A&A 410, L1–L4 (2003)
DOI: 10.1051/0004-6361:20031314-1

Astronomy & Astrophysics

Hadronic gamma-ray emission from windy microquasars

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Received 1 July 2003 / Accepted 2 September 2003

Abstract. The jets of microquasars with high-mass stellar companions are exposed to the dense matter field of the stellar wind. We present estimates of the gamma-ray emission expected from the jet-wind hadronic interaction and we discuss the detectability of the phenomenon at high energies. The proposed mechanism could explain some of the unidentified gamma-ray sources detected by EGRET instrument on the galactic plane.

Key words. X-rays: binaries – stars – gamma-rays: observations – gamma-rays: theory

1. Introduction

Microquasars (MQs) are X-ray binary systems that present non-thermal jet-like features (Mirabel & Rodríguez 1999). The compact jets can be detected at radio wavelengths with flat spectra. The presence of apparent superluminal movements in some cases (e.g. Mirabel & Rodríguez 1994) indicates the existence of relativistic bulk motions in the jet flow. Very recently, Chandra observations have revealed X-ray synchrotron emission from the jet of XTE J1550-564 (Corbel et al. 2002; Kaaret et al. 2003), a fact that indicates the presence of extremely relativistic electrons with TeV energies and shock reacceleration in the jet. The interaction of such highly energetic particles with the ambient photon fields will produce high-energy inverse Compton (IC) radiation. In a series of recent papers, Aharonian & Atoyan (1998), Atoyan & Aharonian (1999), Markoff et al. (2001), Georganopoulos et al. (2002), and Romero et al. (2002) have studied different aspects of the synchrotron and the IC emission from MQs whose jets interact with different photon fields. Recently, Paredes et al. (2000) suggested that the MQ LS 5039 might be responsible for the gamma-ray source 3EG J1824-1514. Kaufman Bernadó et al. (2002) proposed that high-mass MQs with jets forming a small viewing angle (i.e. *microblazars*) might be the parent population of the set of bright and variable gamma-ray sources detected by EGRET along the galactic plane (e.g. Romero et al. 1999; Torres et al. 2001). The main gamma-ray production mechanism for MQs advocated by Kaufman Bernadó et al. (2002) was IC upscattering of UV photons from the stellar companion. However, pair creation absorption processes in the disk and coronal X-ray field might quench the source above a few MeV in many cases (Romero et al. 2002).

In this Letter we present a new mechanism for the generation of high-energy gamma-rays in MQs that is based on hadronic interactions occurring outside the coronal region. The gamma-ray emission arises from the decay of neutral pions created in the inelastic collisions between relativistic protons ejected by the compact object and the ions in the stellar wind. The only requisites for the model are a windy high-mass stellar companion and the presence of multi-TeV protons in the jet[1]. The presence of relativistic hadrons in MQ jets like those of SS 433 has been inferred from iron X-ray line observations (e.g. Kotani et al. 1994, 1996; Migliari et al. 2002), although direct and clear evidence exists only for this source so far. In what follows we describe the model and present the results of our calculations.

2. The jet

The general situation discussed in this paper is shown in Fig. 1. A binary system is formed by a black hole and a high-mass early-type star. A relativistic $e-p$ jet is ejected by the compact object perpendicularly to the accretion disk plane. For simplicity, we shall assume that this is also the orbital plane, but this condition can be relaxed to allow, for instance, a precessional motion (Kaufman Bernadó et al. 2002) or more general situations as discussed by Maccarone (2002) and Butt et al. (2003).

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[1] Interactions of hadronic beams with moving clouds in the context of accreting pulsars have been previously discussed in the literature by Aharonian & Atoyan (1996). For an early discussion in a general context see Bednarek et al. (1990).

