Unidentified γ-ray sources off the Galactic plane as low-mass microquasars?

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Abstract. A subset of the unidentified EGRET γ-ray sources with no active galactic nucleus or other conspicuous counterpart appears to be concentrated at medium latitudes. Their long-term variability and their spatial distribution indicate that they are distinct from the more persistent sources associated with the nearby Gould Belt. They exhibit a large scale height of 1.3 ± 0.6 kpc above the Galactic plane. Potential counterparts for these sources include microquasars accreting from a low-mass star and spewing a continuous jet. Detailed calculations have been performed of the jet inverse Compton emission in the radiation fields from the star, the accretion disc, and a hot corona. Different jet Lorentz factors, powers, and aspect angles have been explored. The up-scattered emission from the corona predominates below 100 MeV whereas the disc and stellar contributions are preponderant at higher energies for moderate ($\sim 15°$) and small ($\sim 1°$) aspect angles, respectively. Yet, unlike in the high-mass, brighter versions of these systems, the external Compton emission largely fails to produce the luminosities required for 5 to 10 kpc distant EGRET sources. Synchrotron-self-Compton emission appears as a promising alternative.

1. Variable γ-ray sources in the Galactic disc

The EGRET telescope has detected 263 γ-ray sources above 100 MeV (Hartman et al., 1999), half of which have been firmly or plausibly associated with flat radio spectrum AGN and a handful of nearby radiogalaxies (Sowards-Emmerd et al., 2003 ; Sowards-Emmerd et al., 2004; Mattox et al., 2001). Six are identified with pulsars. The other 126 sources remain unidentified because of their poor localization, typically within a degree, or their faintness at lower energies.

Thirty three (33) bright sources along the Galactic plane are associated with star-forming regions that harbour many likely γ-ray emitters, steady ones such as pulsars and supernova remnants, and more variable

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ones such as pulsar wind nebulae, massive star binaries, and accreting X-ray binaries (Romero et al., 1999; Grenier, 2004). Nolan et al. (2003) found a group of 17 sources, concentrated in the inner Galaxy, that exhibit variability on timescales of weeks to months, hence ruling out a supernova remnant or a young pulsar origin. This group is brighter than the other low-latitude sources (Bosch-Ramon et al., 2004). Their luminosity ranges from 0.8 to 20×10^{34} $(D/5 \text{ kpc})^2$ erg s^{-1} sr^{-1} above 100 MeV. They may be associated with variable pulsar wind nebulae or with lower-energy versions of the colliding winds from a pulsar and a massive star, as recently observed at TeV energies by HESS in PSR B1259-63 (Kirk et al., 1999).

Kaufman et al. (2002) have alternatively suggested that they are microquasars with persistent jets and high-mass stellar companions. The long-term variability may be caused by the precession of the accretion disc, henceforth of the jet, that is induced by the gravitational torque of the star, or by variations in the accretion rate along an eccentric orbit, or by instabilities and inhomogeneities in the stellar wind. Synchro-self-Compton (SSC) radiation in the expanding radio blobs ejected during sporadic flares shine too briefly to account for EGRET sources (Atoyan & Aharonian, 1999). Three microquasars with high-mass companions indeed coincide with EGRET sources: LS5039 in 3EG J1824-1514, LSI +61 303 in 3EG J0241+6103, and AX J1639.0-4642 in 3EG J1639-4702 (see Ribó et al, these proceedings). The former and the latter do not exhibit variability in the EGRET data (Nolan et al., 2003). The jet from LSI +61 303 is known to precess and the observed γ-ray flux is variable, though it does not correlate with the radio flares (Kniffen et al. (1997); see , however, Massi (2004)). Energetic electrons or pairs in the jet can spawn γ-rays by up-scattering photons from the bright UV star, the soft X-ray accretion disc, a hard X-ray corona, or their own synchrotron radiation. External inverse Compton (EC) emission from a cylindrical jet (Romero et al., 2004), as well as SSC emission or EC emission from an expanding jet (Bosch-Ramon et al., 2004), can both reproduce the observed luminosities. SSC emission predominates for large jet magnetic fields, typically > 100 G. EC emission yields a large variety of γ-ray spectra, depending on the relative contributions of the different radiation fields and on the jet/accretion power ratio. The latter should typically exceed 10^{-4} to power an EGRET source.

