contamination from work at the Center is highly improbable, were contaminated with Y^{88}.

The high specific activity of these particles makes them of interest to the health physicist even if he does not know whether they originated in some new material incorporated in nuclear bombs or in an uncontrolled release from a nuclear establishment.

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Origin of Tektites

Abstract. *A comet of the size recently postulated by H. C. Urey would leave a large crater. It is shown, from aerodynamic theory, from observations of distribution around terrestrial impact craters, and from experimental nuclear explosions, that the observed distribution of tektites cannot be the result of impact on the earth, whether cometary or meteoritic. It is further shown, from aerodynamic theory, from observation of a meteor shower, and from study of the breakup of artificial satellites, that the distribution of tektites can be accounted for as a result of fusion stripping of a satellite, as originally suggested by Suess.*

Urey (*1*) has recently rediscussed the problem of the origin of tektites in the light of new evidence. He shows that it is not reasonable to think of tektites as formed individually by impact at the moon's surface, since in this case the tektites would undoubtedly be scattered more or less uniformly over the surface of the earth, and through at least the Cenozoic strata, which is not observed. We agree with this argument, and we further agree with his opinion that the whole Far Eastern strewnfield, from China to Tasmania, is to be regarded as a single event.

Unfortunately, it appears that his hypothesis of the origin of tektites by cometary impact on the earth contains contradictory elements. On the one hand, it is asserted that the atmosphere arrests the cometary head as it descends, so that the primary effects are not a shock-produced crater in the solid ground, but a mass of heated gas. On the other hand, it is supposed that the tektites produced on the ground by this heated air are not arrested, but rise to the top of the atmosphere with ballistic velocity sufficient to carry them thousands of kilometers.

The laws of aerodynamics do not work this way. It is the small bodies which are stopped by the atmosphere, and the big bodies which get through. The drag pressure is given by

$$p = C_d \, ½ \, \rho \, V^2$$

where ρ is the density of the air, V the velocity of the body relative to the air, and C_d the drag coefficient. The drag coefficient is of the order of 1, and will be omitted from the rest of the discussion, since we are aiming at the order of magnitude. If the area of the body is A, and the increment of distance traversed is ds, then the increment of work, dW, is

$$dW = p \, A \, ds = ½ \, \rho \, A \, V^2 \, ds$$

When the work done becomes of the order of magnitude of the initial kinetic energy, ½ M V^2, (M being the mass of the body), then the body is essentially stopped. Neglecting the variation in velocity, this means

$$½ \, M \, V^2 = \int_{S_1}^{S_2} dW = ½ \int_{S_1}^{S_2} \rho \, A \, V^2 \, ds$$

that is,

$$M = A \int_{S_1}^{S_2} \rho \, ds$$

that is, when the mass of the air encountered is equal to the mass of the body. This principle, though not this derivation, was stated to us by F. L. Whipple.

Since a vertical atmospheric column has about 1 kg of mass per square centimeter, it is to be expected that bodies with less than this mass per square centimeter of frontal area will be arrested. In practice, this means that bodies with a diameter less than something like 5 m will be stopped by the atmosphere, and will reach the ground with terminal velocity. Larger bodies will penetrate and will make craters. This expectation is approximately satisfied by the facts about the largest meteorites and the smallest craters.

The general principle at work here can also be derived from Newton's Third Law of the conservation of momentum. Alternatively, from purely dimensional considerations, it is clear that the total drag must increase with the square of the linear dimensions, while the mass, and hence the energy, increase with the cube; hence once more we see that the larger bodies must be the ones which will penetrate, while the smaller bodies will be stopped.

Even if the density of the cometary head is as little as 0.01 g/cm^3, and the diameter is 10 km, as Urey (*2*) has previously suggested, the mass per square centimeter of frontal area will be much greater than that of the atmosphere, and the body will be stopped, not by the atmosphere, but by the earth. The comet postulated by Urey would have an energy of 5×10^{28} ergs.

