth. Hermes is probably about a kilometer in diameter. On the other hand, much smaller objects may be observed indirectly if they actually enter the earth's atmosphere. These objects are entering the atmosphere almost constantly and are seen as meteors (bright streaks of light in the sky, produced by shock-heating of the atmosphere along the entry trajectory).

The Tunguska fireball

In the size range between the very small things that are seen indirectly as ordinary meteors and the smallest asteroid seen at the telescope, there is a class of objects which is extremely difficult to detect. From time to time these objects encounter the earth and produce very bright meteoric fireballs (bolides). The most spectacular of these on record was the great Siberian meteor of 1908, sometimes called the Tunguska meteor.

The Tunguska bolide entered the atmosphere over a remote part of central Siberia, and the site was not visited by scientists until almost 20 years later. Some phenomena associated with the meteor, however, were recorded on scientific instruments at great distances from its path. A train of low-frequency acoustic waves and gravity waves radiated out from the Tunguska region and was recorded on ordinary weather station barographs in central Asia. The air-wave train was also recorded on microbarographs in western Russia and in Great Britain, and even the reverse wave, formed after the air-wave train had converged at the antipodes, was recorded at some of the microbarograph stations. Moreover, when the air wave slapped the ground near the end point of the meteor's trajectory, it generated a seismic wave train that was recorded as far away as Jena in eastern Germany. Thus, we have a surprisingly good record of some of the more energetic responses of the earth to the entry of the Tunguska bolide into the atmosphere.

In 1927 the Russian scientist L. A. Kulik organized an expedition to the Tunguska region to search for a meteorite crater at the end point of the trajectory. Kulik failed to find any genuine impact craters but did find one very spectacular effect on the ground, which was later documented in great detail by aerial photographs. Fallen trees made it possible to find the end point of the trajectory from their radial pattern of fall, which extended out to a distance of about 40 kilometers. In addition, the trees were scorched out to a distance of about 15 kilometers from the end point. If a bolide like the Tunguska object entered the atmosphere today, anyone under the end point would be quite sure that he had been blitzed with a nuclear bomb. The immediate effects, except for gamma and neutron radiation, are strikingly similar to those of an airburst of a megaton-sized nuclear weapon.

It is possible, with the data now available from large atmospheric nuclear explosions, to calibrate empirically the response of the atmosphere to very large, very strong shocks. It is also possible to calculate what modes of vibration should be observed on the air-wave train propagated away from the region of strong shock. David Harkrider, a Caltech graduate now at Brown University, has worked out in detail the theory of these wave trains.

The total energy released by the Tunguska fireball can be estimated, using the nuclear explosion data, to have been about 10 megatons. The photovisual radiation, which set the trees on fire, was comparable to the scorching that would be produced by a 5-megaton nuclear device. I became concerned, after I had run through these calculations, over what might happen if a similar bolide were to fall over the Soviet Union or the United States today, and whether the resultant fireball would be recognized as a natural phenomenon. As it turns out, smaller events of this type have occurred in the last 10 years, and a number of them have been detected on sensitive microbarographs.

Asteroid or something else?

Another interesting phenomenon accompanying the Tunguska meteor was observed on the night following the fall in a broad region extending westward all the way to western Europe. The sky that night never became completely dark. People were able to read newspapers at midnight at latitudes as far south as southern Russia. The actual sky brightness was about one ten-thousandth that of the ordinary bright sunlit sky. By the following night the phenomenon had disappeared.

From its geographic distribution, it is possible to show that the bright night sky resulted from scattering of sunlight by very high dust, extending as high as 800 kilometers. The dust particles settled rapidly enough that the sky returned to normal darkness the following night.

