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THE ORIGIN OF TEKTITES

J. A. O'Keefe

Goddard Space Flight Center

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by

J. A. O'Keefe

SUMMARY

Tektites are probably extraterrestrial, rather than the result of heating some terrestrial materials, because they are a chemically homogeneous group with definite peculiarities (high silica, excess of alkaline earths over alkalis, excess of potash over soda, absence of water), and because some of them (the australites) appear to have undergone ablation in flight through the atmosphere.

Since comparatively slow heating is required to explain the liquefaction of the tektite material, it is suggested that the tektites arrived along orbits which were nearly parallel to the surface of the earth, and which resulted from the decay of the orbit of a natural satellite. The great meteor procession of February 9, 1913, is an example of such an object. Comparison with the reentry phenomena of the artificial satellite 1957 Beta suggests that the 1913 shower consisted of a single large stone weighing about 400 kilograms, and a few dozen smaller bodies weighing about 40 grams each, formed by ablation from the larger body. It is shown that under the observed conditions considerable liquid flow would be expected in the stone, which would be heated to about 2100°K.

Objects falling from such a shower near the perigee point of the orbit would have a considerable distribution along the orbit as a result of slight variations in height or drag coefficient. The distribution in longitude would be made wider by the turning of the earth under the orbit during the time of fall.

The ultimate source of the body which produces a tektite shower is probably the moon, which appears, by virtue of its polarization and the phase distribution of the returned light, to contain high-silica materials.

It is suggested that the Igast object alleged to have fallen in 1855 is in fact genuine and represents an unmelted portion of the lunar crust.

THE ORIGIN OF TEKTITES*

INTRODUCTION

Tektites may be defined as small glassy bodies containing no crystals whatever, at least 65 percent SiO_2, with about half of the remainder consisting of Al_2O_3, and bearing no relation to the geological formations in which they occur. Tektites are found in certain large areas, called *strewn fields*. The largest strewn field covers most of Southeast Asia (billitonites; indochinites; rizalites; and tektites from Kwang-chow-wan, Hainan, and Siam); another strewn field, possibly related, covers most of Australia (australites); a third lies in Texas (bediasites); a fourth in Georgia (Georgia tektites); a fifth in the Ivory Coast (no special name); and a sixth in Bohemia and Moravia (moldavites).

In addition to these groups of tektites, several other groups of bodies are attached to the class of tektites by some authorities. Among these are the americanites, which have small crystals within them and contain considerable water; Libyan Desert Glass, which is almost pure silica and radically different from any other tektite in composition; and Darwin Glass, which differs from other tektites in its very vesicular structure. All of these classes are excluded from the present discussion in order to narrow the issues.

DESCRIPTION AND COMPOSITION OF TEKTITES

The outer surfaces of many tektites, especially those from the older geological formations, are marked by intricate grooves that give the appearance of worm-eaten wood. These effects are considered by some to be due to the action of soil acids (References 1 and 2). Merrill believed that he had reproduced these markings by etching obsidian pebbles with weak hydrofluoric acid. On the other hand, Oswald (Reference 3) considered them to be the result of motion through the atmosphere; he pointed out that the coarse sculpturing is not found on broken surfaces of moldavites. Lacroix (Reference 2) found the same to be true of indochinites.

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True evidence of motion through an atmosphere is apparently found in the australites. The question has been most carefully discussed by Fenner (Reference 4), who showed that most forms of australites are derived from a button-shaped type consisting of a central lens surrounded by a flange (Figure 1). The form was explained by him as the result of the ablation of an originally spherical body while rotating rapidly. He considered that ablation reduced the sphere to a lens and that at the same time a portion of the glass from the front side of the body flowed around the edge and formed the flanges. This explanation is supported by the flow lines that are visible in thin sections of australites (Figure 1). Although only a minority of australites possess fully developed flanges, Fenner believed, on the basis of very extensive examination of thousands of australites, that the majority of them had once possessed flanges. He also showed that on many of the australites which lack a circular outline flanges had formed and had been broken off.

Underlying these effects of weathering and ablation, Fenner (Reference 4) believed that he could trace a sequence of forms characteristic of a fluid body in rapid rotation. The forms depend on the speed of rotation; and, in order from the slowest to the most rapid rotation, they include spheres, ellipsoids, oval bodies, dumbbells, and teardrop shapes — these last presumably corresponding to the tearing apart of a dumbbell-shaped body. Occasionally there are found canoe-shaped bodies, presumed to be the result of the tearing away of two teardrop forms from a central nucleus. Among these shapes spheres and ovals are the most common, and the more extreme forms are the least common. Fenner pointed out that this sequence of shapes is closely comparable with the shapes assumed on a considerably smaller scale by bits of hot slag called smoke bombs or slag bombs, which are ejected from locomotive smoke stacks. The comparison illustrates the fact that the forms of tektites are comparable in detail with the forms of rotating fluid masses. In the case of all strewn fields except the Australian one, the bodies themselves resemble the forms taken by rotating fluid masses.

As has been mentioned, the internal structure of tektites is marked by flow lines that are visible in thin sections. These marks were examined by Hammond (Reference 5), who found that the streakiness was associated with strains in the glass of the order of 80 kilograms per square centimeter, indicating to him that the glass had cooled at the rate of about 50°C per minute, especially between about 700° and 600°C. Many tektites, especially bediasites (Reference 6), possess elongated inclusions of lechatelierite, i.e., practically pure silica. In addition many tektites contain small bubbles which, according to Suess (Reference 7), "represent a fairly good vacuum"; he finds a pressure of less than 10^{-3} atmosphere. The inside of these bubbles is stated to have a mirrorlike sheen.

Spencer (Reference 8) states that microsections of australites and indochinites exhibit small black spots that show a metallic luster by reflected light. He compares these with the tiny spheres of nickel-iron in the silica glass from Wabar and with similar tiny spheres found in Darwin Glass, which are attracted by a magnet.

The chemical composition of the tektites and some comparison substances is illustrated in Table 1. The first five columns are from Barnes (Reference 6), the sixth from

