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TeV Gamma-rays from X-ray Binary Pulsars

Abstract: A number of categories of celestial very high energy (> 0.2 TeV) gamma ray sources has now been established including X-ray binary sources containing pulsars. We here briefly describe the ground based atmospheric Cerenkov light technique used to detect such very high energy (VHE) gamma rays, and review the evidence for their emission from X-ray binary pulsars. An initial attempt is made to establish patterns in the observed emissions as an aid to understanding of gamma ray production.

1. INTRODUCTION

It is now about 20 years since the first claims were made for the detection of very high energy (VHE) gamma rays from celestial sources. These early results suggested that the Crab pulsar (56) and nebula (45), the enigmatic object Cygnus X-3 (104) and the active galaxy Centaurus A (57) all emitted gamma rays of energy around 1000 GeV. All of these observations depended, as do the more recent results, on the use of the atmospheric Cerenkov light technique pioneered by Jelley (49) and reviewed by Turver (98) and Weekes (106).

It came as something of a surprise in 1983 that a classical X-ray binary pulsar (XRB) - Hercules X-1 - was observed as a source of VHE gamma rays showing an excess of counts which were periodic at the X-ray rotational period (41). Since then other XRBs have been identified as VHE gamma ray emitters with a range of statistical significance. Some identifications are quite firm, some are marginal and it is possible that some of the claims for sources may be ultimately proved to be erroneous. Nevertheless, a review of the evidence for VHE gamma ray emission from X-ray binaries as a basis for the development of models for its production is timely.

In this review we outline the atmospheric Cerenkov light technique which underpins all the VHE observations, report the evidence for emission of VHE photons from XRBs and search for any pattern in these emissions.

2. THE ATMOSPHERIC CERENKOV LIGHT TECHNIQUE

2.1 Cerenkov light in the atmosphere

A celestial high energy gamma ray striking the top of the atmosphere initiates a cascade of electrons and photons which reaches a maximum of development at altitudes of around 10 km above sea level. The electrons - about 1 for every GeV of incident gamma ray energy - produce a brief optical flash through the Cerenkov process in the medium (air). This lasts for a few ns and penetrates with little attenuation to produce a pool of visible light at ground level. For a primary gamma ray with energy 1000 GeV the pool covers an area of ~ 10000 m^2 with typical densities of 50 optical (blue) photons m^{-2}. This brief flash of visible radiation may be readily detected by a simple flux collector which focuses the light onto a photosensor. Due to the width of the light pool, a detector of small physical area (typically a few m^2) will have a large effective collecting area so enabling the low intrinsic VHE gamma ray rate to be translated into a worthwhile rate of detection. Unfortunately this simple and economic technique suffers from a serious background problem owing to the presence of a dominant isotropic background of cosmic ray particles (mainly protons). These produce atmospheric Cerenkov light signatures which are very similar to the gamma ray initiated events. The fraction of gamma-rays is typically a few percent of this background. Recently attempts to overcome these limitations have been made involving different approaches to identify the signatures due to gamma rays (22, 11, 99).

2.2 Atmospheric Cerenkov light telescopes

The simplest Cerenkov telescope comprises two flux collectors and two light detectors (photomultipliers (PMTs) have always been used to date). The fast coincidence between the light flashes detected by the two collector systems ensures that a genuine Cerenkov light flash is detected and a low threshold energy for detection can be attained. Such simple systems were typical of the first Cerenkov telescopes. In recent years more ambitious telescopes have been built and operated. For example, the Whipple collaboration (25) has pioneered a new technique to enhance the proportion of gamma rays in a dataset by using a high resolution camera comprising more than 100 PMTs at the focus of a single large area high quality mirror and exploiting the information in the shape of the Cerenkov light image. The Haleakala collaboration (91) has pursued an alternative approach based on the combination of carefully chosen low noise PMTs and matched mirror areas (¾ in PMTs viewing 60 cm mirrors operated in typically 7-fold coincidence) to provide a fast (sub ns) sample of the Cerenkov photons at the single photoelectron level. The Durham group (10) has developed a range of conventional telescope designs incorporating threefold fast coincidence between photon samples. Recent versions of their telescopes have involved 11 m^2 mirrors, viewed by clusters of 7 PMTs at each prime focus used for rejecting off-axis (background proton) events on the basis of arrival direction.

Since many of the results to be reported here have been obtained with the Durham telescopes they will be briefly described.

2.3 The University of Durham VHE gamma ray telescope

The University of Durham Mark III VHE gamma ray telescope has been operating in Narrabri, NSW, Australia since September 1986. It consists of three paraxial dishes of approximately 11 m^2 effective area and each is formed from 44 smaller spherical mirrors deployed as a close-packed array (see Figure 1).

Each flux collector is viewed by a detector package containing seven 46 mm diameter photocathode PMTs operated in triple fast coincidence between the three dishes. Within each detector package, the central PMT views the area of sky along the telescope's axis, while the other six PMTs view adjacent areas of sky offset by 2° from the central channel. This allows simultaneous measurements of a suspected source region and six surrounding background regions. This type of detector also

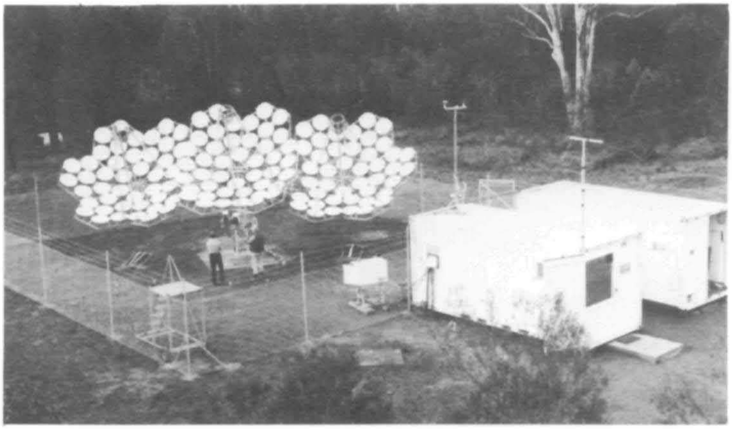

Figure 1. The University of Durham Mark III gamma ray telescope at Narrabri, NSW, Australia.

enables a worthwhile enhancement of the gamma ray to background proton counting rate to be made by rejecting those events recorded by the central (on-source) PMT and any of the guard ring PMTs (11). Such events originate from directions away from the source and have been shown to be predominantly background cosmic ray events.

The time of arrival of each Cerenkov flash is recorded to an accuracy of 1 μs, along with the detail of the detector responses and the charge registered by each PMT. Close to the zenith, a count rate of > 2 Hz per square degree (i.e. per channel) is achieved. A detailed description of the Mark III telescope is given in Brazier *et al* (10); the Mark IV telescope, which was used in 1988/89 in La Palma, Canary Islands and is now operational at Narrabri, is similar in all respects except that the flux collectors are each of area 6 m^2.

3. VHE GAMMA RAYS FROM X-RAY BINARY PULSARS

3.1 Introduction

Table 1 shows a list of the known X-ray binaries which include a pulsar; they are listed in order of increasing rotational period. The objects in Table 1 for which gamma ray observations have been made are summarized in Table 2, where an indication of the status of the search for VHE gamma ray emission is given. The evidence from each gamma ray measurement will now be considered in detail, dealing first with high mass X-ray binaries (HMXRB) and then with the low mass X-ray binaries (LMXRB).

