Reports

Origin of Tektites

O'Keefe and Shute (1961) have recently attempted to account for the tektites as fragments melted from a large object as it passed in nearly horizontal flight through the high atmosphere (*1*). They assume that the object may have made more than one orbit about the earth before it was finally captured and thus may have supplied all the tektites of Southeast Asia and Australia. The tektites of all this area have approximately the same $K^{40}A^{40}$ age of 600,000 years and can reasonably be assumed to have been produced by one event. O'Keefe and Shute maintain that this large object originated from the moon and that its orbit was similar to that of the great Canadian meteor train of 9 February 1913, which was some 1500 kilometers long and was observed at various points between western Canada and the mid-Atlantic Ocean.

No fragments were recovered from this fireball, and therefore we have no knowledge of its composition. However, if it were typical of a tektite fall as O'Keefe and Shute assume, many small objects of a glassy nature should have fallen, and it seems most likely that many would have been recovered. Tektites are quite different in appearance from rocks; they are small and hence do not penetrate soil deeply as they fall, and they are very numerous in known fields. It is likely that this fireball was more like that of the Rochester meteorite. This fireball traveled from Iowa to Pennsylvania, a distance of some 1600 kilometers. At Rochester, Indiana, an object was heard to fall and the next morning a 340-g meteorite was recovered from a field where it had buried itself in the soil. The main mass was not recovered. The meteorite is a common variety known as a spherical chondrite. In contrast to the numerous specimens of a tektite field, the falls of meteorites in a shower are far less numerous. Meteorite falls are often single, and the meteorites are very difficult to find; in many cases no object is recovered at all. If this Canadian fireball was of meteoritic character, it is disappointing but not particularly surprising that no meteorite was found. These two fireballs show that nearly horizontal orbits are possible, but the only evidence points to a meteoritic rather than a tektitic composition.

The total tektite fields of Southeast Asia and Australia extend over the Malay Peninsula, Java, the Philippines, South Australia, and Tasmania. The area may be a rough ellipse 8000 km long and half as wide with an area of 2.5×10^7 km^2. In South Australia, the density of tektites has been estimated as 100 g km^{-2}. North Australia has none. The density in the Philippines appears to be greater. A ton or more of tektites has been recovered from the Philippines, mostly from the Manila area. Possibly an average over the whole area of 100 g km^{-2} is too large. This would give 2500 tons for the total mass. They are easily buried, for much of the area is water, and the land area is covered by jungle or drifting desert soil. It would seem that 1000 tons might not be a bad estimate for the total mass. Probably an estimate of 100 tons is much too low and one of 10,000 tons too high. Let us take 1000 tons for the purposes of argument.

How would a silicate object of 1000 tons be removed in one piece from the moon? Possibly some enormous process might do this, but in that case certainly many objects of this kind would be produced together with much material of sizes ranging down to minute grains. What has happened to all these other objects? Would not some of them arrive like ordinary meteorites and be distributed widely over the earth? It has been suggested to me that the parent object was spongy and of low density, that is, loosely agglomerated dust from the moon, and that this material cannot come through the atmosphere as meteorites do. I believe there is no evidence supporting this argument. In any case, does it not seem utterly incredible that a 1000-ton or even more massive object of such fragile structure should have been accelerated from the moon up to about 2.4 km sec^{-1} and have left the moon in one piece? Or did many small objects leave the moon and become agglomerated in space? This is a most unlikely possibility. A process which should have supplied much larger amounts of material than that represented by the tektites is assumed, and further it is postulated that no vestige of this great mass could have arrived at the earth and been detected. This seems to be most improbable.

Other questions can be asked. How did an object leaving the moon get into an orbit that would barely graze the earth's atmosphere? It has been suggested that the object spiraled in toward the earth due to collision with gas molecules in the neighborhood of the earth. However, a simple calculation shows that such a massive object as required for the tektite parent body would not move toward the earth at a significant velocity due to collisions with molecules. The object might leave the moon with orbital constants such that it would just graze the surface of the earth's atmosphere, but this means that an exceedingly improbable orbit must be invoked. Also in this case, multiple passes about the earth would not account for the large extent of the Southeast Asia–Australian field except by an improbable coincidence, namely, some simple relationship between the orbital period of the tektite parent body and the rotational period of the earth.

