GROUND-BASED VERY HIGH ENERGY GAMMA RAY ASTRONOMY - OBSERVATIONAL HIGHLIGHTS.

K E Turver
Department of Physics,
University of Durham, Durham DH1 3LE, UK.

It is now more than 20 years since the first ground based gamma ray experiments involving atmospheric Cerenkov radiation were undertaken. The present highlights in observational ground-based very high energy (VHE) gamma ray astronomy and the optimism about an interesting future for the field follow from progress in three areas:-

(i) the detection at increased levels of confidence of an enlarged number of sources so that at present claims have been made for the detection, at the 4-5 sd level of significance, of emission from 8 point sources (Cen A in 1973 (1) and more recently Crab pulsar(2), Crab nebula(3), Vela pulsar(4), Cygnus X-3(5,6,7,8), Hercules X-1(9,10,11), 4U0115+63(12), PSR 1953 (COS B source 2CG065 ?)(13),) plus three reports of diffuse emission from the galactic plane(14,15,16)

(ii) the replication of the claimed detections (e.g. Cygnus X-3(5,6,7,8), Her X-1(9,11)) with, for the first time, confirmation of the nature and detail of the emission; we are also seeing the beginnings of the detailed studies of the emission (e.g. Cygnus X-3(17), Crab pulsar(18)).

(iii) the extension of gamma ray astronomy to the ultra high energy (UHE) domain (10^{14-16}eV) with numerous reports of Cygnus X-3(19,20) and single reports of Her X-1(21), and yet to be confirmed at either VHE or UHE, Vela X-1(22) and LMC X-4(23).

At an energy around 1000 GeV (VHE) all observations employ the ground based atmospheric Cerenkov light technique(24). The higher energy studies around 100-10000 TeV (UHE) involve air shower detecting arrays usually involving particle detectors (the Fly's Eye detector operating in the Cerenkov mode is an exception).

The pattern, if any, to emerge from the list of sources claimed so far is that X-ray binary sources (with or without a pulsar as the collapsed object) appear to be copious emitters of gamma rays over at least 4 decades of energy. Looking in more detail at these X-ray sources which behave as VHE and UHE gamma ray emitters:-

(a) <u>CYGNUS X-3</u>. This is a very topical object which will be mentioned frequently during this Conference. It is also the source which has been most involved in the development of the present subject in recent years. Following the radio outburst in 1972, Stepanian at hte Crimean Astrophysical Observatory reported the first of a series of detections of 1000 GeV gamma rays from the object. Initially (1973) these were detections of a DC signal(25), with the first indications at VHE gamma ray energie of the now well known X-ray periodicity at 4.8 hr following in 1975(26). Since then similar detections at energies of 1000 GeV or thereabouts have been made by 5 groups (Tien Shan(27), FLWO/Dublin(5), FLWO/Dublin/Durham/Hawaii/Iowa/Hong Kong(7), JPL/Iowa/UCR(6), and Durham at Dugway,Utah(8)). Typical measurements made since 1980 are shown in Figure 1.

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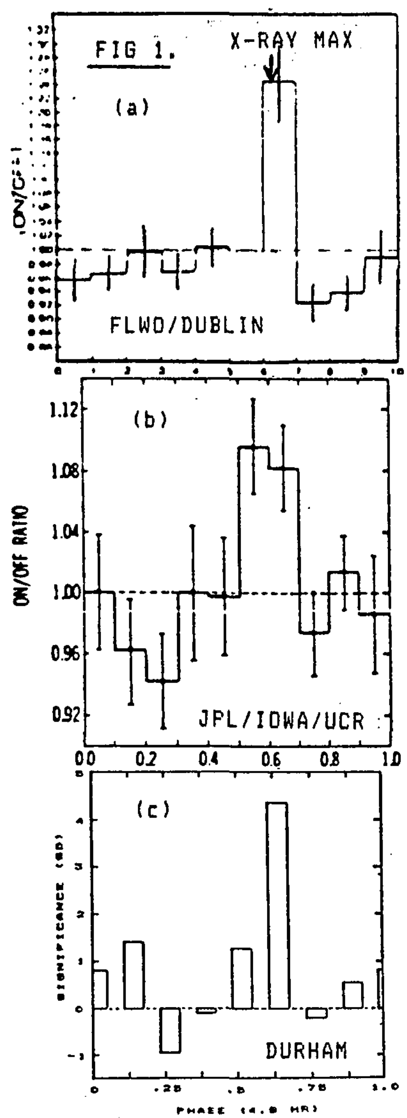