The analysis of the typical weak signal in VHE gamma ray observations of binary systems (a few % of the cosmic ray count rate) requires special treatment of the data. For example, the rotational period of the pulsar after Doppler shifting due to the orbital motion cannot be directly observed, in contrast with the case in X-ray observations. Rather, the effects of the binary motion of the source region for VHE gamma rays must be accurately allowed for by transforming the time of each recorded Cerenkov flash to the rest frame of the binary system. This is followed by a test for uniformity of phase. Such a routine is necessary if a weak signal in a large dataset spanning a wide range in orbital phase is to be recovered. In most cases the sensitivity of this analysis to the assumed parameters of the orbit is not critical; the binary orbital

Table 1. The known X-ray binary pulsars.

Name	Pulsar period (s)	Orbital Period (days)	Classification
1E1024-57	0.061		
A0538-66	0.069	16.7	Massive Be
SMC X-1	0.714	3.89	HMXRB
Her X-1	1.24	1.70	LMXRB
H0850-42	1.78		
4U0115+63	3.61	24.3	Massive Be
V0332+53	4.38	34.25	Massive Be
Cen X-3	4.84	2.09	HMXRB
1E1048.1	6.44		Massive Be
1E2259+59	6.98	0.03 (?)	LMXRB
4U1626-67	7.68	0.03	LMXRB
2S1553-54	9.30	30.6	Massive Be
LMC X-4	13.5	1.41	HMXRB
2S1417-67	17.6		Massive Be (?)
GS1843+00	29.5		
OAO1653-40	38.2		HMXRB
EXO2030+37	41.8	45-47	Massive Be
Cep X-4	66		
4U1700-37	67.4 (?)	3.4	HMXRB
GS1836-04	81.1		
GS1843-02	94.8		
A0535+26	104	111	Massive Be
Sct X-1	111		
X0021.8-72	120.2		LMXRB (?)
GX1+4	122	304	LMXRB
4U1230-61	191		
GX304-1	272	133	Massive Be
Vela X-1	283	8.96	HMXRB
4U1145-61	292	188	Massive Be
1E1145.1	297	5.6 (?)	HMXRB
A1118-61	405		Massive Be
GPS1722-36	414		
4U1907+09	438	8.38	HMXRB
4U1538-52	529	3.73	HMXRB
GX301-2	696	41.5	HMXRB
4U0352+30	835	580	Massive Be

parameters (known from X-ray or optical observations) are usually of sufficient accuracy to allow a satisfactory transformation. Similarly, any uncertainty due to assuming a common origin for the X-ray (or optical) and VHE photons is in most cases acceptable.

3.2 SMC X-1

This X-ray binary consists of a highly magnetized neutron star in a 3.9 d orbit about a B0.5 I supergiant. It is one of the most powerful of the known X-ray binaries with high state X-ray luminosities in excess of 10^{39} erg s^{-1}. The pulsar spin period is 0.7 s and the X-ray observations over an 18 year period indicate that the pulsar is being spun up uniformly.

Table 2. Summary of VHE gamma ray observations

Object	Status of VHE observations		
	Source	Possible source	Flux limit
Cyg X-3	X		
A0538-66			X
SMC X-1		X	
Her X-1	X		
4U0115+63	X		
V0332+53			X
Cen X-3	X		
1E1048.1			X
1E2259+59		X	
4U1626-67		X	
LMC X-4		X	
2S1417-62			X
X0021.8-72		X	
GX1+4			X
Vela X-1	X		
4U1145-61		X	
1E1145.1			X
4U0352+30			X
A0535+26			X

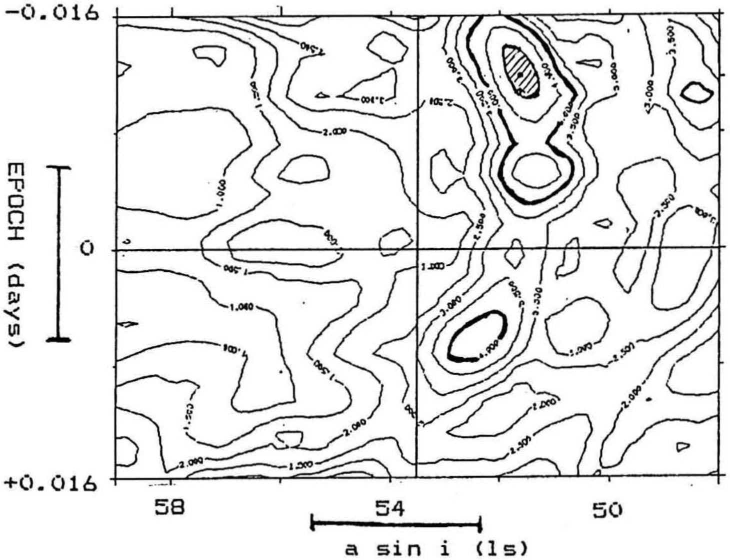

Figure 2. A contour plot for the 1987 July dataset from SMC X-1 taken with the University of Durham telescope at Narrabri . The contours represent the chance probability at the X-ray period plotted as a function of the epoch of mid-eclipse and *a sin i*. The heavy line represents the contourof a chance probability 10^{-4}; the hatched area has chance probability $< 10^{-5}$. × denotes the orbital parameters expected from X-ray measurements. The error flags show the bounds for "sampling" intervals in epoch and *a sin i*.

The only VHE observations of SMC X-1 are those made for a total of 333 hrs on 101 nights between 1986 October 3 and 1989 December 1 with the Durham University Mark III telescope at Narrabri (12, 69). This is the largest dataset for any XRB observed in the Durham program; however the analysis of the data poses problems when attempting to allow for the Doppler shifting of the period because of the short rotational period (0.7 s) and semi-major axis of the binary orbit (53 ls). It is necessary to consider the effects of "sampling" in the dataset not only of the value of the pulsar period but also the values of the semi-major axis *(a sin i)* and the epoch of mid-eclipse. We show in Figure 2 a contour plot of the probability of uniformity in phase according to a Rayleigh test as a function of epoch and *a sin i*. (The test for uniformity at the X-ray period was made on a sample of 9 observations each of typically 3 hrs duration made in an elapsed interval of 10 days in 1987 July; the data from each observation were analysed independently and the probability quoted is derived by combination of the results of tests of the individual datasets). The minimum probability (6×10^{-6}) increases to about 6×10^{-4} when allowance is made for the range of values of pulsar period and orbital parameters tested, and for the effects of oversampling. Similar data are available from later observations.

3.3 Centaurus X-3

Centaurus X-3 is a 4.8 s pulsar in a 2.1 d orbit. The X-ray emission is well studied, with recent observations from the *Ginga* and *Mir-Kvant* spacecraft. VHE gamma-ray emission from Cen X-3 was first reported by the Durham group using the Narrabri telescope (20). The total data set consisted of 207 hours of observations and spanned the whole of the orbit. This is an example of a case where the orbital paparameters from X-ray observations allow an adequate correction for Doppler shifting of the period to be made. Evidence was found, significant at the 10^{-6} chance level, for pulsed emission at the expected X-ray period but the emission is found to be confined to data recorded in a 5% wide orbital phase band around the ascending node - see Figure 3.

Independent confirmation of VHE emission from this object has come from the Potchefstroom group (79). Analysing 71 hours of data accumulated during 1986 May

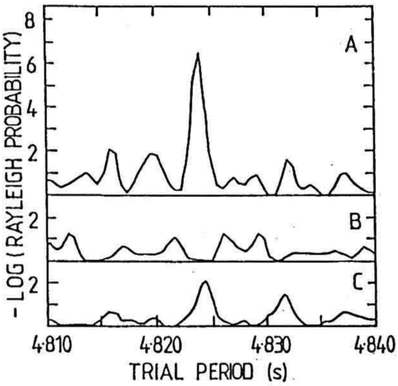

Figure 3. The variation of chance probability with period for data taken in the orbital phase range 0.77 - 0.82 from Cen X-3. (a) uses events which triggered the central detector only, (b) uses events which triggered both the central detector and an outer guard-ring detector and (c) comprises events which triggered an outer guard-ring detector only. The data are from the University of Durham telescope at Narrabri.