Apparently the Tunguska meteor was produced by a small comet, and the dust was derived from the tail of the comet. This comet was not bright enough to have attracted notice prior to its entry into the earth's atmosphere. The diameter of the nucleus was small, probably no more than 25 to 30 meters. It weighed about 20,000 tons and was coming in at a velocity of about 60 kilometers per second. It never reached the ground because the pressure on the front end built up rapidly, and the stress difference between the front and back sides finally exceeded its shear strength; it came apart at an altitude of about 15,000 feet.

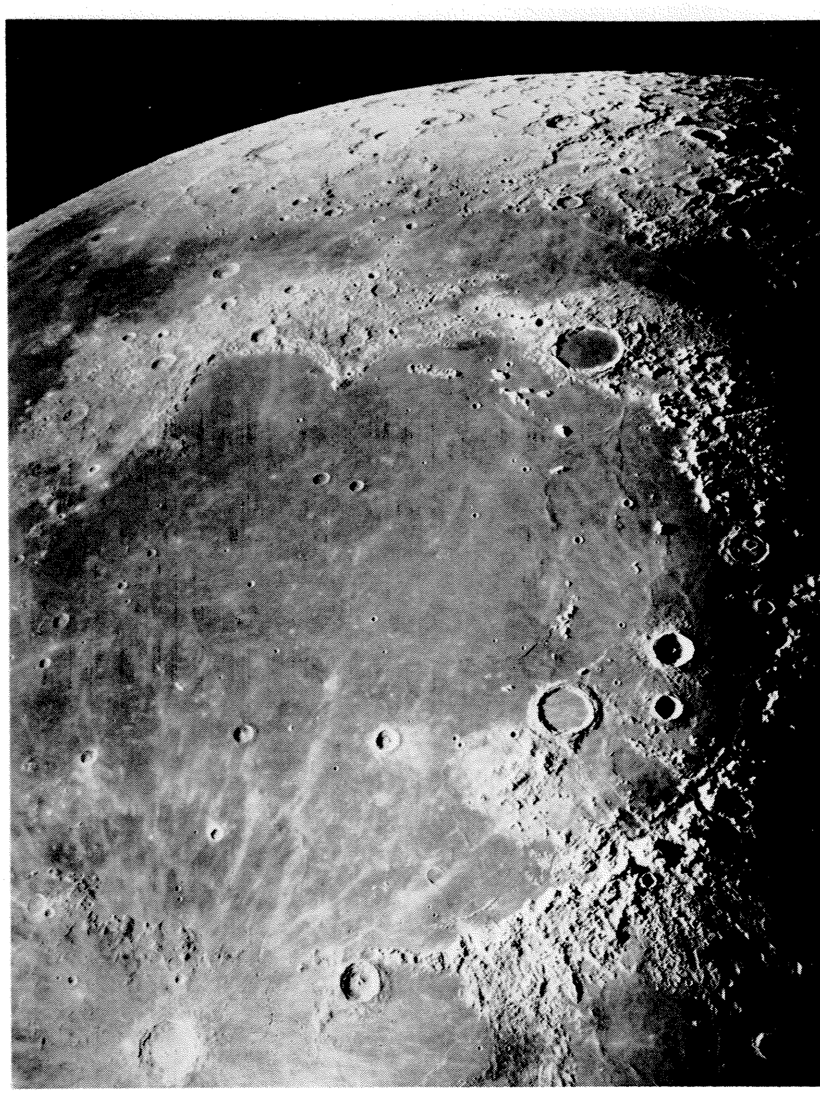
I suspect that the so-called asteroids like Hermes and Icarus are also comets which have passed near the sun so many times that their volatile constituents have been almost entirely driven off. These objects have orbits that are more like those of the comets than of the normal asteroids, which are in orbits between Mars and Jupiter.

