free from any isotropic component. Another useful way of doing this is to take the average difference of observations from two telescopes which have the same response characteristics and which scan the same latitudes in opposite hemispheres. Isotropic variations due to interplanetary modulation are removed in the difference but the asymmetry variations, having a sinusoidal dependence of amplitude on latitude $\delta$, reinforce. The correct latitude-dependent amplitudes are preserved in the averaging of the difference. In fact, if the coupling coefficients are known, a comparative analysis can be carried out with the bi-hemisphere technique on the records from any pair of detectors, preferably high-latitude, in opposite hemispheres.

It has been convenient to choose Mawson underground north and Misato underground north for analysis since they scan almost conjugate latitudes outside the geomagnetic field. In Figure 3 the observed variations of (Mawson UGN − Misato UGN)/$G$ and $G/2$ and Mawson $A_1$ are compared. It can be seen that the 27-day waves observable in the three sets of variations are in phase. If the waves of variation were due only to the North-South asymmetry the average wave amplitudes among the three sets of data should be in the ratio of the respective asymmetry coupling coefficients $C_{10}$. The coupling coefficients for $\gamma = 0.0$ and for an upper limiting rigidity of 200 GV, are as follows:

\[-G/2 : -0.42\]
\[(\text{Mawson UGN} − \text{Misato UGN})/2 : −0.33\]
\[\text{Mawson } A_1 : −0.25\]

Comparing the two upper sets of observations in Figure 3 it is evident that the ratios of the excursions of the variations are approximately in accord with the ratios of their coupling coefficients. On the other hand, the amplitudes of the $A_1$ variations are obviously at least twice those of (Mawson UGN − Misato UGN)/$2$, when they should be comparable to the latter, if they are due only to variations of the asymmetry (indeed, the coupling coefficients suggest that they should be somewhat smaller).

Considering that the daily counting rate errors in $A_1$ and $G/2$ are similar (approximately $\pm 0.07\%$) it is interesting to note that the 27-day periodicity is clearer in $A_1$. This suggests that the additional component in $A_1$ is itself contributing to the sinusoidal nature of the 27-day variations.

On the left of Figure 3 the proposed isotropic (a) and anisotropic (b) contributions to the intensity variations are shown schematically. The depicted phase and amplitude relationships are such as would give rise to the waves seen in the difference variations.

**Discussion**

The 27-day waves in the North-South asymmetry confirm what is already known as to the dependence of the maxima and minima of the asymmetry on IMF sector polarity and in that sense are also in accord with the theory of the asymmetry. The new feature is the presence of 27-day isotropic waves. They are in phase with the waves of North-South asymmetry and evidently have a flat rigidity spectrum. It might be suspected that they are due to systematic changes in the rigidity spectrum of Forbush modulation over the periods of decrease and recovery. There were two clear 27-day recurrences of the July decrease during the period July-October of the analysis. However, the isotropic waves seemed, rather, to be reinforcing the waves of North-South asymmetry, perhaps most significantly over the weeks shown here that preceded the July decrease, when the neutron intensity was relatively undisturbed. The true connections become clearer in an analysis to be described elsewhere of another series of intensity waves, dependent on IMF polarity, that were observed at similar times of the year in 1983 but with no associated Forbush Decrease activity.

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**Ultra-High Energy $\gamma$-Ray Astronomy using an EAS Array: Search for Emission From 100 MeV Sources.**

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**Introduction**

Recently, a new branch of astronomy has emerged following the detection of ultra-high energy (UHE) $\gamma$-ray emission from
Cygnus X-3 by Samorski and Stamm (1983). This discovery was made using the extensive air shower (EAS) array of the University of Kiel, Germany. Such arrays are designed to detect EAS, the cascades of secondary particles (mainly electrons and protons), which are generated in the atmosphere by the interaction of cosmic ray nuclei of energy greater than \( \sim 10^{15} \) eV. These arrays are also sensitive to EAS initiated by primary \( \gamma \)-rays and, depending on their design, have angular resolutions as good as the SAS-II and COS-B \( \gamma \)-ray telescopes which operated at \( \sim 100 \) MeV energies. At present, there is no effective way to veto proton or nucleus-initiated EAS and so one must look for a significant excess of EAS from within a cone of resolution centred on a suspected source direction. Cygnus X-3 showed such an excess. The excess EAS from the direction of this source were also modulated with the 4h.8 orbital period of the Cygnus X-3 system. The Kiel group’s detection of Cygnus X-3 was later confirmed by observations at Haverah Park, U.K., reported by Lloyd-Evans et al. (1983).

