WHY IS CYGNUS X-3 (WITH "RELATED SOURCES") A HIGHLIGHT OF COSMIC-RAY ASTROPHYSICS?

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Cygnus X-3 and some apparently related systems have sprung into remarkable prominence at this conference. I will outline the reasons for this great interest. They may be summarised as follows.

1. Gamma rays of energy up to 10^{16} eV are emitted by Cygnus X-3 (and some other sources), so, in the source, there must be charged particles that have been given energies up to $\sim 10^{17}$ eV.
2. The number of charged particles thus inferred is so great that occasional sources of such a kind could, apparently, easily maintain the Galaxy's flux of ultra high energy particles (at least in the range 10^{15} - 10^{17} eV).
3. Several of these u.h.e. gamma-ray emitters appear to be interacting neutron stars, and ultra-high-energy particle production must be a major feature of the energy budget of close binaries containing a neutron star.
4. The time scale of modulation of the output indicates that acceleration to such energies (e.g. 10^{17} eV) must take place in seconds or less.
5. A quite different reason for current excitement is that there are reports of radiations being detected deep underground apparently related to Cygnus X-3 (having a 4.8-hour repetition period) that cannot be understood in terms of known particles or interaction processes. This will be taken up in another session of highlight talks, and so will receive little attention here.

Some recent developments in the picture of these sources will now be outlined.

1. How widespread is this phenomenon of u.h.e. gamma-ray emission?

Searches for u.h.e. gamma-ray sources have largely focused on "interacting neutron stars" - neutron stars accreting matter from very close non-compact companion stars - normally recognised through the strong X-ray emission, which is modulated with the period of spin of the neutron star (X-ray binary pulsars). Joss and Rappaport (1) listed 8 such binary systems with well-known orbits (and masses), obtained from the observed dop-

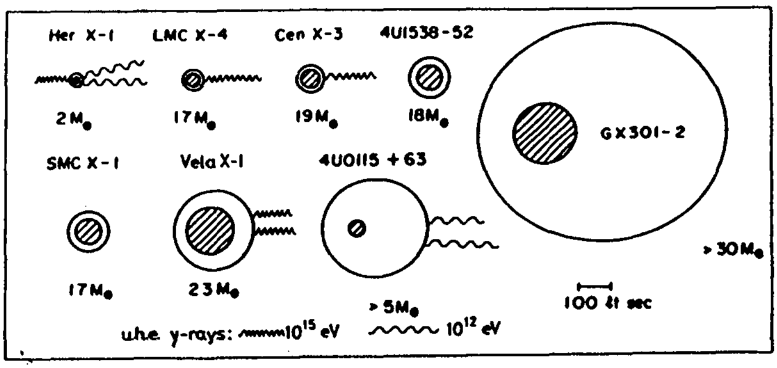


Figure 1. 8 X-ray binary pulsars with well-known orbits (to scale): those from which u.h.e. gamma-ray emission has been reported are marked.

pler shifts of the X-ray pulsation frequency, and figure 1 shows these to scale. Each wavy line attached to a diagram indicates that one research group has claimed to see emission of gamma rays in the 10^{12} or 10^{15} eV range. (The orientation of the rays has no significance.) (Refs: Her: 2,3,4; LMC: 5; Cen: 6; Vela: 7,6; 115+63: 8,9.) Thus, 5 of the 8 are already reported to emit u.h.e. gamma-rays, and although the evidence for Cen X-3 is very weak, and LMC X-4 requires confirmation, the fact that so many have already been reported leads one to guess that probably all such systems emit u.h.e. gamma rays. (The larger and the more elliptical systems probably transfer mass very spasmodically, and more extended observations may be needed to see gamma-ray emission.)

In addition to these, there is Cygnus X-3 - much more powerful (except for LMC X-4, if confirmed), and not on the list because no neutron star pulsation had been detected in X-rays, so no doppler measurement was possible. In the absence of doppler measurements and sharp eclipses there is no clear proof that Cygnus X-3 is a binary system, but the more rounded X-ray intensity curve suggests that we are for some reason getting a blurred view of an accreting close binary.

TeV gamma-ray emission from some non-interacting pulsars has already been reported by Turver's group, and the Crab pulsar is a widely observed emitter, weaker than the binaries. These "isolated" pulsars will not be discussed here.

2. The orbital signature

The vital feature identifying the source of the gamma rays has been a variation of the flux with exactly the same periodicity as the X-rays. Generally this is the binary orbital period - periods are usually of the order of days: some examples are illustrated below.

