U.H.E. PARTICLE PRODUCTION IN CLOSE BINARY SYSTEMS

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ABSTRACT

Cygnus X-3 appears to generate so much power in the form of charged particles of up to $\sim 10^{17}$ eV that the galaxy may need $\lesssim 1$ such source on average to maintain its flux of u.h.e. cosmic rays. Accreting gas must supply the energy, and in a surprisingly ordered form, if it is correct to use a Vestrand-Eichler model for radiation of gammas, modified by the introduction of an accretion wake. Certain relationships between 10^{12} eV and 10^{15} eV gamma rays are expected.

1. Evidence for emission of gamma rays at distinct orbital phases

Ultra high energy gamma-rays have been observed from Cygnus X-3 and a few other X-ray binary sources.

First, to establish that underlying the variability there is a well-established pattern, Figure 1 compares the time profiles of the radiation observed from the direction of Cygnus X-3 by several independent workers. The flux (usually presented as a departure from the normal all-sky background) is plotted (on an arbitrary amplitude scale) against phase of the 4.8-hour binary orbit, with phase zero, as usual, corresponding to the minimum intensity of the X-ray signal, presumed to be when the X-ray source near a supposed neutron star is partly hidden behind the larger companion star. Apart from the early but very lengthy data set 1, the phase in all plots has been calculated from the X-ray data of van der Klis and Bonnet-Bidaud — the orbital period slowly changing with time. The observers do agree on brief periods of emission during the orbit: the 10^{15} eV observations indicated a burst of gamma-ray emission near phase 0.25 in the orbit, whilst at 10^{12} eV the main emission occurs near phase 0.63. However, during the lengthy Crimean observations, the phase of the main emission would switch between roughly these two regions (though the exact alignment of the phase plot from this early date is difficult). And the latest 10^{15} eV observations at Haverah Park (this conference) show the emission much stronger around the 0.63 peak. The Whipple Observatory (Mt. Hopkins) observers have demonstrated considerable month-to-month variability in flux (and two of their time profiles

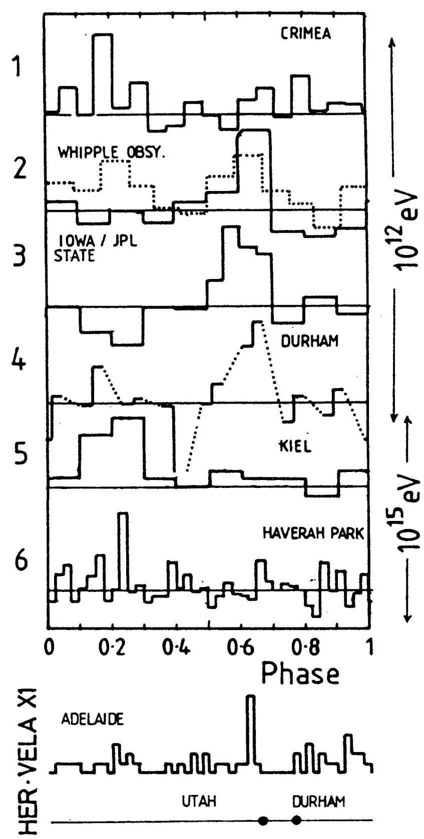

Figure 1. (Refs 1-6) Occurrence of gamma rays from Cygnus X-3 vs orbital phase. Below: Vela X-1 phase plot (7), and observations of Her X-1.

are shown): year-to year variability is also found at Haverah Park.

The particles causing the observed air showers are taken to be photons because (a) they are uncharged, being deflected $<2^{\circ}$ in the 12 kpc or so from Cygnus X-3, (b) they do not decay in the 40,000 year journey, eliminating neutrons and neutral atoms (which would become ionized), and (c) the time dispersion <0.15 orbital period implies a Lorentz factor $>1.5\times10^4$: if the threshold energy is 0.5 TeV, $m_{primary} < 33$ MeV. (For Her X-1, the 1.2-second modulation implies a time spread < 1.5 sec after 5 kpc (1 TeV): $m < 3$ MeV. For the Soudan mine radiation, not discussed here, if $E_{prim} \sim 5$ TeV, $m_{prim} < 400$ MeV.)

