4U 0115 +63 - ANOTHER ENERGETIC GAMMA RAY BINARY PULSAR

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ABSTRACT

Following our discovery of Her X-1 as a source of pulsed 1000 GeV γ-rays, a search for emission from an X-ray binary containing a pulsar with similar values of period, period derivative and luminosity has been successful. The sporadic X-ray binary 4U 0115+63 has been observed, with probability 2.5×10^{-6}, to emit 1000 GeV γ-rays with a time averaged energy flux of 6×10^{35} erg s^{-1}.

1. INTRODUCTION.

In a recent paper [1] we reported the discovery of the emission of pulsed 1000 GeV γ-rays by the short period X-ray binary pulsar Hercules X-1. It might reasonably be expected that other X-ray binary pulsars could be periodic VHE γ-ray sources, especially those with similarly short pulsar periods. We here report the results of further analysis of data from Her X-1 and a recent detection of the 3.6 sec pulsar in the sporadic hard X-ray binary system 4U 0115+63. The data on 4U 0115 were obtained on 1984 September 21-29 using the Dugway γ-ray telescopes which employ the ground based atmospheric Cerenkov light technique [2].

4U 0115+63 was first observed as an X-ray source by the UHURU group [3] and subsequently identified by the SAS III satellite in 1977 [4] as a sporadic 3.6146 s pulsed X-ray emitter with the collapsed object in a 24.3 d eccentric orbit. Further detections of the X-ray pulsar were reported in 1980 by the Ariel 6 group [5], with the latter observation providing more recent details of the period, spin up and orbital characteristics [6]- see Table I. Subsequent observations have coincided with the object being in the low X-ray state [7] and an exact contemporary ephemeris is not available.

2. RESULTS : (A) 4U 0115+63.

The data were obtained during 25 hrs of observation from eight intervals each of about 3hr spread over 9 days. During this time the Dugway telescopes, with typical energy threshold 1000 GeV accurately recorded the time of 37000 light flashes. The individual event times were adjusted to the solar system barycentre and then to the focus of the binary orbit, based on the information in Table I.

PULSAR PERIOD = 3.614664 $\pm$ 0.0000011 s.
PERIOD DERIVATIVE = - 0.000272 $\pm$ 0.000007 per year
EPOCH OF ORBIT = MJD 44586.008
PERIASTRON ANGLE = 47.08 $\pm$ 0.20 deg.
a. sin i = 140.130 ls
ORBITAL PERIOD = 24.3154 $\pm$ 0.0004 d.
ECCENTRICITY = 0.3402 $\pm$ 0.0004

TABLE I.

The three previous X-ray measurements of 4U 0115 suggest that the period changes slowly, if at all, over 14 years - see Figure 3. The very different and large instantaneous values of the period derivative observed could be a consequence of the sporadic nature of the emission and may depend on the detail of the X-ray emission mechanism. We have therefore searched for periodicity over the wide range 3.613 - 3.616s to allow for the detection of the expected 3.6146 ± 0.0001 s periodicity, together with the 24 hr side-bands introduced by the daily observations. Allowance has also been made for the uncertainties in the orbit when the ephemeris is wound forward over 4 years. The results are shown for data on 4U 0115 in Figure 1. Here we have employed a local value for the orbit of 24.3135 d and the epoch and other parameters from Table I. We have evidence of pulsation at a period of 3.61457 ± 0.00001 s, within the range of uncertainty of the extrapolated periods at the 5×10^{-7} chance level. The range of period over which we have scanned comprises about 5 independent samples in our observation and accordingly we reduce the significance of the detection to 2.5×10^{-6}. In addition the relaxation of the orbit to the adjacent sampling peak has introduced a further 2 degrees of freedom leading to a final significance for the periodicity of 5×10^{-6}. An identical analysis of off-source data shows no periodicity in the expected X-ray pulsar period range.

