OBSERVATION OF GAMMA-RAYS FROM LMC X-4 ABOVE 10^{16} eV

R.J. Protheroe and R.W. Clay
Department of Physics, University of Adelaide
Adelaide, South Australia 5001

Abstract Data from the University of Adelaide air shower array at Buckland Park taken over a three year period have been analysed to search for evidence of ultra-high energy γ-ray emission from neutron star binary X-ray sources having known orbital periods. We report the detection of UHE γ-rays from LMC X-4 above 10^{16} eV, the first extragalactic object to be positively detected at these energies.

1. *INTRODUCTION* Gamma-rays at ultra-high energies (UHE) have recently been observed by Samorski and Stamm (1983) and Lloyd-Evans *et al.*(1983) from Cygnus X-3 and by Protheroe *et al.* (1984) from Vela X-1. The discovery that some neutron star binary X-ray sources are emitting ultra-high energy γ-rays has led to considerable interest and speculation about the origin of the γ-rays (Eichler and Vestrand, 1984; Stephens and Verma, 1984; Hillas, 1984; Protheroe, 1984; Porter, 1984; Chanmugam and Brecher, 1985) and to the notion that much of the galactic cosmic radiation above 10^{16} eV may originate from such objects (Hillas, 1984; Wdowczyk and Wolfendale, 1983a,b). Following our detection of UHE γ-rays from Vela X-1, we examined data from the Buckland Park array (Crouch *et al.*, 1981) to test for an excess of air showers from regions around the galactic plane and galactic centre (Clay *et al.* 1984), and from the directions of known sources of γ-rays at 100 MeV energies (Protheroe and Clay, 1984).

In addition to Vela X-1, there are 14 neutron star binary X-ray sources in the southern celestial hemisphere which have known orbital periods. We have recently searched the Buckland Park data for 1979-81 for evidence of periodic emission of UHE γ-rays from these objects (Protheroe and Clay, 1985) and here we summarise the results of this search.

2. *DATA ANALYSIS* For each object, we examined the air showers which had apparent arrival directions within angle θ_c of the source direction. This "resolution angle", chosen to optimise the signal to noise ratio, ranged from 2.1° to 2.7° depending on the source declination. To test for evidence of periodic emission of UHE γ-rays in phase with the orbital motion of each binary system, the arrival time of each air shower was converted to an orbital phase, ϕ ($0 < \phi \leq 1$), after applying a heliocentric correction. Cosmic ray events would be expected to have a uniform phase distribution and the hypothesis of uniformity was tested using the statistic Y_n proposed by Protheroe (1985a) specifically for testing circular data for uniformity while being powerful against alternatives in the form of a uniform distribution plus a small narrow distribution at an arbitrary phase. Y_n exceeded the 1% critical value only for LMC X-4. For the 13 other objects, 95% upper limits were obtained for the γ-ray flux and luminosity and are given by Protheroe and Clay (1985). For LMC X-4, 63 events were recorded within θ_c=2.5° of the source direction and, using the ephemeris of Kelley *et al.* (1983), Y_{63} was 7.55 compared with the 5% and 1% critical values of 7.32 and 7.54 respectively.

The LMC X-4 observation may actually be more significant than suggested by the 1% significance level obtained using the Y_n statistic if the peak in the phase distribution is broader than $\sim n^{-1}$ of the period. The phase distribution of events from within 2.5° of the direction of LMC X-4 is plotted in Fig. 1. There is a significant excess of events between phases 0.90 and 0.95 where we observe 12 events when we expect 2.65 events. The probability, p, of this occuring by chance in a particular bin, obtained using the Poisson distribution, is 2.12×10^{-5}. The phase distribution is shown binned in 20 bins in Fig. 1, but was previously binned in 10 bins and this binning and re-binning must be taken into account when assigning a significance level for the observation. For LMC X-4 alone, the probability must then be increased to $1-(1-p)^{(20+10)} = 6.63\times10^{-4}$ corresponding to a 3.2 standard deviation observation. Since 14 sources were examined for UHE γ-ray emission, the probability that the observed phase distribution for LMC X-4 resulted from a chance fluctuation of cosmic ray background events is $1-(1-p)^{30\times14} = 0.009$. It is therefore likely (99.1% confidence) that the phase distribution is not the result of a background fluctuation.

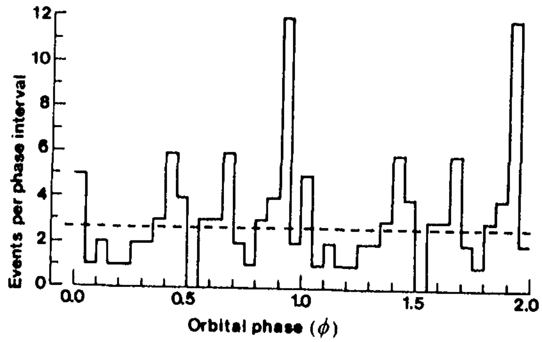

Fig. 1. Phase distribution of the 63 air showers observed within 2.5° of LMC X-4. The ephemeris of Kelley *et al.* (1983) was used. *The dashed line* shows the expected phase distribution of the cosmic ray background events. (Reproduced from Protheroe and Clay, 1985).

