Abstract We present a model to estimate the synchrotron radio emission generated in microquasar (MQ) jets due to secondary pairs created via decay of charged pions produced in proton-proton collisions between stellar wind ions and jet relativistic protons. Signatures of electrons/positrons are obtained from consistent particle energy distributions that take into account energy losses due to synchrotron and inverse Compton (IC) processes, as well as adiabatic expansion. The space parameter for the model is explored and the corresponding spectral energy distributions (SEDs) are presented. We conclude that secondary leptonic emission represents a significant though hardly dominant contribution to the total radio emission in MQs, with observational consequences that can be used to test some still unknown processes occurring in these objects as well as the nature of the matter outflowing in their jets.

Keywords microquasars · radio emission · secondary leptons

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1 Introduction

X-ray binary systems (XRBs) are composed by either a stellar mass black hole or a neutron star, and a normal (non degenerated) star which supplies matter to the compact object through the formation of an accretion disk. Some 260 XRBs are known up to now [1] probably corresponding to an underlying population of some tens of thousands of compact objects in our Galaxy. A few of these sources present also non-thermal radio emission, hence evidencing the existence of mechanism(s) capable of injecting and/or accelerating large numbers of relativistic particles. Some radio emitting X-ray binary systems (REXBs) have been observed showing ejection of material at relativistic velocities and to display jets like those seen in quasars and active galactic nuclei but at $\sim 10^{-6}$ times shorter scales. This analogy is the reason for calling them microquasars (MQs) [2] and making them some of the most interesting objects for astrophysics. Furthermore, attention on these objects has grown since the proposal of Paredes et al. (2000) [3] of MQs as counterparts of some of the unidentified gamma-ray sources of the EGRET catalog [4] and hence pointing them as plausible high energy emitters. A strong confirmation of this association has come from the detections of the MQs LS 5039 and LS I +61 303 at Tev energies using respectively the ground-based Cherenkov telescopes HESS [5] and MAGIC [6], giving support and empowering at the same time a number of previous detailed studies centered on the mechanisms operating in these sources in order to explain the gamma ray domain (see, e.g., [7] and [8]). Moreover, a jet origin of the emission from MQs has been suggested from the observation of synchrotron emission of relativistic electrons/positrons extending from the radio all the way into the X-ray regime. In this sense jet-like models have focused on different approaches regarding the particle origin that could generate the required emission properties in a consistent way. Some of them consider leptons directly injected at the base of the jet and, in extending outwards, Compton-interaction with external/self-created photon fields produces high energy radiation. Other models deal with an hadronic origin of the
high energy emission, through proton-proton interactions and pion decay producing leptons as low energy emitters. The present work refers to the later procedure, focusing on the modelisation of the secondary leptonic synchrotron emission in order to constrain the characterization of MQ jets. An outline of the model is given in the next, followed by the results showing the SEDs and lightcurves under different parameter assumptions and the conclusions that can be extracted from them.

2 Model description

We have taken a binary system formed by a black hole and a high-mass early-type star which feeds the accretion transfer of mass onto the compact object while developing an accretion disk. Part of the accretion power is converted to kinetic and magnetic energy of the accretion flow under the effects of the compact object potential well and a relativistic $e^\pm$-$p$ plasma is ejected in a direction taken to be perpendicular to the plane defined by the accretion disk. This plane is the same as the orbital one, even if this condition can be relaxed to allow a more general situation but for simplicity we assume coplanarity in our model. Jet energetics is assumed to be dominated by accretion, and further energy sources like compact object rotation have been neglected at this stage. The jet will also contain a magnetic field $B_{\text{jet}}$ associated with the plasma. We assume that the matter kinetic luminosity is higher than the magnetic luminosity (or total magnetic energy crossing the jet section per time unit) in the jet regions we are concerned with, although the magnetic field can be still significant once the jet is formed, since the ejection mechanism have likely a magnetohydrodynamical origin.

In this scenario we deal with radiative processes that take place in the jet and can produce significant emission in the radio spectrum. Although the contribution of protons could still be significant from the radiative point of view, we will focus on the leptonic component only. The reader is related to other works (see, e.g., [9] and [8]) for treatments on primary hadrons.