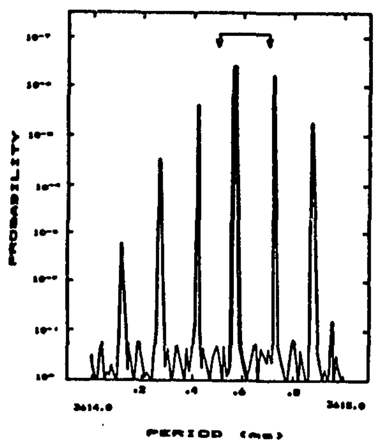

FIGURE 1: The periodicity of our data on 4U0115 in the period range expected from the X-ray measurements.

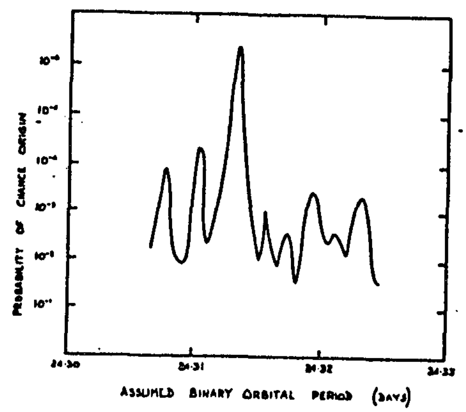

FIGURE 2: The probability of chance origin of periodicity of γ-rays from 4U 0115+63 versus the assumed orbital period.

Figure 2 shows the variation of the γ-ray pulsar periodicity with assumed orbital period, adopting the mean value of all other parameters from Table I. The excess counts ascribed to 1000 GeV γ-rays comprise 2.0 ± 0.4 % of the cosmic ray proton count rate which, for our telescopes, corresponds to a γ-ray flux of $(7 \pm 1.4) \times 10^{-11} cm^{-2} s^{-1}$. We estimate the time averaged luminosity in VHE γ-rays for a source emitting isotropically at a distance of 5 kpc with a differential spectral slope of 3.0 to be 6×10^{35} erg s^{-1}.

The X-ray emission is known to be sporadic for 4U 0115, as is the VHE γ-ray emission from Her X-1, and so, although the production mechanisms are expected to be quite different, we have tested for variability in our γ-ray data. There is no detectable variability in emission over a time of 9 days.

The present measurement of the pulsar period is shown on Figure 3 where it is compared with the earlier values from the X-ray measurements. It is clear that the behaviour of the period is erratic, as noted in the earlier work, with period derivatives which vary widely. We note a similar broad light curve for the emission from Her X-1 and 4U 0115 - see Figure 4. There has not to our knowledge been any previous attempt to observe 4U 0115 at VHE γ-ray energies.

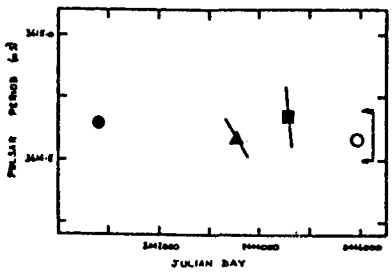

FIGURE 3: The variation of the pulsar period for 4U 0115 +63 since 1978. Earlier X-ray results are shown ● [illegible] ▲ [illegible] and ■ [illegible]. The present result is shown ○ . The solid lines indicate the measured period derivitive at that epoch. The arrows show the regions where the period may reasonably be expected.

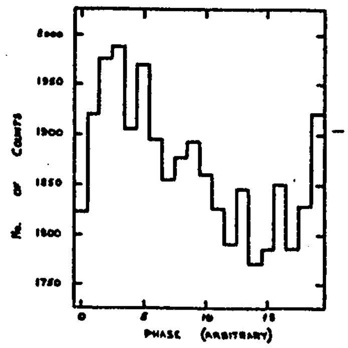

FIGURE 4: The light curve for 1000 GeV emission from 4U 0115+63.

RESULTS : (B) Her X-1.

