Allowance has been made for the lower efficiency of a galactic cosmic ray-type spectrum (of γ-rays) for depositing energy in the region of the atmosphere populated by O_3 (a factor of ~ 25 down in energy density).

Also indicated in Fig. 1 is the energy density integrated over the whole of the SNR (SNR *p* (all time)). This variation would be relevant to those biological processes involving gradual reduction in quality over many generations.

It is interesting to estimate the likely radiological dose rate at the Earth's surface from the big solar flares. The galactic flux generates ~ 30 mR yr^{-1} at ground level (corresponding to $\sim 10^{-2}$ erg cm^{-2} s^{-1} of incident energy. Line *b* extrapolated indicates that a dose of 10^{11} erg cm^{-2}, corresponding to 10^4 R, would occur ~ every 10^5 yr. Allowing for the eventual undoubted fall-off in $P(>\varepsilon)$ below the extrapolated line such a dose (lethal even to very primitive forms of life) would probably still occur more often than once every 10^8 yr. Such large flux densities do not necessarily indicate flares larger by many orders of magnitude compared with those observed in 1959. More likely would be situations where flares just a few orders bigger occurred at a time when a favourable (?) magnetic field geometry focused a significant fraction of the ouput onto the Earth.

Finally, attention is directed to a quite different phenomenon: the possibility of extremely energetic bursts from the galactic centre. Briefly, there is the possibility that the 3 kpc 'ring' is due to a radially symmetric explosive event in the galactic nucleus. With the ejection of $\sim 2\times 10^8\ M_\odot$ the initial energy is at least 3×10^{58} erg (ref. 7). On this model, the explosion occurred $12\text{–}13\times 10^6$ yr ago (or earlier if there is oscillation of the ring). If the explosion resulted from the collapse of a very massive object then γ-ray emission would be very likely and, according to Colgate[18], the fraction of energy in this form would be large. Extrapolating from the value for less massive objects we take $f\sim 10^{-3}$ giving $\simeq 10^{55}$ erg in γ-rays. If $\sim 10\%$ of galaxies were to give bursts of this type then γ-ray bursts would occur at about the observed frequency.

With the γ-flash from the galactic centre the energy density at the Earth is $\sim 10^9$ erg cm^{-2}, a value that again exceeds the flux from local supernovae.

In conclusion, in addition to close supernovae, solar flares and explosions at the galactic centre should be borne in mind when considering possible catastrophes experienced by the Earth in its history. A more detailed study of solar and stellar flare data and ancient records of solar activity would appear to be profitable.

We acknowledge with gratitude discussions with D. H. Clark, W. H. McCrea, K. O'Brien, J. L. Osborne and F. R. Stephenson. The referee is thanked for very helpful remarks and criticisms.

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Received 22 March; accepted 24 June 1977.

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Tunguska's comet and non-thermal ^{14}C production in the atmosphere

THE dramatic explosion on 30 June 1908 over Tunguska, Siberia continues to generate a wealth of literature on the supposed mysterious nature of the phenomenon. Hughes[1] recently summarised the generally convincing case for the hypothesis, first put forward by Whipple[2] and Astapovich[3], that a comet collided with the Earth's atmosphere. Opposition to this theory and consequent support for less conventional hypotheses involving black holes[4], almost critical masses of extraterrestrial fissionable material[5], anti-matter bodies[6] and alien spacecraft[7] have been based substantially on the non-observance of the comet before impact, the explanation of height of the explosion above the Earth's surface, the composition of the glassy spherules found at Tunguska and finally, and of most importance, the apparent occurrence of nuclear phenomena in the explosion as indicated by the subsequent enhancement of radiocarbon in the atmosphere. In the following, we discuss the first and last of these points which are clearly the most important.

