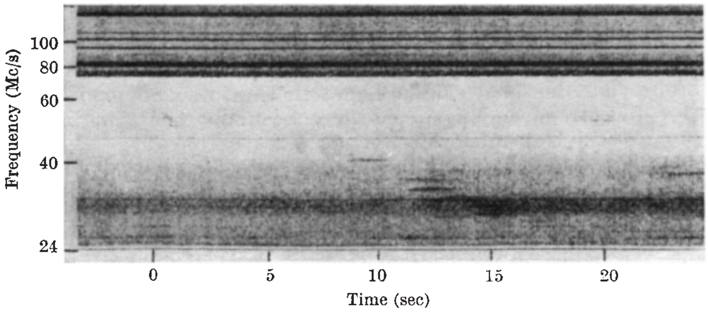

Fig. 1. Wide range record showing split pair group.

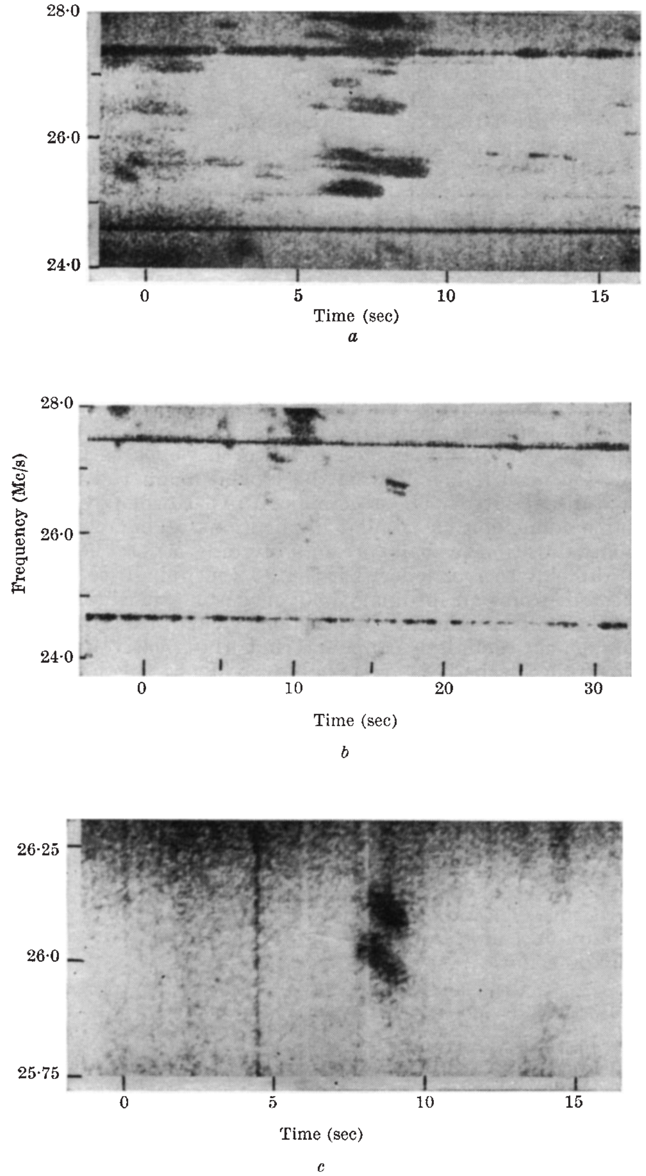

Fig. 2. *a*, 24–28 Mc/s record showing frequency splitting of bursts within a group. *b*, Individual pair. Note the greater intensity of the higher frequency component. *c*, Enlarged record showing frequency-time slope.

mode in the vicinity of the second harmonic of the cyclotron frequency. The frequency will depend also on the direction of emission, and two waves of differing frequencies corresponding to forward and backward emission normally will be observable. The velocity of the guiding centre would need to be only about 0·01 *c* to produce the small frequency splitting observed. If the mean direction of motion is outwards through the corona, then this velocity is consistent with the observed rate of change of the centre frequency. The polarization of both components would be ordinary in this event.

Polarization observations may thus be expected to throw more light on the origin of the split pairs, and in association with directional measurements may produce new information about the dynamics of particles and the magnetic fields in the solar corona.

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G. R. A. Ellis
P. M. McCulloch

Department of Physics,
University of Tasmania.

