LETTERS TO NATURE

PHYSICAL SCIENCES

Cometary Collisions and Geological Periods

SOME fifteen years ago, I suggested that tektites were produced by collisions of comets with the Earth[1-3]. Many detailed investigations of these objects have added much to our knowledge, and these, together with the lunar investigations, have proved this hypothesis to be very probably correct. I have also suggested that the geological periods were terminated by such collisions, but this was published in the *Saturday Review of Literature*, and no scientist except me, so far as I know, reads that magazine. The energy of such collisions and their frequency was roughly estimated at that time, and the number of these collisions has been reviewed again by Durrani[4].

The energy of cometary collisions has been considered by several authors (see ref. 5), but to estimate this energy more quantitatively, I consider the energy of a Halley's comet type collision. Cometary orbits which extend to great distances have velocities at the Earth's distance from the Sun of 42.1 km s^{-1}; the Earth's velocity is 29.8 km s^{-1}. If the comet collides head on with the trailing surface of the Earth, the relative velocity is 12.3 km s^{-1}; if with the leading surface it is 71.9 km s^{-1}; and if with intermediate positions and directions the relative velocities are intermediate. Of course, the escape velocity of the Earth, 11.2 km s^{-1}, must be added, and is considerable for trailing type collisions. The two velocities, including this correction, are 16.6 and 72.8 km s^{-1}. The higher velocity corresponds to nineteen times the minimum energy. The higher energy collisions are more probable because comets generally cross the orbit of the Earth. The ones in the larger orbits, at least, move markedly toward and away from the Sun, so the Earth sweeps across their orbits. In the present calculations, I use an effective velocity of collision with the Earth of 45 km s^{-1} though greater or lesser collision velocities are possible.

The masses of comets are largely unknown, but Russell *et al.*[5] and Whipple[6] give reasonable arguments indicating that Halley's comet may have a mass of $2\times10^{-9}\ M_\oplus$ ($\sim10^{18}$) g, and Russell *et al.* suggest that the comet of 1729 may have a mass of 6×10^{21} g. For calculations, I shall use 10^{18} g.

Table 1 gives some estimates based on these assumptions for the effect of a cometary collision with the Earth. The energy, 10^{31} erg, is double the minimum energy required to remove the atmosphere and permit the tektites to be transported to great distances as estimated by Lin[7]. Of course, the energy was not dissipated in only vaporizing water or heating the atmosphere, or heating the ocean and so on, but the data indicate that a very great variation in climatic conditions covering the entire Earth should occur and very violent physical effects should occur over a substantial fraction of the Earth's surface. For example, the great seismic effects might initiate extensive lava flows. The scattering of melted bits of highly siliceous rocks should be only a very small and insignificant part of the physical effects. I suggest that the termination of a geological period would result and a new one would begin.

The scattering of ocean water over land areas would destroy land plants and animals, though probably such water would not fall uniformly and some would not be killed by this method.

Table 1 Energetic Effects a Cometary Collison with Earth Could Produce

Energy to the Earth from Sun in 1 yr	3.48×10^{31} erg
Earthquake of ninth magnitude	2×10^{25} erg
Energy of comet of 10^{18} g and velocity 45 km s^{-1}	10^{31} erg
Fraction of yearly solar energy	0.29
Energy required to remove atmosphere and scatter australites[7]	$4.4\ \times10^{30}$
If all energy absorbed by	
(1) atmosphere, elevation of temperature	190° C
or (2) ocean water, elevation of temperature	0.175° C
or (3) 100 m of ocean water, elevation of temperature	5° C
or (4) water volatilized at 100° C	4×10^{20} g
Edge of cube to contain this water	74 km
Area of ocean 3 km deep to contain water	1.33×10^{5} km^2
or (5) mass which could be thrown in circle about Earth	3.24×10^{19} g
or (6) earthquakes of ninth magnitude	5×10^{5}

The earthquake effect would be great in the immediate neighbourhood of the collision site, and would be noticeable over the entire Earth. The smog effect due to the ammonia and other compounds of the comet would probably be minor. Because the total energy is equivalent to 0.29 of the energy from the Sun for one year, which would raise the temperature of the atmosphere to 190° C if all heat went into the atmosphere, it seems that a considerable rise in temperature would occur. High temperatures for brief periods would be most destructive to animals and plants, and moderate rises in temperature with high humidity would destroy many living things. It seems that sea animals and plants would fare best if located at some distance where shock would not be important. But would this be true of the air-breathing marine dinosaurs? High humidity and air taken into cool bodies would produce considerable condensation of water in their bodies. Of course, other land based reptiles, such as alligators, as well as the primitive mammals and birds, survived from the Cretaceous into the Palaeocene. Such survival could be due to "good luck"—not all areas were equally affected and some animals and plants took the adverse conditions better than others. But it does seem possible and even probable that a comet collision with the Earth destroyed the dinosaurs and initiated the Tertiary division of geologic time.