2. Variable γ-ray sources off the Galactic plane

The 93 unidentified sources detected away from the Galactic plane are displayed in Figure 1. Their concentration at $3° < |b| < 30°$ and in the
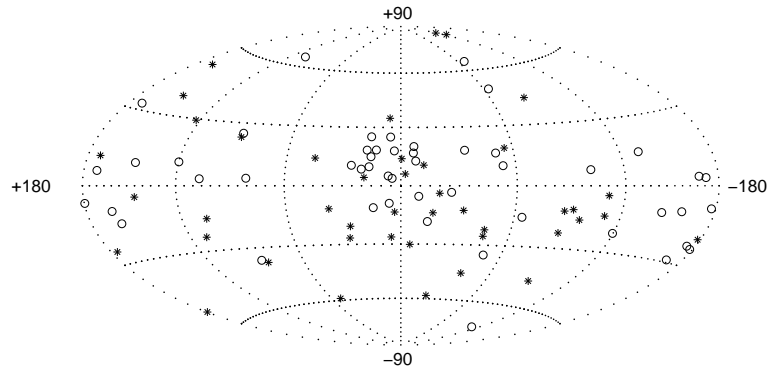
Figure 1. All-sky plot, in Galactic coordinates, of the unidentified EGRET sources at latitudes $|b| > 3°$. The steadier sources associated with the Gould Belt and the variable sources are marked as circles and stars, respectively.
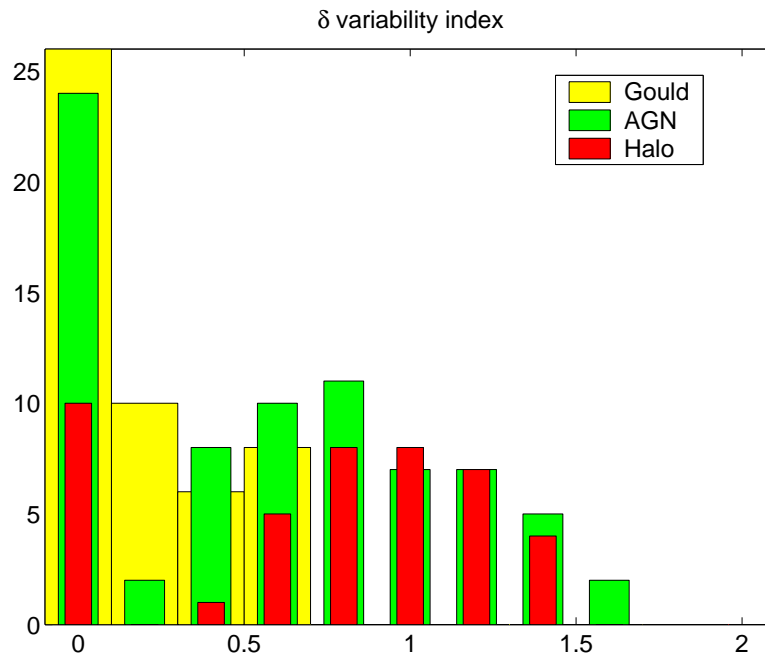

Figure 2. Distributions of the δ variability indices from Nolan et al. (2003) for the firm AGN, Gould Belt, and halo sources at latitudes $|b| > 3°$.

inner half steradian clearly indicates (at a 7σ confidence level) that 70 to 100 % of them have a Galactic origin, depending on the choice of Galactic scale height. Their temporal and spatial characteristics reveal a heterogeneous sample. A subset of steadier sources, marked as circles in Figure 1, has been associated with the nearby Gould Belt (Gehrels et