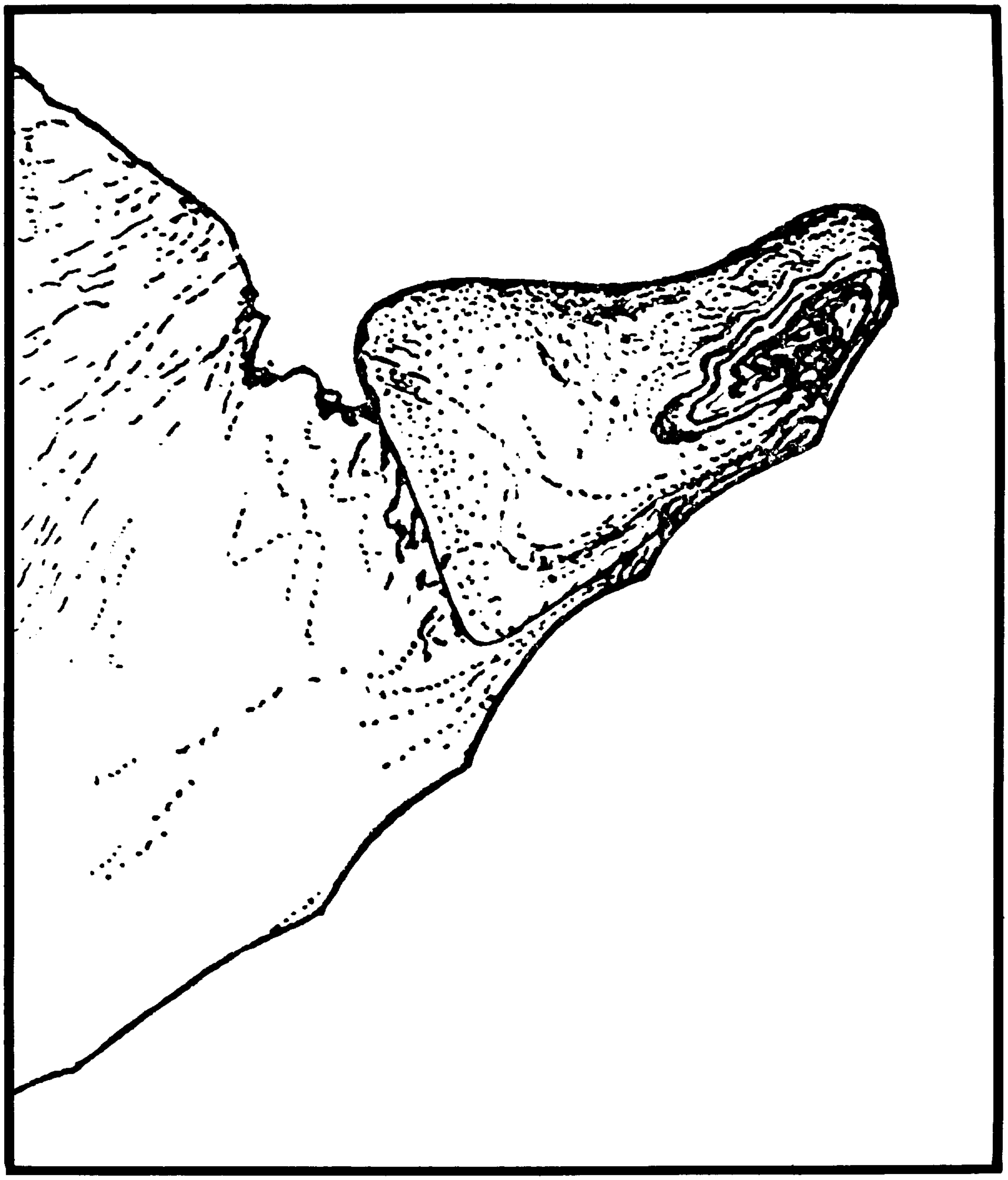

Figure 1 - Section of an australite showing flow structure

Table 1

Chemical Composition of Tektites and Comparison Substances, in Percent

Oxides	Moldavite	Bediasite	Indo-Malayan body	Australite	Ivory coast	Igast	Building sandstone	Shale
SiO_2	80.73	73.52	72.26	76.25	68.60	80.82	84.66	60.15
Al_2O_3	9.61	15.88	13.18	11.30	15.80	9.93	5.96	16.45
Fe_2O_3	----	0.45	----	0.35	0.18	2.45	1.39	4.04
FeO	1.93	4.64	5.32	3.88	6.46		0.84	2.90
MgO	1.59	1.38	2.15	1.48	2.88	1.58	0.52	2.32
CaO	2.13	0.06	2.42	2.60	1.40	0.75	1.05	1.41
Na_2O	0.37	1.30	1.43	1.23	2.35	0.76	0.76	1.01
K_2O	3.60	1.73	2.15	1.82	1.92	3.13	1.16	3.60
H_2O	0.02	0.08	0.20	0.34	----	----	1.74	4.71

Michel (Reference 9), and the seventh and eighth from Clarke (Reference 10). As compared with terrestrial rocks, tektites clearly belong to the acid group along with granites and sandstones. They clearly differ from basalts or shales, which have around 50 to 60 percent SiO_2. The most striking feature is the absence of water. According to Friedman (Reference 11), most tektites have between 20 and 100 parts per million of water. In this respect they differ strikingly from all terrestrial rocks; for example, obsidians have from 800 to 3500 parts per million according to Friedman. In almost all tektites, the K_2O content exceeds that of Na_2O. The iron is mostly in the reduced state (FeO). According to Loewinson-Lessing (Reference 12), tektites differ from all terrestrial rocks in showing a high acidity coefficient and a high RO/R_2O ratio.

Heide (Reference 13) states that the concentration of nickel in tektites in the Indo-Malayan strewn field is greatest in the central zone (Billiton, Borneo, Cambodia, and Cochin-China) as distinguished from the border zones (West Siam, North Indochina, Philippines, and Australia).

The gas composition of tektites has been studied by Döring and Stützer (Reference 14), by Suess (Reference 7), and by Friedman (Reference 11). Friedman's results appear to be the most precise; they supersede those of Döring and Stützer and indicate that there is not more than 1 part per million by weight of gas in the tektites.

Studies of the age of tektites have been made by Suess, Hayden, and Inghram (Reference 15), by Ehman and Kohman (Reference 16), and by Anders (Reference 17). Suess et al. found, from studies of the decay of potassium to argon, that the age of the philippinites and australites was less than 70 million years (since the tektite was last melted). Ehman and Kohman attempted to determine the length of time the tektites had been exposed to cosmic rays in space. By determining the amount of aluminum 26 and beryllium 10, they concluded that the australites must have come from outside the earth's atmosphere and must have spent at least 1 million years in space. Anders was not able to confirm these results, using techniques which should have been more efficient than those of Ehman and Kohman; the effect probably does not exist.

DISTRIBUTION OF TEKTITES

As was mentioned previously, the distribution of tektites is peculiar. It is entirely unlike the distribution of meteorites, which is nearly uniform over the globe; apparent maxima in the meteorite distribution in temperate latitudes or in industrialized areas reflect nothing more than the interest of the inhabitants. On the other hand the known tektite strewn fields have a tendency, as Nininger (Reference 18) points out, to lie between 40 degrees north and 40 degrees south of the equator. This feature is probably real, since the areas involved are less carefully searched than areas such as western Europe or the northern part of the United States, where no tektites have been found.

Within the individual strewn fields there are large variations in density. Fenner (Reference 4) reports that Dodwell found 250 pieces in a single square mile. Beyer (Reference 19) remarks that in some areas in the Philippines the density of tektites rises to 100,000 per square mile. Fenner (Reference 20), in discussing the australite distribution, points out that it is cut off at a definite line in the northern portion of Australia. He is emphatic about the statement (Reference 4) that the distribution of australites observed is very similar to the actual distribution in which they were produced, discounting the possibility that its major features have been changed by the natives or by such agencies as birds. On the other hand, it is important to notice that in the minor features there must have been some redistribution of the australites, since Baker (Reference 21) refers to the discovery of 38 tektites on an old road built in 1879, and 20 on the surface of borrow pits made during the construction of the new road. These finds cannot possibly be explained except as the result of some agency capable of moving considerable numbers of tektites, since the australites as a group certainly date from a period several hundred thousand years ago.

A most important discovery was made by Lacroix (Reference 22), who found a dense deposit of tektites in French Indochina. A single square meter furnished about 9.7 kilograms of fragments; another area of 9 square meters furnished 20.6 kilograms. Lacroix remarks that the pattern of the flow marks in the glass was not as distorted as usual, suggesting slower cooling. He found a similar deposit in Cambodia, which appears to represent falls of single large blocks.