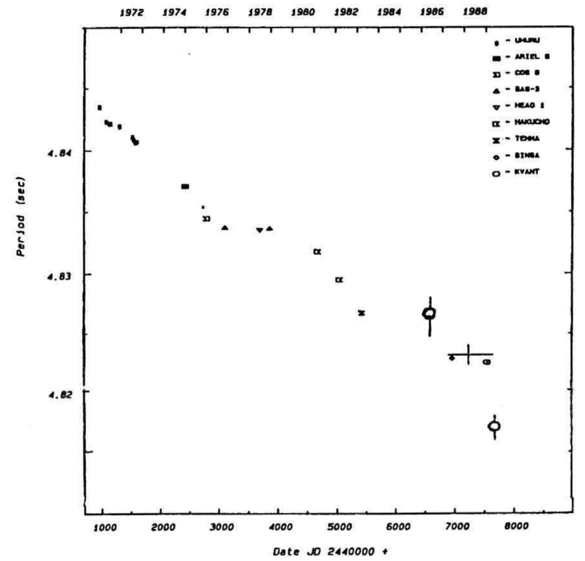

Figure 4. The pulse period history of Cen X-3 based on X-ray measurements from the compilation of Gilfanov *et al* [51]. Legend
o Potchefstroom VHE gamma ray measurements (79)
+ Narrabri VHE gamma ray measurements (20)

1 - 1989 April 5, they found evidence for pulsed emission, also confined to orbital phases 0.7 - 0.8 only, at a chance probability level of 2 x 10^{-4}. However, the large value of the period derivative hinted at by these results contrast with small values demonstrated by the contemporary X-ray and the Durham VHE gamma ray measurements - see Figure 4.

3.4 LMC X-4

The fourth X-ray source in the Large Magellanic Cloud was discovered by Giacconi *et al* (50), using data from the *Uhuru* satellite. Photometric and spectroscopic observations of the optical counterpart revealed the binary nature of the source, the orbital period being 1.408 days. Occasional X-ray flaring episodes have been observed from this object, and a pronounced 30.5 day periodic modulation in the hard X-ray flux has also been observed, similar to that of Hercules X-1. This modulation is also seen in photometric data. The pulsar period is 13.5 s, and it has been measured with the *SAS 3*, *EXOSAT* and *GINGA* satellites (59, 60, 80). Ultra high energy gamma ray data from the direction of this object, taken with the Buckland Park array show modulation with the characteristic 1.4 d orbital cycle which is significant at the 3.2 σ level (82).

The only VHE measurements to date have been made by the University of Durham group. Over 107 hr of data on LMC X-4 were taken with the University of Durham Mark III telescope on 36 nights between 1987 January 26 and 1989 November 29 (12). The first data, from observations in 1987 January and February, were tested for the pulse period expected from the X-ray measurements. Some evidence for periodic behaviour was found in the data recorded at orbital phases 0.5 - 0.7. The pulsed strength for this dataset was found to be 3.8% of the cosmic ray background, corresponding to a VHE gamma ray flux of 2.0 x 10^{-10} cm^{-2} s^{-1}, with a Rayleigh probability of 2.2 x 10^{-4}, after correcting for all degrees of freedom. Further observations of the object were made and the data analysed in the same way. These showed no evidence for pulsed emission. A possible explanation of this apparent variable VHE gamma ray emission may lie with the 30.4 day cycle observed in optical measurements. However observations made in 1989 November at approximately the same phase in the 30.4 day optical cycle as those of 1987 January/February showed no periodicity.

3.5 Vela X-1

Vela X-1 is a 283 s pulsar in an 8.96 d binary orbit. X-ray observations show that the pulse period history is complex, with epochs of spin-up and spin-down behaviour (see Figure 5). At UHE energies, there have been reports of the detection of a signal (81, 96, 103); the first reported detection at VHE energies was by North *et al* (78), using the Nooitegedacht telescopes of the Potchefstroom group. During 1986, they observed pulsed emission which persisted throughout the binary orbit. They also observed a strong outburst of pulsed emission which occurred in phase with the persistent pulsed effect but which lasted for only a few pulsar rotations around the time of entrance to the X-ray eclipse. However, there is a puzzle; the period found in both these observations (282.82 s) is inconsistent with the value provided by later X-ray and gamma-ray measurements. Subsequent observations (85, 86) using the Potchefstroom telescopes in 1987 and 1988 confirmed the persistent emission and the bursts, which were confined to about half the orbit around eclipse. Moreover, the period observed in these later measurements was in accord with that from measurements using the *Ginga* X-ray satellite (69). Observations have been made with the University of Durham telescope at Narrabri during 1986 - 1988 (21). These provided evidence for a persistent emission at the X-ray period throughout the binary orbit, but no evidence for episodes of enhanced emission on a time scale of a few pulsar rotations was found. Observations from the White Cliffs experiment (34) and the JANZOS experiment (9) have produced upper limits for VHE emission which are consistent with the reported fluxes. The VHE gamma ray observations and the measured fluxes are summarised in Table 3. (It should be noted that there are discrepancies between the procedures used for the estimation of fluxes from the Durham and Potchefstroom experiments (31) and that the apparent flattening of the energy spectrum below 1 TeV may not be real).

Persistent emission of VHE gamma rays from Vela X-1 seems well established, corresponding to a source luminosity of $\sim 3.6 \times 10^{34}$ erg s^{-1} for gamma ray energies above 300 GeV. However, the episodes of enhanced emission remain to be confirmed.

3.6 4U1145-619

4U1145-619 is a 292 s X-ray pulsar in a binary system with an orbital period of 186.5 d. X-ray observations show that outburst episodes, lasting ~ 10 d, occur every 186.5 d. It is assumed that this latter value is the period of a binary orbit of undetermined radius. During these outburst episodes, the pulse period is observed to change very rapidly, with a period derivative of $\sim -1.8 \times 10^{-7}$ s s^{-1} observed during the 1985 January outburst (35). This is attributed to the Doppler shifting due to the orbital motion of the pulsar.

The Durham University group observed 4U1145-619 with the Narrabri telescope for 45 hours during 1987 April and 1988 April and June (13). The 1987 April measurements, made exactly 4.5 orbital periods after an X-ray measurement (35), showed evidence for periodicity at the expected X-ray period (292.4 ± 0.5 s) with a chance probability of 1.5×10^{-4}. These data also indicated a value of period derivative of $+ 1.9 \times 10^{-7}$ s s^{-1} (significant at the 2 σ level) , which is equal in magnitude but

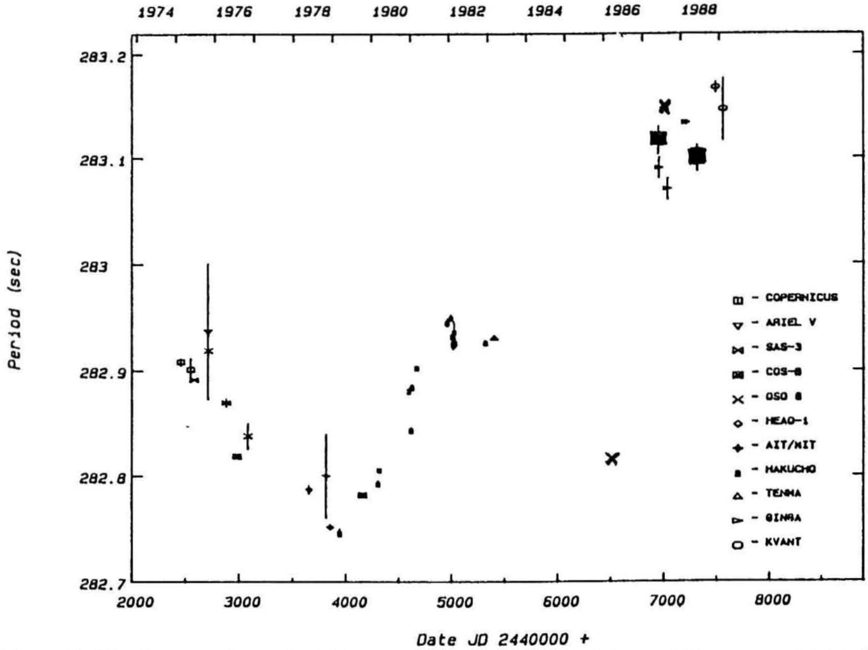

Figure 5. The X-ray pulse period history of Vela X-1 adopted from Gilfanov *et al* (51). The VHE gamma-ray measurements in 1986 - 1988 are shown .