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20031314-1

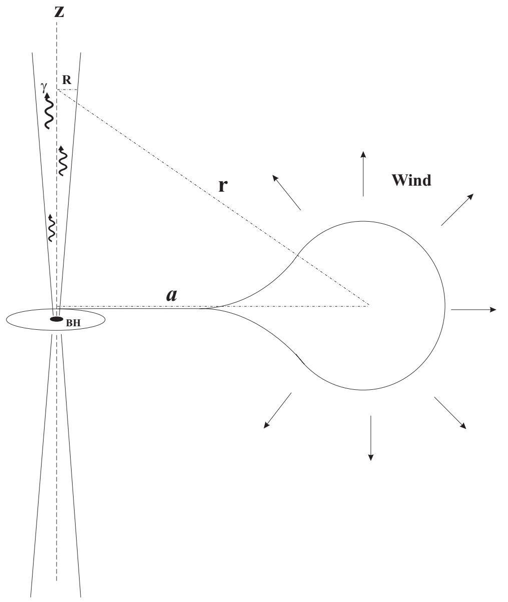

Fig. 1. Sketch of the general situation discussed in the paper. A relativistic $e-p$ jet is injected close to the black hole in a MQ with a high-mass stellar companion. The jet must traverse the matter field created by the stellar wind. The resulting interaction produces gamma-ray emission. In the figure perpendicularity is assumed between the jet and the orbital plane, but this particular assumption can be relaxed in a more general situation.

The jet axis, z, is assumed to be normal to the orbital radius a. We shall allow the jet to expand laterally, in such a way that its radius is given by $R(z) = \xi z^{\epsilon}$, with $\epsilon \leq 1$ and $z_0 \leq z \leq z_{\max}$. For $\epsilon = 1$ we have a conical beam. The jet starts to expand at a height $z_0 \sim$ a few hundred km above the black hole, outside the coronal region. The particle spectrum of the relativistic $e-p$ flow is assumed to be a power law $N'_{e,\,p}(E'_{e,\,p}) = K_{e,\,p}\ E'^{-\alpha}_{e,\,p}$, valid for $E'^{\min}_{e,\,p} \leq E'_{e,\,p} \leq E'^{\max}_{e,\,p}$, in the jet frame. The corresponding particle flux will be $J'_{e,\,p}(E'_{e,\,p}) = (c/4\pi)N'_{e,\,p}(E'_{e,\,p})$. Since the jet expands, the proton flux can be written as:

$$J'_p(E'_p) = \frac{c}{4\pi}K_0\left(\frac{z_0}{z}\right)^{\epsilon n} E'^{\,-\alpha}_p, \tag{1}$$

where $n > 0$ (a value $n = 2$ corresponds to the conservation of the number of particles, see Ghisellini et al. 1985), and a prime refers to the jet frame. Using relativistic invariants, it can be proven that the proton flux, in the observer (or lab) frame, becomes (e.g. Purmohammad & Samimi 2001)

$$J_p(E_p,\theta) = \frac{cK_0}{4\pi}\left(\frac{z_0}{z}\right)^{\epsilon n}\frac{\Gamma^{-\alpha+1}\left(E_p - \beta_{\rm b}\sqrt{E_p^2 - m_p^2c^4}\cos\theta\right)^{-\alpha}}{\left[\sin^2\theta + \Gamma^2\left(\cos\theta - \frac{\beta_{\rm b}E_p}{\sqrt{E_p^2 - m_p^2c^4}}\right)\right]^{1/2}}, \tag{2}$$

where Γ is the jet Lorentz factor, θ is the angle subtended by the emerging photon direction and the jet axis, and $\beta_{\rm b}$ is the corresponding velocity in units of c. The exponential dependence of the cross section on the transverse momentum ($p_{\rm t}$) of the incident protons beams the gamma-ray emission into an angle $\phi < cp_{\rm t}/m_{\rm p}\Gamma \sim 0.17/\Gamma$ along the proton direction, hence justifying the assumption that both directions are similar. Note that only photons emitted with angles similar to that of the inclination angle of the jet will reach a distant observer, and thus θ can be approximated by the jet inclination angle.

In order to determine the matter content of the jet we will adopt the jet-disk coupling hypothesis proposed by Falcke & Biermann (1995) and applied with success to AGNs (see also Falcke & Biermann 1996), i.e. the total jet power scales with the accreting rate as $Q_{\rm j} = q_{\rm j}\dot{M}_{\rm disk}c^2$, with $q_{\rm j} = 10^{-1}$–10^{-3}. The number density n_0' of particles flowing in the jet at $R_0 = R(z_0)$ is then given by $c\pi R_0^2 n_0' = Q_{\rm j}/m_pc^2$, where m_p is the proton rest mass. From here we can obtain n_0'. Additionally, $n'_0 = \int_{E'^{\min}_p}^{E'^{\max}_p} N'_p(E'_p,\ z_0)\ {\rm d}E_p'$. Then, if $E'^{\max}_p \gg E'^{\min}_p$, which is always the case, we have $K_0 = n_0'(\alpha-1)(E'^{\min}_p)^{\alpha-1}$, which gives the constant in the power-law spectrum at z_0.