A similar story emerges from all of these observations made through the early 1980s - intermittent emission (the chance of observing during the ON state seems to be about 1 per 10-20 4.8 hr cycles ?) with a peak flux of about $10^{-10} cm^{-2} s^{-1}$ for energy > 1000 GeV always about the phase 0.62 in the 4.8 hr period corresponding to X-ray maximum, and lasting for a short time, about 10 min or so[8]. In addition there have been suggestions of time variability in the emission which is either sporadic or perhaps regular with long term periodicity involving the complete modulation of the VHE intensity (the long term period may be about 19 days - which is interpreted as possibly arising from apsidal motion according to the X-ray observations- has been mentioned in the context of radio, X- and VHE gamma rays).

At the highest energies the discovery by the Kiel group of a similar 4.8 hr modulated emission at an energy around 10^{15}eV [19]has been followed by other confirmatory analyses of the databases of many air shower arrays ([20], but with possible variability in the strength and a definite change in the 4.8 hr phase of the emission being suggested by later observations - see Figure 2.

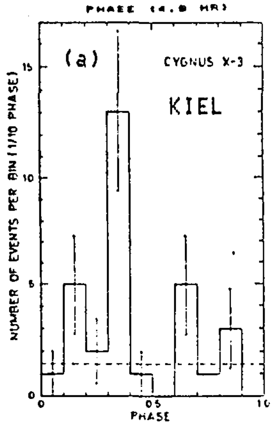
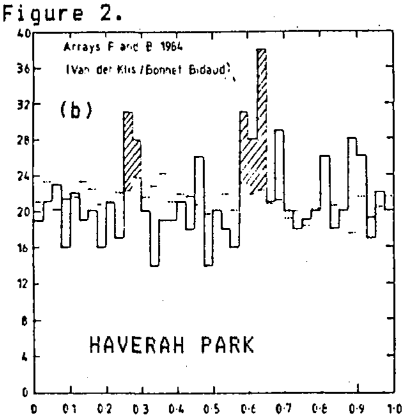


FIG 2.



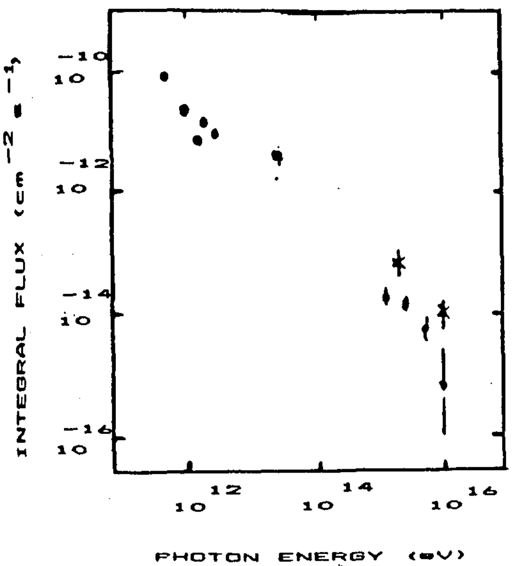


FIG 3.

