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A Search for Ultra-high-energy Gamma-ray Emission from Binary X-ray Systems

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Abstract

Observations have been made with the Buckland park air shower array over a two-year period from June 1984. We have examined events from the directions of six binary X-ray systems to search for any periodic component associated with ultra-high-energy gamma-ray emission above a threshold energy of $\sim 9\times10^{14}$ eV. No statistically significant excess has been found and upper limits to the individual fluxes are presented.

1. Introduction

The first positive detection of ultra-high-energy (i.e. $\gtrsim 10^{14}$ eV) gamma-rays was made by Samorski and Stamm (1983) after examining air shower events from the direction of Cygnus X-3 recorded over the period 1976–79. Since the announcement of that detection, there has been a great deal of effort put into both confirming this observation and searching for other sources. The observational status of UHE gamma-ray astronomy has been recently summarised by Protheroe (1987). Briefly, a number of confirming observations have been made of UHE gamma-rays from Cygnus X-3 but there has been a lack of recent positive detections, suggesting a time variability in the emission process. This variability may be modulated with a 328 d period proposed by Neshpor and Zyskin (1986).

Other sources have been searched for in the northern hemisphere with generally inconclusive or unconfirmed results with Hercules X-1 being the most likely other candidate (e.g. Baltrusaitis *et al.* 1985). In the southern hemisphere, data from the Buckland Park air shower array were used to identify Vela X-1 and LMC X-4 as likely UHE gamma-ray sources with subsequent apparent confirmation of the Vela X-1 observation by other groups (van der Walt *et al.* 1987).

There are aspects of the Cygnus X-3 and Vela X-1 observations which are still not satisfactorily explained. In particular, the light curves do not appear to be consistent between observations (e.g. Protheroe 1987) and there is a perplexing dichotomy between theory and experiment over the muon content and structure of what have been assumed to be gamma-ray initiated showers. On the whole, the observations have not shown the characteristic lack of muons theoretically expected in the showers (e.g. Edwards *et al.* 1985), nor is it clear that the shower development age has been consistent with expectation

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(e.g. Hillas 1987). There is thus no clear recipe for identifying gamma-ray initiated showers except by looking for an excess of events from a favoured direction or by looking for a characteristic period in events from such a direction using periods obtained from, particularly, X-ray observations.

This paper reports a search for emission with characteristic time periods from the directions of six southern hemisphere X-ray binary sources in data obtained by the recently developed Buckland Park air shower array over the two years from June 1984 to June 1986. A later paper will detail the analysis for the period 1986 to mid-1989.

2. The Buckland Park Air Shower Array

The Buckland Park array (latitude 35°S) was established in 1971 (Crouch *et al.* 1981) and has been continually developed since that time. It was used for cosmic ray anisotropy work in the period 1979–81 and the dataset obtained at that time later gave evidence for UHE gamma-ray emission from Vela X-1 (Protheroe *et al.* 1984) and LMC X-4 (Protheroe and Clay 1985). Since 1981, additional detectors have been added to the array in order to lower the size threshold for detectable and analyzable showers and, through the addition of further fast-timing channels, to improve the angular resolution somewhat for the larger showers. The enlarged array has been described in detail by Ciampa *et al.* (1986).

During 1984–86 the array consisted of 27 detectors in total with 11 fast timing channels based on detectors towards the centre of the array. The triggering requirements gave a size dependence of the array collecting area which rose steeply above a threshold of about 10^4 particles so that the array response peaked between 5×10^4 and 10^5 particles for a size spectrum such as that found for cosmic rays (Clay *et al.* 1985). Close to threshold, the array had an angular resolution of ~6° but for events described in this paper (which were required to trigger at least nine timing detectors) the angular resolution was ~2°.

We have carefully investigated the angular resolution of our array both experimentally and theoretically and find that, when we have a shower analysis which provides us with a shower core position and then we make an allowance for shower front curvature, our angular resolution is ~1°. However, with the large dataset described here and difficulties with the nonlinear core location program we were not able to obtain a complete analysis for more than a fraction of our events due to limitations on computer time available to us. The present dataset was therefore analysed with the assumption of a plane shower front, as was the 1979–81 dataset. For our rather compact array, the error resulting from this assumption increases our angular uncertainty to ~2°, that is slightly better than the 1979–81 results. No age or core distance cut has been used. The 2° has been determined both from array simulations and from a comparison of shower directions measured by subsets of our present extended fast timing array.

