Experiment to measure the antimatter content of the Tunguska Meteor

On the morning of June 30, 1908 a meteor caused great damage in the region of the isolated trading station Vanovara in Siberia, Russia. Investigations of this meteor, called the Tunguska Meteor, have been described by Krinov[1]. Light from the meteor was visible even in a sunlit, cloudless sky. There was an explosive wave, with an energy between 3 and 5×10^{23} erg[2], blowing down trees over an area of approximately 2,000 km^2. Thermal energy, estimated to be between 1 and 2×10^{23} erg, caused fires and seared trees up to 18 km from the centre of the blast. But it appears as though the meteor never reached the ground, for no crater was formed, nor have any fragments been found which can be positively identified as part of the meteor.

Table 1 Average chemical composition of continental crust weight %

Element	% (weight)
Oxygen	46.6
Silicon	28.9
Aluminium	8.3
Iron	4.8
Calcium	4.1
Potassium	2.4
Sodium	2.3
Magnesium	1.9
Titanium	0.5
Phosphorus	0.1
Manganese	<0.1

Several explanations have been discussed by Krinov[1]. Cowan, Atluric and Libby have suggested that it was an antimatter meteor[3] and Jackson and Ryan have postulated that it was a black hole[4].

Cowan *et al.* suggested that if the Tunguska Meteor were a rock of antimatter, nuclear processes associated with the annihilation of the meteor would have increased the amount of ^{14}C in the atmosphere. Subsequent assimilation of the ^{14}C by trees might then be detectable. Their analysis of a tree that had been growing in Arizona in 1909 AD showed a smaller increase in the ^{14}C content than they had predicted. The significance of this was difficult to interpret because of what seemed to be random yearly variations of ^{14}C in the local atmosphere. Here I again examine the hypothesis of an antimatter meteor, to ascertain whether other experimental tests can be carried out.

Any event involving nuclear processes should produce radioactive nuclei. Of special interest is the electromagnetic cascade shower. This is produced in air by the decay into γ rays of the π^0s which are produced when antimatter nuclei annihilate. When an electromagnetic cascade shower containing a wide spectrum of γ rays strikes the ground, radioactive nuclei are produced as a result of many different photonuclear processes.

The major constituents of rock and soil are oxygen, silicon and aluminium with smaller amounts of iron, calcium, potassium, magnesium, phosphorous and sodium, in the amounts given in Table 1 (see ref. 5).

To determine which radioactive products might be produced, the reactions (γ, p), (γ, n), (γ, d), and (γ, 2n) on the various isotopes of the elements listed in Table 1 have been considered. Only a few of these reactions (listed in Table 2) produce nuclei which are sufficiently long lived to be detected now approximately 2×10^9 s after the event.

The reactions which produce ^{26}Al have been given special consideration for two reasons. First, silicon, and to some extent aluminium, are abundant elements in rock (Table 1). Second, ^{26}Al decays predominently by emitting a positron, whereas ^{39}Ar decays by emitting a β^- ray, and ^{53}Mn by electron capture. The decay signature of a positron emitter, with the accompanying annihilation radiation, allows the design of systems which will more readily discriminate against background and thus measure smaller total activities.

An experiment to detect the antimatter component of the Tunguska Meteor is thus conceptually simple. The ^{26}Al content of rocks or soil is measured as a function of the distance from the centre of the explosion. The highest concentration of ^{26}Al should be found near the centre. In order to assess the technical feasibility of the experiment, however, the production of ^{26}Al must be examined in more detail.

The number of ^{26}Al atoms, N_{26}, created in the soil and rock by the flux of γ rays is given by the expression

$$N_{26} = \sum_i \frac{A_0}{A_i} f_i \int \frac{dN}{dE} \sigma_i(E)\, dE \qquad (1)$$

where A_0 is Avogadro's constant $= 6.02 \times 10^{23}$ mol^{-1}, A_i is the atomic weight of the nucleus; f_i is the fraction by weight of the nucleus; $\sigma_i(E)$ is the cross section for production for ^{26}Al as a function of photon energy, E, and dN is the number of photons cm^{-2} with energy between E and E + dE. For the problem under consideration here, equation (1) contains only two terms, corresponding to the nuclei of ^{27}Al and ^{28}Si.

