

Possible implications of VHE γ -radiation from the X-ray binary Centaurus X-3

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Abstract. We discuss theoretical models that could explain the existing data from γ -ray observations of Cen X-3. Because of the high energetics required, any reasonable option for γ -ray production in Cen X-3 must be connected with jets emerging from the inner accretion disc of the neutron star. A large-scale quasi-stationary source (on a time scale of days or longer) powered by shocks driven by such jets into the $R_s \geq 10^{13}$ cm surrounding the binary could explain the bulk of the γ -radiation features, except for a modulation of the γ -ray signal with the pulsar spin period. These modulations, if genuine, would require an alternative source with $R_s \ll 10^{11}$ cm. We consider two principal models, hadronic and leptonic, for such a compact source in the jet. Both models predict that the pulsed γ -ray emission should be episodic, and can be expected only at the initial stages (typically less than a few hours) of powerful γ -ray flares, and that γ -ray pulsations should be significantly shifted from the pulsar frequency. Such a source would generally fade, due to expansion, in a few days.

1 Introduction

In the recent literature Cen X-3 appears as the only close X-ray binary to show γ -ray fluxes in both high energy (HE, $E \geq 100$ MeV) and very high energy (VHE, $E \geq 100$ GeV) domains. In the VHE domain episodic γ -ray signals had earlier been reported from a number of X-ray binaries, including Cen X-3 (Bednarek, 2000). Note, however, that these signals were extracted mostly on the basis of their correlations with the X-ray pulsar periods. The reliability of those detections became questionable when the imaging technique was first applied to the data (see Weekes 1992). It is important, therefore, that Cen X-3 is the first X-ray binary to show a significant indication as a VHE γ -ray source with an imaging telescope, the Durham University Mark-6 telescope

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(Chadwick et al., 1998, 2000).

The mean VHE γ -ray flux in the data of observations from Cen X-3 during 1997-1999 is estimated as $F(> 400 \text{ GeV}) \simeq 5 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, at the significance level $\geq 4.5\sigma$. Our recent detailed analyses did not show any correlation of the ‘on - off’ source excess events with the orbital period of the binary; neither was any significant correlation with the pulsar period found in the cumulative data. It is interesting, however, that a strong Rayleigh power peak, with an overall chance probability $p \ll 10^{-2}$ after the number of trials was taken into account, was found in the data of the observation night 21 Feb, 1999 when we searched for short episodes of pulsed emission. As expected, the signal has appeared in ‘soft-cut’ data, and was noticeably shifted from the pulsar spin period (for details see Atoyan et al. 2001a).

Cen X-3 has also been detected as a source of HE γ -rays at the 5σ level (Vestrand et al., 1997) during 2 weeks of observations made in 1994 with EGRET. As in VHE γ -rays, there was no correlation of the HE events with the orbital phase ϕ of the pulsar, with $\simeq 1/4$ of all γ -rays detected in the pulsar eclipse phase $|\phi| \leq 0.12$. The periodicity analysis has shown a Rayleigh power peak R precisely at the X-ray pulsar period, although with a relatively modest chance probability of $p = \exp(-R) \simeq 10^{-3}$.

In this paper we consider possible theoretical implications of the current observational results, noting though that these results still need additional confirmation by future more sensitive detectors.

2 General source requirements

Cen X-3 is a neutron star orbiting ($P_{\text{orb}} \approx 2.1$ d) at a distance $a \approx 1.3 \times 10^{12}$ cm from a massive O-star. The optical/UV luminosity of this star is so high ($\sim 10^{39}$ erg/s) that the opacity to VHE γ -rays produced at the pulsar orbit with respect to $\gamma\gamma$ absorption in the observer’s direction would vary from $\tau_{\gamma\gamma} \sim 0.3$ to ≥ 10 depending on ϕ (Bednarek, 2000), implying a correlation of the γ -ray flux