2.1 Secondary generation

Secondary leptons are generated in $p$-$p$ interactions of hot protons in the jet with the companion star wind that extents out isotropically producing charged and neutral pions ($\pi^\pm$, $\pi^0$) through the reaction channel $p+p\rightarrow p+p+\bar{\pi}_0\pi^0+\xi_{\pi^\pm}(\pi^0+\pi^0)$, where $\xi_{\pi^\pm} \sim 2(E_p/\text{GeV})^{1/4}$ is the charged pion multiplicity. The relativistic injection proton spectrum is a power law $N_p(E_p) = K_p E_p^{-\alpha}$ where $E_p^{\text{min}} \leq E_p \leq E_p^{\text{max}}$. The jet region penetrates into it. When charged and neutral pions are created, the first will decay to muons and subsequently to electrons and positrons, while the second decays to high energy photons through

$$\pi^+ \rightarrow \nu_{\mu} + \mu^+ \rightarrow \nu_{\mu} + e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \bar{\nu}_{\mu} + \mu^- \rightarrow \bar{\nu}_{\mu} + e^- + \nu_e + \nu_{\mu}$$
$$\pi^0 \rightarrow 2\gamma.$$ 

For an injection proton spectrum as the one given above, the pion spectrum (in the jet reference frame) will be a power law and the electron/positron distribution will also follow a power law [10] with a differential pair injection rate given by $J_e(E_e) = K_e(E_e)^{-\gamma}$ where we use a value $\gamma = 2.2$.

2.2 Secondary evolution

This injected electron-positron population suffers subsequent radiative cooling due to synchrotron and inverse Compton losses as well as adiabatic expansion given by

$$\left[\frac{dE_e}{dt}\right]_{\text{syn}} = -2.36 \cdot 10^{-3} B^2 E_e^2 c^2,$$
$$\left[\frac{dE_e}{dt}\right]_{\text{IC}} = -3.90 \cdot 10^{-2} U_{\text{star}} E_e^2,$$
$$\left[\frac{dE_e}{dt}\right]_{\text{exp}} = \frac{2}{3} \frac{V_{\text{exp}}}{R(z)} E_e^2,$$

respectively. Here $U_{\text{star}}$ is the companion star’s photon field given by $U_{\text{star}} = \frac{L_x}{4\pi d^2 c}$ where $d$ is the distance from the star and in our case $L_x = 1.6 \cdot 10^{39}$ erg/s, and $V_{\text{exp}} = dR(z)/dt$ is the lateral expansion velocity of the jet. Fresh electrons and positrons that have been injected at a certain point into the jet suffer the different energy losses modifying in this way the spectral distribution of particles at each height $z$. Moreover, different evolution stages sum at each height since injection of fresh particles occurs all along the jet and therefore a mix

| Table 1 Parameter values used throughout the model. |
|-----------------------------------------------------|
| Parameter | Symbol | Value |
|------------|--------|-------|
| Black hole mass | $M_{\text{bh}}$ | $3M_{\odot}$ |
| Injection point | $z_0$ | $50R_\odot$ |
| Initial radius | $R_0$ | $5R_\odot$ |
| Radius of the companion star | $R_*$ | $15R_\odot$ |
| Orbital radius | $a$ | $3R_\odot$ |
| Luminosity companion star | $L_*$ | $1.6 \times 10^{39}$ erg/s |
| Mass loss rate | $M_\dot{\star}$ | $3 \times 10^{-6} M_{\odot}$ yr$^{-1}$ |
| Jet’s Lorentz factor | $\Gamma$ | 1.02 |
| Jet kinetic luminosity | $Q_\Gamma$ | $10^{36}$ erg/s |
| Proton kinetic Luminosity | $Q_p$ | $10^{35}$ erg/s |
| Minimum proton energy | $E_{\text{min}}^p$ | 2 GeV |
| Maximum proton energy | $E_{\text{max}}^p$ | 100 TeV |
| Leptonic spectral index | $\alpha$ | 2.2 |
| Wind-jet penetration factor | $f_p$ | 0.1 |
| Magnetic field at $z_0$ | $B_0$ | $10^2, 10^3, 10^4$ |
of multiple evolved population of electron/positron distribution arises. To compute it in a consistent way, one has to assume the continuity equation,

$$N_{e^\pm}(E_{e^\pm}, z)dE_{e^\pm} = N_{0,e^\pm}(E_{0,e^\pm}, z_0)dE_{0,e^\pm}$$

where $N_{0,e^\pm}(E_{0,e^\pm}, z_0) = K_0 e^\pm E_{0,e^\pm}^p$ is the initial energy spectrum for the injected particle density. Solving the equations for the evolution of the particle energy along the jet axis, one can find the spectral distribution at each slice, compute differential luminosity at each height and finally integrate to find the total luminosity.