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al., 2000; Grenier, 2000). The others are clearly more variable. Figure 2 shows their variability index distribution which closely follows that of the variable firm AGN sources (Nolan et al., 2003). The two distributions are consistent under the Kolmogorov (K) test or the T test developed by Eadie et al. (1977), and both are significantly at variance with the Belt source distribution (5σ and 4σ). The average $\overline{\delta}$ indices of the three sets are 0.79 ± 0.08, 0.66 ± 0.06, and 0.42 ± 0.06 for the variable, AGN, and Belt sources, respectively. The spectral index distributions of the 3 sets are quite consistent according to the K and T tests, so the slightly softer average index of 2.43 ± 0.05 for the variable sources, compared with 2.23 ± 0.02 for the Belt and AGN sources, is not significant. Taking into account the detection biases (Grenier, 2000), the spatial distribution of the variable sources implies an origin in a thick Galactic disk with a scale height of 1.3 ± 0.6 kpc. A fit to the whole, persistent and variable, source sample with various combinations of Galactic distributions nearly equally shares the sources between the Gould Belt and a large scale height component, with a 3.4σ and a 4.2σ improvement over the single distribution fits. At typical distances of 5 to 10 kpc, the luminosities of the variable sources range from 2 to 30×10^{34} erg s^{-1} sr^{-1} above 100 MeV. They exhibit large luminosity L_γ/L_X ratios of a few hundred.

The compact objects likely to power sources high above the plane include ms pulsars and microquasars with a low-mass star companion, both having migrated away from the Galactic plane or escaped from globular clusters. None of the γ-ray sources coincides with a globular cluster. Pulsed γ-rays have been detected from the ms pulsar PSR J0218+4232, in phase with the radio and X-ray peaks (Kuiper et al., 2002). This object shares many traits with the halo sources: a distance of 5.7 kpc and an altitude of 1.6 kpc, a luminosity of 1.6×10^{34} erg s^{-1} sr^{-1} and a spectral index of 2.6 above 100 MeV. PSR J0218+4232 does not belong to a globular cluster either. Yet, no long-term variability is expected from theory (Zhang & Cheng, 2003). In the next section, we explore whether low-mass microquasars can produce the halo sources despite their intrinsic faintness and softness compared with the young high-mass systems. Their stellar and disc intensities are reduced by 4-6 and 1 order of magnitude, respectively, and their thermal emissions peak a decade or two lower in energy.

3. Emission from low-mass microquasars

Microquasars are found up to very high Galactic latitude and height above the plane (Mirabel et al., 2001). For instance, XTE J1118+480,

at $b = 62°$ and a distance of 1.8 ± 0.6 kpc, lies at 1.6 ± 0.5 kpc above the plane (McClintock et al., 2001a). The central object accretes matter through a disc from a low-mass star via Roche lobe overflow. McClintock et al. (2001a) and Wagner et al. (2001) constrained the companion spectral type to be between K5 V and M1 V. A large mass function, $f(M) \approx 6$ M$_\odot$, strongly suggests that the compact object is a black hole in a fairly compact binary system with a short orbital of 4.1 hr (Wagner et al., 2001). The disc may be precessing under the stellar tidal influence (Torres et al., 2002). The rapid and correlated UV-optical-X-ray variability in the low-hard state is interpreted as a signature of the strong coupling between a hot corona and a jet emitting synchrotron radiation up to, at least, the UV band (Hynes et al., 2003; Chaty et al., 2003; Malzac et al., 2004). So, pairs in the jet can reach 10 GeV in a modest magnetic field of 10 G. Whether the synchrotron emission extends to hard X rays is quite possible since the data requires the jet to dominate the energy budget and drive the variability, so jet pairs could reach hundreds of GeV. The outflow has remained steady through the outburst evolution (Chaty et al., 2003). The coronal emission extends to ~ 150 keV (McClintock et al., 2001b). The optical to hard-X-ray data can me modelled by the Comptonisation in a hot corona or in the inner accretion flow of the soft photons emitted by the outer cold disc with an inner radius of $\sim 55 R_{\mathrm{Schw}}$ and a temperature of ~ 24 eV (Esin et al., 2001; McClintock et al., 2001b; Malzac et al., 2004).