with orbital phase. The absence of modulations of the VHE γ -rays with the pulsar orbital phase then implies γ -ray production at distances far away from the pulsar. This conclusion is also supported by the EGRET detection of HE γ -rays in the deep eclipse phase of the X-ray pulsar. Any model assuming the pulsar or its close vicinity as the γ -ray production site is thus excluded. At the same time the source must be genetically connected to the neutron star. Indeed, the flux detected by EGRET corresponds to a luminosity $L_\gamma(> 100 \text{ MeV}) \simeq 5 \times 10^{36} \text{ erg/s}$, and the average flux of VHE radiation implies $L_\gamma(> 400 \text{ GeV}) \sim 10^{36} \text{ erg/s}$. For the parent relativistic particles this requires an acceleration power $P_{\text{acc}} \geq 10^{37} \text{ erg/s}$. Given the characteristic speed of the stellar wind, $v \sim 10^3 \text{ km/s}$, and the mass-loss rate $\dot{M} \sim 10^{-6} M_\odot/\text{yr}$ (see e.g. Clark et al., 1988) the available kinetic energy produced by the O-star in this binary is only $\dot{M}v^2/2 \simeq 3 \times 10^{35} \text{ erg/s}$. The only remaining option for the prime energy source of particle acceleration in excess of this power is the kinetic energy of the inner accretion disk of the neutron star. Note that in at least a sub-class of close X-ray binaries currently identified as ‘microquasars’ a significant fraction of the accretion disk energy can be ejected from the system in the form of powerful two-sided jets (Mirabel and Rodriguez, 1999).

The principal scenarios for γ -ray production in Cen X-3 should thus be connected with episodes of powerful outflows of energy from the inner accretion disk. In one such scenario the jets would drive strong shocks while propagating through a rather dense supersonic stellar wind of the O-star. Acceleration of particles in these shocks could result in a γ -ray source of a large spatial scale comparable with, or probably even exceeding, the size of the binary ($\geq 10^{12} \text{ cm}$). Obviously, such a model cannot explain the episodes of pulsed γ -ray emission. Note, however, that the pulsed emission, if indeed genuine, comprises only a fraction of the overall γ -radiation from Cen X-3. An interpretation of pulsed γ -ray episodes would require a compact source in the jet/beam region that would suppose a direct supply of energy modulated with the pulsar spin from the central region of the accretion disk. Note that because such a source under the powerful jet should be moving with respect to the neutron star, one should generally expect a significant Doppler shift of γ -ray pulsations from the pulsar spin period. Below we consider the basic predictions of these 2 principal options which are discussed in detail elsewhere (Atoyan et al., 2001b).

3 Spatially extended source

This model assumes acceleration of relativistic particles on the strong shocks driven by the jets in the stellar wind on spatial scales exceeding the orbit of the binary, $R \sim 10^{13} \text{ cm} \gg a$, which ensures an absence of orbital phase modulations for VHE γ -rays, and implies a quasi-stationary source on time scales $\geq 1 \text{ d}$.

This scenario apparently places the X-ray pulsar inside the γ -ray source. This circumstance allows us to exclude

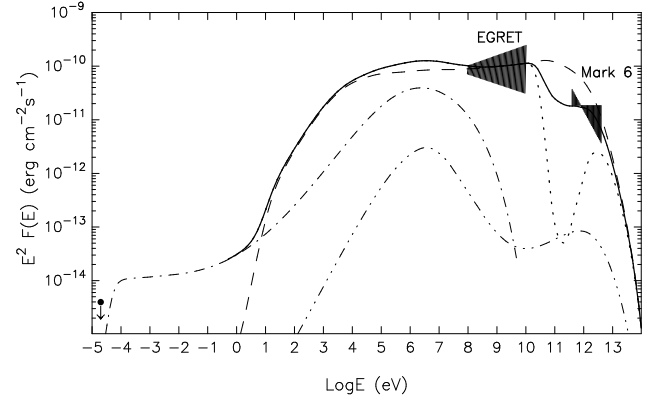


Fig. 1. The spectra of synchrotron (dot-dashed line; for $B = 0.7 \text{ G}$), inverse Compton (dashed), and bremsstrahlung (3-dot-dashed) radiation calculated for a quasi-stationary model with $R_s = 6 \times 10^{12} \text{ cm}$. The heavy solid line corresponds to the total fluxes when photoabsorption of VHE γ -rays is taken into account. For comparison we show with a heavy dotted line the fluxes which would also be expected if the same unabsorbed emission (i.e. the dashed line flux) were to be produced near the neutron star at an orbital phase $\phi = \pm 0.25$. The upper flux limit at 5 GHz, the range fluxes detected by EGRET and by the Mark-6 telescopes are also shown.