Beyer (Reference 23) has drawn attention to the fact that in the Indo-Malayan fall there are four different size groups that occur in different areas. He points out that the rizalites from the Philippines, which lie farthest east, are the smallest and that the tektites of Cambodia and French Indochina, which lie farthest west, are the largest. This fact is undoubtedly of great significance concerning the origin of tektites. With reference to the time of origin, the same author states (Reference 19) that the australites are post-Pleistocene, the moldavites are from the Helvetian (mid-Miocene), and the Ivory Coast group are from the Mesozoic. Barnes (Reference 6) states that the bediasites are Eocene.

In the light of these facts, an attempt will now be made to trace the origin of tektites. The first question to be asked is whether they are from a terrestrial or a nonterrestrial source.

TERRESTRIAL VS. EXTRATERRESTRIAL ORIGIN

Ever since the first paper of F. E. Suess on this subject (Reference 24), it has been held that tektites came from some extraterrestrial source. Suess gave two reasons for this in his early paper: first, the alleged flight markings on the moldavites; and second, the fact that their composition, wherever they are found, is always approximately the same and is totally unrelated to the composition of the local rocks. The argument from the distribution has been greatly strengthened since Suess' time by the extension of finds in the Indo-Malayan strewn field, which covers a very large area with high chemical homogeneity. In addition, the finding by H. E. Suess of empty bubbles in some tektites points strongly to their formation in an area of low atmospheric pressure. An alternative explanation for the bubbles, in terms of steam that afterwards condensed and was absorbed in the rock, is hard to reconcile with Friedman's discovery of the extreme dryness of tektites. If the tektites were permeable to water vapor, it is difficult to see how they could maintain for several millenia a water-vapor pressure that is lower inside the bubble than that of the air outside.

The extreme dryness of tektites differentiates them from all terrestrial rocks. It likewise differentiates them from the Libyan Desert Glass, which has apparently been formed in somewhat the same manner as tektites, but out of terrestrial materials. Friedman (Reference 11) remarks that in order to dry out a terrestrial rock to this extent, it is necessary to heat it up to 2000°C.

Barnes (Reference 6) put forward the hypothesis that the tektites are derived from sedimentary rocks. He based this on a comparison of their chemical composition with that of sandstones and shales given by Clarke (Reference 10). The data that he employed are given in Table 1. It is seen at once that shales are not actually comparable with tektites, since the average shale has less silica than any tektite. This difference is borne out by more recent studies such as those of Pettijohn (Reference 25), which show that only a small group of siliceous shales overlaps the tektites in silica content. According to Mason (Reference 26) 82 percent of the sedimentary rocks are shales, 12 percent are sandstones, and 6 percent are limestones. Thus, seven-eighths of the sedimentary rocks can be excluded at once as sources of tektites.

In studying sandstones, Barnes used the building sandstones (Reference 10, p. 463, column G) rather than sandstones in general (column F). The effect of this choice is to reduce the lime content, since builders tend to avoid calcareous sandstones because they do not weather well (Reference 10, p. 461). In justification of Barnes' choice, it may be urged that a tektite with a high lime content would crystallize and thus become unrecognizable. Again, the alumina of the sandstones cited by Barnes is lower than that of any tektite with the exception of Libyan Desert Glass. It appears clear that the tektites do not really resemble the average sandstones or average shales listed by Clarke.

Mason (Reference 27) pointed out that igneous rocks whose compositions matched the tektites much more closely than this could be found; he tabulated for each group of tektites an igneous rock analysis that matched the tektites surprisingly closely. Urey (Reference 28) replied by listing sedimentary analyses from Pettijohn (Reference 25). Nearly all of these were of sandstones, with the exception of a group of siliceous shales; this confirms what has been said previously to the effect that the tektites are chemically more like sandstones than like any argillaceous (clay-derived) rock. On the other hand, of the 22 analyses referred to by Urey (Reference 28), nineteen show an excess of soda over potash, and the other three a very slight deficiency; in tektites, however, the analyses nearly always show an excess of potash.

The extent of the difference between tektites and terrestrial rocks is illustrated by Figure 2, prepared with the assistance of J. Hochman. The ratio of Mueller (Reference 29) was employed:

$$m = \frac{FeO + MgO}{Na_2O + K_2O}$$

It was noticed, however, in agreement with Loewinson-Lessing (Reference 12), that the success of this ratio in separating igneous rocks from tektites was a function of silica content. Therefore, this ratio was plotted against silica content, and a clear separation was found between the igneous rocks and tektites. It is very clear that tektites were not produced from igneous rocks. The distinction between the sedimentary rocks and tektites is not as clear.

It is often stated that no tektite has ever been seen to fall. On the other hand, Brezina (Reference 30) drew attention to the chemical resemblance between the tektites and the object reported from Igast, Esthonia by Grewingk and Schmidt (Reference 31) as an observed fall. The composition of the Igast object is shown in Table 1; it is seen to resemble closely that of a high-silica tektite such as a moldavite. The fall was unusually well observed, there being two witnesses; one faced the point of fall and was only 50 feet away at the instant of fall. The fall itself was unmistakable, with a flash and a detonation. The pieces were found loose on the grass under some linden trees that had been cut by the detonation.

Despite the chemical similarity, the Igast object is physically unlike a tektite; it resembles a slag containing unmelted grains of sand and feldspar. Some of the smaller

