THE IMPACT OF LARGE METEORITES

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The speed of meteorites at the time they reach the surface of the earth depends largely upon the resistance they have encountered in passing through the atmosphere and upon the hour of day that they fall. A large meteorite[1] will have relatively little surface area compared to its mass; hence will not be greatly retarded by friction of the air. For this reason giant meteorites are apt to arrive with high velocities, provided they fall during the morning hours. It may seem strange, at first thought, that the time of day should have anything to do with the speed with which they arrive. But when we remember that the earth is moving in its journey around the sun with a velocity of over 18 miles per second it will be evident that some impacts will be head-on collisions and some will be rear-end collisions. In some cases the impact will be that of a velocity that is the sum of two velocities, that of the earth and that of the meteorite, while others will be the difference in these values. The front face of the earth, the face that is turned in the direction of its motion, is always that part having morning hours. If we look directly overhead at sunrise, we will be looking in the direction of the earth's motion, while at sunset the point directly overhead is opposite to the direction of the earth's motion. Suppose a meteorite with a velocity of 25 miles per second, strikes from directly overhead at sunrise. The impact velocity will be the sum of 18 and 25, or 43 miles per second. If it comes from the same point in the sky at sunset, the impact velocity will be 25 minus 18 or 7 miles per second.[2]

Since most collisions will be head-on, more large meteorites fall in the morning hours than in the afternoon and evening hours, and their impact velocities will be relatively

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[1]The term "large" should be interpreted to mean a mass of a thousand tons or more.

[2]The motion of the earth is complex, hence this discussion is incomplete and only approximately accurate.

high. The great Siberian fall of 1908 came at seven in the morning, hence it is probable that it arrived with high velocity and that each of the craters produced is large in comparison with the body that produced it.

Resistance Encountered by Large Meteorites

When a body collides with the earth the resistance that is encountered depends upon four factors: rigidity, compression, heat produced, and inertia. If the body is moving slowly at time of impact the resistance will be due largely to rigidity. The majority of impacts with which we are familiar are of this type. A hammer lying upon an anvil is supported by the rigidity of the iron that composes the anvil. If the hammer is made to strike the anvil, inertia, compression and heat all come into play to resist the motion. The greater the velocity the greater these three last named factors become; and this is particularly true of inertia. There is a critical velocity in the science of impacts that is very significant. When the velocity attains a value equal to or exceeding that of the waves it creates in the medium receiving the impact, the resistance due to inertia attains an enormous value. Perhaps this might be called the critical inertia resistance velocity, for it is here that inertia begins to dominate the situation so that other resistance becomes relatively insignificant. It is not difficult to see why this is true. Ordinarily elastic waves run in advance of the impinging body, setting the molecules in motion and giving them time to get out of the way of the oncoming body. If, however, the striking body is moving with a velocity that is as great or greater than the waves that it is creating, the molecules are given no warning of its coming and hence they have almost no time in which to get out of the way. For this reason the acceleration of the particles and the force required to produce this acceleration become extremely great.

Resistance due to inertia is independent of the state of matter. The water of the ocean offers as much inertia resistance to impact as the most rigid solid of equal density. Perhaps this may explain why large meteorites are not found in the waters of the sea. They explode and backfire from the surface of the ocean just as they explode and backfire from the land.[3]

Calculation of Inertia Resistance

The inertia resistance in high speed impacts may be calculated if the velocity of the striking body and the density of the earth are known.[4] When a moving body encounters another body the combined linear momentum remains constant. Let m represent the mass of a meteorite plus the matter, such as earth materials, that it may acquire and take along with it. Let v represent the velocity. For convenience assume the meteorite is in the form of a sphere.