a hadronic (π^0 -decay) origin of γ -rays for the large-scale model. From the condition that the mean energy density of relativistic protons accumulated at radial scales R cannot significantly exceed the energy density of the gas in the gravitational field of the binary, we can estimate the maximum possible luminosity in γ -rays of hadronic origin is:

$$L_{\pi^0}^{\text{max}} \simeq 2.6 \times 10^{34} f_V \frac{M}{20 M_\odot} \left(\frac{N_H}{10^{23} \text{ cm}^{-2}} \right)^2 \text{ erg/s}, \quad (1)$$

where M is the mass of the binary ($\simeq M_{\text{O-star}}$), $f_V \leq 1$ is the volume filling factor of the γ -ray source with characteristic size $R_s (\leq R)$, and $N_H = n_{\text{gas}} \times R_s$ is the gas column density across the γ -ray source which is normalized to a characteristic maximum value 10^{23} cm^{-2} in Cen X-3 (accumulated mostly in the vicinity of the O-star) and is derived from X-ray observations (see e.g. Clark et al., 1988). In order to provide a flux of π^0 decay γ -rays comparable with observations one has to allow unacceptably high gas column densities, where all the X-rays would be completely absorbed.

A large scale source assumes that relativistic electrons accelerated at the shocks are responsible for the observed γ -rays. The main mechanism for γ -ray production in the vicinity of Cen X-3 is the inverse Compton (IC) scattering of electrons on the thermal UV photons of the O-star. The cooling time of electrons at distances R can be estimated as

$$t_{\text{IC}} \simeq 1.1 \times 10^4 (R/10^{12} \text{ cm})^2 \gamma^{-1} \text{ s}. \quad (2)$$

This equation relates to electrons with Lorentz-factors $\gamma \leq 10^4$ responsible for HE γ -rays. For VHE electrons IC scattering on UV photons occurs in the Klein-Nishina regime; therefore t_{IC} does not decrease but rather increases with in-

creasing γ . As a result the IC cooling time of VHE electrons is reduced to $t_{IC} \sim (10^2 - 10^3) \times (R/10^{12} \text{ cm})^2 \text{ s}$. Comparison of this time with the escape time of electrons $t_{esc} = R/v_w$ from the scales R in the stellar wind, with $v \sim 10^3 \text{ km/s}$, suggests that the characteristic size R_s of the source where production of VHE radiation is still efficient should not significantly exceed 10^{14} cm . On the other hand, we need $R_s \gg 10^{12} \text{ cm}$ in order to avoid significant absorption of VHE γ -rays in the UV field. A typical VHE source size should then be $R_s \sim 10^{13} - 10^{14} \text{ cm}$, which also implies a quasi-stationary flux on timescales of at least a few days to weeks.

In Fig. 1 we show the spectra of non-thermal radiation from radio to VHE γ -ray bands calculated for a source with $R_s = 6 \times 10^{12} \text{ s}$, assuming a power-law electron injection with $\alpha_e = 2$, exponential cutoff at $E_0 = 50 \text{ TeV}$ and overall power $P_{acc} = 2 \times 10^{37} \text{ erg}$. Even at these distances the effect of photoabsorption makes the emerging VHE γ -ray fluxes significantly harder. However, the impact of $\gamma\gamma$ -absorption becomes insignificant for a source with $R_s \geq 3 \times 10^{13} \text{ cm}$. Thus, for an extended source model both hard and steep spectra for $E \geq 100 \text{ GeV}$ can be expected. Note that in the latter case, interpretation of the observed VHE flux would require an acceleration power much less than assumed in Fig. 1, so that the HE γ -rays would not be detected by EGRET.

4 Compact source models

Any model for interpretation of fluxes modulated at the pulsar spin period $P_0 \approx 4.8 \text{ s}$ has to assume a source with R_s noticeably smaller than $cP_0/2$, i.e. effectively $R_s \leq 5 \times 10^{10} \text{ cm}$. Another requirement is that the energy loss time t_{loss} of relativistic particles should be smaller than P_0 . Then for $t_{loss} \sim 1 \text{ s}$ the energy density of relativistic particles can be estimated as $\geq 10^4 \text{ erg/cm}^3$ using the relation $W_{rel} \geq L_\gamma t_{loss}$ for the total particle energy. Energy densities that high can be reached in the inner accretion disk around the neutron star, which is excluded as a site for the γ -ray emission. This implies that a source of pulsed γ -radiation in Cen X-3 can not be constrained, so that generally one would expect only rather short episodes of pulsed γ -ray emission.