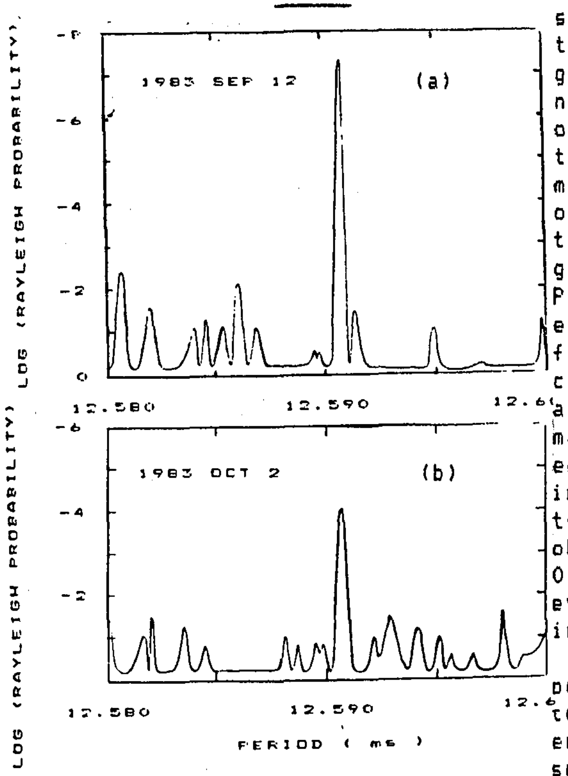


FIG 4.

The VHE and UHE gamma ray flux measurements combine to give an energy spectrum which is exceedingly flat (integral spectrum ~ 1.1) - see Figure 3.

A question which has remained unanswered at all wavelengths is whether or not Cygnus X-3 contains a pulsar as the powerhouse of the system. This has been suggested by Vladimirsky (CAO) as a consequence of a recent supernova, leading to a rotation driven process. Alternatively, it has been suggested by Brecher [28] that the mechanism is that of a unipolar inductor involving the accretion disc of a low field pulsar rotating at equilibrium when accretion is the origin of the energy. To date no suggestions have been made for the pulsar period. Recently our group in Durham [29] have analysed new data taken late in the life of the Dugway facility when our telescopes were operating with maximum sensitivity. At a level of significance which exceeds that of many of the reported VHE gamma ray detections (PSR 0532, PSR 1953, Her X-1, 4U0115 +63 etc), we find prima face evidence for ms periodicity (conservative chance prob $<3\times10^{-7}$). This occurs at those times around X-ray maximum in the 4.8 hr cycle when emission manifested as an increase in the count rate of the telescopes has been detected. The observed period is 12.5908 $\pm$ 0.0003 ms and some of the evidence for the claim is shown in Figure 4.

Confirmation of this periodicity (which may well have to be made at VHE gamma ray energies if dispersion and scattering in the coccoon or stellar wind is occurring) would represent a real highlight !!