We may investigate other possibilities. Thus it may be assumed that a group of objects in a rather tight swarm was aimed at the Asian-Australian fields and arrived in a direct flight from the moon. Of course it must be assumed that such groups of objects were ejected in all directions from the moon with about equal probability.

If their velocity exceeds 2.6 to 2.8 km sec^{-1} as they leave the moon's sur-

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Type manuscripts double-spaced and submit one ribbon copy and two carbon copies.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each. Submit three copies of illustrative material.

For further details see "Suggestions to contributors" [*Science* **125**, 16 (1957)].

face depending on the direction in which they are projected from the moon, they will escape from the earth-moon system in general, and only a fraction will reach the earth. If they leave the moon's surface with velocities less than that required for escape from the earth-moon system, they will remain in the system.

Those objects that leave the system will move in orbits about the sun and will eventually return to the earth or fall into the sun due to the Poynting-Robertson effect. The relative probability for hitting the earth and escaping into solar orbits should be proportional to about the area of a great circle of the earth's surface and the surface of a sphere of radius equal to that of the moon's orbit, that is, $6372^2/4 \times 384000^2$, or 1/15000. Of course the gravitational field of the earth increases its collisional area by a small factor of about 3. But if all the objects that miss the earth return to it at a later date, the density of the general distribution would greatly exceed the densities in the Southeast Asia and Australian fields. Letting the density over this area be σ, the density of the general distribution due to those that missed the earth and returned later would be

$$\sigma \left(\frac{A_t}{A_e} \times 15000 \right) \times 1/3$$

where A_t is the area of the Asian-Australian field and A_e is the area of the earth. This equals

$$\sigma \frac{1/2\ \pi\ 4.000^2}{5.1 \times 10^8} \times \frac{15000}{3} = 250$$

There should be 250 times as many tektites per unit area distributed uniformly over the earth during the mean time that is required for the very special collisions which produced the localized fields. This is a very large factor and probably even 0.01 of the mean density of the Asian-Australian fields would be detected in many parts of the world where there are high densities of populations and intense cultivation of land areas, thus making the factor between calculated expectancy and observation about 2.5×10^4.

This large factor may be too high because the small tektites would fall into the sun because of the Poynting-Robertson effect. The time required for a decrease in radius of an orbit due to this effect by an amount, Δa, is

$$\Delta t = \frac{8}{3} \frac{\pi a c^2 r \rho}{E} \Delta a,$$

where a is the radius of the orbit, r and ρ are the radius and density of the object, c is the velocity of light and E is the total radiation of the sun in ergs per second. Taking r equal to 1 cm, ρ as 2.5 g cm^{-3}, a as 1.5×10^{13} cm, and Δa equal to 1.5×10^{12} cm, that is, assuming some eccentricity of the orbits, gives

$$\Delta t = 3.6 \times 10^6 \text{ years.}$$

The time required for collision with the earth from such orbits is some few million years. Some of the tektites would move toward the sun and be lost. Also the effect might be increased by interplanetary gas, magnetic fields acting on charged tektites, and so forth, but the factor of 2.5×10^4 is very large, and allowance can be made for substantial effects of this kind. Also some few tektites are fairly massive (200 to 1000 g), and such objects would hardly be affected by any of these effects, and if they can be found in Viet Nam they could be found in other areas, especially if they were 250 times as densely distributed over the rest of the earth.

But if the objects just barely escaped from the moon and moved in the earth-moon system, they would eventually be captured by the earth or the moon. It is improbable that they would collide with the earth during the first orbital period. The orbits would cross the moon's orbit at least just after escape from the moon and hence would pass near the moon after some fairly brief time. As a result, the orbits would be markedly perturbed, and these objects would collide with the earth in a great variety of ways. After the perturbation by close passage to the moon, the new orbits would again pass near to the moon's orbit. Even after considerable times, that is, those required for the precession of nodes and perigee, the objects would pass near the moon occasionally. A slow smooth spiral would surely be a rare orbit. Also some escape of such objects from the earth-moon system would occur.