3. Observations and Analysis

The array was operated for two years from June 1984 with an on-time efficiency of ~76%. A total of $\sim4\times10^6$ events was then available for analysis. In the present analysis, only events triggering at least nine of the fast-timing detectors are used. This corresponds to about 19% of the total events with an approximate energy threshold of 9×10^{14} eV, and a median size of $1\cdot0\times10^{5}$ particles or $1\cdot0\times10^{15}$ eV. When this selection of events is made, the broad array properties of this dataset become rather similar to those of the 1979–81 Buckland Park dataset (Crouch *et al.* 1981). The angular resolution for a plane shower front should be only marginally better since the extra central fast-timing detectors are particularly significant only for the smallest detected showers. Additionally, the overall practical angular resolution without allowance for curvature will be about the same since the overall array dimensions are similar and thus systematic curvature effects will also be similar. The above time constraint ensures that most showers used fall inside the array.

Events have been examined within a cone of ~2° half-angle (depending somewhat on declination) from the directions of six binary X-ray systems which are discussed below. Searches were made at appropriate periods, or over period ranges dictated by the uncertainty of X-ray period determinations, after a barycentric correction had been made to event arrival times.

In searching for UHE gamma-ray emission, the Z^2_{10} test of Buccheri *et al.* (1983) is used. Like the Protheroe (1984) test, it is a powerful way to search for narrow peaks in the light curve, whereas the Rayleigh test in circular statistics is sensitive to a strong sinusoidal component in the phase distribution for a test frequency. Another advantage of the Z^2_{10} test is that its behaviour for large numbers of events is well documented. The Z^2_{10} variable is distributed like χ^2 with 20 degrees of freedom. This enables 95% upper limits to be assigned.

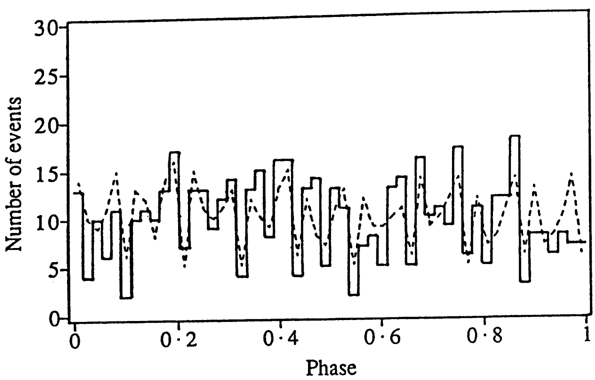

Fig. 1. Phase distribution of events from the direction of Vela X-1. The dashed curve corresponds to the average off-source value. The ephemeris of Deeter *et al.* (1987) is used. Fifty-four bins are used as this is an even multiple of nine and the orbital period of Vela X-1 is very close to nine sidereal days. This gives rise to the uneven background.

(a) Vela X-1

Vela X-1 was detected at UHE energies in the Buckland Park 1979–81 dataset (Protheroe *et al.* 1984) with the use of a shower lateral distribution cut (age >1·3). An excess was found at a phase of 0·63. The BASJE group (Suga *et al.* 1985) found evidence in their early data (1962–67) for emission at a phase of ~0·5 using an age cut and muon-poor requirement. The Potchefstroom group (van der Walt *et al.* 1987) also found positive evidence in a 1979–81 dataset with an age cut of >1·3, but the phase of maximum was exactly 0·5 different from that previously found at Buckland Park.

Table 1. Upper limits to the integral UHE gamma-ray flux from six potential sources

An E^{-2} differential spectrum above threshold was assumed

Source	Acceptance cone half-angle (deg.)	Threshold energy (eV)	Number of events Expected	On source	95% upper limit (photons m^{-2} s^{-1})
0900–403 Vela X-1	2·0	9×10^{14}	557	535	$9\cdot0\times10^{-10}$
0532–664 LMC X-4	2·5	$3\cdot5\times10^{15}$	236	251	$3\cdot6\times10^{-10}$
1516–569 Cir X-1	2·3	2×10^{15}	423	439	$6\cdot8\times10^{-10}$
1119–603 Cen X-3	2·3	2×10^{15}	341	342	$6\cdot1\times10^{-10}$
1617–155 Sco X-1	2·3	1×10^{15}	406	429	$7\cdot1\times10^{-10}$
1822–37·1	2·1	9×10^{14}	629	614	$1\cdot0\times10^{-9}$

Fig. 1 shows the phaseogram for data obtained in the present experiment. Events were accepted from within 2° of Vela X-1. The ephemeris of Deeter *et al.* (1987) was used and a background obtained from 67 off-source regions from the same declination band. There is no suggestion of an enhancement at any phase. The resulting upper limit obtained using the method of Protheroe (1984) is given in Table 1.