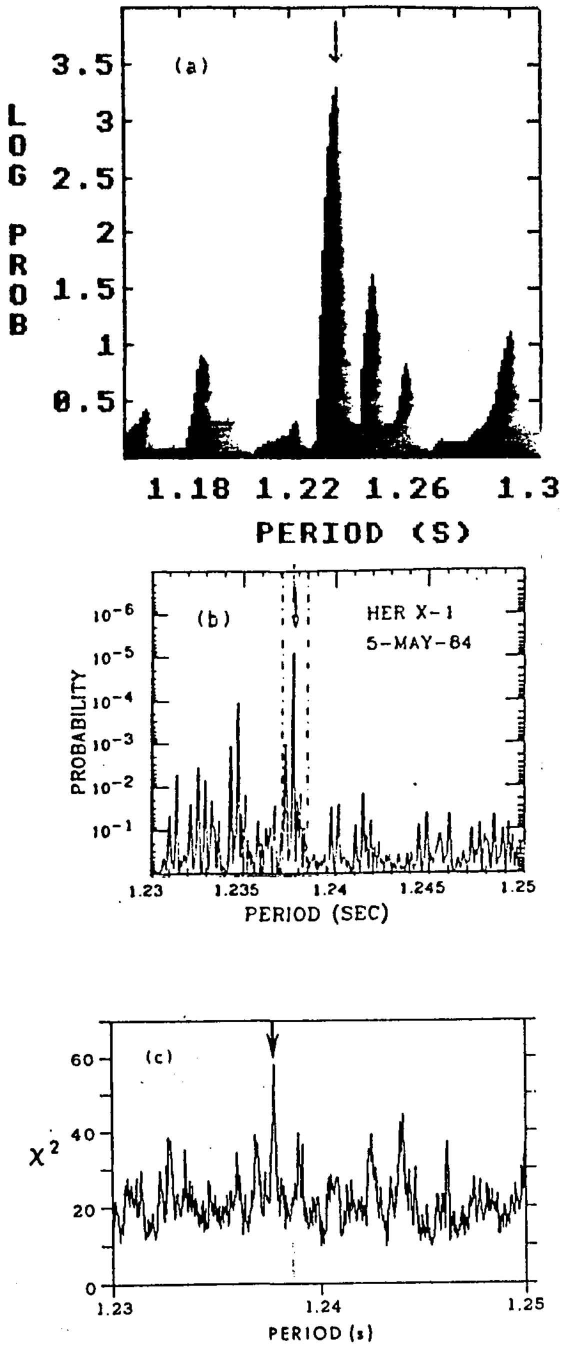


FIG 5.

(b) HERCULES X-1.

A short (3min) outburst of (1.24 s) pulsed gamma rays was detected by the Durham VHE gamma ray experiment in Utah in April 1983[9] - see Figure 5(a). The effect was at phase 0.77 in the 1.7 d orbit and , as far as we can tell, 35 d before an observed switch on of X-ray activity to the high state. The temptation to associate a burst of VHE gamma rays with X-ray switch on should perhaps be resisted - later observations only partially confirm the pattern. The VHE emission is characterized by a broad (X-ray like) light curve and a peak flux of 10^{-9} cm^{-2} s^{-1}at E > 1000 GeV. Replication of this observation, complete in many details, has been reported by the FLWO collaboration[10] - see Figure 5(b).

At energies 100-1000 times higher, the University of Utah Fly's Eye group has recently reported a July 1983 burst of <40 min duration also showing the 1.24 s periodicity of the X-ray pulsar. The light was 10% duty cycle and the observed effect was very strong - an increase of 40% above the cosmic ray background from 50 sq deg of sky - see Figure 5(c). At the same time the colocated 1000 Gev Durham Cerenkov light experiment saw no such marked effect but did observe a rather longer interval of activity (2-3 d) which included the time of the Fly's Eye outburst. This is the first example of simultaneous observations with two systems and certainly with two detectors with such dissimilar energy thresholds; it should be the first of many. If true, these two results suggesting very different origins for the gamma rays of different energies must constrain the choice of models for the Her X-1 VHE and UHE emitting system.

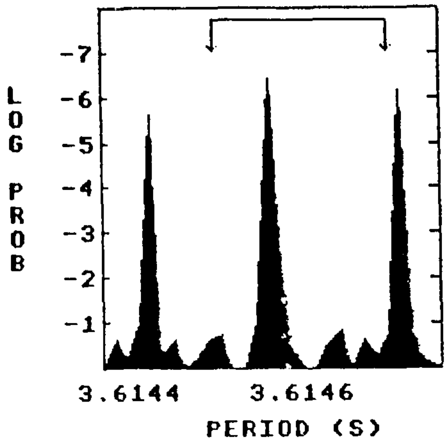


FIG 6.

(c) 4U0115+63

Following the discovery of Her X-1 as a 1000 GeV gamma ray emitter, the University of Durham project targetted 4U0115+63 as the binary system which is most similar to Her X-1 (period and X-ray luminosity) and which shares a claim to cyclotron line emission. A successful search was made in September 1984[12] and the resulting periodogram showing the 3.6 sec periodicity for the VHE gamma ray data is shown in Figure 6. This is the strongest time averaged source of 1000 GeV gamma rays detected in the Durham project (7×10^{-11} cm^{-2} s^{-1}). There is no evidence for other than a steady output over 8 or 9 days - it is certainly not the case that bursts of a few mins of intense activity provide the signal as so often seems to have been the case (e.g. Crab pulsar and Hercules X-1).

(d) VELA X-1 and LMC X-4.