I can find no reasonably probable way by which tektites can come from the moon and arrive at the earth with the observed distribution of the Asian-Australian field.

The comet collision hypothesis proposed some years ago by me (*2*) has some advantages and also some difficulties of its own. Briefly it was assumed that a comet head of density 1 g cm^{-3} or less arrived at the earth with the velocity of some tens of kilometers per second. It compressed the air in front of it to a high density and was compressed itself, and the whole mass was raised to a very high temperature within a fraction of a second and flattened out over an area of the earth. The surface of the earth was melted to some shallow depth. The gases expanded rapidly in all directions, pushed the atmosphere ahead of them, and were partly lost to space. They caught up some fragments of the earth's surface, accelerated them to high velocity and carried them to great altitudes and deposited them at great distances from the collision site. At some time the gases flowed past some of these objects at about 11 km sec^{-1} (*3*), though the objects did not acquire a velocity sufficient to escape the earth's field. A shallow crater was produced because the low density comet head would not penetrate deeply in the earth. Many features of the tektites follow from this, and the comet head collision may account for features that a meteorite collision cannot explain.

But there are difficulties. The tektites are very dry, and all surface rocks of the earth contain appreciable quantities of water. Also, the isotopic composition of the oxygen of tektites is very constant and does not agree well with that of the abundant superficial terrestrial material (*4*). Also, the chemical composition of tektites does not match exactly the composition of terrestrial rocks. Schwartz (*5*) has recently pointed out that soils have a composition close to that of tektites, and this origin is easily accommodated to the comet head collision theory. Possibly in the complicated details of the collision a drying process and isotopic-exchange process would account for these difficulties (*6*).

Details so difficult to explain through known terrestrial processes are not easily and certainly explained by lunar processes. As a first approximation it may be assumed that lunar melting processes would be acting on similar materials and thus would again produce materials similar to those of the earth with respect to water content, isotopic composition, and general chemical composition. But even if the surface of the moon has the composition of the tektites exactly, it is most difficult to understand how the tektites arrived at the earth with the observed surface distributions.

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30 July 1962

Lunar Synodical Period and Widespread Precipitation

Abstract. Precipitation activity over broad areas appears to be closely associated with the monthly lunisolar cycle. Indexes of precipitation in the continental United States over a continuous 50-year period, and 91-year daily histories of individual stations, reveal that heavy rains occur most frequently in the first and third weeks of the synodical month.

Although an effect of the moon on weather has been suggested by many investigators (*1*), no acceptable physical explanation has been offered for any of the effects that have been claimed or suspected. Such complicating factors as seasonal and geographical variations might easily obscure any hypothecated influence. The statistical evidence presented has been quite unsatisfactory because of the scarcity of data or its lack of representativeness. Also, valid tests of significance to distinguish the observed fluctuations from chance have not usually been applied except by van der Bijl (*2*) and Mauchly (*3*). The latter reported a possible relationship between precipitation activity and the moon's phases, noting a significant tendency for less precipitation to fall at selected cities on approximately the second and third days prior to new moon.

In pursuit of the questions raised by these previous studies and in connection with an explorative investigation into possible links between other astronomical factors and weather parameters, a comprehensive plan was devised to cope with the matter. The results that were achieved from following through with this research program, free of most of the limitations of its antecedents, are quite surprising and positive.

Data highly representative of the chronology of heavy precipitation in the continental United States are furnished by Weather Bureau records of the dates and places of maximum 24-hour precipitation per calendar month (*4*). A total of 16,057 maximum precipitation records, representing 6710 individual dates, are provided for the 1544 weather stations which continuously operated over the 50 years 1900–1949. It is reasonable to assume that these data are fairly representative of the occurrence of excessive widespread precipitation in the U.S. during that half-century.