2. Mode of production of the gamma-rays

The basic process put forward by Vestrand & Eichler (8) is still basically the most promising, but it requires modification. In its original form, this model had a neutron star in orbit around the companion, and accelerating protons to high energies, emitting them (roughly) in all directions, and those few that grazed the top of the atmosphere of the large star would suffer nuclear collisions and generate neutral pions and hence gamma-rays. Just at certain points in the orbit, a distant observer would see gamma rays briefly as the source passed behind the star, and later as it re-emerged. At phase 0.25 we might be seeing the re-emergence pulse if the atmosphere were swollen by gas emission. However, a pulse near phase 0.8 is dubious, whilst the prominent pulse at $\sim$0.63 occurs when the neutron star is well to the front of the companion!

This latter phase may not be an accidental feature, as the (sole) report of gamma rays from Vela X-1 (Figure 1) shows sharp emission at the same phase. Is there a gas target in this direction? This is in fact the direction in which an accretion wake is expected if accretion occurs from a stellar wind (see Figure 2). Such a wake is seen as an X-ray absorption in Cen X-3, for instance (9). If the radial wind has a speed v_w and the n-star orbital speed is v_o, the wake will lag behind the outward radius by an angle $\tan^{-1}(v_o/v_w)$: i.e. 45° if $v_w = v_o$ — appearing at phase 0.625, or 35° (phase 0.60) if $v_w = v_{escape} = \sqrt{2}v_o$.

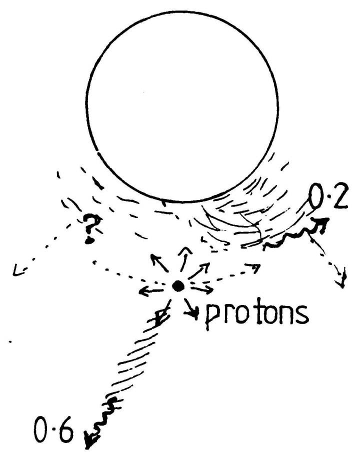

Figure 2. Supposed geometry for Cygnus X-3.

To support the V & E model, one may note that the gamma ray spectrum extends to 10^{16} eV, but that gamma rays cannot pass through a region where $B_{\perp} > 4\times10^{18}\,\text{eV}/E_{\gamma}$ gauss — about 400 gauss in this case. As statistical particle acceleration to such energies is unlikely (especially in weak fields) on the available time scale (10), it is highly probable that the particle acceleration occurs in a region of stronger (e.g. pulsar) field than this, so the gamma rays are produced in a place outside the acceleration region — i.e. on a "target". Electrons are unlikely to survive the strong fields involved in acceleration to 10^{17} eV: hence the assumption of protons (10).

The observation of brief gamma-ray emission from Her X-1 at the time (11) interpreted as the moment of reappearance of the n-star from obscuration by a dense accretion disc also supports a gas-target picture in the case of this source.

3. Significance, for cosmic rays, of magnitude of power output

(a) The cosmic ray power output of Cygnus X-3 may be estimated roughly as follows. Above 10^{15} eV, the Haverah Park flux is $\sim 3\times10^{-14}$ photons cm^{-2} s^{-1}: these bring an energy flux 1.1×10^{-10} erg cm^{-2} s^{-1} per decade (e.g. in the decade to 10^{16} eV). The published time profile indicated a pulse duty ratio ~ 0.02, so if there had been a suitable gas target in place all round the orbit the photon energy received would have been 50 times this. Allowing for absorption of a factor 3 (by pair production on primeval radiation) en route, an efficiency $\sim 1/6$, say, for converting proton energy to gammas, a source distance $r = 12$ kpc, and supposing the particles appear in a solid angle Ω, the total power emitted in the proton beam is

$$W = (\Omega/4\pi)\times6\times3\times50\times1.1\times10^{-10}\times4\pi r^2 = (\Omega/4\pi)\times1.7\times10^{39} \text{ erg s}^{-1} \text{ per decade.}$$

The proton spectrum must extend to $\sim 10^{17}$ eV to produce photons up to 10^{16} eV, and most of these protons should escape into the galaxy. To maintain the present flux of galactic cosmic rays above 10^{16} eV the galaxy probably needs an energy input $\sim 5\times10^{37}$ erg s^{-1} above 10^{16} eV (12) – based on a roughly estimated trapping lifetime $\sim 2.5\times10^{5}$ years at this energy (12). Hence one such object active for only part of the 10^5 year storage time could supply the galaxy's flux of 10^{16}-10^{17} eV protons.