3. The wind

Early-type stars, like OB stars, lose a significant fraction of their masses through very strong supersonic winds. Typical mass loss rates and terminal wind velocities for O stars are of the order of $10^{-5}\ \dot{M}_{\odot}\,{\rm yr}^{-1}$ and 2500 km s^{-1}, respectively (Lamers & Cassinelli 1999). At the base of the wind, the density can easily reach 10^{-12} g cm^{-3}. Such strong winds provide a field of matter dense enough as to produce significant hadronic gamma-rays when pervaded by a relativistic beam.

The structure of the matter field will be determined essentially by the stellar mass loss rate and the continuity equation: $\dot{M}_* = 4\pi r^2\rho(r)v(r)$, where ρ is the density of the wind and v is its velocity. The radial dependence of the wind velocity is given by (Lamers & Cassinelli 1999):

$$v(r) = v_\infty\left(1 - \frac{r_*}{r}\right)^{\beta}, \tag{3}$$

where v_∞ is the terminal wind velocity, r_* is the stellar radius, and the parameter β is $\sim$1 for massive stars. Hence, using the fact that $r^2 = z^2 + a^2$ and assuming a gas dominated by protons, we get the particle density of the medium along the jet axis:

$$n(z) = \frac{\dot{M}_*}{4\pi m_p v_\infty(z^2+a^2)}\left(1 - \frac{r_*}{\sqrt{z^2+a^2}}\right)^{-\beta}. \tag{4}$$

The stability of a relativistic jet under the effects of an external wind has been recently investigated by Hardee & Hughes (2003) through both theoretical analysis and numerical simulations. Their results indicate that jets surrounded by outflowing winds are in general more dynamically stable than those surrounded by a stationary medium. Note that protons pertaining to the wind can diffuse into the jet medium. The wind penetration into the jet outflow depends on the parameter $\varpi \sim vR(z)/D$, where v is velocity of wind, $R(z)$ is the radius of the jet at a height z above the compact object, and D is the diffusion coefficient. ϖ measures the ratio between the diffusive and the convective timescale of the particles. In the Bohm limit, with typical magnetic fields $B_0 \sim 1$–10 G, $\varpi \leq 1$, and the wind matter penetrates the jet by diffusion.

4. Gamma-ray emission

Pion decay chains leads to gamma-ray and neutrino production. The differential gamma-ray emissivity from π^0-decays is:

$$q_\gamma(E_\gamma) = 4\pi\sigma_{pp}(E_p)\frac{2Z^{(\alpha)}_{p\to\pi^0}}{\alpha}\ J_p(E_\gamma,\theta)\eta_{\rm A}. \qquad (5)$$

Here, the parameter $\eta_{\rm A}$ takes into account the contribution from different nuclei in the wind and in the jet (for standard composition of cosmic rays and interstellar medium $\eta_{\rm A}$ = 1.4–1.5, Dermer 1986). $J_p(E_\gamma)$ is the proton flux distribution evaluated at $E = E_\gamma$. The cross section $\sigma_{pp}(E_p)$ for inelastic p–p interactions at energy $E_p \approx 10E_\gamma$ can be represented above $E_p \approx$ 10 GeV by $\sigma_{pp}(E_p) \approx 30 \times [0.95 + 0.06\log(E_p/\mathrm{GeV})]$ mb. Finally, $Z^{(\alpha)}_{p\to\pi^0}$ is the so-called spectrum-weighted moment of the inclusive cross-section. Its value for different spectral indices α is given, for instance, in Table A1 of Drury et al. (1994). Notice that q_γ is expressed in ph s^{-1} erg^{-1} when we adopt CGS units.

The spectral gamma-ray intensity (photons per unit of time per unit of energy-band) is:

$$I_\gamma(E_\gamma,\theta) = \int_V n(\mathbf{r}')q_\gamma(\mathbf{r}')\mathrm{d}^3\mathbf{r}', \qquad (6)$$

where V is the interaction volume.

