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Search for anti-neutrino bursts with an extensive air shower array

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Abstract. A search has been made for anti-neutrino bursts from collapsing stellar systems using the Haverah Park extensive air shower array. No event was detected in time coincidence with the burst reported by Lande *et al* implying that the energy of the anti-neutrinos in that event was less than 85 MeV. Bursts of 100 MeV anti-neutrinos having a flux of 10^{11}–$10^{12}\,\bar{\nu}_e\,\mathrm{cm}^{-2}$ are in principle detectable with our array but none was observed in a recording period of 44 000 h.

1. Introduction

The possibility that collapsing stellar objects might give rise to bursts of anti-neutrinos was pointed out by Zel'dovich and Guseinov (1965), and is of crucial interest from the viewpoint of gaining information on stellar interiors. Lande *et al* (1974) have reported the observation, on 4 January 1974, of a sequence of bursts in underground water-Čerenkov detectors which may have been caused by the electron anti-neutrinos, $\bar{\nu}_e$, expected from such a stellar collapse. The anti-neutrinos would be detected through the reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, of the anti-neutrinos with protons in the water of the detector. From their data Lande *et al* deduce a lower limit to the $\bar{\nu}_e$ flux of $1{\cdot}5 \times 10^{11}\,\bar{\nu}_e\,\mathrm{cm}^{-2}$ for 50 MeV anti-neutrinos. If the burst is indeed caused by anti-neutrinos then a source flux of $1{\cdot}4 \times 10^{53}$ erg at the galactic centre (distance ~ 10 kpc) would supply the observed energy. The energetics of such a source are consistent with the predictions of Zel'dovich and Guseinov (1965).

Additional experimental information relevant to this very unusual event is desirable. Wolfendale (private communication, Pallister and Wolfendale 1974) and Weekes and Porter (1974) have pointed out that some extensive air shower (EAS) arrays might have been expected to record the event, but no such coincidences appear to have been registered. The principal method of detection available to EAS arrays presently in operation would be through the reactions produced within the detectors of the array rather than by the detection of electrons produced by the anti-neutrinos in the atmosphere. The results from arrays with a large mass of detector (many tons), such as the array at Haverah Park which uses deep water-Čerenkov detectors, are of particular interest. However, no event was recorded at Haverah Park close to the time of the anti-neutrino burst candidate; conventional EAS were recorded 45 min before and 100 min after this time.

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Below we describe the characteristics of the array relevant to its use as an anti-neutrino detector, the implications for the interpretation of the 4 January 1974 event of our failure to observe a coincident signal, and the results of an extended search of our records for anti-neutrino burst candidates.

2. The Haverah Park array

Features of the Haverah Park array are well documented (Wilson *et al* 1963, Edge *et al* 1973). The array is triggered when a signal greater than or equal to 60 MeV m^{-3} is recorded in a central detector (volume 40 m^3) in coincidence with similar signals in any two of three identical detectors which circle the central unit at a radial distance of 500 m. Near threshold the energy must be deposited at each detector within about 1 μs. For the 30 coincidences recorded per day, the energy densities are measured at the triggering detectors and at 10 other detectors which surround the centre at distances up to 2·2 km. Figure 1 shows the disposition of these detectors together with their volumes.

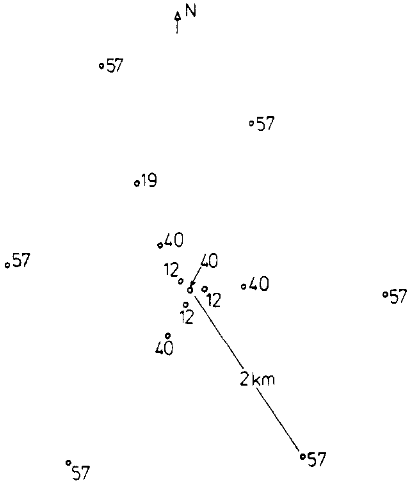

Figure 1. The detector arrangement at the Haverah Park EAS array. The number at each detector corresponds to the volume of water-Čerenkov detector (in m^3) at that point.

Information from the triggering detectors is recorded photographically from oscilloscopes so that relative arrival times, pulse shapes and energy densities (dynamic range $10^4:1$) can be measured for each event. The system dead-time is limited, by the oscilloscope trigger circuit, to 30 μs. The camera takes 200 ms to advance so that multiple bursts of the type recorded by Lande *et al*, which were separated by about 1 ms, would in principle be recorded as superposed triggers on the same film frame. During the last eight years of operation ten photographs have been taken in which pairs of events arrived in less than 200 ms. This number is close to that expected by chance if each member of the pair is a normal air shower: no triple or higher multiplicity events have been observed. All ten observed superpositions are consistent in detail with the postulate that each arises from the near-coincidence in time of two normal and independent showers.