Ben-Menahem[8] re-analysed the old seismograms of the Tunguska event and deduced the parameters of the original explosion by comparing the old data with contemporary records of the seismic and acoustic effects of recent nuclear air explosions. He concluded that the main explosion had an energy of $(5\pm 1)\times 10^{23}$ erg and occurred at a height of 8.5 km. The size of the incident body can be estimated by assuming that its original kinetic energy was entirely converted into explosive energy. Krinov[9] found the geocentric velocity to be between 28 and 50 km s^{-1}, Levin[10] gave a geocentric velocity of 47 km s^{-1}. This latter value gives the body a mass of 5×10 g. Assuming the body is a cometary nucleus, of density 1.14 g cm^{-3} (ref. 11) its equivalent diameter is found to be 40 m. The absolute visual magnitude, m_0 of a comet of mass M (its magnitude 1 AU from both the Sun and Earth) is given by[12]

$$\log_{10}(M \text{ in g}) \simeq 21 - 0.4\, m_0 \tag{1}$$

so the Tunguska comet had $m_0 = +26$.

The apparent magnitude, m of the comet when it is a distance r AU from the Sun and Δ AU from the Earth is given by[12]

$$m = m_0 + 5\log_{10}\Delta + 10.5\log_{10} r \tag{2}$$

The two equations given above are mean, rule of thumb relationships obtained by considering the observed parameters of a great many comets. Some comets are notorious for departing from expected behaviour but in the absence of any observations of the Tunguska comet we can only assume that it was one of the more well behaved members of its species and obeyed the equations given.

Table 1 Apparent magnitude, *m* and time to impact *t* of the comet as a function of its distance from the Earth

Δ(AU)	*r*(AU)	*m*	*t*(min)
0.002	1.0	12.4	104
0.001	1.0	10.9	51
0.0005	1.0	9.4	24
0.0002	1.0	7.4	8
0.0001	1.0	5.9	3

Values of m for certain specific values of Δ are given in Table 1. Also given in Table 1 is the time t taken by the comet to travel, at 47 km s^{-1}, from a point Δ AU away from the Earth to the Earth's surface. At the turn of the century comets were usually discovered at magnitudes around +11. The Tunguska comet is only brighter than this value for about 1 h before it impacts with the Earth, ample reason for it not being seen on its earthward path. Fesenkov[13] finds that, for all possible cometary orbits calculated from the fireball trajectory, the angular distance between the comet and the Sun is small. When the comet encountered the Earth it would be coming from a point in the dawn sky comparatively close to the Sun and would thus be most difficult to detect and observe. The orbital configuration is similar to Comet Mrkos which was only detected after having rounded the Sun and travelled beyond the Earth's orbit.

It is most difficult to calculate the expected flux of these very small cometary nuclei to the Earth's surface because of the lack of relevant observational data. Vsekhevyatskii[14] gives cumulative number data for comets with $1 < \mathrm{mag}_0 < 14$. A wanton extrapolation of Whipple's[15] interpretation of this data gives a value of 7×10^8 for the number of comets brighter than $\mathrm{mag}_0 = +26$ which pass within 1.2 AU of the Sun within 100 yr. Using Everhart's[16] calculations the chance of such a comet striking the Earth is about 5×10^{-2} in 100 yr; so one on average should hit the Earth every 2,000 yr.

Comparing the ablation and deceleration of the cometary nucleus with that of a meteoroid forming a meteor train it can crudely be assumed that one atom (or molecule) of the incident body is ablated (albeit with a high energy) when it is struck by an atom (or molecule) of the atmosphere. The cometary nucleus thus explodes when it has collided with a mass of air equal to its own mass. Assume that the atmosphere has a density, ρ, at a height h of $\rho = \rho_0 \exp(-h/H)$ where ρ_0 is the density at ground level and H is the scale height (~ 7 km). The cometary nucleus (radius r_c, density ρ_c moving on a trajectory inclined at an angle χ to the vertical will intersect a mass M_c in descending to height h_1, where

$$M_a = \pi r_c^2 \sec \chi \, \rho_0 \int_{h_1}^{\infty} \exp(-h/H)\, \mathrm{d}h \qquad (3)$$

M_a is equal to the comet mass $(4\pi \rho_c r_c^3/3)$ at the explosion height h given by

$$h_e = H \log_e \left(\frac{3 \sec \chi \, \rho_0 \, H}{4\pi r_c \, \rho_c} \right) \qquad (4)$$