XTE J1118+480 therefore serves as a good example for a low-mass microquasar and we adopt its characteristics as input to our model (see table I). The spectral energy distributions (SED) of the thermal stellar, disc and coronal components, taken from the afore mentioned publications, are displayed in Figure 3.a. The case of an F star companion is also considered in Figure 3.b. We calculate the EC emission from the three radiation fields assuming a population of $e^+ - e^-$ pairs in a persistent, cylindrical jet, with a power-law E_e^{-p} distribution in number density per unit energy between $E_{e\,\mathrm{min}}$ and $E_{e\,\mathrm{max}}$. The jet is assumed to be parallel to the disc axis, at an angle Φ to the line of sight. It moves with a bulk Lorentz factor Γ_{jet} and carries a total power $P_{\mathrm{jet}} = q_{\mathrm{jet}} \dot{M} c^2$. The coronal emission is assumed to fill a sphere inscribed in the inner disc radius. The particles are isotropically distributed in the jet frame and see the transformed energy densities from the external seed photons. The cross-section for both the Thompson and Klein-Nishina regimes is used. The Compton losses in the different regions modify the injected electron spectrum, introducing a break in the power-law from an index p to $p+1$ at the energy at which the cooling time equals the escape time. This is effective in the disc radiation field. Another important ingredient is the absorption from two-photon pair creation

Table I. Parameter set used in the model

black hole mass	$M_{\mathrm{bh}} = 6.5$ M$\odot$
mass accretion rate	$\dot{M} = 3 \times 10^{-8}$ M$\odot$ yr^{-1}
K-M star bolometric luminosity	$L_{\mathrm{KM}} = 4 \times 10^{32}$ erg/s
F star bolometric luminosity	$L_{\mathrm{F}} = 1.5 \times 10^{34}$ erg/s
star temperature	$kT_{\mathrm{KM}} = 1$ eV and $kT_F = 1.8$ eV
star orbital radius	$D_* = 1.7 \times 10^{11}$ cm
jet/accretion power ratio	$q_{\mathrm{jet}} = P_{\mathrm{jet}}/\dot{M}c^2 = 10^{-3}$ to 10^{-2}
corona luminosity	$L_{\mathrm{cor}} = 7.8 \times 10^{34}$ erg/s
corona outer radius	$R_{\mathrm{cor}} = 10^8$ cm
corona photon index $(dN_X/dE \propto E_X^{-\alpha})$	$\alpha_{\mathrm{cor}} = 1.8$
corona cut-off energy	$E_{\mathrm{cor}} = 150$ keV
disc luminosity	$L_{\mathrm{disc}} = 8.6 \times 10^{35}$ erg/s
disc temperature	$kT_{\mathrm{disc}} = 24$ eV
initial jet radius	$R_{\mathrm{jet}} = 1.9 \times 10^7$ cm
jet bulk Lorentz factor	$\Gamma_{\mathrm{jet}} = 3$ to 10
jet viewing angle	$\Phi = 1°$ to $30°$
jet electron index $(dN_e/dE \propto E_e^{-p})$	$p = 2$ to 3
maximum electron energy	$E_{e\,\mathrm{max}} = 5$ GeV to 5 TeV
minimum electron energy	$E_{e\,\mathrm{min}} = 1$ to 5 MeV