An accurate calculation of the production of ^{26}Al is not possible because of uncertainties in both the incident flux of γ rays and the production cross section of ^{26}Al. Some estimate of these quantities can, however, be made. The γ-ray flux may be estimated in the following way. When a proton and antiproton annihilate, an average of four charged and two neutral pions are produced[6]. Thus about half of the available energy goes into the rest mass of pions and the remainder goes into kinetic energy. Each neutral pion decays into two γ rays which initiate an electromagnetic cascade shower.

The energy density received at the ground is reduced by both the solid angle and absorption in the air. The explosion has been estimated to have occurred between 5 and 6 km up in the atmosphere[3]. The height of the meteor site is approximately 300 m. At a distance of 5 km, the solid angle subtended by each square centimeter of the ground is 3×10^{-13} sr. The air mass, calculated by using a scale height of 8.4 km and integrating from 0.3 to 5.3 km, is 430 g cm^{-2}. The energy absorption coefficient of an electromagnetic cascade shower in air is assumed to be the same as that measured for water, that is 0.013 cm^2 g^{-1} (ref. 7). This means that approximately 0.37% of the initial energy is transmitted through the air to the ground. The total energy, assumed to be 5×10^{23} erg, or 3×10^{29} MeV, is reduced by a factor of 6 because only a sixth of the energy is converted into γ rays, and by an additional factor of approximately 10^{15} resulting from a combination of the solid angle and absorption. Thus the energy flux at ground level is of the order of 5×10^{13} MeV cm^{-2}.

The energy spectrum of photons in the cascade shower is uncertain. Because of the kinetic energy of the π^0s, the initial decay gammas will have a rather broad energy distribution centred at 68 MeV. Processes such as pair production and Compton scattering with subsequent bremsstrahlung by the pair-produced electrons, will further degrade the photon energy spectrum. On the other hand, lower energy photons are more strongly absorbed by the Compton process. (Photoelectric interactions are negligible at the energies considered here.)

Most γ rays produced by cosmic rays and observed in the atmosphere seem to come from π^0 production near the top of the atmosphere[8]. Thus, because the physical process of absorption and creation are similar, the spectrum of the flux induced by the Tunguska Meteor might be expected to be similar to that produced by cosmic rays traversing the same thickness of atmosphere.

If the change in radioactivity is to be detected, the burst of radiation at the Tunguska site must be appreciable when compared with the total cosmic-ray flux integrated over the average lifetime of ^{26}Al. Two estimates of the integrated cosmic-ray flux lead to similar answers. The average radiation background resulting from cosmic rays at sea level is approximately 50 mR yr^{-1}. This implies a total dose of 2.4×10^8 MeV cm^{-2} yr^{-1}. The γ-ray flux integrated for energies of about 30 MeV and extrapolated to sea level is approximately 3×10^{-2} cm^{-2} s^{-1} (ref. 8). The integrated energy in this flux yields an energy of 3×10^8 MeV cm^{-2} yr^{-1}. The average lifetime of ^{26}Al is 1.07×10^6 yr and so the additional flux calculated to have been produced by the Tunguska Meteor represents a 15% increase in the total dose received over the past million years.

TABLE 2 Long-lived isotopes

Parent Nucleus	Reaction	Daughter Nucleus	Halflife (yr)
^{27}Al	γ, n	^{26}Al	7.4×10^5
^{28}Si	γ, d	^{26}Al	7.4×10^5
^{41}K	γ, d	^{39}Ar	269
^{54}Fe	γ, p	^{53}Mn	1.1×10^7
^{55}Mn	γ, 2n	^{53}Mn	1.1×10^7

To obtain the effective production rate, the γ-ray spectrum must be integrated with the cross section as shown in equation (1). The energy spectrum of γ rays in the atmosphere has been measured by Thompson[8]. Very approximately, the energy spectrum of γ rays at a depth of 500 g cm^{-2} can be fit by a power law of the form

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-1.6} \qquad (2)$$

The cross sections for the production of ^{26}Al in the ground state by either of the two reactions listed in Table 2 have not been measured. The cross section for ^{27}Al (γ, n) ^{26}Al*, where ^{26}Al is the 0.239 MeV first excited state ($\tau_{1/2} = 6$ s), has been measured for photon energies up to 62 MeV (ref. 9). If the ^{26}Al is initially formed in a highly excited state, the probability of radioactive decay to the short-lived first excited states with spin and parity of 0^+ should be about the same as for decay to the long lived ground state which has spin and parity of 5^+. For the predicted spectrum, equation (2), and the measured cross section, the integral evaluated by numerical methods is

$$\int \frac{\mathrm{d}N}{\mathrm{d}E}\cdot\sigma(E)\, dE = 3 \times 10^{-15} \text{ photons/nucleus.}$$