Since we are interested here in a general model and not in the study of a particular source, the spectral energy distribution $L^{\pi^0}_\gamma(E_\gamma,\theta) = E^2_\gamma I_\gamma(E_\gamma,\theta)$ is a more convenient quantity than the flux. Using Eqs. (2), (4), (5) and (6), we get:

$$L^{\pi^0}_\gamma(E_\gamma,\theta) \approx \frac{q_{\rm j} z_0^{\epsilon(n-2)} Z^{(\alpha)}_{p\to\pi^0}}{2\pi m_p^2 v_\infty}\ \frac{\alpha-1}{\alpha}\ (E'^{\rm min}_p)^{\alpha-1}$$
$$\times \dot{M}_* \dot{M}_{\rm disk}\ \sigma_{pp}(10\ E_\gamma)\ \frac{\Gamma^{-\alpha+1}\left(E_\gamma - \beta_{\rm b}\sqrt{E_\gamma^2 - m_p^2c^4}\cos\theta\right)^{-\alpha}}{\left[\sin^2\theta + \Gamma^2\left(\cos\theta - \frac{\beta_{\rm b}E_\gamma}{\sqrt{E_\gamma^2 - m_p^2c^4}}\right)\right]^{1/2}}$$
$$\times \int_{z_0}^{\infty} \frac{z^{\epsilon(2-n)}}{(z^2+a^2)}\left(1 - \frac{r_*}{\sqrt{z^2+a^2}}\right)^{-\beta}\mathrm{d}z. \qquad (7)$$

This expression gives approximately the π^0-decay gamma-ray luminosity for a windy MQ at energies $E_\gamma > 1$ GeV, in *a given direction θ with respect to the jet axis*.

Depending on the characteristics of the primary star and the geometry of the system, high-energy gamma rays can be absorbed in the anisotropic stellar photon field through pair production, and then inverse Compton emission from these pairs can initiate an $e^\pm$-pair cascade. This effect has been studied in detail by Bednarek (1997). The main effect of these cascades is a degradation of TeV gamma-rays into a form of softer MeV–GeV emission. Very close systems ($a \sim 10^{11}$ cm) with O stars and perpendicular jets can be optically thick for gamma-rays between ~0.1–100 TeV. If the jet is inclined towards the star, the effect can be stronger (Bednarek 1997). For systems with larger separations, the opacity rapidly falls below unity.

In order to make some numerical estimates, we shall adopt the specific MQ model presented in Table 1. The values chosen for the different parameters are typical for MQs with O stellar companions, like Cygnus X-1. We shall consider a conical jet ($\epsilon = 1$) with conservation of the number of protons ($n = 2$) and a high-energy cutoff for the population of relativistic protons of $E'^{\rm max}_p$ = 100 TeV. The minimum distance from the jet to the primary star is $a = 70\ R_\odot \sim 5\times10^{12}$ cm. In Fig. 2 we show the spectral high-energy distribution for models with proton index $\alpha = 2.2$ and $\alpha = 2.8$, and for different values of the jet/disk coupling parameter $q_{\rm j}$, with the results obtained using

Table 1. Basic parameters of the model.

Parameter	Symbol	Value
Type of jet	ϵ	1
Black hole mass	$M_{\rm bh}$	10 $M_\odot$
Injection point	z_0	50 $R_{\rm g}^1$
Initial radius	R_0	5 $R_{\rm g}$
Radius of the companion star	r_*	35 $R_\odot$
Mass loss rate	$\dot{M}_*$	10^{-5} $M_\odot$ yr^{-1}
Terminal wind velocity	v_∞	2500 km s^{-1}
Black hole accretion rate	$\dot{M}_{\rm disk}$	10^{-8} $M_\odot$ yr^{-1}
Wind velocity index	β	1
Jet's expansion index	n	2
Jet's Lorentz factor	Γ	5
Minimum proton energy	$E'^{\rm min}_p$	10 GeV
Maximum proton energy	$E'^{\rm max}_p$	100 TeV
Orbital radius	a	2 r_*

[1] $R_{\rm g} = GM_{\rm bh}/c^2$.

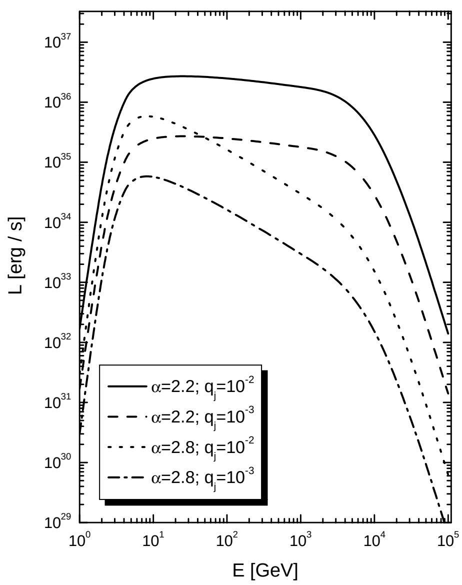

Fig. 2. Spectral high-energy distribution for windy MQs with proton index α = 2.2 and α = 2.8, for different jet/disk coupling constants (q_j). The jet inclination with respect to the line of sight is assumed to be 10 degrees. An angle of 30 degrees reduces the luminosity in about two orders of magnitude.

a numerical integration routine. We have added an exponential-like cutoff at $E_\gamma \sim 0.1 E'^{\rm max}_p$. Since the forward momentum of the protons in the jet is so great, the gamma-rays will be highly beamed, within an angle $\Theta \sim \mathrm{arctg}\,(R/z)$. Hence, only hadronic microblazars would be detected.