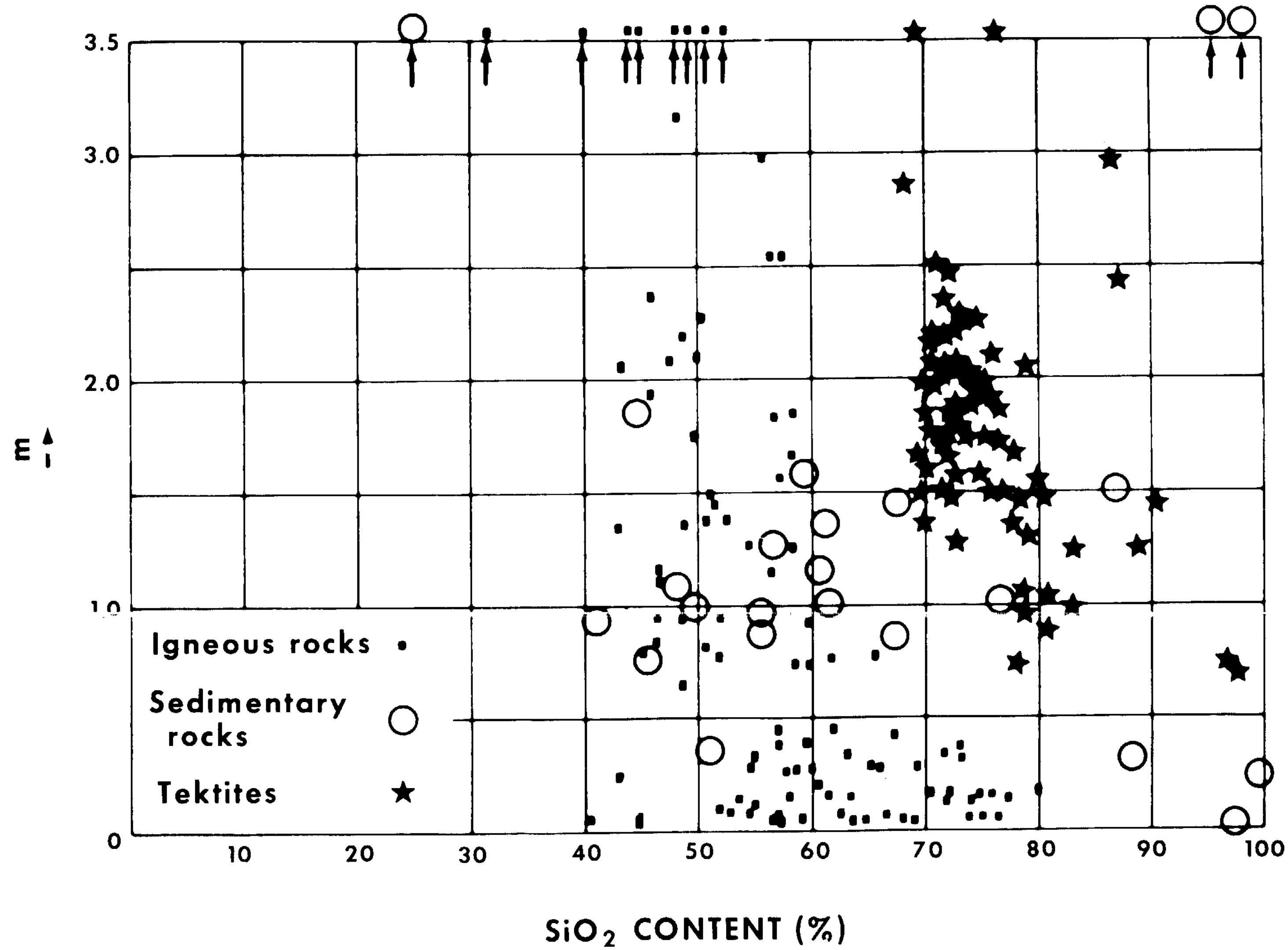

Figure 2 - Plot of m, the ratio of alkaline earths to alkalies, vs. silica

pieces appear to have been partially melted and dripped (abgetropft) from larger masses. In the oxyhydrogen flame, the mass melts at about 2000°C; if there is an excess of hydrogen, the material becomes a streaky olive-green glass, free of bubbles and transparent in places. Grewingk and Schmidt were engaged in a geological survey of this area at the time, and they assert that the object is not a fulgurite and that, if it is of terrestrial origin, they do not know where to find the source material.

On the other hand, Michel (Reference 9), who has been followed by most other meteoriticists, classified Igast as a pseudotektite because of the difference in structure. Michel considered that it might be the product of a glass factory or a brick kiln. For the present purposes, there are strong reasons to reject Michel's arguments since:

(1) Suess pointed out (Reference 32) that numerous investigators have established that glasses of the composition of moldavites do not occur.

(2) Bricks normally contain more alumina and less silica than Igast.

It is assumed in the following that Igast is a genuine fall of an object closely related to the tektites.

In summary, therefore, the tektites are considered to be probably of extraterrestrial origin for the following reasons:

(1) The chemical composition is unrelated to that of the formations in which they are found.

(2) The composition is peculiar; all tektites have certain chemical characteristics that distinguish them from all igneous rocks and from nearly all sedimentary rocks, in addition to those listed in (3) and (4).

(3) They are dryer than any terrestrial rock.

(4) Their voids are reasonably good vacuums.

(5) Some of the australites appear to have suffered ablation in flight through the atmosphere. The forms of the others are those of rotating fluid masses and are not inconsistent with flight through the atmosphere.

(6) The Igast object appears to represent an observed fall of a body closely related to the tektites.

MODE OF ARRIVAL

Dissimilarity to Ordinary Meteorites

If the tektites are of extraterrestrial origin, then it is at once evident that they have not arrived in the same way as ordinary meteorites. The first distinction is in their distribution. As has been pointed out, tektites occur in large patches whereas meteorites occur more or less uniformly over the whole surface of the earth. Urey has pointed out (References 33 and 34) that it is not possible to explain this difference on the ground that tektites have passed through space in the form of dense clusters. He shows that a cluster of the type required to produce the observed distribution of australites by direct impact would be unstable and would be torn apart by the sun's gravitational attraction in a relatively short time. He points out that a density in excess of 10^{-6} gram per cubic centimeter is needed for gravitational stability at the earth's distance from the sun. A possible answer to this argument was given earlier by Fenner (Reference 4) and La Paz (Reference 35), who drew attention to the great meteor procession of February 9, 1913. The meteor procession was an observed case of a cluster of meteors some 1500 miles long and 3 or 4 miles in breadth. Fenner mentioned also that the meteor procession was somewhat narrow compared with the observed breadth of tektite distribution. Possible methods of meeting this objection will be discussed presently.

The second significant difference between tektites and meteorites is indicated by the fact that, although the meteorites have a crust which is a few millimeters or less thick, the tektites give evidence of deeper melting. The case is clearest for the australites, where the glassy material appears to have melted and then flowed back over the surface to form the flange. In discussing this problem, Fenner draws attention to some calculations of Öpik (Reference 36). The difficulty is that the heating from the atmosphere is so great and the loss by evaporation so rapid that in an ordinary meteoric stone the liquid layer is extremely thin; thus it is ordinarily impossible for orderly flow to take place. From this it can be concluded that the australites, if extraterrestrial, should have arrived at the earth along paths that would produce lower temperatures for a longer time than would the paths of ordinary meteorites. This fact points to the same assumption as the evidence from distribution, i.e., that the meteorites arrived along a path similar to that of the great meteor procession of February 9, 1913. The meteor procession followed a path that was very nearly parallel to the surface of the earth and extended for some 5000 to 6000 miles. The velocities of the bodies in this shower were extraordinarily low, certainly less than 10 miles per second. They thus provided the necessary conditions of time and temperature for liquid flow.

An interesting and suggestive idea was proposed by Hardcastle (Reference 37) and Hanuš (Reference 38). They supposed that tektites were formed during the passage of a stony meteorite through the air. They felt that the surface of the stony meteorite would be liquefied and that drops would form which, upon being sprayed off into the air, would give rise to the characteristic forms of tektites as they cooled. This theory in its original form encounters the difficulty that the chemical composition of tektites is entirely different from that of the stony meteorites and that there are cases in which a liquid layer has formed on a stony meteorite that has been recovered; no difference of composition was noticed (Reference 39). On the other hand, if it is supposed that the matrix from which the tektite was removed by ablation was of the same chemical composition as tektites, then the Hardcastle-Hanuš mechanism gives a logical explanation of the formation of tektites. Hanuš' theory was further developed by Oswald (Reference 3). This theory requires that tektites should have been completely melted while in the atmosphere. Since some of them are several centimeters thick, it reinforces the previously mentioned requirement for a long and slow heating in the formation of tektites. This mechanism, on the other hand, explains the low argon ages of tektites as due to the escape of argon during the reentry into the atmosphere.

Krinov (Reference 40) found that small iron droplets were formed on the surfaces of the Sikhote-Alin meteorite and on some others, and were swept off by the air blast during the fall of the body. The droplets are chiefly spherical, with occasional spheroids, teardrops, and bottle shapes; but they are much smaller than tektites, ranging from 0.01 to 0.7 millimeters; they closely parallel the conditions suggested by Hardcastle, except that the more violent airblast has produced smaller droplets.

If it is supposed that the parent body had a composition similar to that of Igast, then the smaller bodies that have dripped off might be considered as representing the first stages in the formation of a normal tektite. In later stages, the mass would be melted; but individual grains of sand might still be detectible as the long filaments of lechatelierite that Barnes found in the bediasites. It should be mentioned that Fenner (Reference 41) supported Hardcastle's idea.