We attribute the excess between phases 0.90 and 0.95, i.e. 9.4±3.5 events, to γ-rays. This corresponds to a time averaged integral flux of $(4.6\pm1.7)\times10^{-11}$ photons m^{-2} s^{-1} above 10^{15} eV, the effective threshold of the array *for* showers incident from declination −66°. Assuming an E^{-2} photon spectrum at the source and taking account of electron-photon cascading in the 3 K microwave background we obtain a luminosity of $\sim10^{38}$ erg s^{-1} per decade which is of the same order of magnitude as that emitted at 2-11 keV energies (Bradt and McClintock, 1983).

3. *DISCUSSION* Since LMC X-4 is in the Large Magellanic Cloud, some 50 kpc away, we would expect γ-rays below about 10^{15} eV to be attenuated on traversing the 3 K microwave background. This topic is discussed in an accompanying paper (Protheroe, 1985b). Recent extensions to the Buckland Park array (Prescott *et al.*, 1983) have made measurements below 10^{15} eV possible for this declination.

LMC X-4 is a massive binary system with a 1.408^d period. The inclination of the system is ~66° (Kelley *et al.*, 1983) and the X-ray source is eclipsed between phase 0.92 and 0.08. If UHE protons are accelerated in the region of the compact object UHE γ-rays could be produced by nuclear interactions in the atmosphere of the companion star. In this case, we would expect γ-ray emission at orbital phases ~0.92 and ~0.08 when our line of sight to the neutron star just grazes the star's surface. The observation of UHE γ-rays at a phase of 0.90-0.95 is consistent with this picture although the absence of UHE emission at phases 0.05-0.10 is puzzling (a similar situation exists for Cygnus X-3 and Vela

X-1 where only one burst of UHE γ-rays is observed per orbit).

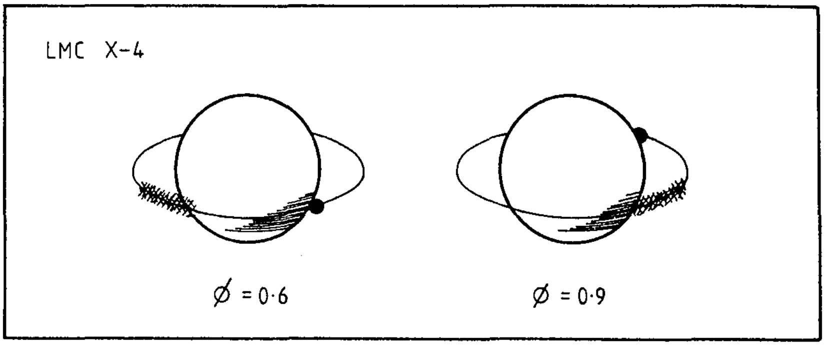

Fig. 2. The LMC X-4 primary star and inclined orbit of the neutron star drawn to scale based on the analysis of Kelley *et al.* (1983). Possible location of material responsible for obscuration of the primary between phases 0.6 and 0.9 (Huchings *et al.*, 1978) is shown cross-hatched, assuming it lies in the neutron star orbit, for an orbital phase of (a) 0.6 and (b) 0.9.

The star appears not to fill its Roche lobe and to have a rather low stellar wind (Huchings *et al.*, 1978). Mass transfer may occur through a trailing accretion stream which may feed the accretion disc. Evidence for this comes from variable obscuration of the companion star between orbital phases 0.6 and 0.9 (Huchings *et al.*, 1978) which could correspond to matter trailing behind the neutron star by between 0.2 and 0.3 of an orbit (see Fig. 2). If this matter is of considerable extent above the orbital plane it could be the target material for interactions of UHE protons produced near the neutron star. Such a scenario could produce γ-rays only at a phase of about 0.9 as observed.