At PeV energies the EAS group at Adelaide has reported evidence for an excess of showers from the directions of Vela X-1 and LMC X-4 showing, in each case, the characteristic orbital periodicity but with no indication of the (long) pulsar period in the case of Vela X-1.

	ORBIT	FLUX	CHANCE PROB	LUMINOSITY
VELA X-1	8.9 d	$9 \pm 3 \times 10^{-11}$ m^{-2} s^{-1}	10^{-4}	2×10^{34} ergs/s
LMC X-4	1.4 d	$5 \pm 2 \times 10^{-11}$ m^{-2} s^{-1}	0.009	10^{38} ergs/s

To sum up what we know about X-ray binaries as VHE and UHE gamma ray sources.

	PULSAR	ORBIT	LONGTERM
CYG X-3	12.5908 ms	4.8 hr	(19 d)
HER X-1	1.24 s	1.7 d	[35 d]
4U0115+63	3.6 s	24.3 d	[sporadic]
VELA X-1	[283 s]	8.9 d	—
LMC X-4	—	1.4 d	—
PSR 1953	6.13 ms	117.3 d	—

[Information in square brackets relates to X-ray data]

The VHE light curve of the binaries is interesting - all X-ray binaries detected so far at TeV energies have broad light curves with duty cycles 30 % or so of the cycle (rather like the X-ray light curves) - see Figure 7.

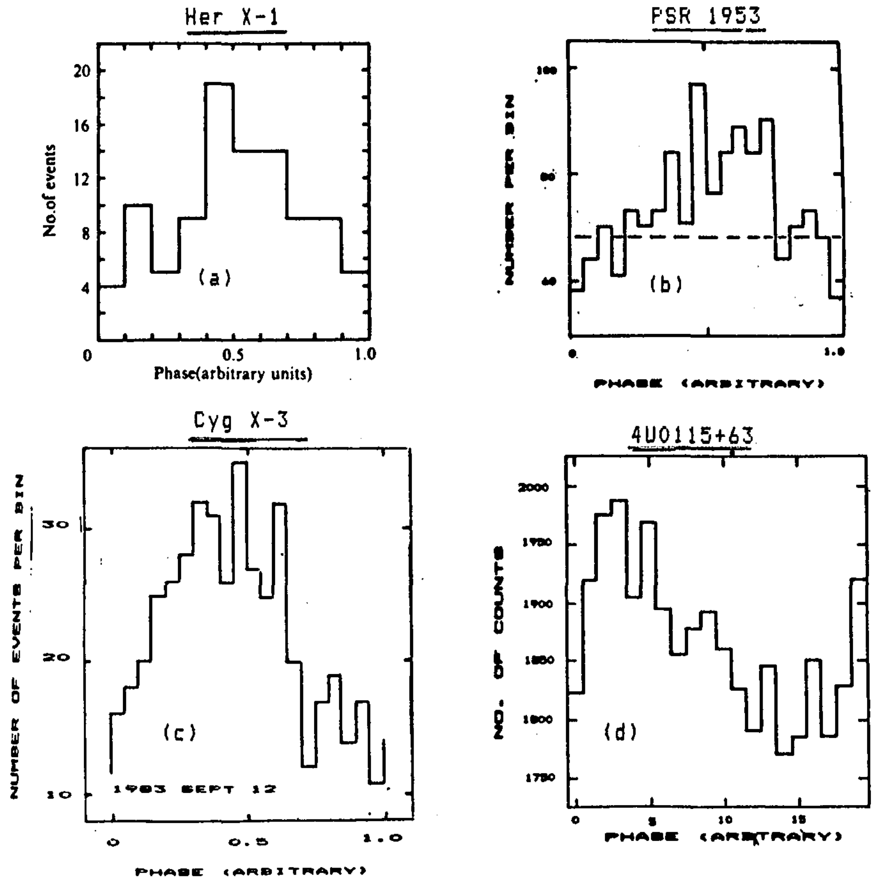
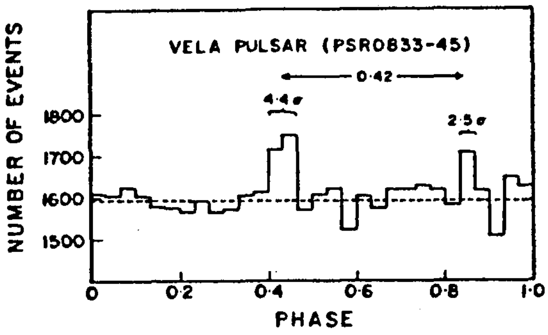


FIG 7.