On May 4th, 1986 an outburst of TeV gamma-rays was seen from Vela X-1, lasting ~19 minutes (North *et al.* 1987). However, the zenith angle of Vela X-1 from Buckland Park at the commencement of the outburst was 90°, and so no coincident events were seen.

(b) LMC X-4

LMC X-4 was first observed at UHE gamma-ray energies by Protheroe and Clay (1985). This source is of particular importance in UHE gamma-ray astronomy since, at the distance of the Large Magellanic Cloud, it would be expected to show evidence in its spectrum for the interaction of UHE photons in the microwave background. Accepting events within a cone of 2·5° half-angle we have obtained a dataset which has been searched for a preferred modulation around previously reported orbital periods. The Z_{10}^2 test (Buccheri *et al.* 1983) was used since it is powerful for a phase distribution such as the one found previously, i.e. containing a narrow peak. We used the Z_{10}^2 test in preference to the Protheroe test since its critical values are more easily obtained for the larger numbers of events dealt with in the present analysis. The results are shown in Fig. 2 and the resulting upper limit in Table 1.

This negative result does not directly contradict the earlier observation of Protheroe and Clay (1985) since the present dataset is significantly smaller and the variability of LMC X-4 at X-ray energies is well documented (e.g. Ilovaisky *et al.* 1984). Also, the present dataset has a rather lower size threshold than the experiment of Protheroe and Clay. Potential events would have been more affected by absorption in the microwave background since this source is predominantly observed at large zenith angles.

(c) Circinus X-1

Circinus X-1 has an orbital period of 16·59 d (Kaluzienski *et al.* 1976). In the search for UHE gamma-ray emission in the earlier Buckland Park dataset, the phase distribution of events from the direction of Cir X-1 exceeded the 5% critical value of the Protheroe test (Protheroe and Clay 1985). As 14 objects were examined, this result was not considered significant.

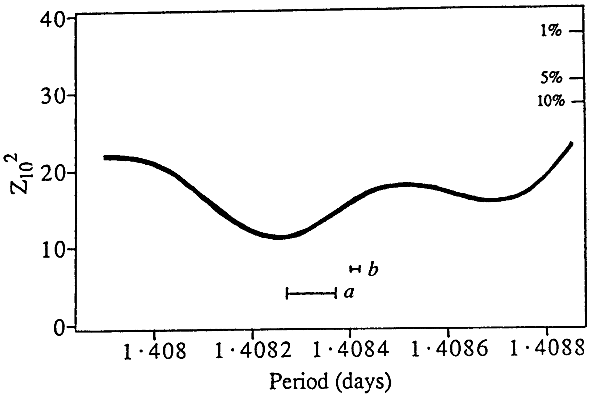

Fig. 2. Results of a period search performed on events from the direction of LMC X-4. Previous determinations of the orbital period by (*a*) Kelley *et al.* (1983*a*) (X-ray) and (*b*) Ilovaisky *et al.* (1984) (optical) are shown.

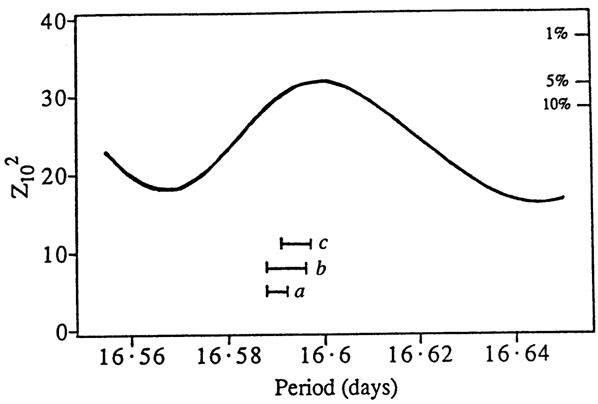

Fig. 3. Results of a period search performed on events from the direction of Cir X-1. Periods obtained by (*a*) Kaluzienski and Holt (see Thomas *et al.* 1978) (X-ray), (*b*) Haynes *et al.* (1978) (radio 6 cm) and (*c*) Haynes *et al.* (1978) (radio 2 cm) are shown for comparison.