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PLANETARY SCIENCE

Anti-matter Content of the Tunguska Meteor

Cowan *et al.*[1] have advanced the hypothesis that the 1908 Tunguska meteor explosion resulted from the anti-matter content of the meteorite. Although their analysis indicates a probable upper limit of 1/7 for the anti-matter content of the Tunguska meteor, this result depends to a large extent on the validity of certain assumptions used in the calculations.

The present analysis should be considered an extension of the former work and assumes as its starting point the previously determined four charged pions produced per nucleon pair annihilated. Whereas Cowan *et al.* assumed that only negatively charged pions are absorbed by atmospheric nuclei (and thus instrumental in producing carbon-14), the cross-section data of Marshak[2] indicate that the mean free path for nuclear absorption is essentially the same for both positively and negatively charged pions. This is reasonable as the pion-nucleon interaction arises mainly from the nuclear rather than electrostatic forces. If the charged pion mean free path σ for nuclear absorption is taken as 80 g cm^{-2} in air[3], it is possible to compare the fraction of pions which decay with the fraction which are absorbed provided the pion mean life is known. Horwitz *et al.*[4] report an average total energy E_T of 380 MeV per charged prong in the $p\bar{p}$ annihilation. The charged pions then have an average kinetic energy E_K of 240 MeV (the rest mass energy E_0 is 140 MeV) and a small relativistic correction to the mean life τ_m of the pion is necessary. A conservative estimate of the increased pion mean life τ' can be made by assuming an essentially constant speed equivalent to $E_k = 240$ MeV. Since $E_T = \gamma E_0$, $\tau'_m = \gamma\tau_m$ ($\gamma = [1-\beta^2]^{-\frac{1}{2}}$), then $\tau'_m = (380/140)\,(2\cdot54 \times 10^{-8}\ \text{sec}) = 6\cdot9 \times 10^{-8}$ sec.

If n_0 represents the total number of charged pions produced initially by annihilation reactions, then the number of pions n remaining at some later time t would be $n = n_0 \exp - \left(1/\tau'_m + \frac{\bar{\rho}\bar{v}}{\sigma}\right)t$, where $\bar{v}$ and ρ represent respectively the average pion speed and atmospheric density along the flight path. Since $\bar{\rho}\bar{v}/\sigma$ is effectively the probability of absorption per unit time, then by letting $\lambda_a = \bar{\rho}\bar{v}/\sigma$ and $\lambda'_m = 1/\tau'_m$, the above expression may be written $n = n_0 \exp - (\lambda_a + \lambda'_m)t$. Since in this form the expression for n is similar to that for branched radioactive decay, branching ratios for decay and absorption may be defined as $R_d = \frac{\lambda'_m}{\lambda'_m + \lambda_a}$ and $R_a = \frac{\lambda_a}{\lambda'_m + \lambda_a}$, respectively. For an explosion at a height of 5 km, $\bar{\rho} = 7 \cdot 3 \times 10^{-4}$ g-cm^{-3}, and if $\bar{v} = 0 \cdot 9\, c$ ($v = 0 \cdot 93\, c$ for $E_k = 240$ MeV), then $R_d = 0 \cdot 983$ and $R_a = 0 \cdot 017$.

Whereas the previous analysis assumed that 50 per cent of the charged pions were absorbed thus producing a 7 per cent increase in radiocarbon activity, the calculations already given indicate only 1·7 per cent are absorbed thus yielding only a 0·24 per cent increase in radiocarbon activity. Although this value may only be correct to within a factor of two owing to over-all uncertainties in the initial assumptions, it is questionable whether a 0·24 per cent increase in radiocarbon activity would be detectable. Cowan *et al.* report an increase equivalent to about 1 per cent in some tree rings around 1909, but Suess[5] finds no change whatsoever in another sample. These results are consistent with the hypothesis that the Tunguska meteor was entirely anti-matter in content.

A closer look at the mechanisms which initiate thermonuclear and anti-matter explosions is now in order. Of the 200 MeV available as a result of uranium-235 fission about 85 per cent is converted immediately into kinetic energy of very short range fission fragments (less than 3 cm in air at sea level), thus liberating a tremendous amount of energy within a relatively small volume. The formation of a fireball from a fission-fusion explosion arises primarily from this phenomenon.

In contrast to this approximately 65 per cent[4] of the energy available in a $p\bar{p}$ annihilation goes into charged pions and the remainder into neutral pions (assuming the kinetic energy is the same as that of the charged pions). The charged pions which are absorbed ($\approx$ 2 per cent of the total) by atmospheric nuclei result in neutron and proton emission from excited nuclei. Because the neutron mean free path in air is much too large to permit much absorption close to the explosion centre, only proton interactions will contribute any significant amount of energy to the growth of the fireball. Thus, of the charged pions which are lost through the process of nuclear absorption, less than 1 per cent are effective in contributing to the thermal yield of the explosion.