There can be two types of models, leptonic and hadronic, for production of episodic pulsed radiation, both assuming a compact source (eg ‘clouds’, ‘blobs’) propagating in the jet. Pulsations could be produced if a powerful relativistic energy outflow, in the form of either an electromagnetic Poynting flux or a beam of relativistic particles, modulated with the pulsar spin period propagates in the jet region and accelerates/injects relativistic particles in the source.

A hadronic ‘beam-target’ model for production of pulsed VHE γ -radiation in X-ray binaries has been suggested earlier by Aharonian & Atoyan (1991, 1996). It assumes that a powerful beam of relativistic protons hits a dense plasma cloud that may occasionally cross the jet propagation region. The gas density in the cloud should be very high, $n_{gas} \geq 10^{15} \text{ cm}^{-3}$, in order to provide fast energy losses of the pro-

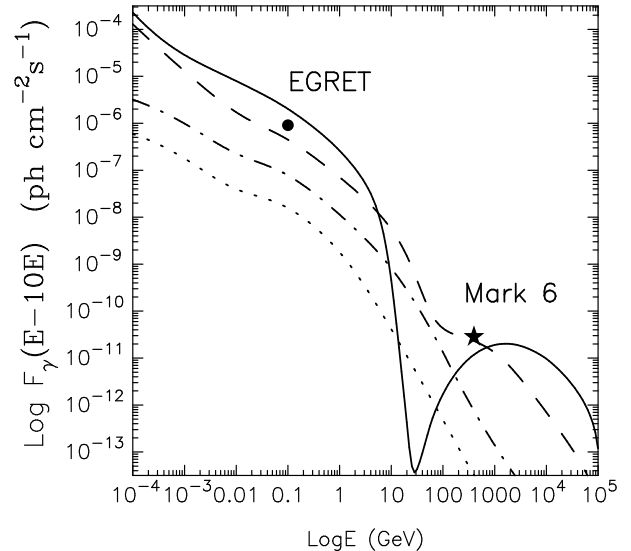


Fig. 2. The radiation spectra emerging at different times $t = 0.5 \text{ h}$ (solid), 3 h (dashed), 1 d (dot-dashed), and 3 d (dotted line) after a compact heavy cloud with $M_{cl} = 10^{22} \text{ g}$ falls under a powerful beam of relativistic protons at an initial distance $D_{cl} = 8 \times 10^{11} \text{ cm}$ from the pulsar. Under the pressure of the beam, the distance D at the shown times is rapidly increasing, reaching $D_{cl} \sim 10^{13} \text{ cm}$ in 3 hours (see Atoyan et al., 2001b for details). Note that the fluxes here are integrated ‘per 1 decade of energy interval’.

tons, $t_{pp} < P_0$. For a cloud with a radius $R_{cl} \sim 10^{10} \text{ cm}$ this implies a mass $M_{cl} \geq 10^{22} \text{ g}$. One may phenomenologically suppose that either such dense plasma blobs are ejected from the massive optical companion star in the binary, or that dense plasma blobs can be ejected from the accretion disk. Note in this regard that very dense and compact ($\sim 10^8 \text{ cm}$) gas clouds responsible for the observed optical emission in the powerful relativistic jets of the prominent binary SS 433, are supposed to be produced/condensed due to thermal instabilities in the jet, e.g. see Panferov (1999).

A relativistic proton beam interacting with the gas in the cloud would produce π^0 -decay γ -rays. Nonthermal radiation in this model will also be contributed by secondary electrons (e^\pm). At the same time some fraction (a few per cent) of the injected proton energy would inevitably go to Coulomb (‘ionization’) losses heating the cloud up to temperatures $T_{cl} \sim (5 - 10) \times 10^4 \text{ K}$. This results in a very high density UV radiation field produced in the cloud, so that its opacity with respect to VHE γ -rays can be very high. Then the spectra of escaping γ -rays are essentially defined by the pair-photon cascade developing in the cloud. At the same time, because of the high pressure created, the source would expand with a speed presumably of order of the sound speed, if not confined by some external pressure. Therefore the radiation spectra predicted in this expanding source should evolve quickly.