Events in the present dataset within a cone of half-angle of 2·3° around Cir X-1 were searched using the Z_{10}^2 test. Fig. 3 shows the result for periods around those previously obtained for Cir X-1. The X-ray period of Kaluzienski and Holt (see Thomas *et al.* 1978) is significant at the 5·5% level. However, Fig. 4 shows that the present dataset does not greatly enhance any of the features of the earlier phaseogram and the result is thus not significant. However, it is possible that there may exist a period derivative for this source which could move any feature of our phaseogram closer to the earlier result.

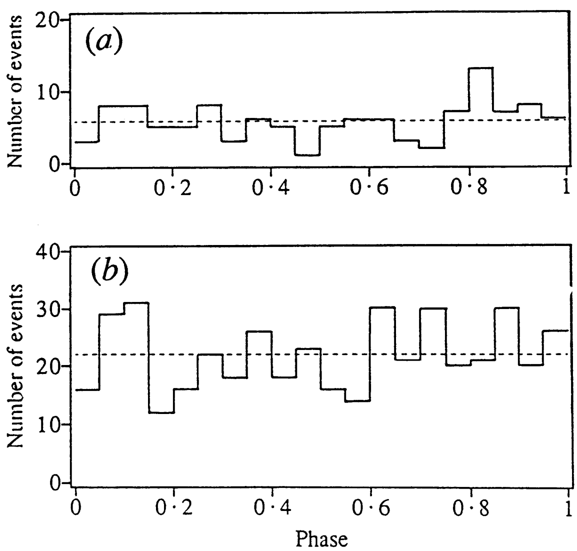

Fig. 4. Phase distributions for events from the direction of Cir X-1 analysed using the ephemeris of Kaluzienski and Holt (see Thomas *et al.* 1978): (*a*) for the 1979–81 dataset and (*b*) for the present dataset.

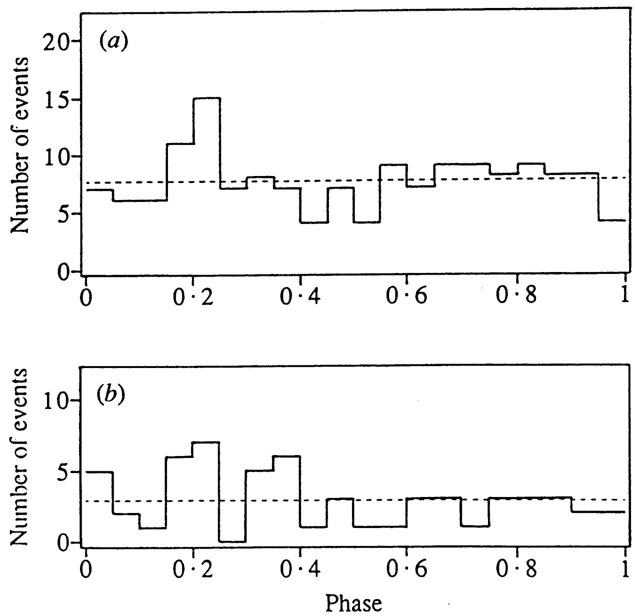

Fig. 5. Full phase analysis of events from the direction of 1822–37·1 using the 1979–81 dataset, and the ephemeris of Mason *et al.* (1982) (X-ray): (*a*) all ages and (*b*) ages >1·3.

(d) Centaurus X-3

This object has a 2·087 d orbital period and has episodes of high state activity. It may have been detected in UHE gamma-rays in BASJE data (1962–67) (Suga *et al.* 1985) with an energy threshold of $\sim 10^{14}$ eV. We have examined events within 2·3° of Cen X-3 and we find no period within the reported ranges (Kelley *et al.* 1983*b*; Howe *et al.* 1983; Murakami *et al.* 1983) which is significant at better than the 10% level.

The two most accurate determinations of the orbital parameters of Cen X-3 involve period derivatives of the order of $\sim 1 \times 10^{-8}$. Using the ephemeris of Murakami *et al.* (1983) a range of period derivatives of this magnitude were trialled, none of which showed any appreciable increase in significance.