Object	*Orbital period*
Cygnus X-3	0.19968 days
Vela X-1	8.965 days
LMC X-4	1.408 days
Centaurus X-3	2.087 days

though in some cases the emission has had a short duration and the shorter X-ray periodicity attributed to the neutron star's spin has served for identification:

Object	*n-star spin period*
Hercules X-1	1.24 sec
4U 0115+63	3.61 sec.

In general, the air showers from the direction of the source do not stand out clearly from the large flux of background proton showers, without an identification by period, though the first and last sources on the list have also been seen simply as point sources.

3. Orbital phase terminology: e.g. Cygnus X-3

Phase zero corresponds to the time when the neutron star (or at least the X-ray source) is at its furthest distance, behind the companion star - in most cases in mid-eclipse. At phase 0.5 in the orbit the neutron star will be in front. In the case of Cygnus X-3, we do not know the exact furthest point of the orbit, as no sharp eclipse is seen: the X-rays instead follow a smoother rise and fall, giving the impression that there is much scattering of the X-rays and their source region is large:

and the variation is asymmetrical, with a faster fall and slower rise. Van der Klis and Bonnet-Bidaud (10), whose ephemeris is generally adopted, define phase zero as the minimum of a sine wave fitted to the intensity curves, and the true flux minimum then occurs near phase 0.96. The asymmetry is quite likely to indicate ellipticity in the orbit, but the phase is taken to change uniformly with time, from 0 to 1. Hence, for two reasons, the position of the neutron star at a given phase is not known with great accuracy.

4. <u>Generation of gamma rays by particles</u> (with emphasis on Cygnus X-3)

As it is hard to see how electrons could reach energies above 10^{16} eV because of rapid energy loss (30), protons (or nuclei) are at present considered much the most likely primary particles generating gamma rays in the Cygnus X-3 system, and the picture put forward by Vestrand and Eichler (11,12), in which a wide-angle hadron beam from the neutron star generates π^0 mesons and hence gamma-rays, is illustrated in figure 2.

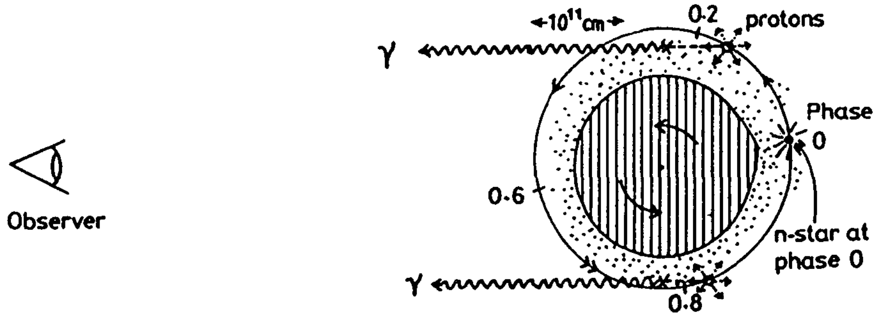


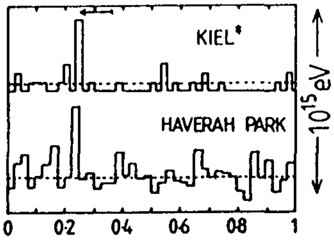
Figure 2. Schematic diagram of motion of n-star round 4.8-hour orbit. n-star emits protons in all (?) directions: at two points on orbit γ-rays will be seen as source is seen through fringe of gas surrounding companion star.

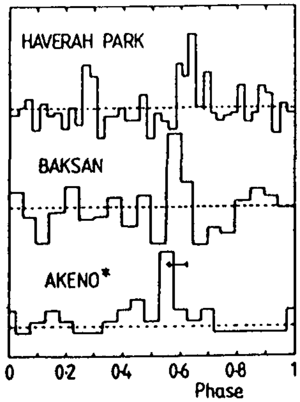
Somewhere near phases 0.2 and 0.8 of the orbit we might thus see the source through a thin layer of gas surrounding the companion.

Emission near phase 0.25 was prominent in the early 10^{15} eV signals (Samorski & Stamm, 13, Lloyd-Evans et al., 14) as published in 1983, as shown in figure 3(a); and in the early Crimean 10^{12} eV observations (15) radiation was at times detected near 0.2 and 0.8 (see figure 3c). But most of the reported detections near 10^{12} eV reported since 1979 have occurred near phase 0.6 - 0.7 (placed more precisely by the Durham group (20) at 0.63). The latest observations just below 10^{15} eV (figure 3b) also show the main emission near this latter phase of the orbit. The variation of gamma-ray signal with orbital phase is illustrated in figure 3, where the departure of the counting rate from a background rate (dashed line) is plotted on an arbitrary scale, with no attempt to assess the significance of the peaks: attention is focused on a comparison of the phases at which the signals are reported to occur. (In two cases - marked * - the time zero has been shifted from the published version, as an approximate correction to the "standard" ephemeris used by the other groups.)