In Fig. 2 we show the radiation spectra expected in this model at 4 different times t , from half an hour to 3 days, after a cloud with a mass $M_{cl} = 10^{22} \text{ g}$ and an initial size $R_{cl} \leq$

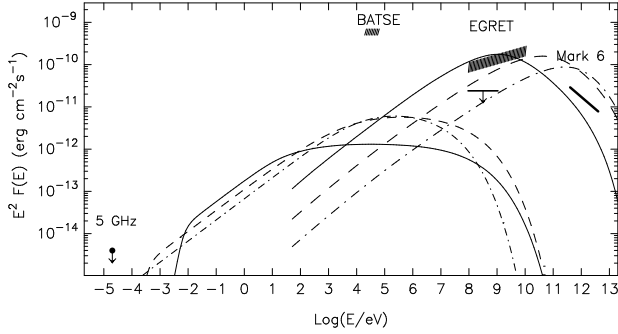


Fig. 3. The spectra of synchrotron (thin lines) and IC (heavy lines) radiation from a compact fast cloud propagating in the jet calculated for 3 different times after ejection: $t = 100$ s (solid), $t = 1$ h (dashed), and $t = 1$ d (dot-dashed). $P_{\text{acc}} = 10^{37}$ erg/s is assumed.

10^{10} cm falls under a powerful beam of relativistic protons at an initial distance $D_{\text{cl}} = 8 \times 10^{11}$ cm from the neutron star. The beam power supposed, assuming an opening angle of the beam of 5° , is $P_{\text{beam}} = 1.8 \times 10^{39}$ erg/s. Note for comparison that the collimation angle of the jets in SS 433 is $\theta_j \leq 1.4^\circ$, and the jet kinetic energy is estimated up to several times 10^{40} erg/s.

Under the pressure of such a powerful beam the expanding clouds would be expelled from the binary, reaching speeds of order 10^4 km/s. For the cloud mass supposed in this case one could expect a pulsed emission only during the first ≤ 1 h, since at $t = 3$ h the gas density in the cloud drops below 10^{15} cm $^{-3}$ so that the proton cooling time t_{pp} exceeds P_0 . Note, however, that calculations in Fig. 2 have assumed a free expansion of the cloud with the sound speed, with no external pressure present. In fact, the expansion of a fast cloud may be significantly confined due to the ram pressure of the external gas for up to a few hours, which defines the maximum possible extension of the phase of pulsed emission.

The principal leptonic model for Cen X-3 basically coincides with the model developed earlier for microquasars (Aharonian and Atoyan, 1999). Generally, this model assumes that the inner accretion disk of the compact object in the binary sporadically ejects a pair of ‘clouds’. In the case of disks around stellar-mass black holes the speed of the ejecta may reach typically $\geq 0.9c$, whereas in the case of neutron stars jet speeds of $\sim 0.3c$ are expected (see Mirabel and Rodriguez (1999)). The electron acceleration should be powered from the central engine by the relativistic wind/Poynting flux modulated with the pulsar spin, resulting in a similar (but Doppler-shifted) modulation of the γ -ray signal. As in the hadronic model, pulsations would inevitably disappear in a few hours, at times when the source expansion (and size) could not be further confined.

In Fig. 3 we show the broad-band radiation flux predicted by this model at 3 different times after ejection of the cloud(s) from the accretion disk. We have assumed the cloud expands with a speed $\simeq 10^7$ cm/s so that the cloud radius by $t \sim 1$ h would still be $< cP_0/2$. The magnetic field behavior in the expanding cloud is approximated as $B(R) \propto R^{-1.5}$, with a normalisation to $B_0 = 50$ G at $R_0 = 10^{10}$ cm. In such high magnetic fields, at the initial stages when the cloud is compact, synchrotron losses can prevent acceleration of electrons beyond an energy of $E_{\text{max}} \simeq 50/\sqrt{B/1\text{G}}\text{TeV}$. This explains a suppression of TeV radiation at $t = 100$ s in Fig. 3. Note that the spectra of pulsed radiation predicted by both leptonic and hadronic compact source models are rather hard.

In conclusion, confirmation of episodes of pulsed VHE γ -radiation will support the suggestion that powerful energy outflows/jets exist in X-ray binaries.

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