■ Carramiñana *et al* (21)

× North *et al* (78, 86)

Table 3. VHE gamma ray observations of Vela X-1. (a) denotes fluxes for persistent pulsed emission, (b) denotes pulsed fluxes observed during episodes of enhanced emission, (c) denotes a DC measurement.

Telescope	Observation Dates	Period (s)	Integral Flux (10^{-11} cm^{-2} s^{-1})	Energy (GeV)	Reference
Nooitgedacht	1986 Apr 2 - 1986 May 10	282.82	2.0 ± 0.4 (a) 78 ± 9 (b)	3000	(78)
Nooitgedacht	1987 Apr 29 - 1987 May 30	283.14	1.5 ± 0.4 (a)	3000	(85)
Nooitgedacht	1988				(86)
Narrabri	1986 Nov 1987 Mar - 1987 Apr 1988 Mar - 1988 May	283.15 283.115 283.09	7.4 ± 1.5 (a)	300	(21)
JANZOS	1989 Mar - 1989 Apr		< 2.5 (95% CL)	1000	(9)

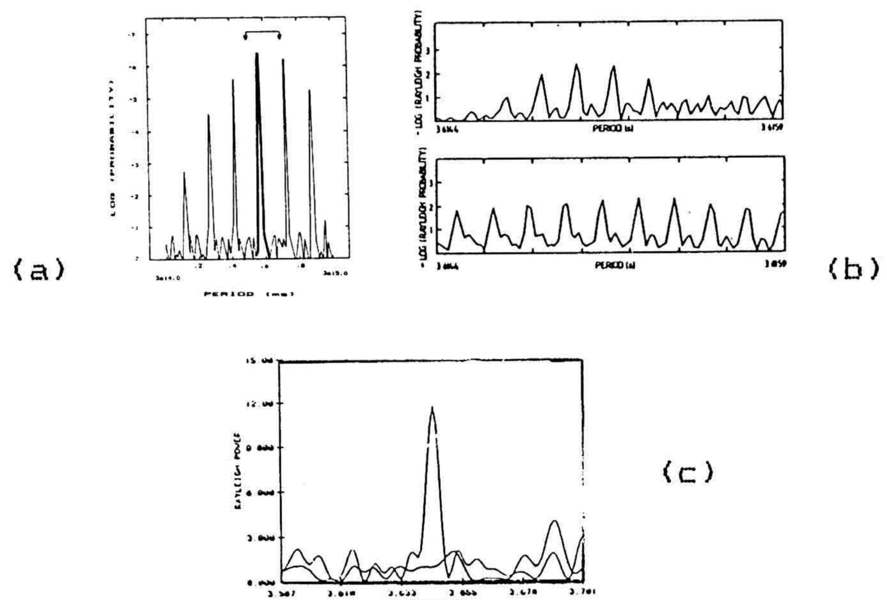

Figure 6. (a) Measurement of 4U0115+63 made from Dugway, Utah by the University of Durham telescopes (26).

(b) Measurements of 4U0115+63 made from La Palma by the University of Durham telescope (14).

(c) Measurements of 4U0115+63 made by the Gulmarg group (83).

opposite in sign to that shown by the X-ray data at a position on the opposite side of the (assumed) orbit. The further observations in 1988 April (1.9 orbital cycles after the 1987 April detection) and 1988 June (2.2 orbital cycles later) showed no evidence for VHE emission.

In a recent report (48) the suggestion has been made that an excess in the shower count rate measured by the SPASE PeV gamma ray project could be due to this source (or the close-by source 1E1145-61).

3.7 4U0115+63

This transient X-ray binary has a pulse period of 3.61 s and an orbital period of 24.3 d. The system is also known to show transient optical activity. Following the discovery of VHE gamma rays from Her X-1, 4U0115+63 was chosen as a candidate gamma-ray source by the Durham group working at Dugway, Utah. This object resembles Her X-1 in many ways (similar period, period derivative, luminosity and probable cyclotron line emission) but differs in at least two marked features - the mass of the companion and the mechanism for mass transfer. Data were accumulated over 8 consecutive nights in 1984 September (26). Due to a lack of a contemporary X-ray ephemeris, the parameters of the orbit used in the analysis had to be relaxed, as well as searching over a small range in pulsar period. Evidence was found, at a chance probability level of 10^{-5}, for VHE emission at the expected pulsar period (see Figure 6(a)). This corresponds to a gamma ray flux at energies > 1000 GeV of (7 ± 1.4) × 10^{-11} cm^{-2} s^{-1}. No evidence for variation of the gamma ray flux through the range of orbital period sampled was found.

It has been suggested (63) (on the basis of positional association) that 4U0115+63 is the VHE gamma ray source Cas Gamma-1 detected in DC measurements by the

Crimean group in 1971 and 1972 (94).

Confirmation that 4U0115+63 is a VHE gamma ray emitting object was provided by the Whipple and Haleakala VHE telescopes (64, 90). The Whipple telescope observed this source between 1985 September - 1986 January and identified one three-day interval which showed evidence for the 3.6 s period at a threshold energy of 600 GeV. Further data collected by this group during 1986 September - 1987 February showed no evidence for pulsed emission (23). The Haleakala observations were made from 1989 August - December and showed evidence for three episodes of sporadic emission. The Durham group, using their La Palma telescope, made observations of 4U0115+63 during two 7 day periods in 1988 September - October. Evidence for persistent emission throughout each of these observations was found, leading to a gamma ray flux of 4.4×10^{-10} cm^{-2} s^{-1} for an energy threshold of 400 GeV (14) (see Figure 6(b)). The Gulmarg group (83) report one episode of pulsed emission, lasting for ~ 1950 s on 1987 Nov 14, from ~ 40 hours of observation (see Figure 6(c)). The Tata group working at Pachmarhi (1) have also accumulated ~ 40 hours data from 4U0115+63 during 1987 and 1988, but report no evidence for pulsed emission.

4U0115+63 can thus be regarded as an established, but possibly sporadic VHE gamma ray emitter, with a luminosity of about 1.7×10^{36} erg cm^{-2} above an energy of 400 GeV.

3.8 1E2259+586

1E2258+586 is a 7 s X-ray pulsar coincident with the remnant of a supernova explosion. It is thought to be a member of a binary system but there is no strong evidence of orbital effects; there are some indications of a 2300 s periodicity in the X-ray observations of Fahlman and Gregory (44), and indirectly from IR observations (74). A recent paper (60) tentatively suggests an orbit with period 2120 s and *a sin i* of 0.038 ls. Other studies have provided flux limits in this range of values.