In summary, therefore, the distribution of tektites suggests that they have reached the earth along paths similar to that of the great meteor procession. The depth to which melting has proceeded suggests the same origin. Therefore, a detailed study of what is known of the meteor procession of February 9, 1913 is now in order.

Great Meteor Procession of 1913

The accounts of the meteor procession were collected by Chant (References 42 and 43). The procession was first seen in the towns of Mortlach and Pense in Saskatchewan and was then observed at many points in the province of Ontario; it left Canada, passing near Toronto, where loud detonations were heard. In the United States Chant collected only two accounts, but the section of the path from Buffalo to New York was filled in by accounts collected by Mebane (Reference 44). Between New York and Bermuda it was sighted by three ships whose accounts are given by Pickering (Reference 45); it was then sighted at Bermuda (Reference 46). Beyond Bermuda, it was observed by two more ships whose accounts were obtained by Denning (References 47 and 48).

The procession, as observed, consisted of five or six groups of meteors, each of which consisted of about six individual bodies. All the objects followed the same path across the sky; the total duration of the display was a matter of about 5 minutes. Each individual group took a minute or two to cross the sky. Individual meteors, with tails attached, frequently broke up as they passed across the sky. These individual bodies released small sparks that were observed to go out. The angular width in the sky occupied by the whole procession was not more than about 4 or 5 degrees; by triangulation, Pickering estimated the physical size to be on the order of 4 or 5 miles. According to Mebane there is at least one observation by the Weather Bureau at Alpena, Michigan which indicated that the later members of the shower followed a path west of the earlier members.

The Canadian and British computers who studied the shower at the time felt that the bodies of the shower must have been traveling in a satellitic orbit around the earth (References 42, 49, 50, 51). This view was strongly espoused by Pickering (References 45, 52, 53, 54) in a series of articles in Popular Astronomy. These calculations indicated that it was not possible to obtain an accurate idea of the time of flight of the object, since the time had not been noted by observers, and since the procession itself took such a long time to pass a given point that it was difficult to define a reference time. The evidence for a satellite orbit lay in the fact that the bodies had been observed over an arc some 6000 miles long at the height at which meteoric bodies can be observed, namely, between 40 and 60 miles. If it were certain that the same bodies were observed throughout the whole track, there could be no question that their orbit was satellitic. However, Fisher (Reference 55) remarked that the detonations heard near Toronto meant that some pieces must have been below 24 miles and that these bodies could not have gone much further. He felt that this "satellite meteor," as he called it, must have consisted of a group of bodies of which only the lower members were incandescent at any one time. He suggested that the bodies had been arrested by passing through the denser atmosphere at the earth's equatorial bulge. He recalculated the orbit that Chant had originally given, allowing for the effect of the earth's rotation.

In 1939 Wylie (Reference 56) attacked the whole concept of a satellite meteor. He gave a radiant which, he stated, would satisfy the observations within the errors of untrained observers. Wylie also asserted that the detonations heard in Toronto must have belonged to a body which was only accidentally associated with the meteor shower. The investigations of Mebane, however, showed that the noises had progressed in New York State as far as Elmira. This appears to demonstrate that the connection between the detonations and the meteor shower is real. When the apparent radiants that would have resulted from Wylie's true radiant at each observation station were calculated (Reference 57) it appeared that Wylie's radiant could not account for the observations of the two southernmost ships; the shower should have been invisible from these points. It also appeared that no possible rearrangement of the space radiant which would make the shower visible at the two southernmost stations would agree with the firm statements of numerous witnesses in Canada that the flight was nearly level. Thus it appeared that no explanation of the shower was possible except that it was satellitic.

ORIGIN OF THE METEOR PROCESSION

Physical Aspects of the Sputnik II Descent

A remarkable feature of the great meteor procession is its resemblance to the descent and destruction of the artificial satellite Sputnik II (1957 Beta) as described by Jacchia (Reference 58). Both objects were visible by their own light (as distinct from reflected sunlight) over a path some thousands of miles in length; both developed long tails. In the case of Sputnik II, the tail was some 100 degrees long just before the body disappeared; the tails on the meteoric procession were only about 10 to 15 degrees in length. The tail on Sputnik II was not attached to the head, but separated from it by a dark space. According to Mr. W. L. Haight of Parry Sount (Reference 42), the same was true of the largest body of the 1913 shower; Mr. Haight made a drawing that Chant reproduced to illustrate this point.

Small "globules" were observed to detach themselves from time to time from the rocket, develop tails, and disappear. Many witnesses described the same phenomenon with respect to the meteor procession; for example, Col. A. R. Winter, of Hamilton, Bermuda, speaks of the body "coruscating," or breaking into small pieces. As these pieces separated from the parent body, they developed trails of sparks and gas (Reference 42). Jacchia noted that the particles which separated from the rocket were probably liquid, since they tended to break in two. This phenomenon was not specifically noted in the meteoric procession; but the descriptions do not by any means exclude it. If the detached objects were liquid drops, they would correspond almost exactly to the requirements of Hardcastle's theory.

The globules detached from 1957 Beta had masses in the range of the tektites; this follows from the total amount of radiation produced. With mass M and velocity w, the available energy, which is for all intents and purposes only the kinetic energy of the rocket, is $Mw^2/2$; the integrated light, assuming constancy, is jt if j is the average luminosity and t the duration. Hence (Reference 59),

$$jt = \frac{\beta M w^2}{2}$$

where β is the so-called visual efficiency. The visual efficiency is defined as 1 at the peak of visual efficiency around 5100A; for other wavelengths it is proportional to the sensitivity of the eye. For a mixed radiation it is proportional to the total number of lumens per watt. Converting to logarithms and replacing luminosity by "absolute magnitude" m, equal to the apparent magnitude that the object would have at a distance of 100 kilometers, Öpik (Reference 59, p. 148) finds that

$$\log M = 10.02 + \log L - \log \beta - 3 \log w - 0.4m \,.$$

Here the time has been replaced by the quotient of path length L and velocity.

To evaluate [illegible], the observations on the integrated light of the rocket are used. According to Jacchia, the absolute magnitude of the whole object including the coma and tail was -9 to -10 at maximum brightness near latitude 13 degrees. It is clear that the total brightness should be taken rather than the luminosity of the head alone, since the source of the energy in the tail was the energy of the globules and gas liberated from the head. It appears that the head lost most of its kinetic energy through mass loss, since the tail (which was fed by debris from the head) was — together with the coma — several magnitudes brighter than the head alone.

It should also be mentioned that the total mass is obtained by this method even if the whole mass is not consumed, since the whole of the kinetic energy is certainly consumed in the atmosphere. When any meteoric body weighing less than hundreds of tons reaches the ground, its velocity is so low that nearly all the kinetic energy has been wrung out of it.

The path length that should be adopted is that along which the body was at, or near, maximum brightness. Over the continental United States, the absolute magnitude was near 0, that is, about one ten-thousandth of the maximum brightness; hence this portion of the path may be ignored. There follows a gap in which no observations were made. Then, from about latitude 24 degrees to latitude 10 degrees, a period of 247 seconds, the satellite was reported as highly luminous. During this time, it appears from Jacchia's orbit that the satellite covered a distance L of 1690 kilometers at an average speed w of 6.8 kilometers per second. These last values are adopted.