An anti-neutrino burst which triggered the Haverah Park array would be expected to look like an air shower in which the energy density gradient across the array was nearly zero; similar densities would be recorded at widely spaced detectors. The arrival direction would be measured to within 3° in the normal way and the corresponding celestial coordinates determined. For anti-neutrino events, however, the array has 4π sensitivity and the arrival directions would be ambiguous as to the hemisphere. Further, the time structure of the arrival of energy in EAS has been extensively studied (Baxter *et al* 1966, Watson and Wilson 1974) and it is well established that the shower front becomes thicker as the axial distance increases and thinner as the zenith angle increases. In contrast, anti-neutrino candidates would be expected to exhibit a time structure which is independent of distance and zenith angle, although of similar magnitude to that found in EAS (Lande *et al* 1974).

Anti-neutrino events might thus be detected and identified with our recording system.

3. The 4 January 1974 event

As stated above, no event was recorded by the Haverah Park array close to the time of the anti-neutrino burst candidate. If the 4 January 1974 event was indeed caused by anti-neutrinos our null observation sets limitations on the characteristics of such signals. In total the Pennsylvania group recorded 24 interactions and, ignoring their fourth burst which was incompletely recorded, the maximum observed interaction density for a single sub-burst was about $0{\cdot}75\ \mathrm{m}^{-3}$. Lande *et al* (1974) suggest that the energy released per interaction is in the range $20 < E < 100$ MeV.

The triggering probability of the Haverah Park array has been estimated as a function of the energy E released per interaction in the water-Čerenkov detectors and the interaction density n. If p_t is the probability of a single $40\ \mathrm{m}^3$ detector recording an energy density greater than $60\ \mathrm{MeV\ m}^{-3}$ then the probability p of the event being registered is $p_t^3(3-2p_t)$.

Values of p are shown in table 1 for combinations of n and E and it is clear that with the observed interaction density ($0{\cdot}75\ \mathrm{m}^{-3}$) the probability of the array being triggered by a single sub-burst is very low for all but the highest energies of the range deduced by Lande *et al.* However since at least four sub-bursts were observed it is relevant to calculate the probability of recording *at least one* of N sub-bursts which is $1-(1-p)^N$. This probability is also shown in table 1. Hence we conclude that the absence of a coincidence at the Haverah Park array simultaneous with the Lande *et al* event implies that the anti-neutrino energies were less than 85 MeV since four sub-bursts of the interaction density observed with this energy would have triggered the Haverah Park array with 90% probability.

Recently Bludman and Ruderman (1975) have given theoretical arguments against the interpretation of the 4 January 1974 event as a $\bar{\nu}_e$ burst unless the anti-neutrino energy exceeds 100 MeV, and this is not in conflict with the argument developed here.

4. Search for other anti-neutrino candidates

If the event of 4 January 1974 is indeed an anti-neutrino burst then it is reasonable to suppose that a spectrum of bursts exists which reflects the energies of the sources and

Table 1. Probability of recording the 4 January 1974 event at Haverah Park for various assumptions about the anti-neutrino signal.

n, interaction density of sub-burst (m^{-3})	Energy deposited per interaction (MeV)	Probability p of array triggering for a single sub-burst	Minimum sub-burst number for 90% probability of triggering the array
0·75	60	$1{\cdot}2\times10^{-4}$	2×10^{4}
0·75	80	0·25	8
0·75	85	0·44	4
0·75	100	0·82	1·34
1	60	0·25	8
1	64	0·44	4
1	80	0·93	0·84
1	100	0·99	0·44

their spatial locations. From table 1 it is seen that for interaction densities not much greater than $0{\cdot}75\,\mathrm{m}^{-3}$ the Haverah Park array would be an extremely effective anti-neutrino detector. Consequently two periods of our records, from 1 July 1969 to 21 December 1973 and 18 March 1974 to 31 March 1975, have been searched for events displaying the unusually flat lateral density function which is expected to be the signature of anti-neutrino events. During the period 21 December 1973 to 18 March 1974, in which the Lande *et al* event occurred, the array was triggering normally but only the central seven detectors (figure 1) could be operated because of electricity supply difficulties; the conclusions drawn in § 3 are in no way affected.