VHE gamma ray observations have concentrated on searches for the pulsar period in the data. Observations with the Whipple telescope in 1985 September - 1986 January and 1986 September - 1987 February failed to detect any persistent pulsed emission and established an upper limit (95% CL) to the flux above 600 GeV of 9.0×10^{-10} cm^{-2} s^{-1} (23). Further measurements with the Whipple telescope in 1987 and 1988 led to a flux limit of 2.2×10^{-10} cm^{-2} s^{-1} (without imaging enhancement) and 2.7×10^{-11} cm^{-2} s^{-1} (using the imaging technique) (24). Similar flux limits have been reported by the Haleakala group (107). The Durham group, using the La Palma telescope, observed this source in 1988 October and 1989 September (18). The 1988 data show evidence (significant at the 10^{-4} level) for periodic emission at the second harmonic of the expected X-ray period, leading to a flux ($E > 400$ GeV) of $(2.0 \pm 0.8) \times 10^{-11}$ cm^{-2} s^{-1}. Similar observations in 1989 failed to detect any persistent emission and give a 3σ flux limit of $(2.0 \pm 0.8) \times 10^{-11}$ cm^{-2} s^{-1} at a similar energy threshold.

The observations indicate that 1E2259+586 may be a variable gamma ray source over time scales of years or months; further observations of this unconfirmed VHE source are required.

3.9 Hercules X-1

The LMXRB Hercules X-1 displays a wide range of well-measured X-ray periods: a 1.24 s pulsation associated with the pulsar rotation period, a 1.7 day variation due to the orbit of the pulsar, and a 35 day period. The origin of the 35 d period has attracted a number of explanations. Trümper *et al* (97) have suggested that it is due to precession of the neutron star, while others (58) have argued that it is due to precession of the accretion disc. In addition, the X-ray source sometimes enters an extended low state, lasting between months and years.

VHE gamma rays from Her X-1 were discovered during observations using the Dugway atmospheric Cerenkov telescopes in 1983 (41). A 3 minute outburst of VHE emission was observed, and was found to be periodic at the contemporary X-ray pulsar period. At the time of the outburst, the X-ray pulsar in the binary system was at the ascending node in the orbit, and the "switch on" of the 35 day cycle was imminent. Following this discovery, more observations of Her X-1 were made by the Durham group at Dugway. Evidence was obtained for persistent, weak periodic emission during 1983 July (17, 28). Observations were made using the University of Durham Mark IV telescope on La Palma in 1988 July; a short burst of pulsed activity was observed on 1988 July 16, similar in all aspects to that first noted in 1983. Once again this occured close to the ascending node and at a time close to turn on in the 35 d cycle.

Independent confirmation that Her X-1 is a source of VHE gamma rays came from observations made with the Whipple Observatory in 1984 March-May (53). These initial observations showed 3 episodes of pulsed emission, occurring on timescales of a few hours or less. An extension of these observations resulted in a total of 8 episodes of pulsed emission being observed by the Whipple group (52, 65).

The first instance of pulsed VHE gamma ray emission observed with the Whipple telescope occurred on 1984 April 4, when Her X-1 was in the HIGH ON state in its 35 day cycle. At the same time, observations of Her X-1 were made using the University of Durham telescopes at Dugway, Utah (29). Both the Whipple and Durham measurements detected the X-ray period of 1.2376 ± 0.0004 s. This represents the first simultaneous detection of a VHE gamma ray source by two independent sets of telescopes.

A burst of pulsed VHE gamma ray emission observed with the Whipple telescope on 1985 June 16 is also remarkable (54). The observed emission took place just after the neutron star had passed behind its companion and entered X-ray eclipse. If the effect is real, this indicates that the site of at least some of the VHE gamma ray production differs from that of the X-rays.

Observations of Hercules X-1 with the Haleakala VHE gamma ray telescope started in 1985, when Hercules X-1 was observed for 29 hours (89). During this time, three bursts of pulsar activity were observed, all of which were in the LOW ON portion of the 35 day cycle. One episode of pulsed emission was observed at ingress to X-ray eclipse.

Further observations of Hercules X-1 were made by the Haleakala group in 1986 (92). On 1986 May 13 a burst of approximately 15 minutes duration was detected, with a pulse period of 1.23593 ± 0.00018 s. This period differs significantly from the period expected from X-ray and optical observations, being 0.15% lower. However, this period is in good agreement with an observation made at the Whipple Observatory in 1986 June (65) and with an episode of pulsed emission observed at energies above 10 TeV with the Cygnus Air Shower Array in 1986 July (39). A further detection of such a blue-shifted period was made by the Haleakala group in 1987 June (4), in agreement with the 1986 observations. The observed period shift is two orders of magnitude greater than the transient changes observed in X-rays, and 2.8 times the maximum orbital Doppler shift possible in the Her X-1 system. A convincing explanation for these detections of an anomalous period remains to be found.

A 15 minute burst of VHE gamma ray emission was observed with the Gulmarg gamma ray telescope on 1988 June 12 (87). The period is indistinguishable from that expected from the X-ray measurements, and is compatible with the period observed 34 days later in July of the same year by the Durham group. However, observations made

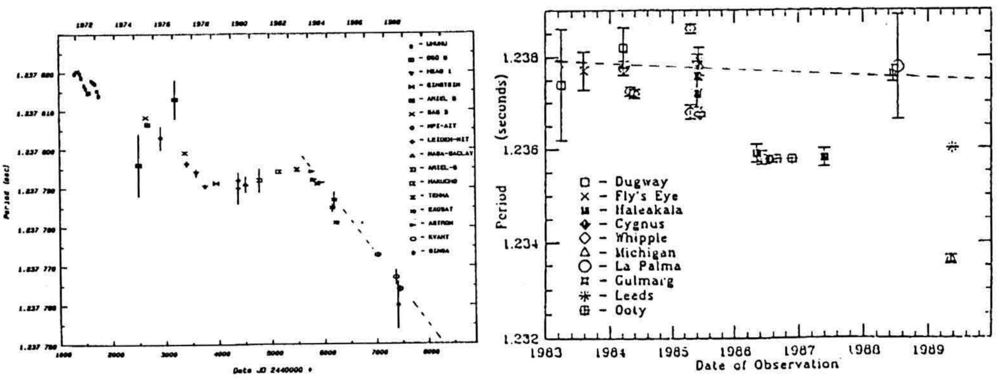

Figure 7. (a) The X-ray pulse period history of Hercules X-1 after Gilfanov *et al* (51).
(b) The VHE gamma ray period history. The broken line depicts the X-ray period measurements from Figure 7(a).

with the Pachmarhi telescopes in 1987-1989 show no evidence for any bursts of pulsed emission from Her X-1 (7). A further negative result for bursts of pulsed emission has been reported by the γ^* experiment (2), which observed Her X-1 from 1988 May to 1989 June. No evidence for bursts of periodic emission at the X-ray period was found.

The largest bursts of VHE emission from Her X-1 was observed by the Pachmarhi group on 1986 April 11, early in the life of this experiment (105). A burst of events, resulting in a 54% increase in the cosmic ray counting rate and lasting for 14 minutes was seen, corresponding to an excess significant at the 42 σ level. Unfortunately, there were problems with the recording equipment during the observation which precludes a meaningful search for pulsar periodicity in these data.

In Figure 7, we show the time evolution of the X ray period from Her X-1 and the VHE gamma ray periods measured between 1983 and 1989.

3.10 4U1626-67

4U1626-67 is an X-ray pulsar with a period of 7.68 s. The X-ray data has not revealed an orbital period but optical observations have given indications of a period of around 42 min (73). There is some uncertainty in the precise value of the orbital period from optical measurements but the best estimate is 2485 s. X-ray measurements indicate that the projected semi-major axis, *a sin i*, is very small, less than 13 lt s, which implies that the binary is being viewed at a very high angle of inclination (67). This is an unusual situation and an implication of this for VHE gamma ray observations is that correction of the data for the effects of orbital motion may not be necessary for periodicity to be detected.