The duty cycle of a "pulse" of emission has often been reported to be only ∿2% of the orbit (13,14,20: see also 7), though one gets the impression that the 0.6 pulse may wander a little.

These observations evidently call for some reconsideration of the simplest "atmospheric target" model for gamma-ray production in Cygnus X-3





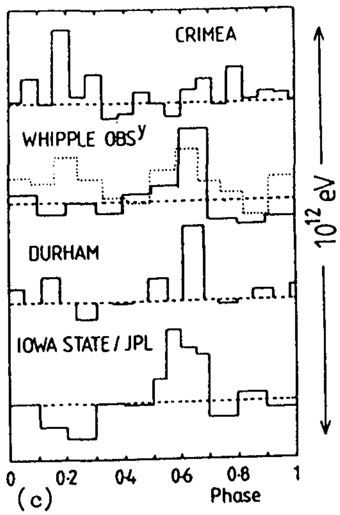


Figure 3 (a)↑ (b)→

γ-rays from Cygnus X-3: counting rate as function of orbital phase (background rate marked by dashed line). (a) $E_\gamma > 10^{15}$ eV before 1983. (Refs 13,14). (b) $\sim 10^{15}$ eV, mostly in 1984 (refs. 21,22,23). (c) $\sim 10^{12}$ eV (references 15;16 & 17; 18;19).

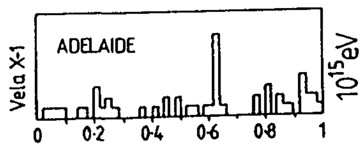


Figure 4 →
10^{15} eV gamma-rays from Vela X-1, as function of orbital phase (ref. 7).

(and also Vela X-1): they raise three questions.

(a) The most prominent emission is at the wrong phase (0.63), when the neutron star is *in front* of the companion! (The same phase is also reported in Vela X-1: figure 4.) Is there a gas target here?
(b) Since the gamma rays are emitted in a well-defined direction, the particle beam must be almost undeflected before collision, despite the fact that a 10 TeV proton's gyroradius would be $<10^{-2}$ of the travel distance if there is a magnetic field >30 gauss. (10 TeV might be a suitable proton energy to generate 1 TeV gammas.)
(c) Are we after all wrong in supposing that the gamma-ray beam is related to the position of a gas target: is the particle beam only accelerated in a special direction?

The three queries will be considered in turn, to show that it does seem possible to retain the basic Vestrand-Eichler process.

(a) Is there a special gas target at a phase near 0.63? If accretion takes place from high-speed gas streaming from the companion, there should be an accretion wake or tail near the direction shown in figure 5, as the outflowing gas is deflected by the gravitational field of the neutron star and collects in a dense column behind it, after being shocked, and falls back onto the neutron star. The trailing angle of the tail depends on the relative velocity of the wind and the orbital motion: very reasonable wind velocities would make the neutron star lie behind the tail at phases somewhere in the range 0.55 - 0.66 (calculated for a circular orbit). In another binary, Cen X-3, X-ray absorption due to such a feature has been seen (25) at this phase (in Cyg X-3 the X-ray source is diffused), and optical absorption at the same phase is known in some other close binaries. Vela X-1 is consistent with this picture, as it is accreting

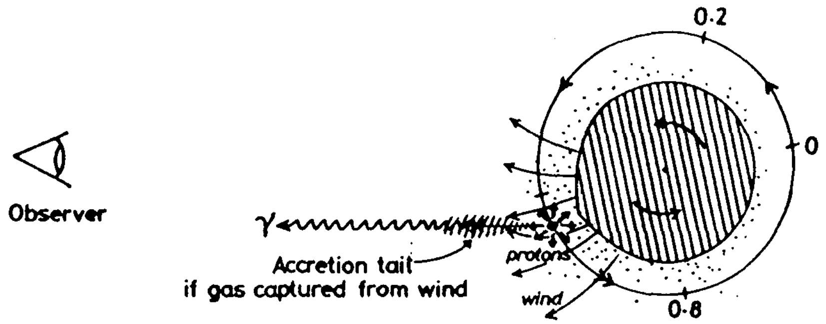


Figure 5. Accretion wake collecting behind neutron star as wind sweeps past, and forming a target for protons from n-star when it is at phase near 0.63, as seen by a distant observer.

from a wind. If the accreted mass powers the luminosity of Cygnus X-3, the column must be very massive. Some variation in wind speed due to local heating would cause the trailing angle to vary a little.