On the other hand, Shoemaker finds (*3*) that an energy only a little more than the above, namely, 7.5×10^{28} ergs, was required for the formation of the lunar crater Copernicus, 80 km in diameter, with walls 4 km above the floor. Hence we would expect that a conspicuous terrestrial crater would have been formed by the impact which, on Urey's theory, produced the Far Eastern strewnfield. The crater would presumably be nearer the northern end of the field, since the tektites are much more numerous there. It would be marked by a large circular lake. No such lake can be found, however, either in Laos, or in Thailand, or Burma, or Yunnan Province, China. It happens that Yunnan Province is covered by a 1 : 50,000 map series which one of us personally examined during World War II and compared with Army Air Forces astronomical positions. The series is adequate to show a lake of this size, which would, in fact, cover a dozen sheets of the map. The lake is not there.

Urey also considered a comet 70 kilometers in diameter, which would produce a lake 7 times wider. This is excluded a fortiori.

In any case, why a comet? There are nickel-iron spherules in tektites, but no volatiles; hence, one's first guess would be a meteorite. The spherules make it reasonably sure that the impacting body did mix physically with the ground which it struck; then why the mechanism of compressed hot gases to keep the two apart?

Consider next the second postulate of the cometary theory, which it shares with all theories of terrestrial origin, namely, that tektites were melted by impact and then ejected through the atmosphere. The very small mass per square centimeter of frontal area, which never exceeds about 25 g, is far from meeting aerodynamic requirements. Adams and Huffaker (*4*) have pointed out that a typical tektite would suffer an acceleration of 96,000 times terrestrial gravity. It would be arrested in a very short distance.

To meet this problem Urey suggests that a portion of the atmosphere may be blown outward by the explosion, carrying the tektites with it. Calculation based on the theory of Taylor (*5*) shows that such a thing can only happen for an explosion of about the size postulated in Urey's first paper, namely about 5×10^{28} ergs. It is necessary that the blast wave carry the tektite with ballistic velocity up to a level of 70 km or so, where further atmospheric resistance can be neglected. Ballistic velocity is here taken as 4.5 km sec^{-1}, the velocity required to span the radius of the Far Eastern strewnfield. It turns out that weaker explosions would decay before reaching the effective limit of the atmosphere.

We have already seen that an impact of this kind is too big to escape notice if produced in the relatively recent past.

The external form of the tektites presents a serious difficulty for all theories which imply that tektites were melted by the impact and then ejected through the atmosphere. They appear to have been large liquid drops whose form is due to surface tension. In rare cases, they have contained large bubbles within them. Liquid drops of this size are extremely delicate—far more delicate than an egg, for instance—and to find them emerging intact and at ballistic velocity from a great impact, in which rocks are reduced to a fine breccia, would be paradoxical.

In actual fact, the impure glass from the Ries Kessel is found no more than 10 km from the rim. Larger blocks are found at distances up to 70 km. The ejecta at Wabar, Henbury, and the Arizona craters are likewise within 10 km of the crater rim.

On the experimental side, Glasstone (*6*) gives data on velocities and distribution of particles from atomic explosions. It turns out that particles over 300 μ in diameter are distributed within a very limited radius of the impact. The wide distribution of smaller particles is a consequence of air currents and not of ballistic trajectories. Pebbles and flying solid objects in atomic explosions are mostly the result of the air blast on bodies in the immediate vicinity. A limit on the order of 1 or 2 km appears to be reasonable for material thrown out from the center of even the greatest atomic explosions.

Thus, there is neither theoretical nor observational nor experimental evidence that tektites can be distributed in the observed manner from any reasonable ground impact.

We have suggested that the impact took place on the moon, and that among the ejecta were large solid blocks. Urey inquires whether large blocks could be impelled at velocities of 2.4 km sec^{-1} by impact. Let us note the secondary craters around Copernicus (*3*) which are apparently produced by much larger blocks than these we have supposed, moving, it is true, with somewhat lower velocities, on the order of ½ to 1 km sec^{-1}.