The angular difference between the apparent longitudes of the moon and sun at Greenwich noon is expressed as hundredths of the synodical month of 29.53 days (*5*). When their longitudes coincide, at the event of new moon, the "synodic decimal" is 0.00, and when the lineup called full moon takes place, the decimal becomes 0.50. Quadrature aspects, which mark the phases popularly known as first and last quarters, are expressed as 0.25 and 0.75, respectively. The synodic decimal advances about 0.03 per day. A ten-unit moving total of a distribution within successive classes, each 0.01 in width, therefore equates roughly to a 3-day moving total.

The tabulation of synodic decimals for each storm date was performed in two parts, the precipitation history being separated into 25-year halves, for 1900–1924 (with 7856 cases), and for 1925–1949 (with 8201 cases). Treatment of the first 25-year series was completed without prior knowledge of the comparable outcome that resulted from handling the second series in the same way. Figure 1 shows a similarity between the abnormal distributions, which should behave normally and independently if no lunisolar influence were at work, that is quite pronounced. Correlation between the two curves is 0.805, while harmonics fitted to the series account for highly significant percentages of the variance.

The quantitative nature of the indicated lunation effect is clear from a separate plotting of the 185 dates which registered as precipitation maxima at ten or more stations. The amplitude of the diphasic 29.53-day cycle is remarkable, since the dates of the most extreme widespread rainfalls in the U.S. history are 3 times more frequent during the cyclic peak periods than during the cyclic trough periods.

That this effect is not due to an unsuspected bias introduced into the processing of the data is evident from a randomized test. The correlation between curves when the 185 "wettest days" are divided into two 25-year series is 0.63, whereas the correlation after scrambling (pairing off storm dates with the synodic decimals for randomly selected dates within the same period) is −0.03.

Other investigative approaches, in which different sorts of basic data

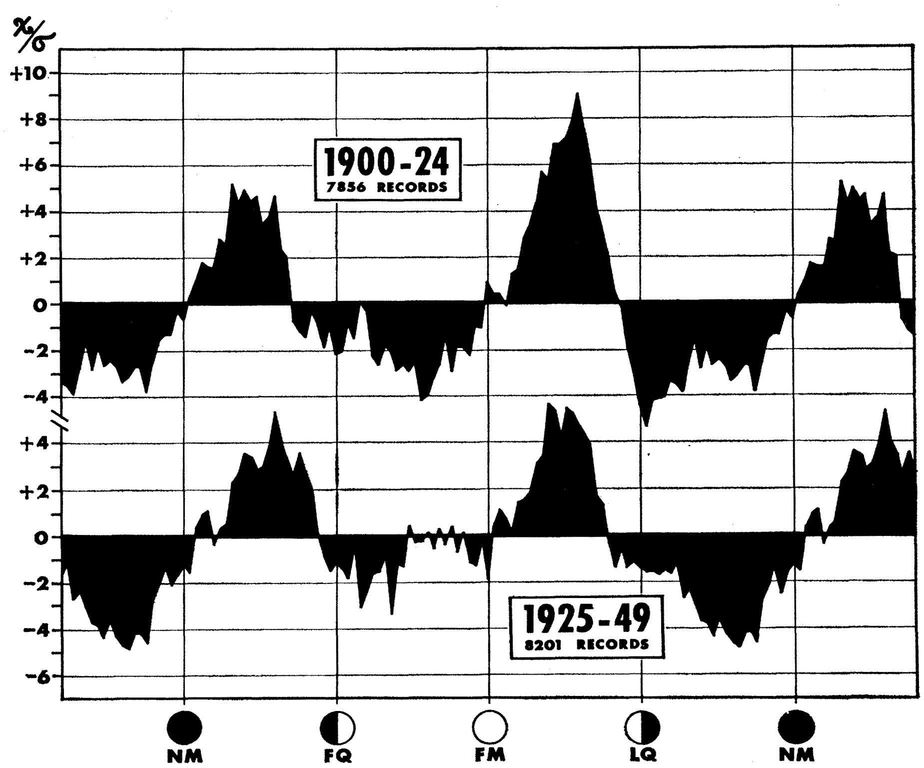

Fig. 1. Deviations (in terms of standard measure) of ten-unit moving totals of synodic decimals for 16,057 record dates of maximum 24-hour precipitation at 1544 U.S. stations, 1900–1949, treated in separate 25-year series for correlative comparison.