Putting $h_e = 8.5$ km, $H = 7.1$ km, $\rho_0 = 10^{-3}$ g cm^{-3}, $r_c = 2.1 \times 10^3$ cm and $\rho_c = 1.14$ g cm^{-3} gives $\chi = 1.5°$. Fesenkov[13] concluded that χ was between 65° and 70° and probably larger, Levin[10] calculated χ to be 82°. The low value calculated above is probably due to the initial assumption of a one to one ratio between collision atoms and ablated atoms. The formation of an aircap around the nucleus in the lower, denser, regions of the atmosphere will lessen the ablation and enable it to traverse a longer atmospheric path and thus have a higher value of χ.

Magnetite and silicate globules, 80–100 μm in size, were recovered from the soil near the explosion site. Detailed analysis of these revealed small amounts of Co and Ni as well as traces of Cu and Ge[17] and this has been offered as partial proof of the 'alien spacecraft' hypothesis. It must be remembered, however, that these elements are most probably present in the dust of the cometary nucleus at their normal cosmic abundances. Their high values of ionisation potential vitiates against them showing up in cometary spectra.

One of the major stumbling blocks of the cometary impact Hypothesis is the ^{14}C anomaly that is said to have occurred in 1909. Cowan *et al.*[6] found that the ^{14}C activity was higher in that year than normal and deviated from the mean by over two standard deviations (but see ref. 18). Cowan *et al.*[6] manufactured this extra radiocarbon in the atmosphere by proposing that 1/7 of the Tunguska energy was due to anti-matter annihilation. Hunt *et al.*[5] produced this ^{14}C excess by a nuclear explosion at Tunguska. A sudden influx of ^{14}C into the Earth's atmosphere will be observed as a positive anomaly in the graph of radioactive CO_2 content as a function of time, this anomaly having a width (to half maximum values) of about 2.4 yr. This is because atmospheric CO_2 is continually being removed by plants in the biosphere, converted to humus and then returned to the atmosphere as this humus decays; 5% is absorbed each year in this way. CO_2 also dissolves into the oceans, rainfall helping considerably, and this removes about 20% yr^{-1} (see ref. 19). So 25% of the atmospheric CO_2 is being locked away each year, remains locked away for between 10 and 50 yr and is subsequently slowly returned by plant decay and oceanic evaporation.

Now, if all the kinetic energy of the comet (5×10^{23} erg) were converted into heating its constituent particles and an equal mass of the atmosphere (mean mass 12) the temperature obtained would be about 2×10^6 K. Since this is substantially sub-nuclear it has been argued that normal cometary impact could not have produced the observed radiocarbon. It is entirely fallacious to suppose that sub-nuclear temperatures cannot produce nuclear effects as can be seen by consideration of the solar flare phenomenon. In a flare, the mean temperature of the particles is certainly less than 2×10^7 K, that is an energy of order 10^{32} erg distributed among some 10^{16} g. Even at the low densities of the solar atmosphere, many associated high energy phenomena are seen to occur—the production of X and γ rays, MeV electrons and GeV nuclei[20]. The mechanism by which these are produced is still not properly understood but qualitatively may be attributed to stochastic acceleration of particles in the turbulent spectrum of plasma waves generated in the flaring atmospheres by the primary energy release. Although this process is magnetohydrodynamic in character the solar magnetic field need not play any direct part (other than as the source of energy) since the large particle velocities and the ionisation produced by any explosion can generate the necessary magnetohydrodynamic conditions. Similar results are, therefore, to be expected in the Earth's atmosphere following a cometary impact.