(b) Collimation of beam: 10^{17} eV protons? (or neutrons?). One way to maintain the directionality of the beam is to suppose that most of the power goes into particles near 10^{17} eV - a monoenergetic proton beam, or at least a very flat spectrum. Then the particles need not be greatly deflected before collision, where they produce gamma-rays in a forward direction, most notably around 10^{15} - 10^{16} eV. Provided that the gas thickness is at least about a radiation length, the gamma-rays will produce electron-positron pairs, and then a very rapid photon shower can develop by synchrotron radiation if there is a magnetic field exceeding a few tens of gauss. Surprisingly, at these high energies, synchrotron radiation is so rapid that there is no significant deflection before radiation occurs. The result (26) would be a photon spectrum very like what is observed. Enough TeV photons emerge without requiring production by, say, 10 TeV protons in the beam. (In the absence of a magnetic field, a normal electron-photon cascade could occur, but would require a greater thickness of gas.) Taking this further, one might try to explain the smaller content of TeV photons in the pulse near phase 0.25 by supposing that this signal arises in a thinner gas layer, with less cascading.

It will later be shown that Cygnus X-3 can hardly be a minor contributor to the general cosmic ray flux. Hence, if the main contribution to the proton flux is above 10^{16} eV, and one is to generate the observed steep spectrum of cosmic ray protons in the Galaxy, there are probably many more binaries that only emit protons less energetic than this.

Alternatively, Kazanas and Ellison (preprint) have proposed that particle acceleration occurs in an accretion shock near the neutron star, and many of the accelerated protons are transformed into neutrons in collisions: one then has a neutral hadron beam travelling undeflected to the gas target (any high-energy gamma-rays generated in association with the neutrons can be absorbed by the strong magnetic fields in the acceleration region).

(c) Is a gas target involved? Supporting evidence from Hercules X-1.

There is evidence from X-ray and optical work on Her X-1 that the X-rays originate near the neutron star, which is surrounded by a thick accretion disk which tilts back and forth, obscuring the neutron star for a large part of a 35-day cycle. This precession may be connected with the way in which a gas stream is wound onto the edge of the disk. High energy gamma-rays have only been detected from this source on a few occasions (by the Durham, Fly's Eye and Whipple observatory groups: 2,3,4), and not at fixed orbital phases in this case, but just when the X-ray source was emerging from obscuration by the outer part of the disk, and at certain times when short bursts of X-ray obscuration suggested that thicker blobs of gas were running round the outer disk, presumably fed by a burst of accretion (4,27). All observers have interpreted these observations as evidence that the gamma-rays are indeed seen when a thin gas target intervenes between the neutron star and the observer. (A very thick disk stops all radiation: or with no intervening matter no π^0 production occurs: only the thin edge is effective.)

Hence the production of gamma-rays by u.h.e. protons in gas streams ejected from the companion is at present a tenable model, though some special asymmetry must be introduced to suppress a pulse near phase 0.8.

5. <u>How are particles accelerated to 10^{16} - 10^{17} eV?</u>

Several acceleration processes have been considered.

Mechanism	*Authors*	*Difficulties*
v×B field of pulsar	Michel, Dessler:28,29 Eichler & Vestrand:30	Rotation too slow in Vela X-1 (but perhaps not in Cyg X-3)
v×B field of accretion disk	Chanmugam & Brecher (31)	B too high to allow fast disk? ($>10^{12}$ G in Her X-1)
Field reconnection in accretion disk	Wang: 32	
High-speed shock in accreting gas	Kazanas & Ellison: 33 Eichler & Vestrand:34	
"Magnetospheric grindstone"	Kundt: 35	The various observed phases

Some features of the observations have an important bearing on the mechanism. Firstly, the prominence of interacting neutron stars as u.h.e. gamma-ray emitters (unless merely a consequence of the searching programme) suggests that the energy is derived from accretion. And in Cygnus X-3 at least, there is probably much more energy put into ultra high energy protons than into thermal radiation, so the infall has to be cushioned in some way to avoid thermalisation. One way of achieving this may be by a strong collisionless accretion shock, which may be able to convert most of the gas kinetic energy into high-energy particles - if they can then escape! Otherwise we want a dynamo to extract the kinetic energy near the neutron star very efficiently. It is noteworthy also that the observed particle emission is in directions close to the plane of the accretion disk (in Her X-1) or the orbit: it is not confined to the near-polar directions normally considered in dynamo models (though not in 29): so the magnetic field must be very different from a dipole form.