in the ambient radiation (Romero et al., 2002). It turns out to be quite effective near the disc while the coronal and stellar fields are optically thin to the γ rays. Back to the observer's frame, and to observed energies shifted by the Doppler factor $D = \Gamma_{\mathrm{jet}}^{-1}(1 - \beta_{\mathrm{jet}} \cos \Phi)^{-1}$, the stellar and coronal contributions to the SED ϵL_ϵ are amplified by D^{2+p} and the disc one by $D^{2+p}(1 - \cos \Phi)^{(1+p)/2}$ because of the anisotropic seed field (Dermer et al., 1992; Dermer & Schlickeiser, 2002). The former amplification factor peaks along the jet axis and the latter near $\Phi = 15°$ for $\Gamma_{\mathrm{jet}} \sim 3$ and $p = 2$ to 3. The jet synchrotron emission is only amplified by $D^{(3+p)/2}$.

This scenario differs from that of Georganopoulos et al. (2002) who have imposed a much lower energy cutoff to the electrons so that the hard X-ray emission result from their EC interactions with the stellar and disc photons rather than from a hot inner accretion flow or from a hot coronal plasma energized by magnetic flares above the disc.

Figure 3 shows the SED obtained per steradian in the laboratory frame, adding the contributions from the three external photon fields. The coronal component (in the Klein-Nishina regime) is preponderant in the COMPTEL 3-30 MeV band whereas the disc component (in the

Thomson regime) takes over above 100 MeV. This is why the maximum γ-ray luminosity is reached for Φ close to $15°$, reflecting the angle dependance of the disc amplification factor. The disc component is rather weak because of the local absorption. It has a photon spectral index of 2.5 between 0.1 and 1 GeV. The stellar component is small at all viewing angles, so the star spectral type has little impact on the γ-ray flux. These results show that, even though the spectral index in the EGRET band matches that of the unidentified sources, the maximum predicted luminosity, $L_{max} \sim 4 \times 10^{29}(E/100\,\mathrm{MeV})^{-0.5}$ erg s^{-1} sr^{-1}, is 5 orders of magnitude too faint to account for the halo source flux at distances of 5 to 10 kpc.

The relative contributions of the three EC components change in the case of an extreme microblazar where the bulk Lorentz factor Γ_{jet} reaches 10, electron energies extend to 5 TeV, and where the jet axis is close to the line of sight ($\Phi = 1°$). The generation of such a highly relativistic outflow, with $\Gamma_{jet} \geq 10$, has been recently observed from Circinus X-1, a neutron star with a stellar-mass companion (Fender et al., 2004). Particle energies as high as 10 TeV have been inferred in the jets of the stellar-mass microquasar XTE J1550-564, 0.1 pc away from the black hole, even though the jet is seen deccelerating in the interstellar medium (Corbel et al., 2002). High-mass extreme microblazars are unlikely counterparts to the low-latitude EGRET sources because of their extreme brightness. Bosch-Ramon et al. (2004) predict a luminosity of 3×10^{37} erg s^{-1} sr^{-1} at 1 GeV, well in excess of any EGRET source. Such an event would appear as bright as Vela at 5 kpc. Figure 4 shows the result for a low-mass system. The soft EC emission from the corona predominates up to several hundred MeV for an F star and to several GeV for a K-M star, beyond which the harder, $E^{-2.3}$, stellar component takes over. The disc EC emission is negligible because of the lesser amplification at small aspect angle. The 35 times larger energy density that the jet encounters around an F star compared with the K-M one results in a modest luminosity increase by a factor < 5 in the EGRET band. Anyhow, the very low luminosities, as well as the very soft spectra, with photon indices ranging from 3 to 4, however, cannot account for the EGRET source characteristics. Nor would these systems be detected above 100 GeV by the new-generation Cerenkov telescopes since the predicted luminosity falls orders of magnitude below their sensitivity at a few kpc distance.