In evaluating the contribution of the charged pions which decay (greater than 98 per cent of the total generated) to the thermal yield it is well to note that the decay products are muons and neutrinos ($\pi^+ \rightarrow \mu^+ + \nu$). The neutrinos, of course, contribute essentially no energy whatsoever to the thermal yield. The muon contribution depends on the average energy at which the pions decay. Using pion range-energy curves[3] a value of $-dE/dx = 2 \times 10^{-3}$ MeV/cm is deduced for rate of energy loss of 200 MeV pions in air at sea level. More than 98 per cent of the pions decay within six half-lives, and using the above datum, calculations show that the pions suffer little energy loss during this interval (less than 15 MeV on the average). By calculating the maximum and minimum muon energies (in the laboratory system) resulting from pion decay, the average muon kinetic energy is taken as about 160 MeV. Owing to the extremely large absorption mean free path in air, nearly all the muons will decay before being absorbed. Because the maximum kinetic energy of the electron from muon decay is 52·3 MeV in the muon reference frame, a certain portion of these decay electrons will possess enough energy in the laboratory system to initiate electronic showers and with lower energy decay electrons will aid in the development of a fireball.

As mentioned earlier, more than 30 per cent of the $p\bar{p}$ annihilation energy is channelled into neutral pions. Owing to the extremely short mean life ($\approx 10^{-15}$ sec) these pions disappear rapidly yielding mostly high energy quanta (99 per cent) and a smaller proportion (1 per cent) of electrons and positrons. The absorption mean free path[6] of 50–100 MeV quanta in air is about 67 g cm^{-2}, implying that most of this energy will be absorbed at large distances, thus adding relatively little to the thermal yield of the explosion. Thus, the over-all contribution to fireball growth from neutral pion decay electrons and positrons may be about the same as for those from muon decay.

Although qualitative in some respects, these calculations permit a comparison to be made of the energy distribution between an ordinary nuclear explosion and an anti-matter explosion. In an air burst[7] of a fission-fusion device roughly 50 per cent of the energy is dissipated in blast and shock effects, 35 per cent of the total yield appears as thermal radiation, 5 per cent as initial nuclear radiation, and 10 per cent as residual radioactivity. These percentages are of course dependent on altitude. The significant point for this type of explosion is that a major proportion of the particles emitted in the fission-fusion reactions dissipate their energy within a short distance, thus producing conditions favourable for the formation of a fireball.

In contrast the greater percentage of primary particles produced in an anti-matter explosion rapidly decay, and the secondary emissions will in general be absorbed over a relatively large volume. Qualitatively it might be expected that within a certain critical volume near the explosion centre the secondary and to a lesser extent the primary emissions would produce conditions favourable to the development of a fireball. Under these conditions it would not be surprising if the percentage of thermal yield from an anti-matter explosion was considerably less than that resulting from an ordinary nuclear explosion.

The observations of an eye-witness to the Tunguska meteor explosion are significant at this point. As Cowan *et al.* point out, the fireball did not last long. S. B. Semenov, an observer, just managed to lower his eyes as the explosion occurred, and when he looked again the fireball had disappeared. The account of P. O. Kosolopov in the same connexion has similar implications. This relatively short duration fireball (presumably only several seconds) is difficult to reconcile with the 33 sec fireball[7] to be expected from an ordinary 30 megaton thermonuclear explosion (the calculated equivalent yield of the Tunguska burst). It definitely appears that the relatively short duration fireball is reasonable evidence against the Tunguska explosion being thermonuclear in nature. A Monte Carlo calculation would be necessary to evaluate properly all the parameters involved, but it certainly seems possible that an anti-matter explosion of this yield would have a fireball of only a few seconds owing to the vastly different nuclear interactions inherent in the process itself. Finally, very recent studies indicate the possibility that certain shock haloes in biotite are of anti-matter origin[8].

ROBERT V. GENTRY

Institute of Planetary Science,
Columbia Union College,
Takoma Park, Maryland.

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Strontium : Calcium Ratio in Tourmalines from South-west England

GOLDSCHMIDT has pointed out[1] that during the cooling of an igneous magna the earliest formed calcium minerals would be poor in strontium relative to calcium while later calcium minerals would show a progressively higher