Most small bodies that enter the earth's atmosphere are decelerated to very low velocities before they reach the solid surface; also, objects in the size range of 1 millimeter to 100 meters are generally torn to pieces by aerodynamic forces. Iron meteorites are the only objects in this size range that are strong enough to survive passage all the way through the atmosphere and make a crater. The iron meteorites constitute about five percent of the meteorites observed to fall. At present, craters formed by impact of iron meteorites are known at 12 localities on the earth. The biggest of these craters is the Arizona meteorite crater, near Flagstaff, which is about 1.3 kilometers in diameter. The energy required to produce this crater was about 4 to 5 megatons TNT equivalent, and the meteorite was probably about 30 meters in diameter.

Age of the lunar surface

If an object like the Tunguska bolide hits the earth once every 50 years, which is the approximate expected rate of encounter, similar objects will hit the front side of the moon about once every 1500 years. An object the size of the Tunguska bolide would make a crater about 1.5 kilometers across on the moon—which would be easily resolvable telescopically. Objects the size of Hermes and larger hit the moon at least once every three million years and form craters tens of kilometers across.

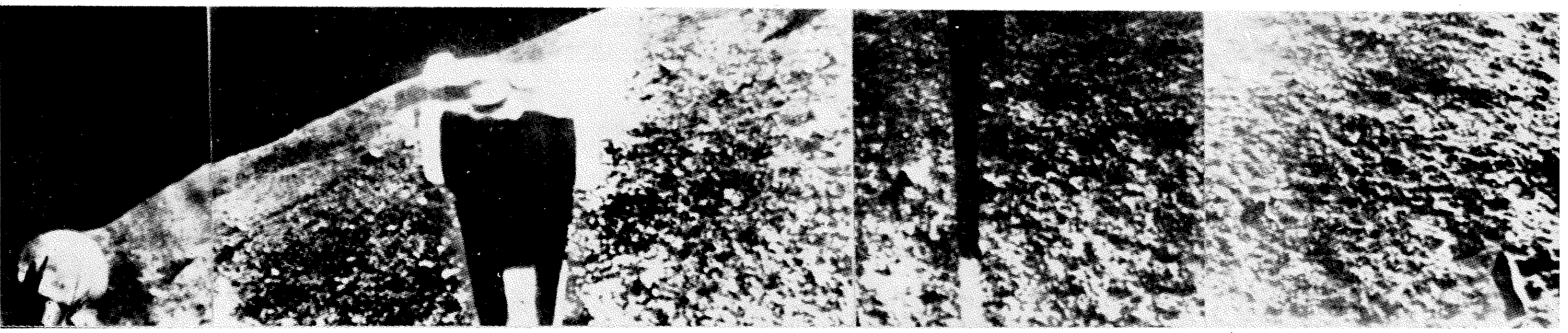
If this present rate of encounter is approximately the same as the rate in the past, we may use the number and distribution of observed craters to estimate the age of different parts of the lunar surface.



Mare Imbrium, the moon's largest circular basin, may be only one billion years old. This makes it considerably younger than the moon itself, whose age is probably on the order of four and one-half billion years.

One of the most obvious things about the moon is that the lunar terrain can be divided into two fairly distinct classes. One terrain class consists of the rather smooth, dark parts of the surface (which can be recognized with the naked eye). Galileo called the dark, smooth regions *maria* (seas) because, with his small telescope, he couldn't see the craters and other features on them, and he thought the maria were actually water surfaces. The other terrain class includes the bright, higher, more heavily cratered regions, which he called the *terrae*.

The spatial densities of the small, telescopically resolvable craters on the different maria are about the same, which leads us to suspect that most of the individual mare surfaces were formed at about the same time in lunar history. When observed in close



The best view of the moon so far—pictures from the Soviet Union's Luna 9, from about two feet off the moon's surface.

detail, the maria are found to have features similar in form to small volcanoes and volcanic flows on earth. Probably the mare surfaces were built up as a series of overlapping volcanic deposits. This episode of volcanism is a significant part of the history of the solar system, and the question is: When did it happen?