We can estimate the ^{14}C production in the Tunguska cometary impact by a rough scaling comparison with the flare results, without specifying the detailed process. The collisional production of energetic neutrons by the accelerated particles varies as $nNQV\tau$ where n is the atmosphere number density in the heated atmosphere, N the total number of particles in the heated volume, Q the neutron production cross section, V, the mean particle velocity, and τ the duration of the event. Thus if υ is the number of neutrons produced and the comet and flare characteristics are denoted by subscripts C and F then

$$\upsilon_c = \upsilon_F \frac{n_C N_C Q_C V_C \tau_C}{n_F N_F Q_F V_F \tau_F} \qquad (5)$$

From the cometary mass of 5×10^{10} g we have $N_c \simeq 2 \times 10^{33}$ while the atmospheric density at 8.5 km gives $n_c \simeq 2 \times 10^{19}$ cm^{-3} and for a flare $N_F \leq 10^{40}$. The density in the flare acceleration region is uncertain but is probably around $n_F \simeq 10^9$ cm^{-3}, and the typical flare duration is $\tau_F = 100$ s. Chupp *et al.*[21] have set an observational upper limit to the number of 20 meV neutrons formed even in a 2B flare as $\upsilon_F \leq 10^{25}$. Thus from equation (5) we have

$$\upsilon_C \simeq 3 \times 10^{26} \left(\frac{Q_F V_C}{Q_F V_F} \right) \tau_0 \qquad (6)$$

The factor in parentheses in equation (6) is uncertain because the detailed process of neutron formation is unknown. Certainly the typical nuclear collision speed V_c in a cometary impact explosion may be less than that in a flare (V_F) since the explosion temperature driving the plasma process is lower. On the other hand, the neutrons proposed by Cowan *et al.*[6] for radiocarbon formation are only of about 10 MeV energy so Q_C/Q_F may be substantially larger than unity. If, therefore, we estimate the whole parenthetic term in equation (6) as unity then we expect 3×10^{26} τ_C neutrons to be formed in a Tunguska-type cometary impact. By comparison Cowan *et al.*[6] estimate that about 10^{27} neutrons are required to explain the radiocarbon data. Thus, if the necessary hot plasma conditions were sustained in the Earth's atmosphere for at least 3 s (a very plausible figure compared with the duration of enduring meteor trails, overdense diffusion times, etc.) then the required neutron formation would probably ensue by non-thermal plasma processes.

We conclude, therefore, that within the uncertainties of the effect of chemical composition on collective plasma acceleration processes and on collisional neutron production, the number of neutrons expected in the Tunguska impact, as scaled from solar flares, is in remarkably good agreement with the radiocarbon data requirements. Also the low mass of the comet (5×10^{10} g) coupled with its extreme faintness ($mag_0 = +26$), and its position in the dawn sky, just before impact makes its prior discovery extremely unlikely. These points strongly support the suggestion that the Tunguska explosion was caused by an impacting small comet and that nothing more exotic need be invoked.

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Received 24 January; accepted 23 June 1977.

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Antarctic topography from balloons

ANTARCTIC ice surface elevation maps are far from being complete, due to the difficulties in applying regular surveying and mapping techniques in Antarctica. A new wealth of ice sheet surface topography data is now available, from many balloons, floating at an altitude of about 12.5 km, which traversed the Antarctic during its 1975 summer. These balloons were part of 411 constant density balloons launched in the Southern Hemisphere during the Tropical Wind, Energy conversion and Reference Level Experiment (TWERLE)[1]. Each balloon carries three sensors: radio altimeter[2], pressure sensor[3] and ambient temperature sensor. The balloon transmits data once per minute, as long as its solar panel is sufficiently illuminated[4]. The data are received by the Random Access Measuring System (RAMS)[5] on board the NIMBUS–6 satellite, whenever the balloon is within line of sight.

The near Polar orbit of NIMBUS–6, and the continuous summer daylight combined to allow continuous coverage of TWERLE balloons, south of 66°S, during December 1975 and January 1976. Continuous coverage means 13–14 passes per balloon in 24 h. The longest pass is an overhead one, which lasts more than 15 min, hence the data consists of 15 transmissions, or less, per pass. In addition to recording the balloon's sensors data, RAMS also measures the received carrier frequency. The Doppler history of up to 15 transmissions during an overpass yields the balloon position[6]. Two consecutive passes can produce the wind information.

The average balloon life during TWERLE was slightly more than two months, with some balloons lasting more than a year. The launching strategy and the general circulation at balloon height caused a typical daily concentration of about 40 balloons south of 45 °S, during December 1975–January 1976. Many of these ballons traversed the Antarctic Continent.