The mass of 1957 Beta has been estimated by NASA (Reference 60) as 4 tons. Substituting these values in Öpik's-formula gives

$$\log \text{[illegible]} = -2.05.$$

This value is remarkably large. Possible sources of error are:

(1) The estimated path length: Judging from the light curve given by Öpik, the path length that should be used with the maximum luminosity to give the correct integrated brightness is roughly twice the distance from the point of maximum brightness to the end. In the present case, this would work out to roughly 900 kilometers rather than 1700.

(2) The estimates of the maximum total brightness: These were particularly difficult because it was necessary to obtain from inexperienced observers an estimate of the integrated stellar magnitude of a diffuse object 20 to 100 degrees in length. The assertion that an illumination was noticed on the ground, however, sets a definite lower limit to the total radiation which is not far from the brightness given by Jacchia. Moonlight is not conspicuous before first quarter, which corresponds to about magnitude -9 to -10.

(3) The estimates of the mass of the satellite: At the time of the launching of the Atlas satellite by the U. S., the Soviet embassy protested against statements that the weight of the Atlas was as great as the weight of 1957 Alpha I, the rocket carrier of the first Russian satellite Sputnik I. Since Atlas weighed 4 tons, there is an implication that the weight of Sputnik II (1957 Beta) was substantially greater.

From all these sources of error, it seems reasonable to expect a discrepancy of 10 in the value of the luminous efficiency. On the other hand, the calculation of the luminous efficiency by the methods given by Öpik (Reference 59, ch. 8) yields an efficiency of the order of 10^{-4}. The discrepancy seems to be more than observational error.

The luminous efficiency is divided by Öpik into three components, namely the component due to collisions of atoms vaporized from the meteor with air molecules, that due to collisions among the vapor atoms, and black-body radiation from the solids and liquids present. Of these, the first has an efficiency of 4×10^{-5}; the second, 0; and the third, from 10^{-4} to 10^{-5} in the range of temperature from 1800° to 2400°K, that is, roughly from fusion to vaporization.

There does not seem to be any process that would enhance the luminous efficiency due to the first two processes, but there may be an overlooked factor in the third process. If the gaseous iron from the rocket is present in sufficient quantity, it is imaginable that part of it would recondense into liquid smoke droplets after the vapor had left the surface of the rocket and had cooled slightly; this would leave a gap between the head and the tail. The smoke particles would still possess most of the velocity of the rocket, and, owing to their larger areas, would have considerably higher radiative efficiency. In this way, most of the energy might escape from the mass in the form of radiation.

The fact that an observer reported a black smoke trail left behind by the object supports this hypothesis. In addition, it is noteworthy that most of the luminosity came not from the head, but from the tail. It does not appear that the globules of the tail can explain the extra brightness; one observer states that there were about thirty in view at once. Since each had a brightness of about -3, the total luminosity should have been about -6; but what has to be explained is a luminosity of -9 to -10. It cannot be supposed that the luminosity was due to many small droplets sprayed from the object because there is a lower limit to the size of droplets that can be sprayed and this limit is near the size of the globules observed.

On this hypothesis, the dark region between the head and the tail is like the transparent section of a steam column just beyond the spout of a teakettle, or at the opening of a locomotive smokestack where steam is present but in gaseous form. The total luminous efficiency should be close to the black-body luminous efficiency for some temperature below that of rapid vaporization. If the temperature is as high as 2000°K, an efficiency of 4×10^{-3} is to be expected.

Since the calculation of the masses of the globules is exposed to much the same sources of error as that for the satellite as a whole, and since the mechanism of light production is likely to be the same, the same luminous efficiency will be employed here. This assumption permits the ratio of the mass of the globule to that of the satellite as a whole to be considered as equal to the ratios of the product jt.

The observers on the ship "Regent Hawk" reported, according to Jacchia (Reference 58), that the globules were about twice as bright as Sirius, i.e., about magnitude -2.4

apparent — or, allowing for the distance, -4 "absolute." The same observers stated that the globules lived for about 1 second. The ratio of luminosities, globule to satellite, is therefore 160; the ratio of times is 250; the ratio of masses comes out as 40,000. Thus the masses of the globules are about 100 grams. The corresponding radii are about 1.5 centimeters if the globules are iron (from the rocket engine) or about 2.1 centimeters if they are aluminum.

Jacchia points out that the bodies were probably liquid, since they were observed to break in two by observers in Barbados. He calculated the height of the object near Barbados as 70 kilometers; at this height, with a velocity of 6.8 kilometers per second and air density $\rho = 10^{-7}$ gram per cubic centimeter, according to the Rocket Panel (Reference 59, p. 13), the drag pressure is given by Öpik (Reference 59, p. 37, Equation 4-23):

$$p_s = \frac{\rho w^2}{4}$$

$$= 11{,}000 \text{ dynes/cm}^2, \text{ or } 0.167 \text{ lb/in.}^2 .$$

This pressure is less than one-thousandth of that necessary to break even the weakest ordinary kinds of stones or bricks. It is, however, sufficient to break up a liquid iron globule of this size. The critical radius r is given by Öpik (Reference 59, p. 84) as

$$r = \frac{4S}{p_s} .$$

With a surface tension S of 1200 dynes per centimeter, as for iron, r is 0.4 centimeter; for aluminum the surface tension is 840 dynes per centimeter, yielding a radius of 0.3 centimeter.

The discrepancy between the two determinations of the radius (from total light and from surface tension) is probably not significant; for example, it could be reconciled by a change of 4 kilometers in the assumed height. The important point is that the globules were in the size range of the tektites, not in the size range of the small iron droplets (less than 0.04 centimeter in radius) which Krinov (Reference 40) has found coming from ordinary iron meteorites. If masses of the order of those found by Krinov are attributed to the rocket drops, there is a discrepancy in the luminous efficiency which is five orders of magnitude worse than that found for the rocket as a whole. The masses were unquestionably in the fractional kilogram range, not the milligram range.

A critical test of the drop explanation of the sparks seen in the case of 1957 Beta can be made by calculating the temperature at the top of the liquid layer on the meteor from which the flow takes place. This test is critical because, if the temperature is too high, vaporization will take the place of liquid flow. It is ordinarily found that iron will flow under meteoric conditions but that stone will not.

The ratio of heat lost by radiation to that lost by evaporation is given by Öpik (Reference 59, Table XXXII, p. 98); it appears that the critical surface temperature for iron is 2100°K; below this temperature, liquid flow is expected to occur freely because evaporation is less important than radiation as a method of heat loss. Hence, the liquid layer will not be greatly thinned by evaporation.

To calculate the actual surface temperature, start at the bottom of the liquid layer where the liquid is in contact with the solid and the temperature is that of fusion, about 1800°K. The difference ΔT between this temperature and that at the top depends on the rate at which heat is being supplied, the thickness of the layer Δr, and the thermal conductivity k_t (Reference 59, p. 104, Equation 6-43):

$$\Delta T = \frac{1}{2} \frac{\gamma \rho w^3 \Delta r \cos \alpha}{k_t}$$

where γ is the fraction of the incident kinetic energy that goes to heating the surface and α is the angle between the normal to the surface element and the direction of motion of the body. For the present calculation set α equal to zero, since this will be the critical value.