By the momentum law

(1) mv=constant. Both m and v are variable. Differentiating

(2) $m \frac{dv}{dt} + v \frac{dm}{dt} = 0$

$\frac{dm}{dt} = \pi r^2 \rho v$ ρ is the density of the earthy matter

$m \frac{dv}{dt} = ma = f.$ a is accleration

(3) $f = -\pi r^2 \rho v^2$

Let $p = \frac{f}{\pi r^2}$ =pressure per square centimeter

Then $p = -\rho v^2$ dynes per square centimeter

Or $p = \frac{\rho v^2}{980}$ grams per square centimeter

If English units are used

$p = \frac{-\rho v^2}{32}$ pounds per square inch (1)

[3]For a discussion of the theory of backfiring of meteorites, see Fairchild, H. L. "Nature and Fate of the Meteor Crater Bolide," Science, n.s., Vol. LXXII (1930) pp. 463-467; Spencer, L. J., "Demonstrations in the Mineral Department, British Museum of Natural History," Proceedings of the Geologists' Association, Vol. XLV (1934) Part 4, pp. 407-411; and Boon, J. D., and Albritton, C. C. Jr., "Meteorite Craters and Their Possible Relationship to Cryptovolcanic Structures," Field and Laboratory, Vol. 5 (1936), p. 6.

[4]The writers are indebted to Dr. F. R. Moulton for a number of helpful suggestions concerning high speed impacts.

Application to Meteor Crater

Meteor Crater of Arizona should be considered: first, as the product of a small body moving with high speed; and second, as the product of a much larger body moving with much lower speed.

Case 1. High speed impact.

During a high velocity impact, inertia holds the earth still so that only those molecules that are actually struck are set in motion. Bodies having the velocity of meteorites may be considered aggregations of unconnected and unrelated molecules traveling in parallel paths free from all forces except those due to inertia. It is true that other forces exist, but they are relatively so small that they may be neglected. It is this that prevents side-slipping of earthy material ahead of the meteorite. The matter that lies directly in front of the impinging object must remain in front; it can only move downward. This prevents any appreciable increase in the cross-section of the projectile as it penetrates the earth. The parallel motion of the molecules of the meteorite is not heat, for heat is random motion. Heat will come later when the molecules have had time to recover from being crowded too close together. This situation continues to hold so long as the body is traveling faster than the waves produced, and to some extent after this time.

That there is little side-slipping, even in small meteorites with low velocities, is well illustrated by conditions attending the fall of a 660 pound stone at Knyahinya, Hungary. The body penetrated the ground eleven feet. When the meteorite was removed, the underlying soil was found to be of stony hardness, indicating that it had been highly compressed.[5]

Suppose that Meteor Crater was produced by a body 250 feet in diameter moving with a velocity of 100,000 feet per second, and that the earth encountered had a density of 170

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[5]Recounted by Merrill, G. P., "The meteor crater of Canyon Diablo, Arizona; its history, origin and associated meteorites," *Smithsonian Misc. Coll.*, Vol. 50 (1908) p. 491.

pounds per cubic foot. Pressure created by inertia may be found by equation (1). The calculations give 3.67×10^8 pounds per square inch or about 25 million atmospheres. If the density of the meteorite was 460 pounds per cubic foot, the kinetic energy at the time of impact must have been 6.1×10^{17} foot pounds. Assuming that the average diameter of the crater at the time of formation was 3,200 feet and that its depth was 1,350 feet, the mass of ejected material becomes 18×10^{11} pounds. The initial kinetic energy divided by the mass of material ejected reveals energy sufficient to lift this matter to a height of 65 miles. No one would claim that all of this energy was used in lifting the earthy matter out of the crater, for much of it must have been used in other ways. The reason for introducing this datum is that it appears to indicate that the energy was sufficient to do all of the work that has been done at Meteor Crater.[6]

Neglecting, for the time, the shock-waves produced, it is now possible to obtain a value for the maximum penetration of the matter driven ahead of the meteorite. For convenience the penetration will be divided into two intervals.

First interval (in which the meteorite is traveling faster than elastic waves can travel in the medium): If the impact velocity is 100,000 feet per second, and the wave velocity of the medium 20,000 feet per second, the meteorite must lose four-fifths of its velocity before a wave begins to get ahead of it; hence at this time by the law of conservation of momentum, the mass in motion must have increased to five times its initial value. In other words the meteorite now drives ahead of it a mass of earth material four times its own mass. These relations may be expressed by the following equation, where σ is the density of the meteorite.

$$4 \cdot \frac{4}{3} \pi r^3 \sigma = \pi r^2 h \rho \qquad (2)$$

If we solve this equation for h, the depth to which the motion penetrates, the answer is found to be 1,750 feet.