Urey has suggested that the probability of arrival at the earth in a grazing orbit from the moon is very small. If we consider those bodies which leave the moon with velocities greater than 2.3 km sec^{-1}, and which therefore do not fall back at once, they can be divided into two classes, depending on whether they escape at once from the earth-moon system, or are temporarily trapped. Theoretically there is a third class, which is permanently trapped, at least in the realm of validity of the restricted problem of three bodies; but Kopal has shown (*7*) that this class corresponds to a negligibly small range of velocities.

Let us define the residual energy as the energy of the body, after subtraction of the energy of escape; and let us further define the residual velocity as the velocity corresponding to the residual energy. The vector sum of the residual velocity and the moon's orbital velocity is the geocentric velocity; if this exceeds 1.4 km sec^{-1} in absolute value, the body will escape the earth-moon system at once, and will go into orbit around the sun. After a very long time it will probably strike the earth. The encounter is not likely to be at grazing incidence, and hence such bodies will not form tektites.

If the absolute value of the geocentric velocity is less than 1.4 km sec^{-1}, then the body will temporarily describe an eccentric orbit around the earth, more or less perturbed by the sun and the moon. A few numerical integrations of this problem are now available; they indicate that under some circumstances bodies in such orbits will be perturbed by the moon in such a way as to produce large, long-term oscillations in the eccentricity. The consequent variation in perigee height is so large, in some cases which have been studied, as to bring the perigee below the surface of the earth. Because of the gradual nature of these perturbations, it is clear that the likelihood of encounter with the atmosphere is much greater than would be expected from purely geometrical considerations. Once the atmosphere is touched, the eccentricity and the semimajor axis of the orbit will be rapidly reduced, the perigee height remaining approximately the same, so that the further influence of lunisolar perturbations can be disregarded. The body will eventually enter the atmosphere along a grazing orbit.

From general considerations, as well as the few numerical integrations now available, it appears that in such orbits, the quantity

$$J_r = (1 - e^2)^{1/2} \cos i$$

where i is the inclination of the orbit to the plane of the moon's orbit, will be nearly constant up to the time when the atmosphere is encountered. In order to reach sufficiently large values of the eccentricity, and hence sufficiently small values of $(1 - e^2)^{1/2}$ it is necessary that J_r be small; and this is certain to occur if the inclination is large. Numerically, it appears that an inclination to the plane of the moon's orbit greater than 60° is sufficient.

Further work along this line is needed and is being done; but these results show that the situation is not a simple one, and that Urey's geometric approximation is not adequate to give even a rough estimate.

Adams and Huffaker (*4*) have worked out the mechanics of Suess's suggestion (*8*) that tektites were formed in the skipping entry of a large parent body in the earth's atmosphere. They find that fusion stripping will work, provided that allowance is made for the heating of the parent body by radiation from the very strong shock which is produced. The parent body must be reasonably transparent to the radiation. Convective heating will not penetrate sufficiently deep.

As noted in Urey's paper, we have managed to show how bodies which are breaking up in orbit around the earth may be distributed over a broad area on the ground. The mechanism which we have proposed is independent of the manner of breakup, provided that it is within the atmosphere. At the present time, we feel that the stage of melting and dripping discussed by Adams and Huffaker (*4*) may have followed an earlier stage of mechanical breakup, and that the dripping may account both for the indomalaysianites and for the australites as successive stages in the dripping of a single group of bodies. The geometrical situation is not, however, greatly altered by this fact. The significant point is that the fragments of a body which breaks up while moving in a moderately elliptical orbit will probably be distributed over one or several areas which have an extension in longitude as well as along the path.