These objects can remain quiescent for years or decades before brightening by as much as 10^7 in X rays in a week. One should, however, keep in mind that the adopted keV luminosity of $\sim 10^{35}$ erg s^{-1} sr^{-1} corresponds to such a flaring state, i.e. to a bright X-ray source with a νF_ν flux of 2.6×10^{-4} $(D/5\,\mathrm{kpc})^{-2}$ MeV cm^{-2} s^{-1}. The GeV emission
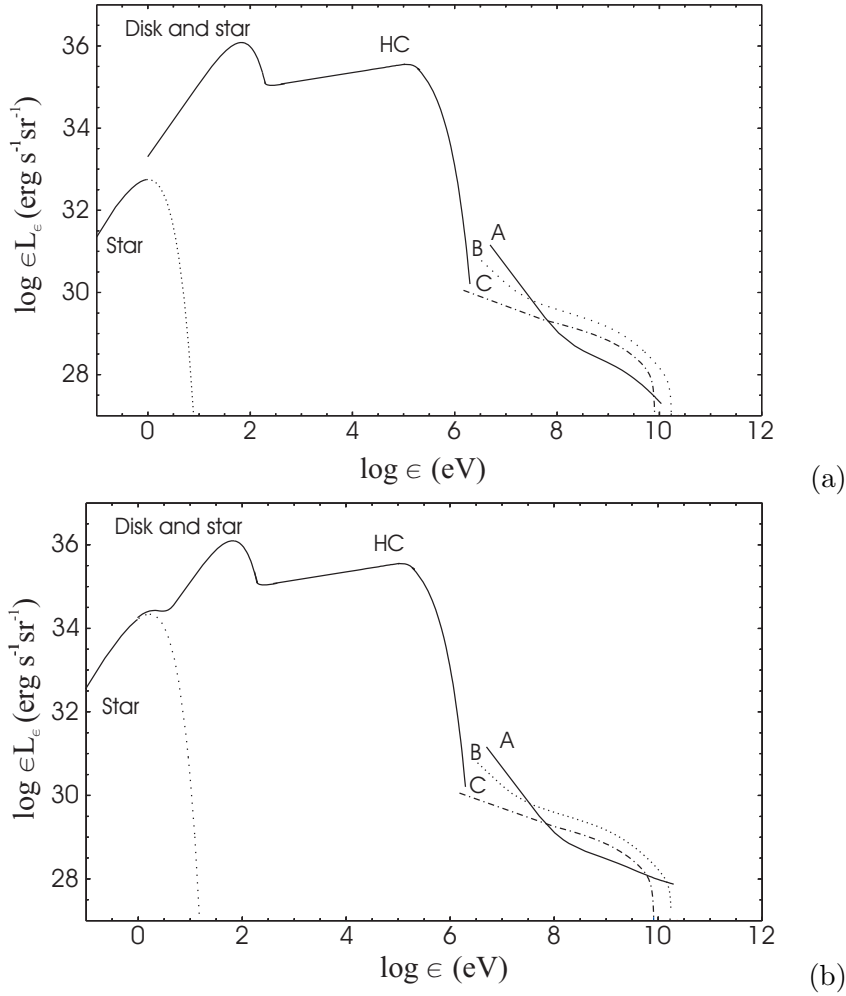
Figure 3. Spectral energy distribution of the EC emission from the jet of a micro-quasar with a K-M star (a) or an F star (b) companion, seen at angles of $5°$ (A), $15°$ (B), and $30°$ (C) from its axis, for $\Gamma_{jet} = 3$, $q_{jet} = 1\%$, and an $E^{-2.3}$ pair spectrum between 1 MeV and 5 GeV.

being mainly due to the disc or corona (depending on the more or less extreme conditions in the jet), the predicted luminosity should be considered as an upper limit for comparison with the unidentified sources. Therefore, EC emission in low-mass microquasars largely fails to explain the variable EGRET sources at large scale heights.