### 2.3 Secondary emission

Secondary electrons and positrons will radiate through synchrotron process since we assume the presence of a magnetic field which is tangled to the plasma and oriented randomly in direction. The resulting emission will be isotropic in the jet reference frame; to compute the expected luminosity, we have used the formulae presented in [11], where expressions for the specific emission and absorption coefficients are given by

$$\varepsilon_{\nu} = C_\nu B \int_0^{E_{\nu j}} N_{e^\pm}(E_{e^\pm}) F(x) dE_{e^\pm}$$

$$k_{\nu} = -\frac{2}{2\nu r} C_\nu B \int_0^{E_{\nu j}} E_{e^\pm}^2 \frac{N_{e^\pm}(E_{e^\pm})}{E_{e^\pm}} F(x) dE_{e^\pm}$$

with the function $F(x)$ given by $F(x) = x \int_x^{\infty} K_{5/3}(z) dz$ being $K_{5/3}$ the modified second kind Bessel functions, $x = \frac{\nu e^\pm}{\nu_{c^\pm}}$, where $\nu_c = \frac{3e}{4\pi m_e c^2} E_{e^\pm}^2 \approx 6.27 \cdot 10^{18} E_{e^\pm}^2$ Hz is the critical frequency, and the constant $C_\nu \approx 1.87 \cdot 10^{-23}$ (in CGS units).

Then, the specific differential luminosity at a certain height $z$ in the jet can be expressed as

$$\frac{dL_{syn}(z)}{dz} = 2\pi R(z) \frac{E_{\nu j}}{K_{\nu}} (1 - e^{-l_j/\nu_{\nu j}})$$

where $l_j$ is the typical size of the synchrotron emitting plasma region. Now, integrating over the entire jet length we find the spectral energy distribution,

$$\nu L_{syn} = \nu \int_0^{\infty} \delta(z) \frac{dL_{syn}(z)}{dz} dz$$
where $\delta = \left[ \Gamma (1 - \beta \cos \theta_{\text{obs}}) \right]^{-1}$ is the Doppler boosting factor.

### 3 Model results and conclusions

SEDs are obtained for different magnetic field values, electron/positron spectral indices and spatially distributed disks. We have estimated also the expected emission along the jet at 1 and 5 GHz. Leptons are injected in the context of hadronic secondaries generation within a detailed model that takes into account in a consistent way particle injection mechanisms and cooling due to radiation processes and adiabatic expansion. The luminosities obtained are slightly lower than in the models based on primary leptons injection, and must be considered complementary to them. However, we note that within our model there is no requirements of acceleration processes along the jet to obtain the final emission results. Such acceleration processes are still not well understood, although. They could come from diffusive shock acceleration along the jet when fresh ejecta interact with previous blobs of plasma already outflowing at lower velocities. Other scenarios assume a continuous energy transfer mechanism from the magnetic field to the matter content of the jet in such a way that the resulting parsec-scale radio emission can be explained. The fact of studying alternative models were particles are directly injected until a certain height along the jet can constrain the amount of acceleration required and contribute to the understanding of the physical mechanisms that can lead to such processes.

Signatures at different distances along the jet and specific spectral features detectable for reasonable parameter values treated in our numerical simulations have the potential to be an important clue for determining the matter content of jets. In particular, highly resolved observations at 1 and 5 GHz could determine if leptons are present at heights $10^{12}$–$10^{13}$ cm at the edge of the binary system typical region where wind matter from the companion is still significant. If electrons/positrons still show high energies due to a recent injection from hadronic interactions at these parts of the jet, it could be a signature of secondary generation without the necessity of invoking additional acceleration processes.

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