The calculation of γ is carried out according to Opik's precepts for a large meteorite; it is found to be 0.0545 for iron. To calculate Δr, the equilibrium between the rate at which fluid is produced by melting and the rate at which it is removed by drag must be considered. The most important parameter here is the viscosity η, which for iron has the value 0.01 poise. From these considerations, Öpik (Reference 59, p. 103, Equation 6-38) finds the equation

$$\Delta r = \left[\frac{r w \eta \gamma}{2 h_f \delta (1 - q) \cos \alpha}\right]^{\frac{1}{2}}$$

where h_f is the heat of fusion, δ is the density (7.8 gm/cm^3 for iron), and q is related to the coefficient of accommodation $\kappa = 0.522$ (Reference 59, p. 51, Table X) by the equation

$$q = \sqrt{1 - \kappa}$$

Because of the low viscosity of liquid iron, the liquid layer is very thin — about 1.7×10^{-3} centimeter. The corresponding value of ΔT is 0.3°K; and the temperature at the surface is therefore practically at the temperature of fusion, 1800°K. At this temperature, about twelve times as much heat is lost by radiation as by evaporation; and it can be concluded that the iron will actually flow in the manner required by this hypothesis. Therefore, it is concluded that, as 1957 Beta descended through the atmosphere, it sprayed drops of liquid iron whose size was comparable with that of the tektites.

Physical Aspects of the Meteor Procession

The similarity between the phenomena of the descent of 1957 Beta and those of the meteor procession suggests that very similar processes were at work. There are, however, some important differences in the physical parameters, especially the viscosity and the surface tension. On the observational side, the heights are not as well determined, principally because there is no assurance that the bodies seen at one point are the same as those seen at another; hence the dynamical arguments cannot be employed with confidence. Nevertheless, it appears that the same physical assumptions used to explain 1957 Beta will also explain the phenomena of the meteor procession.

To determine the mass of the largest body, it is noted that at only two locations out of over one hundred reported was there a noticeable illumination of the ground: at Fonthill, near Niagara Falls, and at Fort Francis, Ontario (Reference 42). Both observations were close below the path; hence the magnitude was between -4, at which the effect is barely detectible when searched for, and -10, at which it is conspicuous (e.g., the moon at first quarter). A magnitude of -7 as seen from the ground appears reasonable. The observers quoted were at ground distances of 10 and 55 kilometers, respectively, from the trace of the path on the ground. Allowing for a height of 70 kilometers, the distance corrections are 0.25 and 0.75 magnitude; the "absolute magnitude" thus appears to have been about -6.5.

The minimum value that can be taken for the path length is the distance from Fort Francis to Fonthill, roughly 1250 kilometers. The adopted value is 2500 kilometers, namely the distance from Mortlach, near Regina, Saskatchewan where the meteors were first noticed to the area of Toronto and upstate New York, where loud detonations indicated that at least some of the larger bodies fell. The velocity is taken as 6.8 kilometers per second, as for the terminal phase of 1957 Beta; the observations of time are not sufficiently accurate to permit a correction of this calculation. If, however, the 1913 shower consisted of bodies in orbit around the earth, the velocity cannot have differed greatly from this value.

For the luminous efficiency a value of 10^{-2} is taken. This value probably includes some effects of systematic error in the estimates of brightness, as for 1957 Beta. The mechanism of light production may have been similar, since several observers reported smoke and since a dark space was seen behind the head of the largest body. If, however, the radiation was actually from a vapor, the efficiency should be lower for tektites than for iron by a factor of 10.

For the mass of the largest body (from Reference 59, Equation 8-26) the value is 370 kilograms. In general, the smaller bodies were seen to cross the entire field of view, although some were seen to break up. Therefore, lives of the order of 1 minute and path lengths of the order of 500 kilometers can be assigned to them. Their brightness was estimated by observers at Aylmer and Ridgeway; in addition, there is the drawing of Mr. Gustave Hahn (Reference 42, p. 145). From all of these, the "absolute magnitude" comes out, with reasonable consistency, as +1.8. The resulting masses are about 35 grams.

The observed "sparks" are poorly described; their luminosities must have been considerably less than those of the lesser meteors and brighter than the lower limit of meteor magnitudes, which is about the fifth magnitude; it is reasonable to adopt an absolute magnitude of 4. Their durations may have been only a second or two, from the word "spark" used in describing them. By adopting 10 kilometers as the path length, the masses are found to be about 0.1 gram.

The determination of the height presented considerable difficulty because of the presence of large systematic and accidental errors in the observations (References 42, 43, 47, 48, 49, 61). The most straightforward procedure is to apply a reduction of one-third to all reported angular altitudes, as recommended by Denning (Reference 47). The result is given by Chant (Reference 43, p. 444) as 70.1 kilometers. (See also References 48 and 61, where a value of 42 miles or 67.5 kilometers is the last result for the height.)

From Öpik's formulas, as given, a radius of 0.14 centimeter is calculated for the sparks. This is to be compared with a radius of 0.21 centimeter that follows from the calculated mass and an assumed density of 2.5. The agreement is satisfactory.

The most critical point, however, is whether the liquid stone will flow at all. As mentioned herein, Fenner (Reference 4) quotes an unpublished remark of Dodwell based on Öpik's work (Reference 36) to indicate the difficulty of accounting for flow in stone meteorites. The point is that the heating due to friction is so strong that in an ordinary meteorite the liquid layer is very thin and, because of the high viscosity of liquid stone and its high rate of vaporization, flow does not take place. In the present case, however, flow will occur, since the heating of a body in a satellite orbit is much less than that in a normal meteoric orbit.

To prove that flow can occur for a body in a satellite orbit, it first is noted that the treatment of a stone object cannot be the same as that for an iron object. When the same calculation as that made for iron is performed, it is found that the losses by vaporization exceed those by radiation. Hence the temperature at the top of the liquid layer will be controlled by the equilibrium between vaporization and heating, rather than that between flow and heating as in the case of the iron.

A numerical calculation for the case represented by the smaller bodies of the 1913 shower is made: 35-gram spheres, of density 2.5 and radius 1.5 centimeters, traveling at 6.8 kilometers per second at a height of 70 kilometers.

The heat received per second is given by

$$\frac{1}{2} \gamma \pi r^2 \rho w^3 \sin^2 \alpha$$

where γ is the coefficient of net heat transfer to the meteor, r the radius of the body, ρ the atmospheric density, w the velocity, and α the angle from the direction of motion to the radius through the spot under consideration (Reference 59, p. 37, Equation 4-25; p. 102, Equation 6-37). The average heat supplied from $\alpha = 0$ to $\alpha = \alpha_0$ per unit area is found to be

$$U = \frac{1}{4} \gamma \rho w^3 (1 + \cos \alpha_1)$$

The half-energy range λ is about 0.6 centimeter for the pressure of 9.74×10^{-8} gram per cubic centimeter (which corresponds to a height of 70 kilometers according to the Rocket Panel). The quantity γ is determined from λ and from κ, the coefficient of accommodation for which a value of 0.722 follows from Öpik (Reference 59, p. 51). The resulting value of U, for $\alpha_0 = 45$ degrees is 7.74×10^9 erg per square centimeter per second. This heat is expended on the following:

(1) Raising the stone to 2100°K: this requires roughly 1.8×10^{10} erg per gram;

(2) Melting the stone: 0.3×10^{10} erg per gram;

(3) Vaporizing the stone: 6.0×10^{10} erg per gram.