In contrast with high-mass systems where the external radiation energy density largely surpasses the magnetic one, SSC emission is likely to dominate even for a modest field strength of ~ 10 G in the jet for which the magnetic energy density compares with that of a K-M
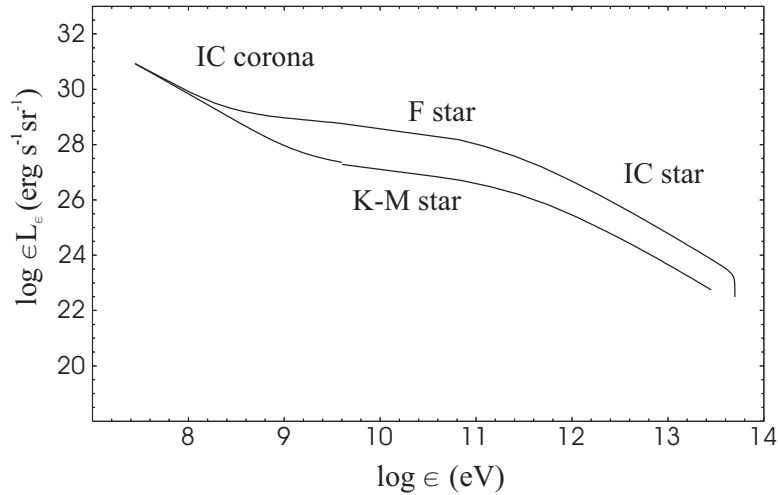
Figure 4. Spectral energy distribution of the EC emission from the jet of an extreme microblazar with an F or K-M star companion, seen at $1°$ from its axis, for $\Gamma_{\text{jet}} = 10$, $q_{\text{jet}} = 1\%$, and an $E^{-2.3}$ pair spectrum between 5 MeV and 5 TeV.
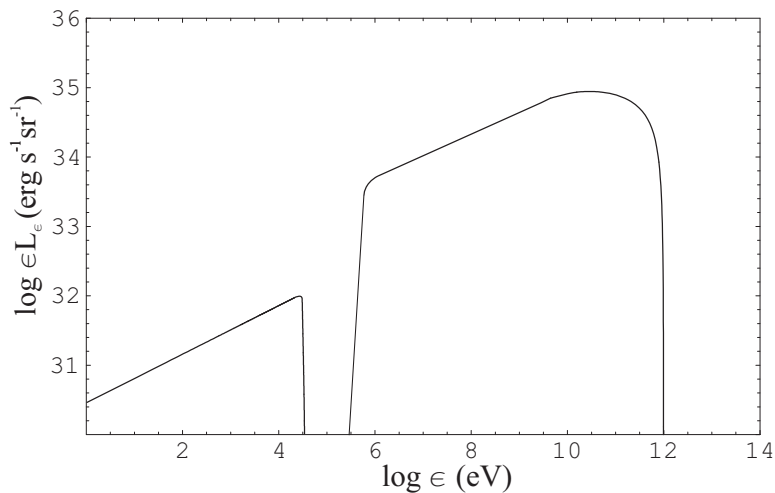

Figure 5. Spectral energy distribution of the synchrotron and SSC emission from the jet of an extreme microblazar, with a 10 G magnetic field, seen at $1°$ from its axis, for $\Gamma_{\text{jet}} = 10$, $q_{\text{jet}} = 0.1\%$, and an $E^{-2.3}$ pair spectrum between 5 MeV and 50 GeV.

star. Applying the model developed by Bosch-Ramon et al. (2004) to a cylindrical jet, one gets luminosities in excess of the necessary EGRET ones (see Figure 5). The synchrotron part of the spectrum is 100-1000 times fainter than the near-IR to UV synchrotron emission recorded from XTE J1118+480 during the outburst, the adopted electron index in Figure 5 being softer than that of XTE J1118+480 to avoid too hard

spectra at high energy. The latter softens beyond 10 GeV because of Klein-Nishina effects. One should keep in mind, however, that $\gamma\gamma$ absorption against the disc photons is not included although it efficiently limits the emerging γ-ray flux. Adiabatic losses in an expanding jet would also modify the result although not severely. Nevertheless, SSC emission in a low-mass microquasar appears as an interesting possibility to be investigated in greater detail, bearing in mind that modelling the high-energy radiation from these fascinating objects is severely limited by the highly uncertain choice of the jet bulk motion and magnetic field.