To identify anti-neutrino candidates we have characterized the flatness of each lateral distribution by a parameter F, where

$$F=\frac{\text{standard deviation of all observed densities}}{\text{mean observed density}}.$$

The use of F has an advantage over alternative selection procedures, such as chi-squared, in that it makes use only of the measured densities without reference to any other shower parameters.

The number of density samples available in an event depends upon the operational efficiency of the detectors of figure 1 and was about 90% for the period in question. This factor, combined with the variation of F with zenith angle, makes it exceedingly difficult to predict the distribution of F expected for EAS events. The zenith angle dependence of $\bar{F}$ for all events was found to be $\bar{F}\simeq1{\cdot}3+\cos\theta$. The observed F distribution for 56 770 showers is shown in figure 2 and a more detailed representation of the distribution for $F<1$ is displayed in figure 3. The smallest observed values of F correspond principally to events in which only a small number of density samples was available or for which the zenith angle was large (>60°).

Since it is not possible to calculate accurately the expected F distribution for all EAS events, to identify possible anti-neutrino burst candidates it is necessary to calculate the expected F distribution for hypothetical anti-neutrino bursts and compare the results with observation.

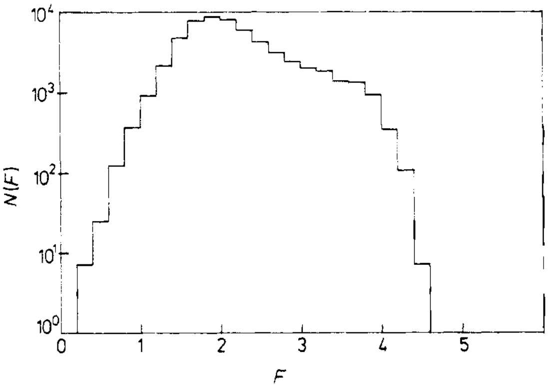

Figure 2. Distribution of the flatness parameter F (see text) for 56 770 showers. Small F values correspond to 'flat' shower events.

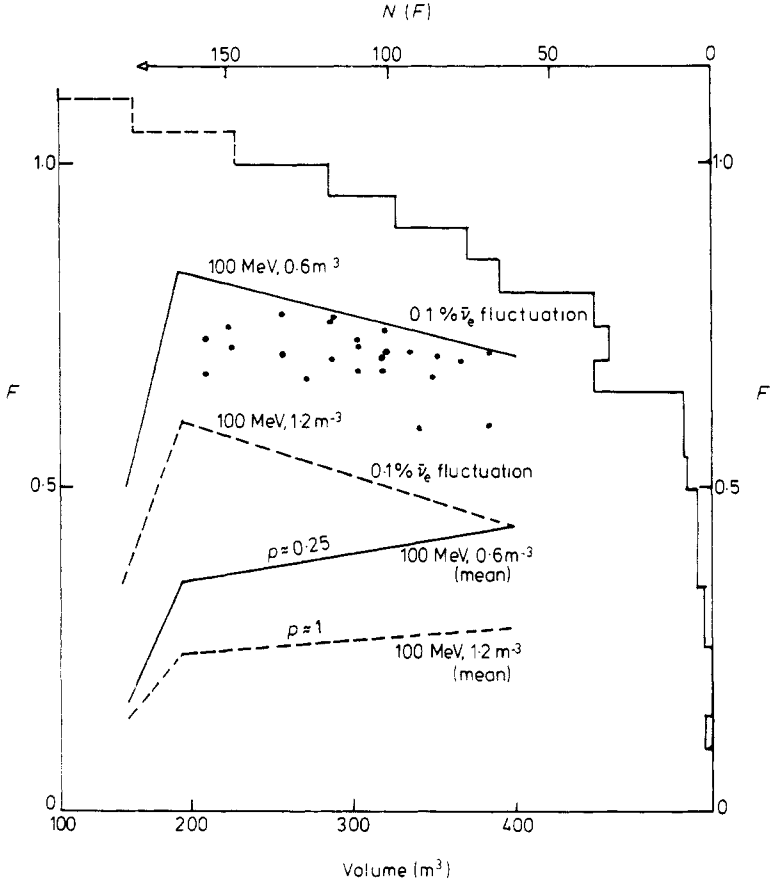

Figure 3. Comparison of the expected F values for alternative $\bar{\nu}_e$ signals. The two lower lines correspond to the mean value of F expected for the $\bar{\nu}_e$ signals indicated; the two upper lines correspond to the F values which would arise from these signals with 0·1% probability. The 23 points represent EAS events selected as in the text. The low F tail of the histogram of figure 2 is in the top right-hand area of the figure. The meaning of p is defined in the text.