Our original detection of 1000 GeV γ-rays from Her X-1 was based on a short outburst of intense periodic (1.24 s) emission at JD 2445441.86 and some evidence for a weak effect in data taken on 8 nights in 1983 July. The University of Utah Fly's Eye EAS detector has provided evidence for sporadic emission at a γ-ray energy of 5×10^{14}eV lasting for less than 40 min at JD 2445526.72.[9] The duty cycle of the light curve was 10% and the pulsed component was 40% of the cosmic ray background from a 50 sq deg area of the sky. At the same time the 1000 GeV Cerenkov telescopes located near the Fly's Eye were operating and were tracking Her X-1. A burst of similar strength would have appeared in the γ-ray telescopes (aperture about 5 sq deg) as an increase in the cosmic ray counts of 400%. No indication was seen of such a strong outburst at 1000 GeV with a light curve with duty cycle of 10% in the 40 min at JD 2445526.7. However in a routine reanalysis of our data using a test based on a generalization of the Hodge-Ajne test [10] and sensitive to emission with a narrow duty cycle (typically 0.5%) activity with period 1237.798 ms on JD 2445525-28 and especially around JD 2445526.7 is indicated - see Figure 5. On the basis of this observation a search for similar periodicity on the other 7 nights when Her X-1 was observed was made. The strongest indication of activity (at period 1237.779 s), significant after allowing for the degrees of freedom at the ~2 σ level, was at JD 2445615.66 - see Figure 6. We make no attempt to attach a rigorous statistical significance to this occurrence but it is interesting to note that this activity, lasting 30 min, was 173.8 d (5x34.76d) after the 1983 April 17 outburst and 172.35 d (5x34.47d) before the EXOSAT observed X-ray switch-on[11].

On this basis the JD 2445526.7 activity was at phase 0.44 after switch on in the 34.76 d cycle. The phase in the 1.7d orbit of the 3 intervals of activity are similar. The activity at JD 2445615.66 was at phase 0.94 in the orbital period; this may be compared with the value of 0.77 for

1000 GeV γ-rays on JD 2445441.86 and approximately 0.66 for UHE and VHE γ-ravs on JD 2445526.7.

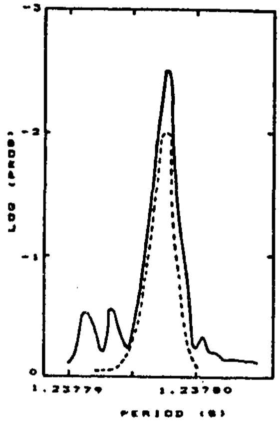

Figure 5 : The probability of chance origin of periodicity. The solid line is for data for 1983 July 9-12. The broken line is for data from 1983 July 10 only.

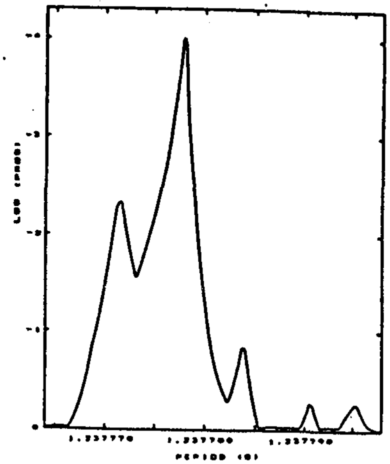

Figure 6: The probability of chance origin of periodicity on 1983 October 7.

3. CONCLUSIONS

We have some evidence of additional emission by Her X-1 which occurs 5x34.76 d after the 1983 April 1000 GeV γ-ray burst and 5x34.47 d before the observed X-ray switch-on and which is characterized by a narrow light curve. A measurement at the same time as that made by the Fly's Eye in 1983 July suggests that the strong outburst was confined to the EAS energies although there are indications of some activity at 1000 GeV during the whole of the night in question and perhaps on adjacent nights but again with a short duty cycle light curve. Observations of 4U 0115 +63 made on the basis of its similarity to Her X-1 show evidence for pulsed VHE γ-ray emission at the X-ray period, significant at the 2.5×10^{-4} level. We note that the VHE γ-ray luminosity of Her X-1 and 4U 0115 appear to be similar to within a factor of three, the emissions have similar broad light curves and that these two binary pulsars (and Cygnus X-3) are seen to exhibit cyclotron line emission indicating strong surface magnetic fields.

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