(b) *Accelerated spectrum?* Perhaps the neutron star can generate a power-law spectrum of protons (like the observed gamma spectrum), but alternatively, for direct (non-statistical) acceleration it may emit most of its power near the upper energy limit – say 10^{17} eV, the roughly $E^{-2}dE$ spectrum of gamma rays resulting from cascading in the target area. (It has been shown elsewhere (12) that if a magnetic field exceeding a few tens of gauss is present in the target area one can generate a cascade rapidly by synchrotron radiation following pair production, without needing very much matter – and the result has a spectrum very much like the overall gamma spectrum from Cygnus X-3.) The power in the 10^{17} eV protons then has to be sufficient to supply the energy in several decades of gamma rays.

If such a powerful source is indeed not often present, we are evidently lucky to see it! Is the existence of other sources then an embarrassment? The other 10^{15} eV sources in this galaxy (Vela X-1 and Her X-1) are in fact much weaker – but there may turn out to be many more. If the accelerated beam is quasi-monoenergetic, one must indeed expect a greater number of sources that emit particles of lower energy, to yield the known cosmic ray spectrum: there must be more TeV sources. Is the source 4U 0115+63 – found to be intense at 10^{12} eV (preprint from Turver's group) but not seen at 10^{15} eV – a member of such a population? The evolutionary history needed to explain the overall spectrum of particles in the galaxy is as yet unknown, and it is not apparent that a power law would emerge in any simple manner.

(c) *Mode of acceleration?* Acceleration by a large-scale emf generated by moving conductors in a strong magnetic field seems most likely, but the pulsar action of the neutron star itself is probably inadequate, (i) because Cygnus X-3 is probably an old n-star, whose rotational energy store would have run out long ago, and (ii) Vela X-1 has a spin period of 5 minutes, from X-ray evidence – much too feeble. Hence the accreting matter is presumably supplying the energy and also the high speed necessary. (See also (13)). However, the particles we detect are not emitted near the normal to the orbit (or to the Her X-1 disc), but closer to the plane of the disc (or at least the orbit) – probably closer to Michel's (14) picture than Lovelace's. It is remarkable that the particle power is not small compared with the X-ray power – as though accretion energy is efficiently converted to electrodynamic energy rather than heat.

4. Possible observations

If the gamma-ray spectrum is generated by cascading from 10^{17} eV protons, the TeV gammas are seen where the gas target is thicker, and the 10^{15} eV gamma pulse should appear somewhat displaced – at the tenuous edge of the gas (but with much overlap). (To check this, contemporaneous measurements are needed, as the exact pulse position wanders somewhat.)

The phase of the prominent pulse, on this picture, is determined by the angle of the accretion wake; hence wandering of the wake probably signals changes in wind speed and may be related to variations in source power, and possibly to impending outbursts.

If the upper limit of the gamma spectrum is limited by transmission through a magnetic field (15) rather than by the primary proton beam, it is likely to be different for the pulse at phase 0.25 (generated close to the large star) and that near 0.63 – generated well away from the star.

If, as widely believed, there is a stellar wind in Cygnus X-3 that has a significant optical depth to X-rays – say 5 g cm^{-2} – $\sim$10% of the protons will interact even outside the special "gas target" positions, giving a widely spread weaker flux of gamma rays. If this is not present, it will constrain the angle into which the protons are emitted, and we may then need to explain the pulses in terms of real directional acceleration of the charged particles. (This has seemed less likely at present, unless the particle acceleration occurs so far away from the neutron star that the position of the companion plays a part in determining the field orientation.)

Puzzle: Where are the X-rays generated? The source must be very large if it is not occulted by the gas target that is being supposed to intervene at phase 0.63: the X-ray intensity is a maximum here (unlike Cen X-3).

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