The extent of Antartic coverage by the TWERLE balloons is summarised in Fig. 1. This gives the total coverage from all the balloons during the period 1 November 1975–19 March 1976. Each symbol on the map indicates the total number of measurements over a square of 55×55 km. A measurement is the average of up to 15 balloon transmissions, 1 min apart, recorded during the satellite overpass. As Fig. 1 shows there is almost complete coverage over Antarctica, with many squares being traversed more than once.

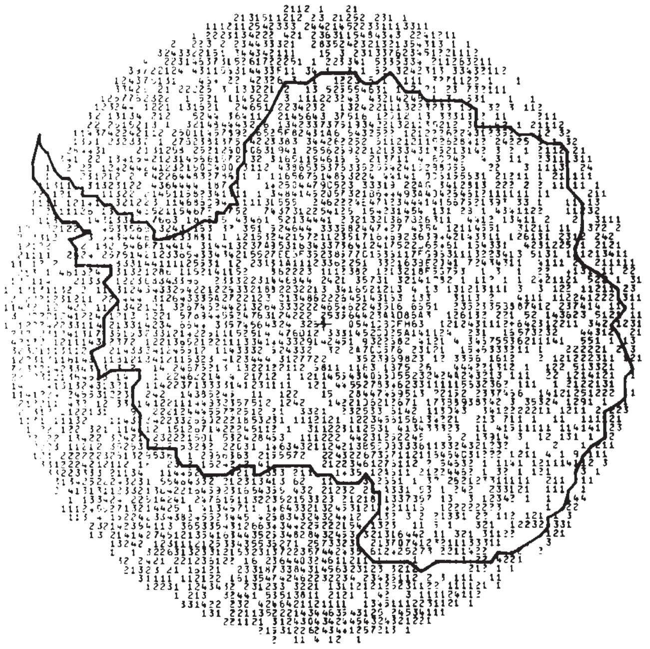

Fig. 1 TWERLE balloons coverage over Antarctica 1 November 1975–19 March 1976. Each symbol indicates the number of measurements over a square 55×55 km ($1 = 1, \ldots. 0 = 10$, $A = 11, B = 12, \ldots..$). The data boundary corresponds to 65 °S, and 0° longitude is up.

The radio altimeter data over Antarctica resembles over-water data, as far as standard deviation of the 15 altitude readings per pass. This small standard deviation is due to the flatness of the ice cover. The ice flatness further contributes to the measurement accuracy by reducing the adverse importance of position error, which is specified at 5 km.

To obtain the surface elevation from the altimeter readings it is necessary to know the balloon's altitude above sea level (a.s.l.). Constant altitude could not be assumed because (1) the altitude of a constant density level is not constant, and (2) the balloon equilibrium density changes following diurnal cycles. What can be assumed constant, for several hours at least, is the altitude a.s.l. of a pressure level along the balloon trajectory. This is the result of the quasi-geostropic nature of the wind. In other words, the balloon, which follows the wind, is moving parallel to the isobars. It can be concluded that the balloon altitude a.s.l. could be calculated if the altitude of a reference pressure surface above the balloon subtrack is known once a day. 150 mbar was chosen as this reference pressure, because it is the standard radiosonde level nearest to the balloon flight level.

The relation between the surface elvation, the altitude of the 150 mbar pressure surface and the altimeter reading is

$$E = Z(150\ \text{mbar}) — (P + P_{\text{corr}} - 150)\,(0.2T + 53.7) + \\ + (75 \cos^2\Phi - 15) - h \qquad (1)$$

where E is the surface elevation a.s.l. in metres, Z(150 mbar) is the altitude of the 150 mbar surface in geopotential metres, P is the pressure sensor reading in mbar, P_{corr} is the pressure sensor correction in mbar, T is the ambient temperature reading in °C, Φ is the latitude and h is the altimeter reading in metres.

The second term on the right hand side is the altitude difference between the balloon's pressure level and the 150-mbar pressure level, using a linear approximation to the hydrostatic