Values of the cross section for the second reaction ^{28}Si (γ, d) ^{26}Al have not been reported. The cross section for ^{32}S (γ, d) ^{30}P has, however, been measured from threshold to 80 MeV (ref. 10). If this measured cross section is used, a numerical value of the integral is obtained.

$$\int \frac{\mathrm{d}N}{\mathrm{d}E}\cdot\sigma(E)\, \mathrm{d}E = 2 \times 10^{-15} \text{ photons/nucleus}$$

In the following discussion a value of 2×10^{-15} photons/nucleus is adopted for both reactions.

The amounts by weight of silicon and aluminium in average rock are 29 and 8% respectively (Table 1). The production of ^{26}Al in rock at the centre of the meteor site, is therefore estimated to be 4×10^9 atoms per kg of rock. With an ^{26}Al half life of 7.4×10^5 years, this corresponds to an induced specific activity of approximately 10^{-2} d.p.m. kg^{-1} rock.

Tanaka *et al.*[11] have attempted to measure low levels of activity due to ^{26}Al found in deeply buried rock. They report an upper limit of 10^{-2} d.p.m. kg^{-1} rock, a value which is approximately the size of the predicted effect.

Most detection systems for measuring very low levels of positron emission consist, at least in part, of opposing NaI(Tl) crystals which detect in coincidence the two 0.511 MeV γ rays from the annihilation of the positron[12,13]. For such a system, and for a given observing time, the sensitivity, S, is defined as the ability of a detector to measure activity, and

$$S \propto \frac{\epsilon N}{\sqrt{B}} \qquad (3)$$

where ϵ is the detector efficiency, N is the number of nuclei that can be placed in the detector and B is the background rate. Tanaka *et al.*[11] suggested that the sensitivity of their instrument could be improved if larger detection crystals were used and if purer and more concentrated samples were obtained. These ideas suggest that considerable increase in sensitivity should be possible. For example, NaI(Tl) crystals are available with an area up to 100 times that of detectors used by Tanaka *et al.*[12] and Roedel[13], and three times as thick. Even if the background increases linearly with the volume of detector, sensitivity would be increased by a factor of six because more sample could be placed between the crystals. In addition, such large NaI(Tl) would increase the photo-fraction efficiency and thus the sensitivity.

The use of pure aluminium, rather than the Al_2O_3 used by Tanaka *et al.* would increase the reported sensitivity by a factor of about two because more Al nuclei could be introduced into the same volume.

It might be possible to select rocks, such as quartz or limestone; which are largely free from aluminium. The extraction of aluminium from such rock samples would increase the specific activity of ^{26}Al in the sample by more than an order of magnitude.

In addition to the ideas discussed above, a promising method of reducing the background in β^+ counting systems, by observing the positron in coincidence with the annihilation γ rays, has been developed[14]. We have recently developed a simple version of such a system which yields a gain in sensitivity of a factor of two over an equivalent two-γ-ray detector system.

With the technical improvements in detectors that seem feasible, a system with an increase in sensitivity of almost two orders of magnitude could be planned. This would allow the detection of an increase of only a few % in ^{26}Al content. The proposed experiment could then be readily carried out.

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Comets, solar wind and the D/H ratio

I WISH to speculate on the consequences of considering together two astronomical observations. First, the Sun emits a matter flux of $\sim 10^{12}$ g s^{-1} in the form of a solar wind[1]. The chemical composition seems to be rather similar to the solar photospheric composition[2]. So it incorporates a fractional mass of about 1% of atoms which are good candidates for grain formation (ices as CH_4, NH_3, H_2O; dusts as silicates and irons). Thus a flux of $\sim 10^{10}$ g s^{-1} of condensable matter flows away in the remote parts of the Solar System.