The University of Adelaide has operated for several years an EAS array at Buckland Park, near Adelaide, similar to the Kiel system (Crouch et al. 1981). Except for maintenance, this array was run continuously from 1 January 1979 to 31 December 1981 and recorded \( \sim 1.3 \times 10^5 \) EAS due to primary particles at energies above \( \sim 3 \times 10^{15} \) eV. This data base is currently being examined for evidence of UHE \( \gamma \)-ray emission from various galactic objects. We have already reported elsewhere (Protheroe et al. 1984), our detection of UHE \( \gamma \)-ray from Vela X-1 modulated with the 8d.965 period at a time-averaged flux of \( (9.3 \pm 3.4) \times 10^{11} \) photons m\(^{-2}\)s\(^{-1}\). Here, we will describe the performance of the Buckland Park EAS array as a \( \gamma \)-ray telescope and report the result of a search for UHE \( \gamma \)-ray emission from known 100 MeV \( \gamma \)-ray sources. Finally, some consequences for cosmic ray origin of the UHE \( \gamma \)-ray observations will be discussed.

The Buckland Park EAS Array as a \( \gamma \)-Ray Telescope

The design and performance of the Buckland Park array as a cosmic ray detector has been described by Clay et al. (1981) and Crouch et al. (1981). During 1979-1981 the array consisted of eleven 1 m\(^2\) plastic scintillator detectors deployed as shown in Fig 1(a). The central 5 detectors had fast timing capability and, by measuring the arrival times of the shower front at these detectors, the arrival direction of the EAS could be reconstructed from trigonometry (Fig 1(b)).

There is a timing uncertainty, rms deviation \( \sigma_t \) at each detector due to the detector sampling air shower particles behind the shower front (EAS particles can be considered to be confined to a disc of thickness \( \sim 1 \) m and radius several hundred metres), as well as the finite time resolution of the electronics. This timing uncertainty leads to an uncertainty in the reconstruction of the shower arrival direction.

The use of 5 timing detectors gives redundant timing information which can be used to estimate the angular resolution. From the array symmetry, the arrival times at sites A, C and D \((t_A, t_C \text{ and } t_D)\) can be used to obtain the timing uncertainty \( \sigma_t \). For \( \sim 10^3 \) nearly vertical showers, the quantity \( (t_A - t_C + t_D - t_C) \) had a gaussian distribution with a mean of 0 (as expected) and standard deviation 5.36 ns. Thus we obtain the timing uncertainty at each detector, \( \sigma_t \approx 5.36 \text{ ns/} \sqrt{6} \approx 2.19 \) ns.

By analysing simulated vertical showers which have had a suitably sampled timing error applied to each timing detector, we have obtained the angular resolution of the EAS array to nearly vertical showers. This is shown by the solid line in Fig 2. and is well represented by

\[
\frac{dN}{d\theta} = \frac{1}{2\pi - \sigma_\theta \sigma_\gamma} \exp \left( -\frac{\theta^2}{2\sigma_\theta^2} \right)
\]  \hspace{1cm} (1)

where \( \sigma_\theta = 1.25^\circ \). This has a HWHM of \( \sim 1.5^\circ \), comparable with that of COS-B. For non-vertical showers the angular

Figure 1. (a) Plan of the Buckland Park EAS Array (ca. 1979-81) showing the location of 1 m\(^2\) plastic scintillator detectors (the central 5 detectors have fast timing capability and are used for arrival direction determination). (Adapted from Crouch et al. 1981).
(b) Illustration of arrival of EAS at zenith angle \( \theta \) (Adapted from Longair 1981, Fig 10.2).
resolution may be approximated by equation (1) provided \( a_0 \) is replaced by \( a = a_0 \sec \theta \) where \( \theta \) is the zenith angle.

When considering showers arriving at the array from the direction of a particular astronomical object, one must obtain an average value of \( \sec \theta \) taking account of the drop-off, due to atmospheric attenuation of EAS, of array efficiency, \( \varepsilon \), with zenith angle:

\[
\varepsilon = \cos \theta, \quad (\cos \theta > 0) \quad (2)
\]

As the Earth rotates, an EAS array located at latitude \( B \) will view a particular celestial direction at different zenith angles. The zenith angle distribution of EAS from direction \((\alpha, \delta)\) will then depend on \( \delta \) and \( B \) can be found using equation (2) and so the average value of \( \sec \theta \) can be found.

For the Buckland Park array (located at latitude 35°S) we obtain,

\[
< \sec \theta > = 0.065 + \sec (\delta + 35^\circ) \quad (3)
\]

for showers from declination \( \delta \). As an example, the angular resolution for showers from declination \(-40^\circ\) is shown by the dashed line in Fig 2.