This gives a total of 8.1×10^{10} erg per gram. Hence, the amount of stone vaporized is 9.2×10^{-2} gram per square centimeter per second. The corresponding temperature, calculated from the formula of Öpik (Reference 59, p. 161) is

$$T = 2094\,°K .$$

The difference between the top and bottom of the liquid layer is then $\Delta T = 294$°K, assuming a temperature of fusion of 1800°K. If transport of heat by conduction is assumed, then

$$\Delta T = \frac{U' \Delta r}{k_t}$$

Hence, a thermal conductivity k_t of 2×10^5 erg per centimeter per second per degree (Reference 59, p. 162) gives

$$\Delta r = 0.03 \text{ cm}.$$

Next the tangential component of the drag

$$p_t = (1 - q) \rho w^2 \cos \alpha \sin \alpha ,$$

is calculated. It is found to be 1.21×10^4 dynes per square centimeter at an angle α_0 of 45 degrees from the direction of flight (Reference 59, p. 102, Equation 6-36, using the definition $q = \sqrt{1 - \kappa}$ from p. 35). This drag will produce an average velocity of flow v given by the equation (Reference 59, p. 103)

$$\frac{2 v \eta}{\Delta r} = p_t$$

whence $v = 4$ centimeters per second, assuming the value 50 for the coefficient η of viscosity of liquid stone.

A layer thickness Δr of 0.3 millimeter and a velocity v of 4 centimeters per second account in a satisfactory manner for the sparks of the 1913 shower. They also account for the appearance of the australites. Here it is seen that the flange has been produced by the backward flow of a thin liquid layer that has been coiled on itself. The velocity of 4 centimeter per second appears to be somewhat higher than that required to produce the observed flanges in a few minutes; but the discrepancy is not larger than could be explained by reasonable errors in viscosity.

Inferences from the Analyses

From a preliminary physical analysis, the Hardcastle-Hanuš mechanism for the formation of tektites therefore appears to work in a satisfactory way, provided that the tektites entered the atmosphere along trajectories nearly parallel with the horizon. The importance of this condition was pointed out by Öpik in private conversation; he remarked that his Equation 5-35 (Reference 59, p. 76) shows the dependence of the effective density ρ_1 of the atmosphere (at the level where the ablation effectively takes place) on the cosine of the zenith angle Z. Meteorites coming in at steep angles suffer ablation at low levels in the atmosphere; those coming in at shallow angles are ablated at much higher levels and low densities, and should therefore yield much larger droplets. The equation is

$$\rho_1 = \frac{\phi r_0 \cos Z}{w^2} ;$$

here ϕ, which is a parameter measuring the ablation, varies rather slowly with the height. Low values of ρ_1 are possible only when cosine Z is near zero, that is, for nearly horizontal orbits.

The great meteor procession thus has the principal characteristics required to explain the observations of tektites. Because of the form of its orbit, falls from it must have taken place over a wide area, although none have been recovered. The area was extended in length by the long distance over which the shower passed at small elevation; it was extended in longitude by the earth's rotation while the shower was passing overhead. This is the probable explanation for the observations made by the Weather Bureau at Alpena, referred to earlier. It is true that in this case the area covered must have been narrower than either the australite strewn field or the Indo-Malayan strewn field. On the other hand, it would seem reasonable to suppose that in some cases bodies of a cluster have survived several passages through the lower atmosphere and, hence, that the strewn field consists of several narrow zones at a distance from one another. If the shower had covered a larger portion of the orbit, this also would have tended to broaden the strewnfield in longitude. The latitude of the strewn field was presumably that of the perigee of the orbit. The extent in latitude presumably depended on the distance over the earth at which the bodies were near perigee, i.e., on the eccentricity of the orbit. It is also natural to relate the observed concentration of tektite falls toward the equator with the fact that the earth's atmosphere is about fifteen times denser for a given value of the radius vector at the equator than at the poles (Reference 62).

Turning to the previous history of the great meteor procession, it is difficult to doubt that this was originally a single body which was broken up by drag in the earth's atmosphere. Had it not been a single body then, as pointed out by Urey (Reference 33), its lifetime as a cluster — whether in the solar system or in the neighborhood of the earth — would have been very short. Since the density of the cluster as observed was well below Roches' limit, tidal forces would have disrupted it very rapidly.

It is possible to approximate the time that passed between the breakup of the original body and its first sighting. The maximum range in the heights of visible fireballs is about 55 miles, which would correspond to a range in period of about 1.6 minutes. Hence the observed range in time of passage, which amounted to not less than 2 minutes, required at least one and probably two or more orbital periods to establish. In other words the breakup of the original body probably occurred more than 1-1/2 hours, and less than 12 hours, before its first discovery.

As the previous history of this body is examined, it is plausible to assume that it resembled the history of the artificial satellites, which ended their lives with similar orbits — that is to say, that the orbit previously had been both larger and more eccentric. Going back in time, it is logical to believe that the tendency is toward an extremely large and extremely eccentric orbit.

The entry of the satellite into this orbit presents very great difficulties if it is supposed that it was captured in some way in space. The difficulty is the following: If the body had the velocity in space that corresponded to a normal meteoric velocity, then it might conceivably be captured into an orbit around the earth by a single encounter with the earth's upper atmosphere. It would lose at the same time enough energy to reduce its geocentric velocity from some 20 kilometers per second to something below 11 kilometers per second. However, in such a body the next pass would have resulted in the fall of the body to the earth, since in all probability it would have passed closer at the second perigee. In this case there would not have been the observed nearly circular orbit nor the observed spread of the bodies along the path. Encounters with the moon can change the velocity by a maximum of 2 kilometers per second. It appears that the most plausible source for a body in a long-lived elliptical orbit around the earth is the moon.

LUNAR ORIGIN OF TEKTITES

Nininger (Reference 63) suggested that the tektites originated as the result of the impact of ordinary meteorites on the moon. The theory of a lunar origin receives support from several other facts:

(1) There is direct evidence from the length of the lunar rays that some material has been ejected from the craters with a velocity of the order of the circular velocity around the moon (Reference 64). It is plausible to suppose that a smaller quantity reached the velocity of escape (References 65 - 69).

(2) Possible trajectories exist by which lunar material ejected at 2.9 kilometers per second or thereabouts can reach the earth (Reference 70).

(3) The reflecting properties of the lunar rays (References 65 - 69) are best explained by the presence of transparent glassy spheres (References 62 and 71). These suggest an acid silicate as the principal constituent of the lunar crust. They are probably not identical with the tektites but may have been formed by analogous processes in the fireball around the point of explosion.

(4) The polarization of light from the moon's surface suggests a finely divided acid silicate (Reference 72).

(5) The radar reflectivity of the lunar surface is so low that it is difficult to explain except as a consequence of a finely divided acid silicate (Reference 73).

It is therefore concluded that the moon's surface has a chemical constitution similar to that of the tektites and that its physical structure may be represented by the Igast object.

Certain conclusions about the nature of the processes that have formed the moon follow from these ideas:

(1) The lunar rocks appear to contain small but measurable quantities of chlorides; at least such are found in the Igast object.

(2) The large ratio of uranium and thorium to radiogenic lead found by Tilton (Reference 74) requires the supposition that they were injected into the rock in comparatively recent times (not later than 50 million B.C.).

(3) A considerable portion of the moon's surface appears to consist of porous material. This is suggested by the Igast object and is supported by the extremely low value of the dielectric constant of the moon's surface found by Senior and Siegel (Reference 73): the value is so low that it can only be explained by a porous material.

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