On the observational side we have drawn attention (*9*) to the existence of at least one meteor shower whose observed properties are quite sufficient to explain the length of a tektite strewnfield. This is the Cyrillid shower (the great meteor train of 9 February 1913). Although the region over which this shower was observed was very narrow, it is nevertheless helpful in understanding tektite strewnfields, first because the moldavite strewnfield is just about as narrow and secondly because the slight amount of broadening which was observed in this field conforms to the theoretical mechanism of our paper as mentioned above and in fact suggested our mechanism. We find that a satellite which ends its trajectory in an orbit of low eccentricity will be distributed over a long and narrow strewnfield, in contrast to the broadened distribution that is expected in the orbits of high eccentricity.

The comparison which Urey makes between the Cyrillids and the Rochester meteorite is invalid. The Rochester procession was seen over a distance of about 1600 km and was about 6 km in length (*10*); it might easily have resulted from the breakup of a normal meteorite (*11*). The Cyrillid stream was seen over 10,000 km, and was 1500 km in length; it could only have resulted from the breakup of a natural earth satellite (*12*).

On the experimental side, there is now evidence from the distribution of fragments of the MA-6 sustainer (Lieutenant Colonel John Glenn's sustainer) that distribution over large fields is possible. Pieces were found in South Africa over a belt some 850 km long by 100 km wide; and other pieces were found in Brazil along the same orbital path.

In discussing the problem of distribution, Urey raises what we feel to be a most fundamental and interesting question, namely, what happens to the lunar ejecta which does not graze the earth's atmosphere and is not in large blocks? He points out that such material should be far commoner than ordinary tektites. While we do not agree that the probability of a grazing impact is as low as he suggests, for reasons of celestial mechanics which one of us (B.E.S.) has outlined (*13*), Urey's main point is undoubtedly correct, namely, that nongrazing encounters should greatly outnumber the grazing encounters. Why, then, do we find tektites but not the other material?

It is risky to try to answer the question, because to do so means a guess at the nature of the tektite parent bodies. Up to this point our argument has been solidly founded on physical principles; but here we must speculate. It seems to us likely, however, from the glassy inclusions seen in some tektites that the parent bodies are also glassy and possibly slaggy. If so, they might resemble Darwin Glass, a slaggy material found in large quantities over a very limited area in Tasmania. It was accepted as tektite by Suess (*14*) and others. It may be an impactite, since nickel-iron spherules were reported by Spencer (*15*) and coesite by Reid and Cohen (*16*). It resembles Wabar glass in its physical form (*17*). No crater has yet been found in its vicinity.

Another possibility is the Igast object (*18*), a slaggy body with a tektite composition which was reported by reliable witnesses to have fallen with the usual meteoritic accompaniments of sound and flash. Igast was generally discredited after Michel (*19*) attacked it; but O. Schiener has allowed us to examine the hand specimen from which Michel worked. Lowman and O'Keefe (*20*) found evidence that Michel's hand specimen is unrelated to the witnessed fall; in particular it weighs 10 g more than all the material collected from the fall, so that the possibility of lunar origin remains open.

The fate of the Igast object is perhaps one clue to the fate of the directly falling bodies; nobody believes they are meteorites because their chemistry is wrong.

A second clue is also afforded by Igast; it appears to have contained larger than usual amounts of chlorides. Combined with a porous structure, this would guarantee rapid dissolution. Tektites, on the other hand, have little chloride, perhaps because it escaped in the fusion-stripping stage; and they constitute a solid glass, low in alkali and high in silica, of remarkable durability. Hence the finds are likely to be weighted in favor of tektites. A further point is that solid glass attracts attention as a semiprecious stone; slag does not.

Thus it is possible that among the hundreds of slaggy objects which are annually offered to museum curators around the world as meteorites, a few are genuinely from the sky. We urge that museum curators test these objects with a blowpipe before rejecting them; objects with high melting points, which do not froth when they melt, and do not give off hydrogen sulfide when broken, should be studied for density in the powdered form and index of refraction. If the density is between 2.30 and 2.50 and the index of refraction between 1.47 and 1.52, the objects should be chemically analyzed.

Against the theory of lunar origin the strongest argument is that it makes the source of the tektites remarkably like the earth in its chemical properties. Perhaps, however, the moon really is much like the earth in its chemistry.

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