(e) Scorpius X-1

Sco X-1 is an exceptionally bright X-ray source with an orbital period of 0·787313 d (Cowley and Crampton 1975). This period has, however, not been seen in X-ray data presumably due to the inclination of the binary system. The results of a period search for events within 2·3° of Sco X-1 show that, at the period of Cowley and Crampton, the significance is only at the 30% level and hence no evidence for emission is claimed. Recent Mt Chacaltaya UHE data show evidence for an excess of events from Sco X-1 (Matano *et al.* 1988). These data were obtained during May 1986 with an energy threshold of $\sim 10^{14}$ eV. We have examined our events recorded during May 1986 from Sco X-1 and find no evidence of any non-random effect.

(f) 1822–37·1

This object has many properties similar to Cygnus X-3 (White *et al.* 1981) and is thus a candidate for UHE gamma-ray emission. Data from the 1979–81 period at Buckland Park have previously been presented (Ciampa *et al.* 1987) but the result of a more complete analysis is shown in Fig. 5, with and without a lateral distribution age cut at 1·3. Neither distribution exceeds the 10% critical value of the Protheroe test.

There is, however, some suggestion of a peak at a phase of ~0·2. A similar peak in the present data may be an indication of UHE gamma-ray emission. We note that the proposed accretion disk corona model for 1822–37·1 of White and Holt (1982) includes an accretion disk with bulges at phases of ~0·8 and ~0·2, either (or both) of which could conceivably provide target material for the production of UHE gamma-rays.

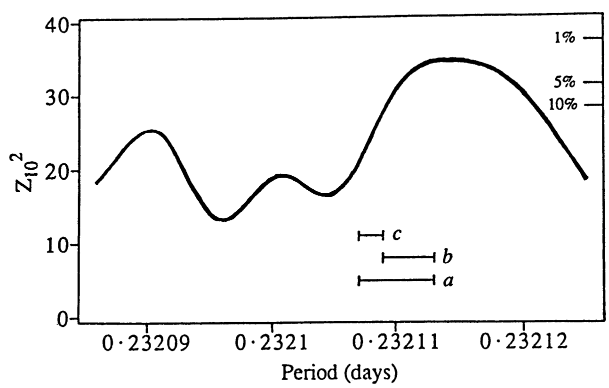

Fig. 6. Results of a period search performed on events from the direction of 1822–37·1. Periods obtained by (*a*) Cowley *et al.* (1982) (optical and X-ray) and Mason *et al.* (1982) (X-ray), (*b*) Mason *et al.* (1982) (optical) and (*c*) White *et al.* (1981) (X-ray) are shown.

Fig. 6 shows data from the present set which indicate that a period search reaches a peak just outside the range of published periods (at 0·232114 d). At this period, the Z_{10}^2 statistic corresponds to a 2·3% probability of arising from random fluctuations. However, since the distributions for the two datasets are at mutually exclusive periods, we conclude that there is no compelling evidence for the emission of UHE gamma-rays from this source.

4. Discussion

Six potential sources have been examined for evidence of ultra-high-energy gamma-ray emission over the two-year period June 1984 to June 1986. No significant excess of events has been found for any of these sources and upper limits to the fluxes calculated using the method of Protheroe (1984) and Buccheri *et al.* (1983) are given in Table 1. We note firstly that the numbers of events and upper limits in Table 1 are not inconsistent with previous results of Protheroe *et al.* (1984) and Protheroe and Clay (1985) for a source spectrum $\sim E^{-2}$. Several possibilities present themselves as explanations of these negative results. Clearly, not all of these candidates are UHE gamma-ray sources. We note that an age cut has not been used in the present analysis. While theoretical arguments (Hillas 1987) and some observations (e.g. Lloyd-Evans *et al.* 1983) indicate that the use of an age cut is not necessary, other observations have relied upon the use of this cut.

In several of the period searches the most significant trial period lies just outside the range of the X-ray periods. We note the importance of using recently determined X-ray periods and also that the lengths of UHE datasets put stringent demands on period determinations made over limited periods by satellite experiments.

Finally, the time variability of UHE gamma-ray sources is an unfortunate but inescapable fact. Further, and where possible, contemporaneous and/or simultaneous observations of candidate sources are the only solution.

Acknowledgments

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