Such a calculation has been carried through to produce distributions in F for a range of anti-neutrino energies ($20 < E < 100$ MeV) and for a range of interaction densities. The interaction density is given by the product $\Delta\rho\sigma$ where Δ is the number of anti-neutrinos/m^2 integrated over the burst time, ρ is the density of nuclei and σ is the cross section. Appropriate cross sections were derived from Domogatsky and Zatsepin (1966). It was assumed, for the purposes of calculation, that the neutrino burst was mono-energetic. A range of interaction densities corresponding to total energy depositions from 60 to 120 MeV m^{-3} was considered for total detector volumes of 160 m^3, 193 m^3 and 400 m^3 divided as in the Haverah Park array. The simulation procedure accounted for the following random variations.

(*a*) Poissonian sampling fluctuations about the expected number of anti-neutrinos in a volume V.

(*b*) Poissonian sampling fluctuations about the expected number of photo-electrons (60 per GeV energy loss) produced at the photocathodes of the photomultipliers in the detectors.

(*c*) Gaussian sampling fluctuations about the expected energy deposition which result from calibration and measurement uncertainties.

Simulated events were accepted if, after stages (*a*) and (*b*), the density signals at the triggering detectors satisfied the array triggering criteria.

Typical results from our calculation are shown in figure 3 for anti-neutrinos of energy 100 MeV in bursts which produce 0·6 and 1·2 interactions/m^3 in water. The lower pair of curves correspond to the mean value of F expected for a burst of 100 MeV anti-neutrinos in which the mean interaction densities are 0·6 and 1·2 interactions/m^3. The upper pair of curves show the values of F below which 99·9% of $\bar{\nu}_e$ bursts of the type considered are expected to lie. Corresponding curves for anti-neutrino energies less than 100 MeV would be displaced downwards towards the x axis. Detailed study of the probability distribution of F from $\bar{\nu}_e$ bursts shows that the array most effectively differentiates between $\bar{\nu}_e$ events and EAS when the total available detector volume is above 200 m^3. This condition was satisfied for 99·3% of the search period.

The points shown in figure 3 represent the 23 events from the sample for which the total detector volume was above 200 m^3 and for which the measured values of F were smaller than those expected, with 0·1% probability, from $\bar{\nu}_e$ bursts having $E =$ 100 MeV and $n = 0{\cdot}6$ m^{-3}. None of the 23 events lie below, or close to, the mean value of F expected to be associated with anti-neutrino bursts. This fact does not of itself exclude the possibility that at least one of the 23 events might be an anti-neutrino candidate, the signals from which have fluctuated in an improbable way, but it is very much more probable that the events correspond to conventional EAS. Figure 3 also shows that none of the 23 events could have arisen from 100 MeV $\bar{\nu}_e$ at an interaction density of 1·2 m^{-3}, unless the fluctuations associated with a real $\bar{\nu}_e$ burst were very unusual.

During the 0·7% of the search period for which the total available detector volume was less than 200 m^3, 38 events were recorded with F values below the 0·1% probability line and are contained in the tail of the F histogram of figure 3. These events are most probably EAS recorded in a period when our ability to distinguish between EAS and $\bar{\nu}_e$ candidates was very poor.

We thus conclude that no $\bar{\nu}_e$ events of the type expected to be detectable at our array have been observed in 44 000 hours. To be specific, we believe that bursts of 100 MeV anti-neutrinos having a flux at the earth of about 10^{11}–10^{12} $\bar{\nu}_e$ cm^{-2} are detectable by the Haverah Park array provided the bursts have time structure characteristics similar to those of the burst seen by Lande *et al.* A collapsing star emitting 10^{52} erg in the form of 100 MeV anti-neutrinos would have been detectable at a distance of about 10 kpc. Such collapsing objects have been predicted to occur at a rate of about four per galaxy per year so that our present result can be used to set limits on the nature of the expected $\bar{\nu}_e$ signal from them.

5. Conclusions

(i) No event was observed at the Haverah Park array in time coincidence with the unusual event observed by Lande *et al* (1974). If that event was indeed produced by an anti-neutrino burst then the energy of the anti-neutrinos is probably less than 85 MeV.
(ii) In an operating period of 44 000 h no events showing the expected $\bar{\nu}_e$ burst signature have been observed. Bursts containing 100 MeV $\bar{\nu}_e$ at flux levels of 10^{11}–10^{12} $\bar{\nu}_e\,\mathrm{cm}^{-2}$ would have been readily detectable.
(iii) The present results set limits on the frequency and energy characteristics of other short time constant, high energy phenomena.

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