One idea is that the maria are very old. Estimates that these dark, smooth surfaces are almost as old as the earth itself—about four and one-half billion years—are common in the literature of the moon. At the present rate of impact, however, all the craters on the maria could be accounted for by the accumulated influx of about half a billion years. Thus, the maria may be only about one-tenth the age of the earth.

This estimated age for the maria is radically different from the age I would have given half a year ago. I would have said then that the mare surfaces were several billion years old. It was a recalculation of the energy of the Tunguska object, along with new data on other very large meteoric fireballs, that has permitted this drastic revision of the time scale of the moon. The maria now appear to be about as young as some of the older fossiliferous rocks here on earth. Placed in the geologic time scale, they would be late pre-Cambrian or early Paleozoic in age.

Thus, it is possible to revise the estimated ages of some of the other prominent features on the moon as well. For example, the largest circular basin on the moon is the Mare Imbrium basin, which appears to be a very large impact crater almost filled with lava. On the basis of the number of smaller craters superimposed on the exposed rim of the basin, it turns out that the basin was formed about a billion years ago, which makes it much younger than the moon. Moreover, existence of this "young" basin on the moon suggests that similar huge impact scars may have been formed on the earth during the latter part of geologic history. While normal surface geologic processes tend to obscure most craters formed very long ago, one as big as the Imbrium basin (several hundred kilometers across) might be more difficult to hide in a billion years. The large circular basin in the southern part of Hudson Bay in Canada may well be a crater like Mare Imbrium, as suggested by the Canadian astronomer C. S. Beals several years ago.

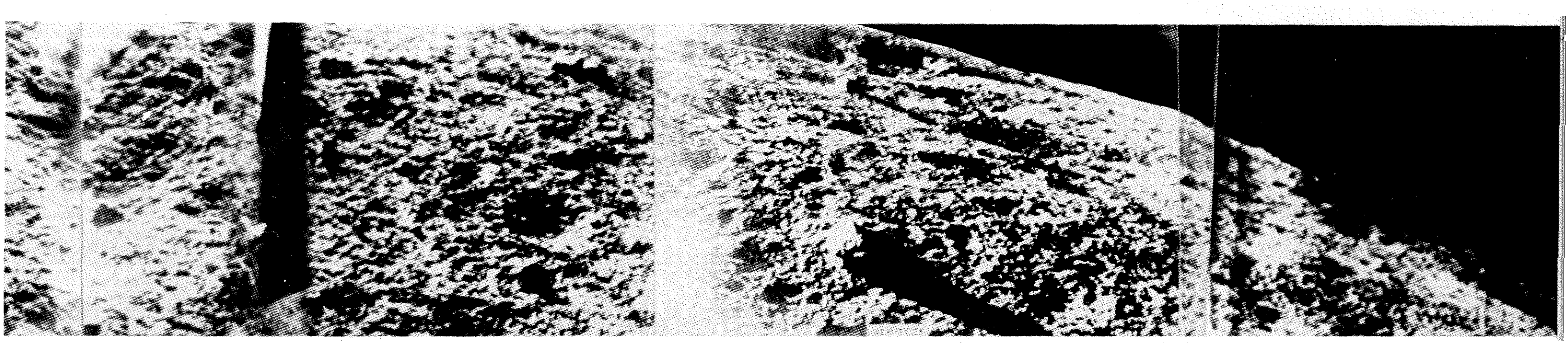
The parts of the moon most densely populated with craters have roughly 10 times as many large craters as do the maria. These heavily cratered parts of the terrae may be nearly as old as the moon.

The pictures transmitted from Mariner IV showed that parts of the surface of Mars look rather startlingly like the terrae of the moon; the regions observed on Mars are populated by large, overlapping craters. A good deal of argument has transpired in the last half year about how old the Martian surface is. I think most of the arguments are unsound. It has been assumed by most people that the craters were formed by asteroids, because the asteroids have orbits relatively close to Mars. If most of the craters on earth and the moon are formed by comet nuclei, however, the impact rate of comets on Mars may be greater than that of asteroids. The impact rate of comets per unit area on Mars probably is within a factor of two or three of the estimated rate for the earth and the moon. For a given area, craters should be formed more rapidly on Mars than on the earth and moon, but we do not have sufficient information as yet to know what the difference in impact rate should be.