![Figure 2. Angular resolution of Buckland Park EAS Array for vertical showers (solid line) and showers arriving from declination \(-40^\circ\). \( \psi \) is the angle between the true and measured arrival directions of EAS.](image)

To maximise the chances of detecting any excess from a source candidate we have looked at EAS arriving from within the resolution angle \( \theta_c \) of a suspected source direction. Since the significance of any excess events from within \( \theta_c \) would depend on the standard deviation of the number of events expected from cosmic ray EAS \( (\alpha \sqrt{\theta_c^2}) \), we have maximised the quantity

\[
\frac{N_{CR} (\theta < \theta_c)}{\sqrt{\sigma^2}} = \frac{N_{CR} (\theta < \theta_c)}{\sqrt{\sigma^2}} \quad \frac{\int_0^{\theta_c} dN \, d\alpha}{\int_0^{\theta_c} dN \, d\alpha} \quad (4)
\]

to obtain the best value, \( \theta_c = 1.59 \sigma \). This resolution angle contains \( \sim 72\% \) of all events incident from the source direction.

**Search for \( \gamma \)-Ray Emission from 100 MeV Sources**

We have searched for evidence of \( \gamma \)-ray emission above \( 3 \times 10^{15} \) eV from the 14 sources in the second COS-B catalogue (Swanenburg et al. 1981) which have declinations south of \( \delta = 0^\circ \). This complements the northern hemisphere search by Stamm and Samorski (1983). Only two of the southern hemisphere COS-B sources have been identified: 2CG 263–02 with the Vela pulsar, and 2CG 353 +16 with \( \zeta \) Oph. The former, being one of the youngest pulsars would seem a likely candidate for \( \gamma \) emission while \( \zeta \) Oph could be a candidate if acceleration of cosmic rays is taking place in the vicinity of the cloud complex (Montmerle 1981), although this is at present uncertain (Issa et al. 1981). The remaining sources have yet to be identified and some of these could be due to local enhancements in the (inert) interstellar medium irradiated by cosmic rays, (see e.g. Houston and Wolfendale 1983), which we would not expect to observe at ultra-high energies.

We have found no evidence in the Buckland Park data of UHE \( \gamma \)-ray emission from any of the COS-B sources. The result of the search is presented in Table 1 which shows the number of EAS observed, \( N_{ON} \), within the resolution angle, \( \theta_c \). In each case this is consistent with the best estimate of the expected number of EAS, \( \hat{N} \), based on EAS arriving at the same declination but from different right ascensions (the exposure ratio, \( \alpha \), is the ratio of the solid angle contained within \( \theta_c \) of the source direction, to the solid angle used to compute \( \hat{N} \)).

Upper limits at a 95% level of confidence were obtained using the method described by Protheroe (1984b) and are given for (a) the maximum number of EAS from within \( \theta_c \) which could be attributed to \( \gamma \)-rays, \( N_{\gamma} \), and (b) the flux of \( \gamma \)-rays above \( 3 \times 10^{15} \) eV are also given. The northern hemisphere search by Stamm and Samorski (1983) also failed to detect UHE \( \gamma \)-ray emission from COS-B sources, with the possible exception of 2CG 135 +01.

**Discussion**

We have described the EAS techniques which are currently being used for \( \gamma \)-ray astronomy above \( 10^{15} \) eV. So far, UHE \( \gamma \)-rays have been detected from Cygnus X-3 and Vela X-1, and a search for evidence of UHE \( \gamma \)-ray emission from other binary X-ray sources is currently in progress at Adelaide. Extensions currently being made to the Buckland Park array (Prescott et al. 1983) will improve its angular resolution and also enable studies of this type to be made at lower energies.

It is worth pointing out some consequences of the recent observations. Perhaps the most important is that neutron star
binary X-ray sources are probably sources of at least some of the cosmic rays above $10^{15}$ eV, particularly if the $\gamma$-ray emission is due to interactions of protons or nuclei which have been accelerated by the object. This seems likely since the energy loss rate of electrons in the high radiation energy density environment would be high. It is interesting to note that the differential energy spectrum of the $\gamma$-ray from Cygnus X-3 is $\sim 1/E$ spectrum at production is just the source spectrum of cosmic rays required to explain the cosmic ray data, at least up to $\sim 10^{14}$ eV (Protheroe 1984a).

Finally, if the spectra of these objects continues with the $E^2$ form, about one power flatter than the cosmic ray spectrum, to $\sim 10^{16}$ eV, then the unexpected flatterning in the cosmic ray spectrum at these energies (see e.g. Linsley 1981) could be due to $\gamma$-rays at these energies (Clay et al. 1984).

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