The Durham group, using the Narrabri telescope, have made observations of this object during 1987 April - July and 1989 May (13). The longest single observation (a 9 hr observation taken on 1987 June 1) shows evidence for periodicity at the period expected from the X-ray data (7.664 s) throughout the observation with a chance Rayleigh probability of 2×10^{-5}. The other datasets show no evidence for periodicity at a similar period. This result is interpreted as a time-averaged 3 sigma flux limit for 300 GeV gamma ray emission of $(7.6 \pm 1.3) \times 10^{-11}$ cm^{-2} s^{-1}.

3.11 X0021.8-7221

This is a transient X-ray source with a period of 120.2 s in the globular cluster 47 Tucanae (3). The nature of the source is unclear from the X-ray observations, a low mass X-ray binary or a cataclysmic variable being possible. The Potchefstroom group have detected the X-ray period in VHE gamma ray data taken between 1989 July 7 and September 3 (38), with a chance probability of 3×10^{-4}. The VHE emission was found to be highly variable, with a peak luminosity of about 10^{36} erg s^{-1} at a threshold of about 5 TeV suggesting that this object is a low-mass X-ray binary observed at high inclination and is not a cataclysmic variable. Observations made by the Durham group at Narrabri on four occasions in 1988 and 1989 show evidence that on two occasions (in 1988 July and October) emission was detected (70). In 1989 July an indication of a periodicity at 118.5 ± 0.02 s was obtained significant at the 10^{-5} level; in 1988 October a signal at a period of 117.87 ± 0.01 s was obtained with chance probability 3 $\times 10^{-7}$. In both these datasets there were indications that the period was decreasing rapidly suggesting a period derivative of -1.3×10^{-7} s s^{-1}. We interpret this as a consequence of Doppler shifting in an orbit. The observations in 1989 October and November (when the object was observed at a large zenith angle) provided a small dataset and no evidence for a periodic signal.

3.12 Scorpius X-1

Sco X-1 is the brightest continuous X-ray source in the sky. It is accepted as a LMXB with an orbital period of approximately 0.787 d and is thought to be a candidate for a system including a millisecond pulsar, but no clear evidence for pulsation yet exists. Candidate periods of 4.53 ms (75) and 2.93 ms (66) have been suggested from X-ray data, but these remain to be confirmed. There have been reports of detection at UHE energies (72).

In view of the lack of a confirmed X-ray pulsar period, VHE gamma ray observations have concentrated on a search for DC emission. The Potchefstroom group have reported a flux of $(1.7 \pm 0.2) \times 10^{-11}$ cm^{-2} s^{-1} for energies greater than 1000 GeV (37). This measurement was made without a system of background light stabilisation and so a correction for varying background light conditions was made. The Durham group observed this object in 1988 May - June and 1989 May, using the chopping technique with background light stabilisation (16). A time-averaged DC signal, significant at the 3.1 sigma level in each measurement was seen, corresponding to a flux of $(1.2 \pm 0.4) \times 10^{-10}$ cm^{-2} s^{-1} for energies greater than 300 GeV. The emission appears strongest at orbital phase around 0.35 although the significance is marginal.

Searches for millisecond periodicity in the VHE gamma ray data have been made . Using the Rayleigh test, the candidate periods of 2.93 and 4.53034 ms were investigated but no evidence for periodicity was found. The Potchefstroom group have also searched for evidence of the QPO seen in X-rays, with an upper limit of 0.9 $\times$ 10^{-11} cm^{-2} s^{-1} being established for such oscillations in VHE gamma rays (84).

Unpulsed VHE gamma ray emission from Sco X-1 has been detected by two experiments, leading to a VHE gamma ray luminosity of $(2.3 \pm 0.7) \times 10^{34}$ erg s^{-1}. Further observations of this object are required to confirm the detection, to investigate the orbital variation of the flux and also with the hope of detecting short bursts of enhanced VHE emission upon which a sensitive *ab initio* search for millisecond periodicity could be performed.

3.13 Cygnus X-3

This remarkable object has been the subject of many detailed reviews, e.g. (33, 106). We here confine ourselves to a review of the TeV gamma ray observations.

Cygnus X-3 was first detected as a VHE gamma ray source by a Soviet group working at the Crimean Astrophysical Observatory in 1972, just after the first known radio outburst from this object. The 4.8 hr. X-ray period was identifiable: initially, two equal gamma ray maxima were observed, one at phase 0.15 - 0.2, and the other at 0.6 - 0.8. (These data were analysed using a definition of X-ray minimum due to Canizares *et al* (19), which was not used in later measurements either by the Crimean group or by others). Further observations and a new analysis of data from 4 years of observation showed the phase 0.2 peak to be stronger (95). Sporadic bursts were observed, specifically in September 1973, August 1974 and October 1980, the last observation being preceded by a radio outburst (47). The Crimean detection was followed by confirmation by a group in T'ien Shan using a similar telescope (77).

Further VHE gamma ray detections of Cygnus X-3 came in 1981 from the collaboration between University College, Dublin and the Harvard-Smithsonian Center for Astrophysics working at Mt. Hopkins, Arizona (36). The data were also found to show 4.8 hr. periodicity, with the maximum emission between phase 0.7 and 0.8. This phase was determined using an ephemeris derived from the Crimean observations. If the data are analysed using the 4.8 hr. ephemeris of Van der Klis and Bonnet-Bidaud (101), which rapidly became the standard for VHE gamma ray observations of this object in the 1980s, the emission is found to be at phase 0.6 - 0.7. The few observations made at other phases showed no significant excess.

Observations made by Lamb *et al* (62), using two 11 m solar concentrators of the Jet Propulsion Laboratory's Solar Energy Facility at Edwards Air Force Base as a VHE gamma ray telescope, showed an excess of events from Cygnus X-3 between phase 0.5 - 0.7 of the 4.8 hr. cycle.

Data taken during 1981 - 3 by the Durham group operating at Dugway, Utah, showed a 4.4σ excess lasting for about 10 min at phase 0.64 ± 0.03 with respect to the Van der Klis and Bonnet-Bidaud 1981 ephemeris, after allowing for the non-uniform background in the Cygnus region (40). Table 4 gives a summary of these and other results from Cygnus X-3.

Cygnus X-3 has long been suspected to contain a fast pulsar (92 - 96). However, the high column density of hydrogen in the region of Cygnus X-3 (it lies almost directly along a spiral arm of the galaxy) represents a severe limitation on searches for

Table 4. Fluxes from Cygnus X-3.

Group	Energy (TeV)	Flux (photon cm^{-2} s^{-1})	Phase	Epoch
Crimean Astrophys. Obs.	2	1.6×10^{-11} to 1.6×10^{-10}	0.15 - 0.2	1972 - 80
Tien Shan	5	1.6×10^{-10}	0.15 - 0.2	1977 - 78
Whipple	2	1.5×10^{-10}	0.6 - 0.7	April - June 1980
Observatory	0.8	$(5.1 \pm 1.1) \times 10^{-10}$	0.58 - 0.67	October 1983
ISU-JPL-UC	0.5	8×10^{-11}	0.5 - 0.7	Aug - Sept 1982
Durham	1	3×10^{-10}	0.625	1981 - 82

short period pulsation in the radio region due to the effects of frequency dispersion. This is not a problem for pulsed high energy radiation. However, the search for a fast pulsar in sparse VHE gamma ray data does present two problems:

(i) In the case of Cygnus X-3, the orbital parameters are unknown, so it is impossible to adjust event arrival times to remove the effect of the motion of the pulsar about a companion. The data must therefore have been taken over a short time interval and be searched for a Doppler shifted period.