Pieces of the moon

One of the consequences of a high-speed impact is that some material is ejected from the target at very high velocity. A projectile striking a dense solid surface on the moon at speeds greater than 6 kilometers per second will eject more than its own weight at escape velocity (2.4 kilometers per second). Thus, one of the things to look for on the earth would be pieces of the moon that have been thrown off during the formation of impact craters.

Little pieces of the moon must be falling on the



The lunar surface around the landing site is covered with a debris layer in which there are some small craters.

earth all the time. Moon dust is in the air we breathe; the trouble is we don't know how to tell the moon dust from earth dust. On rare occasions, however, a great squirt of shock-melted material ejected from a big lunar impact crater should hit the earth. When the liquid jet diverges as it goes out into space, it will break up into little globs that surface tension will tend to make into spheres (or other rounded shapes if they are spinning). The melt will congeal to glass before it hits the earth. Thus, we might expect to find small spherical and rounded bodies of glass scattered about the earth, and indeed we do. They are found in a number of restricted, but still large, strewn fields on various parts of the earth and are called tektites.

Evidence that tektites are likely to have come from the moon rests on surface features produced by aerodynamic ablation as they entered the earth's atmosphere. Dean Chapman, a Caltech graduate now at the Ames Research Center of NASA, has shown that the amount of ablation, the thickness of the remelted layer, and the spacing of ring waves on the ablated surfaces on some tektites from the Australasia field indicate that these objects entered the earth's atmosphere at about 11 kilometers per second, which is very close to the escape velocity from earth. Thus, Chapman's analysis indicates the Australian tektites came from some place essentially on the earth's orbit. The most likely place is the moon. These silicious glasses might be derived from silicious volcanic rocks in the maria.

Other lunar material

In addition to tektites, there are some other materials that are possible fragments of the moon. Harold Urey has suggested that most of the stony meteorites are derived from the moon and have been knocked off by cometary impact. I think it even more likely that the meteorites known as basaltic achondrites, which are similar to terrestrial basalts, may be pieces of the moon. These too might be samples of volcanic rocks in the maria.

The Luna 9 pictures

Most types of meteorites and much smaller particles of the type that produce the ordinary meteors in the earth's atmosphere are striking the moon's surface at about the same rate per unit area as they encounter the earth. These form craters of the size observed in high-resolution Ranger pictures and in the pictures obtained from the Soviet Union's spacecraft, Luna 9, which soft-landed on the moon on February 3, 1966.

In addition to craters formed by extra-lunar particles, large numbers of small craters are produced by flying fragments of the moon ejected from large impact craters. It turns out that the secondary fragments of the moon produce far more small craters than does the primary flux of interplanetary debris. The cumulative effect of this bombardment is the formation of a layer of fragmental debris covering most parts of the moon, the upper surface of which is pockmarked with small craters.

This debris layer with small craters on it is well portrayed in the Luna 9 pictures above. The pictures were acquired by a rotating scanning system located about two feet above the lunar surface. The axis of the scanning system is inclined eastward, toward the sun; and, near the central part of the panorama, fragments only a few centimeters across can be seen near the spacecraft. To the north and south larger fragments and small craters are scattered about the surface, and craters that are probably many meters in diameter occur near the horizon. Much of the near surface has a rubbly appearance.

A debris layer such as this will be of great interest for study in the first manned lunar landing. In most places it will contain pieces derived from both local and distant parts of the moon. By careful sampling of the debris layer it should be possible for us to learn a great deal about the variety of rock types that are exposed over the lunar surface and to determine whether, in fact, tektites and certain kinds of meteorites really are pieces of the moon.