Quite apart from the gamma-ray evidence, neutron stars have been the most attractive sites for acceleration of the general galactic u.h.e. cosmic rays (36): this new window on an accelerator at work may revitalise the search for viable mechanisms.

6. Power emitted by Cygnus X-3 in ($\sim 10^{17}$ eV) protons

Adopting the flux of gamma-rays reported by Haverah Park (14), *(a)* the energy flux carried by the photons above 10^{15} eV, at the Earth, would be $\sim 3\times10^{-10}$ erg cm^{-2} s^{-1} (averaged over time) if one restored the losses due to interactions with the primeval microwave radiation (in 12 kpc). *(b)* The pulse was detected for about 2% of the orbital cycle; and as we take this pulse to be seen when a thin gas target intervenes, we should have seen 50 times more power had a suitable gas converter been available all round the orbit. Furthermore, *(c)*: only $\sim$10% of the energy of a 10^{17} eV proton is converted to gamma rays (1/3 of the energy radiated in collisions goes into π^os, not all above 10^{15} eV, and part is carried away by nucleons from the thin target). Finally, *(d)*: if the source is at a distance $r = 12$ kpc, we can estimate the power in the proton beam emitted in all directions:

Total power in protons ($\sim 10^{17}$ eV) accelerated in Cygnus X-3
$$= 3\times10^{-10} \times 50 \times 10 \times 4\pi r^2 \times (\Omega/4\pi) \quad \text{erg s}^{-1}$$
$$= 3\times10^{39} \times (\Omega/4\pi) \quad \text{erg s}^{-1},$$

if we take the beam to appear in a solid angle Ω rather than being isotropic. The main part of these protons will escape into the Galaxy. But the rate of input of particles above 10^{16} eV needed to maintain the Galaxy's normal cosmic ray flux is probably $\sim 5\times10^{37}$ erg s^{-1} - though this is only known roughly, as the assumed trapping time of $\sim 2\times10^{5}$ years at such energies is only a rough estimate (26). Hence one apparently needs one Cygnus X-3 type of source to be present for only part of the time (averaged over 10^5 years) to maintain the cosmic ray flux in the 10^{16}-10^{17} eV region. (We could reduce the extravagant total energy by assuming a small solid angle Ω of proton emission - say 1% of 4π - but are then faced with another problem, as we should presumably see only 1% of all such sources, and so we could hardly suppose such a large number to be present for only a small fraction of the time.) (* See footnote at end.)

7. Are the particles from Cygnus X-3 exotic?

Of the underground proton decay detectors, three have detected fluxes of particles, deep underground, apparently related to Cygnus X-3: they show the 4.8-hour periodicity. These will be reported in a later group of highlight talks, but the difficulty in explaining these observations may be pointed out briefly, by referring to one example. The Soudan Mine experiment detects muons of about 2/3 TeV (vertical), and has reported a flux of $\sim 7\times10^{-11}$ cm^{-2} s^{-1} apparently from Cygnus X-3 (corrected to vertical threshold). Primary particles generating such muons must have energies above 1 TeV (normally well above), and much more than 1 primary above 1 TeV would be required for each secondary 2/3 TeV muon. But the reported muon flux exceeds the flux of 1 TeV primaries entering the atmosphere from that direction (or at least depositing energy in it, to generate air showers, detectable by Cerenkov radiation). The Durham group, for example, see a time averaged flux $\sim 3\times10^{-11}$ cm^{-2} s^{-1} of showers above 1 TeV from Cygnus X-3. The reported underground signals cannot be understood in terms of known primary particles and interaction processes.

The primary particles responsible for the signals seen above ground by the Cerenkov detectors (discussed in this paper) must be neutral, to maintain their alignment with distant sources, and limits can be set on their rest masses. The radiations from Her X-1 have travelled for 15000 years, but the dispersion in their travel times has not greatly smeared out the 1.24-second modulation. They are not monoenergetic: those detected have an energy spread around 1 TeV: so the rest mass must be < 10 MeV to retain considerable modulation on this time scale. If a 12-ms modulation is indeed present in the Cygnus X-3 signal ($\sim$40,000 yr travel time), as just reported by Turver, the rest mass of these particles must be < 1 MeV. Gamma-rays meet the requirements best - certainly not hadrons.

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* Footnote: At the conference, J. Elbert mentioned a very unusual occurrence in June this year, when Cygnus X-3 was apparently emitting u.h.e. gamma-rays over a wide range of phases. This would imply that the charged particle beam was indeed not narrowly collimated. (An extensive emission of gas may have occurred.)