(ii) As the pulsar period is obviously unknown, many trial periods must be searched.

It follows that a large number of events is required if any detection is to be statistically significant, and since from (i) the data must be taken over a short period of time, it is necessary to observe a strong burst of events from the object if a pulsar search is to be worthwhile.

During observations made in 1983 August - October with the Durham University telescopes, just such a burst was observed. On 1983 September 13, a count rate excess was noted, lasting for 7 minutes and representing an excess of 20% in the number of counts above the background. The events within the burst were tested for periodicity between 10 and 50 ms using the Rayleigh test. The resulting probability distribution was in agreement with chance, with the exception of one trial period: 12.5908 ms, which had a probability of chance origin of 4.8×10^{-8}. Six other datasets taken within one month were also tested for periodicity; one observation (1983 October 2) showed 12.5908 ms periodicity during the corresponding 7 minutes in the 4.8 hr cycle (27). Further, weaker evidence for 12.59 ms periodicity was found from analyses of data taken with the Dugway telescopes before 1983 (the telescopes were less sensitive prior to this), and also from analysis of data taken in 1985 October and November using a single, sensitive telescope (30). These results suggested that the pulsar was spinning down with a period derivative of $(2.8 \pm 0.4) \times 10^{-14}$ s s^{-1}. A new telescope (the Mark IV) was operated by the Durham group at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias on the island of La Palma during 1988 June - October. Observations of Cygnus X-3 made in 1988 June/July and September (15) showed 12.59 ms periodicity in data taken in a 600 s interval close to the maximum of the X-ray cycle as defined by the most recent X-ray ephemeris (102). The period and period derivative observed were compatible with the earlier Dugway measurements (30). No related periodicity was detected in observations in 1988 October. On the basis of these observations it was possible to predict the interval of activity and the pulse period appropriate to 1989 observations.

The discovery of a 12.59 ms pulsar in Cygnus X-3 prompted searches for the pulsar by other VHE gamma ray astronomy groups. The database from the Whipple collaboration at Mt Hopkins, Arizona consists of observations made in the tracking mode, each of approximately 28 minutes duration (46). The data were taken between April 1983 and November 1986. Each scan was split into six 8 minute segments overlapping each other by 4 minutes. These were then subjected to periodicity analysis. It was noted that, although there is a "tail" of periods with low chance probabilities around 12.59 ms in the power spectrum, no significant evidence is found for periodic emission when the number of trials is taken into account. In this, and a later paper (68) indications of 12.6 ms pulsed emission is reported, significant at the 3×10^{-3} level. However, the lack of an increase in count rate coincident with the pulsed emission when compared with the count rate in earlier and later intervals is cited as counter evidence, relying on the assumption that all gamma ray emission is confined to the eight minute test segment showing strong periodicity. Marshak (71) has recently criticised the statistical analysis adopted by the Whipple group and concludes that the Whipple data do, in fact, provide some evidence for the 12.59 ms periodicity.

The telescope on Haleakala in the Hawaiian Islands operated by the Universities of Hawaii, Wisconsin and Purdue made observations of Cygnus X-3 for some 133 hrs during the Summer and Autumn of 1985. On 1985 October 12 (when a pulsar detection was made in Durham), a 60s burst of events was observed from the direction of Cygnus X-3, at phase 0.74 of the 4.8 hr X-ray cycle (88). While preliminary analysis of the data taken on October 12 showed some evidence for a 12 ms pulsar signal, a subsequent *ab initio* period scan of the events occurring within the burst showed no significant evidence for pulsar activity when the large number of degrees of freedom, consequent upon the wide range of periods searched (10 ms - 2.2 s), were taken into account.

The Tata Institute telescope at Pachmarhi accumulated 10 hr. of data in 1986 October-November covering the orbital phase range 0.2 to 0.8 (6). The whole data set has been tested for periodicity covering the period range 12.5850 - 12.5967 ms. No evidence for 12.59 ms periodicity was found when the large number of degrees of freedom were taken into account.

The above negative results must be treated with caution if they are to be considered as being in conflict with the University of Durham claim. The hyphothesis to be tested is that there is sporadic pulsed emission at a well defined period at specific parts of the 4.8 hr cycle on some but not all occasions. In many of the attempts at independent confirmation this precise hypothesis has not been tested.

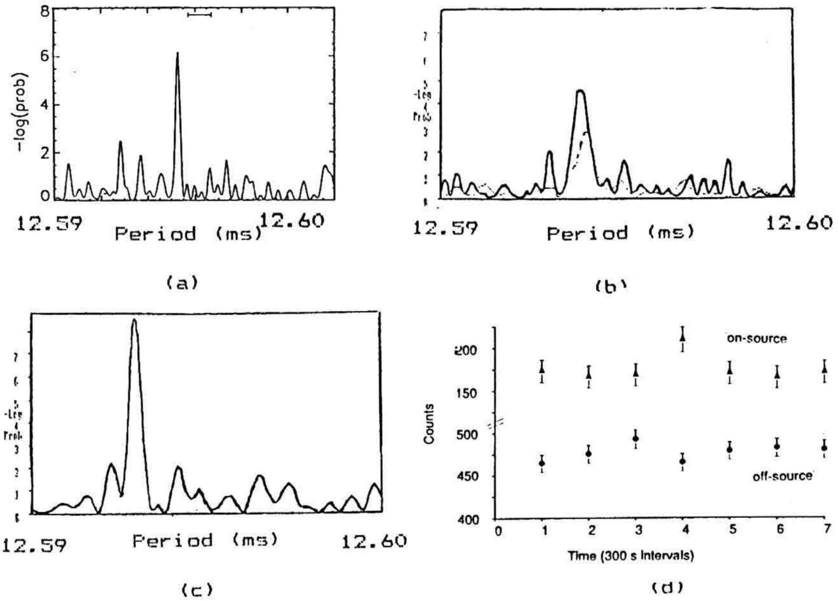

Figure 8(a) The chance probability for periodicity in the 600 s dataset in the observations of Cygnus X-3 at Woomera on 1989 September 1 and 2 (55).

Figure 8(b) The chance probability of periodicty in a corresponding 600 s dataset recorded during an observation of Cygnus X-3 on 1989 September 1 at La Palma (100) (broken line). The solid line shows the similar plot for a 300 s segment of data at the centre of the 600 s dataset.

Figure 8(c) The chance probability for periodicity in 300 s of data from an observation of Cygnus X-3 on 1989 September 7.

Figure 8(d) The count rate profile during the observation of Cygnus X-3 on Septemer 7. Interval #4 corresponds to the data set analysed in Figure 8(c).

Follow-up observations were made in La Palma in 1989 by the Durham group after the large radio outbursts in June and July. These observations failed to provide evidence at the period (12.5960 ms) in the specific window of the 4.8 hour cycle predicted from earlier results.