Acknowledgements

References

Atoyan, A. M. & Aharonian, F. A. 1999, MNRAS 302, 253

Bosch-Ramon V., Romero G. E., Paredes J. M. 2004, A&A, submitted, astro-ph/0405017

Chaty, S., Haswell, C. A., Malzac, J., Hynes, R. I., Shrader, C. R., & Cui, W. 2003, MNRAS, 346, 689

Corbel, S., Fender, R. P., Tzioumis, A. K., Tomsick, J. A., Orosz, J. A., Miller, J. M., Wijnands, R., & Kaaret, P. 2002, Science, 298, 196

Dermer, C. D., Schlickeiser, R., & Mastichiadis, A. 1992, A&A, 256, L27

Dermer, C. D. & Schlickeiser, R. 2002, ApJ, 575, 667

Esin, A. A., McClintock, J. E., Drake, J. J., Garcia, M. R., Haswell, C. A., Hynes, R. I., & Muno, M. P. 2001, ApJ, 555, 483

Eadie, W. T., et al. 1977, Statistical methods in experimental physics, North-Holland Publ., p 279

Fender, R., et al. 2004, Nature, 427, 222

Gehrels N., Macomb D.J., Bertsch D.L., Thompson D.J., Hartman R.C., 2000, Nature 404, 363

Georganopoulos, M., Aharonian, F. A., Kirk, J. G., 2002, A&A, 388, L25

Grenier, I. A. 2000, A&A, 364, L93

Grenier, I. A. 2004, in: Cosmic gamma-ray sources, Eds. K. S. Cheng & G.E. Romero, Kluwer Academic Publishers, in press

Hartman R.C., Bertsch D.L., Bloom S.D., et al., 1999, ApJS 123, 79

Hynes, R. I., et al. 2003, MNRAS, 345, 292

Kaufman Bernardó, M. M., et al., 2002, A&A, 385, L10

Kirk, J. G., Ball, L., & Skjaeraasen, O. 1999, Astroparticle Physics, 10, 31

Kniffen, D. A. et al. 1997, ApJ, 486, 126

Kuiper, L., et al., 2002, ApJ, 577, 917

Malzac, J., Merloni, A., & Fabian, A. C. 2004, MNRAS, 351, 253

Massi, M. 2004, A&A, 422, 267

Mattox, J. R., Hartman, R. C., & Reimer, O. 2001, ApJS, 135, 155

McClintock, J. E., et al. 2001, ApJ, 551, L147

McClintock, J. E., et al. 2001, ApJ, 555, 477

Mirabel, I. F., et al. 2001, Nature, 413, 139

Nolan, P., et al. 2003, ApJ, 597, 615

Paredes, J. M., Marti, J., Ribo, M., Massi, M., 2000, Science, 288, 2340

Romero, G. E., Benaglia, P., & Torres, D. F. 1999, A&A, 348, 868

Romero, G. E, Kaufman Bernardó, M. M., Mirabel, I. F. 2002, A&A, 393, L61

Romero, G. E, Grenier, I. A., Kaufman Bernardó, M. M., Mirabel, I. F., Torres,
    D. F. 2004, Proc. Vth INTEGRAL workshop, Munich 2004, ESA SP-552, in
    press, astro-ph/0402285

Sowards-Emmerd, D., Romani, R. W., & Michelson, P. 2003, ApJ, 590, 109

Sowards-Emmerd, D., Romani, R. W., Michelson, P. F., & Ulvestad, J. S. 2004,
    ApJ, 609, 564

Torres, M. A. P. et al. 2002, ApJ, 569, 423

Wagner, R. M., et al. 2001, ApJ, 556, 42

Zhang, L. & Cheng, K. S. 2003, A&A, 398, 639