Second, the number of newly arriving comets (of long period) is about one a year with a mean mass of $\sim 10^{18}$ g (ref. 3) and a comet can be pictured plausibly as a conglomerate of ices and dusts[4]. Thus a mean flux of $\sim 3 \times 10^{10}$ g^{-1} of cometary matter flows inwards from the remote part of the Solar System.

These fluxes seem to agree within one order of magnitude or better. I assume that this is not a pure coincidence.

The process could be pictured in the following way. The ionised atoms of the solar wind follow the laminar flow lines until they reach a boundary where, presumably because of interaction with the interstellar magnetic field, the wind becomes turbulent. There, they are progressively decelerated, recombine, form molecules and eventually grains of increasing sizes. (Although very little is known about how the grains are formed, observations of interstellar matter indicate that the process must be very efficient; otherwise, how could the striking depletion of the refractory elements in the interstellar gas[5,6] be explained?) The grains are carried away by the turbulent gas and collide with each others. Dust and ices will mix and stick together, thus generating the embryos of comets.

These objects are subjected to two forces: the inward gravitional pull of the Sun and the drag force of the turbulent motions with its residual outward component. As the size of the object increases the second force becomes gradually weaker than the first. The outward motion is decelerated until the object start moving toward the Sun. A comet is born.

So we have a picture of a stationary cloud in which matter is fed in through the solar wind, and out through conglomerates of ices and dusts. The cloud has, in the past, grown to a stage at which the feeding out just compensates the feeding in, thereby explaining the rough equality between the two fluxes.

Before this model becomes credible several points will have to be clarified, several quantitative estimates (of the location and properties of the cloud, of the accretion rate in the cloud and so on) will have to be carried out and several 'tests' will have to be 'passed.' For example, the observed distribution of kinetic energies, of ellipticities and of orbital inclinations of the comets should find a reasonable explanation within the frame of the model.

The orbital planes of the long-period comets do not seem to raise any problem: they are tilted in all directions as expected from the plausible spherical symmetry of the solar wind. The eccentricities would be assigned to such effects as the random drag velocities of the cells.

But at present, instead of pushing this discussion further, I stress the importance of measuring the D/H ratio in cometary matter by showing its relevance to the problem of the origin of the comets.

The D/H ratio in interstellar space is 1.5×10^{-5} (ref. 7). In oceanic and meteoritic water, on the other hand, the ratio is 1.4×10^{-4}; the increase is probably due to molecular exchange reaction at the time of formation of the water[8]. In the solar wind $D/H < 3 \times 10^{-6}$, (ref. 9) compatible with the fact that the Sun burned its deuterium in its early days.

Clearly this model of comet formation would predict essentially no D ($D/H \ll 10^{-5}$). If, on the other hand, the comets were made early in the history of the Solar System, by matter left over from the protosolar condensation (the Oort's cloud), depending on their formation temperature we should have in the various cometary molecules a D/H ratio of anything from 10^{-5} to 10^{-4} and possibly even more (see tables in ref. 10). Measurements of DCN/HCN, CH_3D/CH_4, OD/OH in comets would be of the utmost importance.

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Evolution of dense galactic nuclei through dwarf star collisions

STELLAR collisions are important in dense galactic nuclei[1–3]. QSOs, N galaxies and Seyfert galaxies release energy on similar short time scales[4–7] but detailed models of stellar collisions have been limited so far to collisions between two main sequence stars, with the conclusion that for an initial relative velocity $V_{rel} \lesssim 10^3$ km s^{-1}, and small impact parameter, coalescence follows. At $V_{rel} \sim 5{,}000$ km s^{-1} two colliding main sequence stars are largely disrupted and a non-negligible amount of relativistic particles is formed[8]. Here we draw attention to the fact that a very important type of collision in dense galactic nuclei is one in which a white dwarf (WD) is involved.

Van den Bergh[3] has pointed out that most collisions in the nuclei of 'normal' galaxies such as M32 involve two dwarf M stars or one M dwarf (dM) and one late-type giant. The reason is the high abundance of dM stars and the large cross section of giants. The evolution of a nucleus therefore depends on the outcome of WD-WD, WD-dM, dM-dM and dM-giant collisions. We neglect dM-giant collisions because most of them will occur in the highly rarified atmosphere of a giant and consequently will have a very small effect. For simplicity we discuss only dM-WD collisions with impact parameter p smaller than $0.75R$, where R is the radius of the red dwarf.