Observations of Cygnus X-3 were made by the University of Adelaide group using their VHE gamma ray telescope which is similar to the Durham Mk III telescope and is located at Woomera, South Australia. These were the first measurements using the large zenith angle technique suggested by Elbert and Sommers (93). The data showed no evidence for pulsed VHE gamma radiation in 1989 August/September at the period and phase in the 4.8 hr cycle suggested by (15). However they did observe periodicity in their data (55). The most significant effect they observed was a periodic signal in a 600 s window centred 950 s *before* the time predicted from the 1988 Durham observation in La Palma and at a period ~ 1 μs shorter. The strongest such episodes were during observations on the nights of 1989 September 1 and 2 with a chance probability $< 10^{-4}$ - see Figure 8(a). This result may provide the long-awaited independent confirmation of the 12.6 ms pulsar in Cygnus X-3 and also expose an interesting change in the pulsed emission and the orbital motion of the VHE emitting region. Corresponding 600 s segments of observations with the Durham telescope in La Palma were available on each night between 1989 September 1 - 7 (108). The observation made on 1 September at La Palma was two 4.8 hr cycles after that made at Woomera and referred to as September 1 and three 4.8 cycles before that referred to as September 2. For these data from La Palma in the *precise* 600 s in the 4.8 hr cycle identified by the Adelaide group a pulsed signal was noted at a period of 12.5939 ± 0.0004 ms - see Figure 8(b). In accord with our earlier results, which suggest that the interval of activity is no more than 400 s, we have investigated the distribution of the pulsed signal within the 600 s sample. We find that the emission lasts for about 300 s during which the pulsed signal is 23% of the cosmic ray background. We did not observe an accompanying increase in count rate. In addition, we find a second interval of emission lasting 300 s during an observation on September 7 on this occasion. The pulsed signal was 30 % of the background count rate and the period was 12.5930 ± 0.0004 ms - see Figure 8(c). A corresponding increase in count rate was detected on this occasion - see Figure 8(d). This 300s burst of emission occurred 250 s later in the 4.8 cycle than the activity noted at La Palma and Woomera on 1 - 2 September.

It may be helpful that X-ray observations using the Ginga spacecraft were made on 1989 Aug 31 - Sept 1 (61). The analysis of these data is awaited with keen interest; in particular we wish to know if the epoch of X-ray maximum has advanced since observations pre-1989, as appears to be the case for VHE gamma rays.

3.15 Other systems

A number of other X-ray binary systems with well established pulsar periods have been observed at VHE gamma ray energies without any detection of gamma rays. The flux-limits derived from the observations are summarised in Table 5.

4. PATTERNS IN VHE EMISSION

4.1 Introduction

It is quite likely that VHE emission from X-ray binaries, many of which show transient behaviour, is itself also highly variable. Here, we attempt to identify any pattern in the VHE emission, whilst acknowledging that for most observations the

Table 5. limits to VHE gamma ray emission from other X-ray binary pulsars.
(a) limited data sample prevents calculation of a meaningful flux limit.

Object	Telescope	Pulsar Period (s)	Flux Limit (10^{-11} cm^{-2} s^{-1}) (GeV)	Energy Threshold	Reference
V0332+53	Whipple	4.375	98 (95% CL)	600	(23)
4U0352+30	Whipple	835.64	(a)	600	(23)
A0535+26	Whipple	103.34	82 (95% CL)	600	(23)
GX1+4	Nooitgedacht Narrabri	93.4	7.7 (3σ) 7.2 ± 1.3 (3σ)	1000 300	(84) (13)
2S1417-62	Nooitgedacht	17.6	7.0 (3σ)	1000	(84)
1E1048.1	Narrabri	6.4	5.0 (3σ)	300	(100)

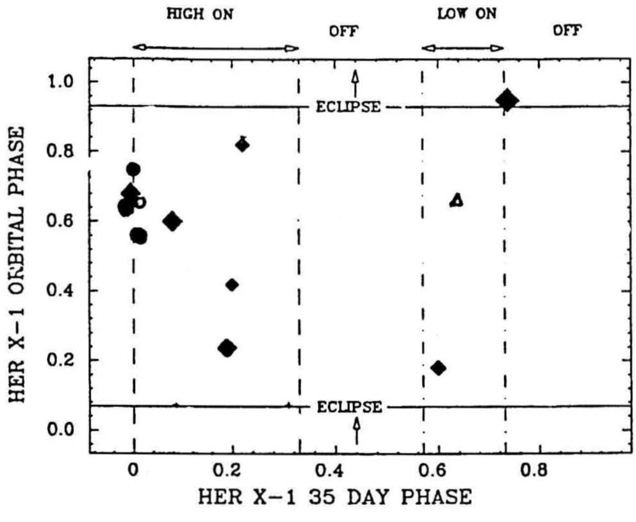

Figure 9. Distribution of VHE gamma ray measurements of Her X-1 in 1.7 day and 35 day phase.

identification of instances of strong emission is difficult, due to the difficulty of separating the statistical variation in telescope counting rate for a constant source from that of a source with truly varying VHE gamma ray luminosity.

4.2 Sporadic emission / long term variability

There are two objects for which clear evidence exists for sporadic or long-term variations in VHE emission - Cygnus X-3 and Hercules X-1.

Cyg X-3 is clearly not always producing VHE gamma rays; in the Durham observations it shows a probability of about 5 - 10% of being detected in any measurement at the most favourable part (X-ray maximum) of the 4.8 hour cycle. There is some evidence that there may be a 19.2 d cycle in the strength of the VHE emission (42).

For Hercules X-1 there is evidence for 35 d modulation of the VHE emission (see Figure 9). Episodes of bursts of VHE emission appear to be confined to the high on and low on parts of the 35 d X-ray cycle, with strong VHE emission being particularly favoured coincident with the 35 d "switch on" (and at the ascending node in the 1.7 d orbit - see Section 4.3).

The evidence for sporadic emission from 4U0115+63 is not clear. The Durham group detected emission lasting for periods of ~ 5 d apparently at a constant strength during three observations. However, detections made by other groups have been predominantly of short bursts of emission lasting for a few minutes or hours.

Insufficient data has so far been accumulated from studies of other XRBs to attempt to draw any firm conclusions about their long-term VHE gamma ray behaviour.

4.3 Orbital phase dependence of emission

The evidence for orbital phase dependence of VHE emission is well established in a number of sources, with Centaurus X-3 and Cygnus X-3 (if the 4.8 hour X-ray cycle is indeed orbital in origin) providing the best examples.

Cygnus X-3 has clearly shown the 4.8 hour modulation since its discovery in VHE gamma rays, with emission confined to regions close to X-ray phase 0.2 and 0.65 (in the past 10 years all observed effects have been close to X-ray maximum). Detection of the 12.6 ms periodicity has also been confined to regions close to X-ray maximum.

The observed VHE emission from Cen X-3 is confined to a narrow (5% wide) band of orbital phase, centred at X-ray phase 0.73, close to the ascending node.

The situation with Hercules X-1 is not so clear (see Figure 9). Emission occurs at all phases but there appears to be a clustering of bursts of VHE emission around orbital phase 0.6 - 0.7. The phase region corresponding to X-ray eclipse seems devoid of episodes of pulsed emission, except for two episodes which occur just after the onset of X-ray eclipse.

4U0115+63 is another well studied source, but evidence for any preferred orbital phases for emission is not obvious. Again, there is some evidence of bursts of emission being confined to the later portion of the orbit, but in this case this may be a selection effect.

If any broad hint of preferred orbital phase for emission exists it points to phase 0.6 - 0.7.

5. FUTURE PROSPECTS

Important advances in VHE gamma ray astronomy have been made through the 1980s, using telescopes of sensitivity such that most detections are just above threshold (a not unusual situation in the early stages of any new field). Although evidence has been built up for a number of X-ray binaries as VHE gamma ray emitters, it has not been possible so far to recognise clear patterns in VHE emission which may constrain the possible explanations so far advanced.

Methods of improving the signal to noise ratio by identifying the γ-rays (imaging, time structure of the signal) and by optimising the telescope design (larger collectors, smaller apertures) are continuing. Implementation of these ideas through the 1990s should provide further more significant and detailed evidence for VHE emission and a sound future for VHE gamma ray astronomy's studies of accreting binary systems. The prospect of simultaneous ground-based gamma ray observing and observation from space using *The Gamma Ray Observatory* in 1991/2 should ensure a continued and succesful evolution of the field.

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