Were the ages of Tertiary times determined by the fall of comets which produced the tektite fields? Table 2 lists the ages of these recent geologic periods and the ages of tektites. Rough agreement exists. Errors are probably present in both the geological estimates and the physical measurements of the tektite ages which are my averages of recent measurements. Probable errors in the Moldavites, Libyan Desert Glass and the Bediasites are about 2 m.y. The agreement is satisfactory. I wonder if tektites might not be found at some other boundaries between the Eocene, Palaeocene and Cretaceous periods? Lin[7] required nearly as great an energy as calculated here in order to account for the Indochina and Australian tektites, and this produced only a minor discontinuity in geologic strata, so it seems probable that the energy required for the termination of the Cretaceous was much greater than that estimated here.

Table 2 Ages of Geologic Periods and of Tektites

Geologic period	Ages[8] (m.y.)	Ages[9] (m.y.)	Tektites
Pleistocene		0.71 ± 0.10	Australites
	1	1.2 ± 0.2	Ivory Coast
Pliocene			
	13	14.7 ± 0.7	Moldavites
Miocene			
	25	28.6 ± 2	Libyan Desert Glass
Oligocene			
	36	34.7 ± 2	Bediasites
Eocene			
	58	?	?
Palaeocene			
	63	?	?
Cretaceous			

It seems likely that interesting studies could be made by biologists and palaeontologists in regard to the selection of survivors of such catastrophes. It will most probably be millions of years before the next collision occurs, but survivors of such an event would now most probably need to be able to survive the intense radioactivity from nuclear power plants which will be scattered over the entire Earth's surface. As I stated previously, "If the present suggestion gives the true origin" of tektites and also of breaks in the geologic record, "all will agree that any demonstration of the process would cost far more than the scientific knowledge gained would justify."

I am indebted to Professor Shao-Chi Lin for some suggestions in regard to this paper.

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Received December 1, 1972.

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Origin of Elements

We believe the recent report in *Nature*[1] under this title to be misleading in the light of recent observations. The recent measurement[2] of $a = {}^{12}C/{}^{13}C = 75$ (+25, −15) for the ζ Oph cloud is interesting but not surprising because it can be regarded as a confirmation of earlier work[3], as pointed out in ref. 1, and the conclusion that the relative abundance of ^{13}C in the ζ Oph cloud seems to be terrestrial is quite straightforward. It would be an unwarranted assumption to extrapolate the results from ζ Oph (and other tenuous clouds) to the dense, dusty regions of both the galactic centre and the Orion Nebula.

Zuckerman *et al.*[4] noted the possible presence of regions of high ^{13}C abundance in both Sgr A and Sgr B2 in their initial detection report of the ^{13}C isotope for formaldehyde. Whiteoak and Gardner[5] have continued the study of $H_2{}^{13}CO$ and find optical depths which are consistent with a $^{12}C/^{13}C$ abundance ratio no greater than half the terrestrial ratio—a result which supports an earlier conclusion[6] (from $H_2C^{18}O$ observations) that the $^{12}C/C^{13}$ abundance ratio in Sgr B2 is considerably less than the terrestrial value. In addition, Fomalont and Weliachew[7] have now used interferometric measurements to determine $^{12}C/^{13}C \sim 25 \pm 5$ for Sgr A and ≥ 20 for Sgr B2. We believe that the abundance anomalies in formaldehyde reported by Zuckerman *et al.*[4] have been substantiated by three independent types of subsequent observations.

Within the solar neighbourhood, the HCN detection report[8] ($J = 1$–0) indicated that the $^{12}C/^{13}C$ abundance ratio is possibly anomalous in the Orion Nebula; but saturation effects were unknown at the time. Since then, Wilson *et al.*[9] have measured the $J = 2$–1 transition and reported $H^{13}C^{14}N/H^{12}C^{15}N$ to be consistent with the terrestrial ratio, a result which has been interpreted to mean that the $^{12}C/^{13}C$ abundance ratio is probably normal. Subsequently, the hyperfine components of the $J = 1$–0 $H^{12}C^{14}N$ line were observed in Orion (L. E. S. and D. B., unpublished) and found to have almost normal intensity ratios—suggesting that this line is not heavily saturated and hence $H^{13}C^{14}N$ may be overabundant. Finally, the recent detection[10] of DCN gives a DCN/HCN abundance ratio more than an order of magnitude greater than terrestrial. Thus abundance ratios determined from measurements of HCN isotopes in the Orion Nebula may well be non-terrestrial; at present the correct interpretation is uncertain.

We note that recent radio measurements[11] of diatomic molecules such as CO give isotopic ratios consistent with terrestrial values in the Orion Nebula. It is possible that simple molecules have abundance ratios close to terrestrial while more complex species do not; thus isotopic abundances may reflect the dominant formation mechanism for each interstellar species. For example, if interstellar CO is formed primarily in the vapour phase, we might expect CO isotopic ratios which are similar to those of the ambient atoms (possibly terrestrial) but, if HCN formation or depletion relies on interstellar dust grains, we may find non-terrestrial HCN isotopic abundances. Optical abundance determinations from diatomic molecules such as CH^+ which are (by necessity) observed in tenuous interstellar clouds should be applied with great caution to dense dusty regions. Finally, although interpretation of radio measurements is often non-trivial, we believe that in the long run radio observations promise to be the most powerful ground-based tool we have for abundance ratios.

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