5. Discussion

Neutrinos are also generated by pion production chains. The signal-to-noise (S/N) ratio for the detection of such a ν-signal can be obtained analyzing the event rate of atmospheric ν-background and comparing it with the event rate from the source (see e.g. Anchordoqui et al. 2003 for details). The S/N ratio in a km-scale detector (like ICECUBE) in the 1–10 TeV band (including the effects of neutrino oscillations) is ~3 for one year of operation, assuming an inclination angle of 30 degrees, $\alpha = 2.2$ and that the neutrino spectrum roughly satisfies (e.g. Dar & Laor 1997): $\mathrm{d}F_\nu/\mathrm{d}E_\nu \simeq 0.7 \mathrm{d}F_\gamma/\mathrm{d}E_\gamma$. This S/N is high enough as to justify speculations on the possibility of detecting a hadronic microblazar first from its neutrino signal (a serendipitious discovery in a detector like ICECUBE), and only later from its gamma-ray emission (through a pointed observation). Note that this neutrino flux is different from, and in some cases can even be stronger than, the neutrino flux produced by photomeson processes within the coronal region (Levinson & Waxman 2001; Distefano et al. 2002), thus the detection of the neutrino emission from MQs seems promising. It is not possible to separate in the neutrino signal the contributions form the photomeson and $p-p$ channels, but simultaneous X-ray observations can help to determine the characteristics of the relevant photon fields to which the inner jet is exposed, making then possible estimates of each contribution in particular cases.

Another interesting aspect of the hadronic microblazar is that $e^\pm$ are injected outside the coronal region through $\pi^\pm$ decays. These leptons do not experience the severe IC losses that affect to primary electrons and pairs (Romero et al. 2002). These secondaries will mainly cool through synchrotron radiation (at X-rays, in the case of TeV particles) and IC interactions with the stellar seed photons (that would result into an additional source of MeV-GeV gamma-rays). The spectrum of secondary pairs roughly mimics the shape of the proton spectrum. Hence, synchrotron emission from these particles will present indices $\alpha_{\rm syn} \simeq (\alpha - 1)/2$, which for values of $\alpha \sim 2$ are similar to what is observed in MQs' jets at radio wavelengths. The losses of the primaries in the inner source lead to a soft particle spectrum that is then injected in the region where the particles produce IC gamma-rays through interactions with stellar UV photons. Pure leptonic models for the gamma-ray flux (e.g. Kaufman-Bernadó et al. 2002) then require particle re-acceleration in order to explain the flat radio-spectrum of sources like LS 5039 far from the core. In the hadronic model, the leptons are injected in situ with the right spectrum through hadronic decays, avoiding the problem.

At TeV gamma-ray energies hadronic microblazars which are optically thin to pair production can be detected as unidentified, point-like sources with relatively hard spectra. This kind of sources could display variability. In the near future, new ground-based Čerenkov telescopes like HESS and MAGIC might detect the signatures of such sources on the galactic plane. Hadronic microblazars might be part of this population, as well as of the parent population of low latitude unidentified EGRET sources.

Acknowledgements. G.E.R. is very grateful to F. Aharonian, H. Völk and all the staff of the Max-Planck-Institut für Kernphysik at Heidelberg for their kind hospitality during the development of this research. We thank valuable comments by F. Aharonian, P. L. Biermann, L. Costamante, I. Grenier, C.-Y. Huang, D. Purmohammad, and M. Ribó. G.E.R. is supported by Fundación Antorchas (also M.M.K.B.), ANPCyT (PICT 03-04881), and CONICET (PIP 0438/98). D.F.T. research is done under the auspices of the US Department of Energy (NNSA), by the UC's LLNL under contract W-7405-Eng-48. This research benefited from the ECOS French-Argentinian cooperation agreement. We thank an anonymous referee for valuable comments.

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