[6]Oliver, C. P., in his book, "Meteors" (Williams and Wilkins) page 250, quotes from G. P. Merrill's estimate of the size and velocity of this meteorite. Merrill's figures yield about 60% of the above kinetic energy.

It should be remembered that this is not the penetration of the meteorite, but rather the depth of the under surface of the mass in motion. The actual depth of the meteorite is difficult to find since the pressures that would prevail are far greater than those man can produce; therefore the amount that the earthy material would be compressed remains conjectural. As stated above, the figure for the maximum penetration was obtained by neglecting the shock-waves. It is true, however, that shock-waves exist and that they become more significant as the deceleration of the meteorite proceeds; hence the figure given is too large.

Second interval (in which the waves outrun the meteorite): During the time that the velocity of the bolide was greater than the waves that it was tending to produce, inertia was the only resistance worthy of consideration. The moment that the velocity falls below this value the situation changes rapidly, for at this time waves begin to outrun the meteorite. For the first time the vast amount of heat and compression produced finds directly in front a shoulder against which to react. This aids in retarding the projectile. The power of these new forces arising from heat and compression must be very great, perhaps great enough to completely compensate for the rapidly diminishing inertia resistance. How much deeper the mass penetrates the earth would be difficult to say, but it is quite certain that having spent four-fifths of its energy it cannot go much deeper.

Where was the transformed kinetic energy stored at the moment that the body was brought to rest? Elastic waves could not have transferred any great amount of it, for during most of the time of penetration the bolide was traveling faster than the waves. Heat could not have disseminated it, for heat travels by conduction—the only method possible in this case—very slowly. That heat conduction is a very slow method of energy transfer is well illustrated by the fact that only the thinnest skin of meteorites is heated in flight through the atmosphere, and yet manifestly they spend far more time in plunging through the air than in plowing their way into the earth. The present writers believe that the moment the meteorite was brought to rest, by far the greater portion of this energy was stored in the mass of matter compacted ahead of the driving body. Allocating only half of it to this locality and assuming that the initial orderly motion had all been transformed into random motion of heat, it is possible to calculate the temperature produced. Taking the specific heat of earth matter as .2 calories per gram, the astonishing temperature of 100,000 degrees centigrade is obtained. Can one imagine a meteorite remaining at rest over any mass of matter at this temperature? Is there any force known on the surface of the earth that could resist the explosive forces created by a temperature so great?

In discussing the things likely to occur when a meteorite plunges into the earth, it is often said that if water is encountered an explosion will take place as a result of the steam produced, so that the meteorite will be back-fired. It is not clear why steam is considered essential for meteorite explosions. The temperatures produced must be sufficient in almost all cases to volatilize the most refractory substance known.

Case 2. Low speed impact.

Did the meteorite that produced Meteor Crater remain in the earth? Much drilling and surveying has been done in an effort to answer this question. In spite of the fact that most surveyors believe they have located large masses of iron beneath the walls and bed of this crater, the writers are inclined to consider the question unsettled. The conclusions reached are not convincing. Until the present time no large mass of meteoritic material has been found in an explosion crater. The meteoritic craters of Estonia indicate rather clearly that the bodies that produced them were back-fired and shattered to fragments. If a large mass of iron should be found in Meteor Crater, its presence can only be explained by the assumption that the meteorite was very large in size and came with low velocity. Such a body would distribute its energy far more widely than a smaller body having high speed. Therefore it would produce far lower temperatures, so that the probability of an explosion sufficiently violent to backfire the entire mass would be reduced. It is possible that backfiring depends upon whether or not the velocity of the projectile is greater or less than the velocity of waves in the medium penetrated; this in turn may depend on whether the meteorite strikes the earth head-on or overtakes it. Any way this crater is viewed, it is evident that it marks the site of an exceedingly violent explosion which resulted in ejection and pulverization of vast masses of rocky material along with many tons of iron meteorite fragments. How much iron was ejected will never be known, for a large part of it must have been blown to dust.

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The preceding discussion gives a roughly quantitative idea of the tremendous resistance the earth offers to penetration by giant meteorites. At the instant of maximum penetration a meteoritic projectile is seated on a charge of material that is heated and compacted beyond comprehension. It is difficult, therefore, to conceive how meteorites, after driving into the earth to depths of hundreds or thousands of feet, could escape being blown back out of the ground and shattered.