As far as other VHE gamma ray sources are concerned the Vela pulsar was detected by the TATA group [8] and was found to show the double peaked light curve observed at radio wavelengths - see Figure 8. The detailed study of the VHE emission from the Crab pulsar by the Durham group [18] is an example of a new phase in gamma ray astronomy - the systematic study of the detail of the VHE emission. The width of the light curve around the radio main pulse is observed to be < 1% (<0.4 ms FWHM) - see Figure 9. This is the shortest duty cycle of emission from the Crab pulsar at any wavelength other than radio and confirms the trend first reported 12 years ago by Greisen and his collaborators [30] during gamma ray observations at energies of a few GeV. The constraints placed on models for 1000 GeV gamma ray production in pulsars by such observations are severe.

The 6 ms low-field radio pulsar (PSR1953) discovered in a binary system with a 117.3 d orbit and located within the error box of the COS B source 2CG065 (but not firmly associated with it) has been seen to produce 1000 GeV gamma rays[13] - see Figure 10. Although recently the COS B collaboration has expressed doubt that some of the first quadrant point sources are genuine (and maybe the result of enhanced amounts of molecular material irradiated with cosmic rays), our VHE measurement would suggest that 2CG065, a weak radio pulsar, is also a copious VHE gamma ray source.

The VHE data from the original 1.5 ms high-field radio pulsar has recently been analysed with the benefit of a radio ephemeris of unprecedented accuracy[31]. An indication of VHE emission in phase with the radio main pulse and significant at the 3×10^{-4} chance level has been obtained from the Durham experiment - see Figure 11.



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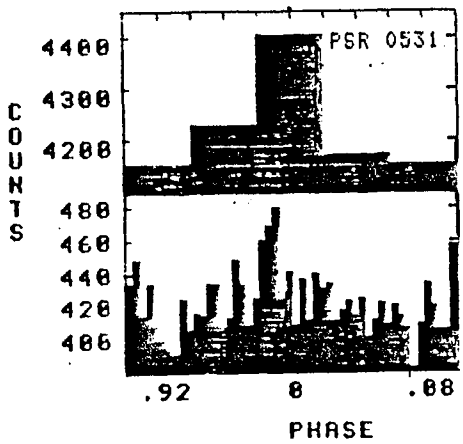

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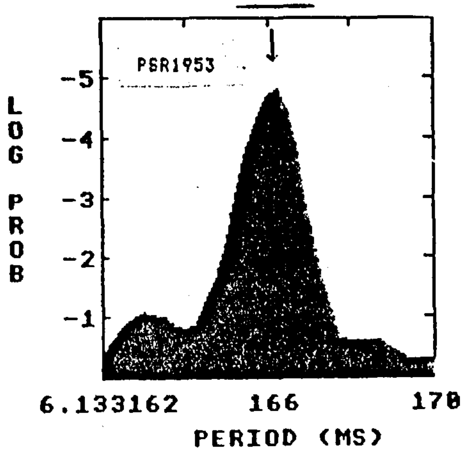

FIG 10.

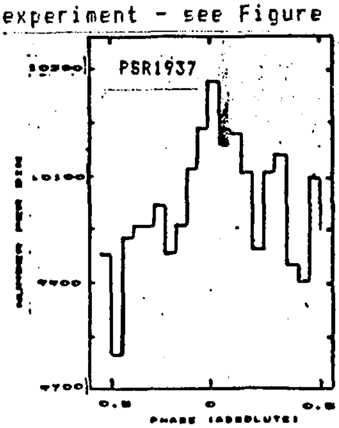

FIG 11.

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