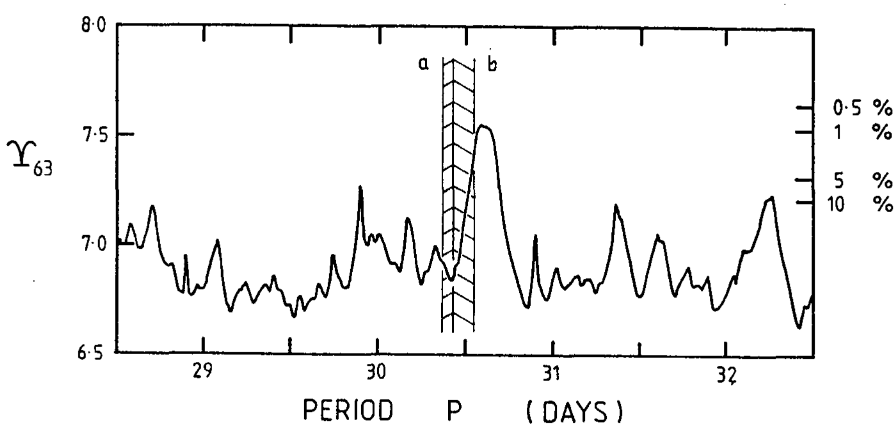

Fig. 3. The statistic Υ_{63} derived from the phase distribution of the 63 events arriving within 2.5° of LMC X-4 plotted as a function of precessional period. The precessional periods found by: (a) Ilovaisky *et al.* (1984), and (b) Lang *et al.* (1981) are indicated.

The X-ray source has high and low states associated with a ~30^d period (Lang *et al.*, 1981) attributed to precession of an accretion disc. The 30^d period is also seen at optical wavelengths and an ephemeris based on observations taken over seven years has recently been published by

Ilovaisky *et al.* (1984). We have searched for evidence of modulation by the 30^d period. We plot in Fig. 3 Y_{ea} against precession period for periods in the range 28.5^d to 32.5^d. Y_{ea} displays a prominant feature near 30.6^d, highly suggestive of modulation by the precession period, and exceeds the 5% critical value for some periods within 1σ of that found by Lang *et al.* (1981). However, for the period found by Ilovaisky *et al.* (1984), $P = 30.40^d \pm 0.03^d$, Y_{ea} is less than the 5% critical value. There is therefore no firm evidence for modulation of the UHE γ-rays by the 30^d period although such modulation may be revealed in subsequent data. If the UHE γ-rays are modulated with the precession period the light curve may be expected to be symmetrical about the time of X-ray minimum. A search for such modulation has also been carried out using the ephemeris of Ilovaisky *et al.* (1984) and was negative.

4. *CONCLUSION* We have searched the data taken during 1979-81 with the Buckland Park air shower array for evidence of UHE γ-ray emission by neutron star binary X-ray sources. In addition to our detection of Vela X-1 reported elsewhere (Protheroe *et al.*, 1984), we have detected UHE γ-ray emission from LMC X-4 modulated with the 1.408^d period.

Acknowledgements We acknowledge the efforts of P.R. Gerhardy in obtaining the data-base analysed in the present work. Others particularly responsible for the development of the Buckland Park array have been J.R. Prescott, J.R. Patterson, A.G. Gregory, P.C. Crouch and many graduate students over the years. This work has been supported in part by the Australian Research Grants Scheme.

REFERENCES

Bradt, H.V., and McClintock, J.E., Ann. Rev. Astron. Astrophys., 21, 13-66 (1983)
Chanmugam, G., and Brecher, K., Nature, 313, 767-768 (1985)
Clay, R.W., Protheroe, R.J., and Gerhardy, P.R., Nature, 309, 687-688 (1984)
Crouch, P.C., *et al.*, Nucl. Instrum. Methods, 179, 467-476 (1981)
Eichler, D., and Vestrand, W.T., Nature, 307, 613-614 (1984)
Hillas, A.M., Nature, 312, 50-51 (1984)
Huchings, J.B., Crampton, D., and Cowley, A.P., Ap. J., 225, 548-556 (1978)
Ilovaisky, S.A., *et al.*, Astron. Astrophys., 140, 251-258 (1984)
Kelley, R.L., *et al.*, Ap. J., 264, 568-574 (1983)
Lang, F.L., *et al.*, Ap. J. (Lett.), 246, L21-L25 (1981)
Lloyd-Evans, J., *et al.*, Nature, 305, 784-787 (1983)
Porter, N.A., Nature, 312, 347-348 (1984)
Prescott, J.R., *et al.*, Proc. 18th ICRC (Bangalore), 6, 257-260 (1983)
Protheroe, R.J., Nature, 310, 296-298 (1984)
Protheroe, R.J., Astronomy Express, submitted (1985a); see also these proceedings paper OG 9.5-13.
Protheroe, R.J., these proceedings paper OG 2.7-13 (1985b)
Protheroe, R.J., Clay, R.W., and Gerhardy, P.R., Ap. J. (Lett.), 280, L47-L50 (1984)
Protheroe, R.J. and Clay, R.W., Proc. Astr. Soc. Austr., 5, 586-589 (1984)
Protheroe, R.J. and Clay, R.W., Nature, in press (1985)
Samorski, M., and Stamm, W., Ap. J. (Lett.), 268, L17-L22 (1983)
Stephens, S.A., and Verma, R.P., Nature, 308, 828-830 (1984)
Wdowczyk, J., and Wolfendale, A.W., Nature, 305, 609-610 (1983)
Wdowczyk, J., and Wolfendale, A.W., Nature, 306, 347-349 (1983)