High energy neutrino and gamma-ray emissions from the jets of M33 X-7 microquasar

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Abstract. In this work, after testing the reliability of our algorithms through numerical simulations on the well-studied SS 433 Galactic microquasar, we focus on neutrino and γ-ray emissions from the extragalactic M33 X-7 system. This is a recently discovered X-ray binary system located in the neighbouring galaxy Messier 33 which has not yet been modelled in detail. The neutrino and γ-ray energy spectra, produced from the magnetized astrophysical jet of M33 X-7, in the context of our method are assumed to originate from the decay (and scattering) processes taking place among the secondary particles produced assuming that, first, hot (relativistic) protons of the jet scatter on thermal ones (p-p interaction mechanism).

Keywords: Microquasars, stellar mass black holes, astrophysical outflows, Messier M33 X-7, X-ray binaries

1. Introduction

During the last few decades, collimated outflows have been observed to emerge from a wide variety of astrophysical objects. Among these objects, the class of microquasars (MQs) and the X-ray binary systems possess prominent positions [1, 2]. These systems consist of a compact object at the center (a stellar mass black hole or a neutron star) and a companion (donor) main sequence star. Due to the strong gravitational field of the compact object, mass from the companion star is accreted onto its equatorial region forming an accretion disc. Such systems constitute excellent laboratories for investigating astrophysical flows in our present study [3,4,5]. They are usually treated as magnetohydrodynamical flows emanating from the vicinity of the compact object, the stellar mass black hole. We assume spinning black holes with masses up to few tens (30-50) of the Sun mass [2, 3, 4].

From the observed characteristics of MQs we came to the conclusion that they share a lot of similarities in their physical properties with the class of Active Galactic Nuclei (AGN) even though the latter are enormously different in scale compared to microquasars. In this work we restrict ourselves to magnetized astrophysical outflows characterized by the hadronic content in their jets. We concentrate on numerical simulations of their γ-ray and neutrino emissions [6, 7].

In the present calculations, after fixing our model parameters and testing our algorithms on the reproducibility of some well known properties of the well-studied SS 433 Galactic microquasar [3, 9, 10], we performed detailed simulations for the Galactic Cyg X-1 system and the extragalactic M33 X-7 [11]. The latter system is a recently discovered X-ray binary
system located in the neighboring galaxy Messier 33 \cite{11}. The neutrino and γ-ray emissivities (spectra), that may be obtained in the context of our method originate from the decay (and scattering) processes taking place among the secondary particle produced assuming that non-thermal (relativistic) protons of the jet (a small portion of them equal to about 0.1\%) scatter on thermal ones (p-p scattering mechanism) \cite{4}.

2. Hadronic Mechanisms for astrophysical outflows

In the models considered in this work, an accretion disk is present around the compact object, and a fraction of the accreted material is expelled in two oppositely directed jets \cite{2}. We assume conical jets with a half-opening angle $\xi = 7^\circ$ for the M33 X-7 and radius $r(z) = z \tan \xi$, where the injection point is at a distance $z_0$ from the compact object. When $z = z_0$ the radius of the jet is given by $r_0 = z_0 \tan \xi$. Assuming an initial jet radius $r_0 = r(z_0) = 5R_{sch}$, where $R_{sch} = 2GM_BH/c^2$, we find that the injection point is at $z_0 = r_0/\tan \xi \approx 1.9 \times 10^8$ cm for the M33 X-7 ($M_{BH} = 15.65M_\odot$).

In Table 1 we tabulate the parameters of the model for the system M33 X-7.

| Parameter                        | Symbol | Value          |
|----------------------------------|--------|----------------|
| jet’s launching point            | $z_0$  | $1.9 \times 10^8$ cm |
| extent of acceleration region    | $z_{max}$ | $5z_0$        |
| jet’s bulk Lorentz factor        | $\Gamma_b$ | 1.66          |
| jet’s half-opening angle         | $\xi$  | $7^\circ$     |
| viewing angle                    | $\theta$ | 74.6°         |

2.1. The p-p Collision Mechanism

The collision of relativistic protons with the cold ones (p-p collision mechanism) inside the jet, produces pions, kaons, eta particles, etc., through the following reactions

\begin{equation}
\begin{align*}
p + p &\rightarrow p + p + a\pi^0 + b(\pi^+ + \pi^-) \\
p + p &\rightarrow p + n + \pi^+ + a\pi^0 + b(\pi^+ + \pi^-)
\end{align*}
\end{equation}

where $a$ and $b$ denote the pion multiplicities \cite{3}. Charged pions ($\pi^\pm$), afterwards, decay to charged leptons (electrons or positrons and muons) and neutrinos as

\begin{equation}
\begin{align*}
\pi^+ &\rightarrow \mu^+ + \nu_\mu, & \pi^+ &\rightarrow e^+ + \nu_e \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu, & \pi^- &\rightarrow e^- + \bar{\nu}_e
\end{align*}
\end{equation}

Furthermore, muons also decay giving neutrinos and electrons (or positrons) as

\begin{equation}
\begin{align*}
\mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu, & \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu.
\end{align*}
\end{equation}

Me mention that neutral pions decays give γ-rays according to the reactions

\begin{equation}
\begin{align*}
\pi^0 &\rightarrow \gamma + \gamma, & \pi^0 &\rightarrow \gamma + e^- + e^+
\end{align*}
\end{equation}

In our present study we consider both types of pion decays \cite{6,7}.
3. Cooling rates for some important processes

The rate of p-p collisions between the relativistic protons with the cold ones is given by

\[ t^{-1}_{pp} = n(z)\sigma^{inel}_{pp}(E_{p})K_{p} \]  (5)

where the inelasticity coefficient is \( K_{p} \approx 1/2 \), the corresponding cross section for inelastic \( p-p \) interactions is given in Ref. [12]. \( n(z) \) is the density of cold particles in the jet at a distance \( z \) from the black hole given by

\[ n(z) = \frac{(1 - q_{ad})}{\Gamma_{c}} \frac{L_{k}}{m_{c}^{2} \pi r_{j}^{2} v_{b}} \]  (6)

Charged particles of mass \( m \) and energy \( E = \gamma mc^{2} \), emit synchrotron radiation at a rate

\[ t^{-1}_{sync} = \frac{4}{3} \left( \frac{m_{e}}{m} \right)^{2} \frac{\gamma \sigma_{T}B^{2}}{m_{e} c^{2} 8\pi} \]  (7)

Finally, because the jet is expanding with a velocity \( v_{b} \tan \xi \) the adiabatic cooling rate is

\[ t^{-1}_{ad} = \frac{2}{3} \frac{v_{b}}{z} \]  (8)

4. Method of calculating particle distributions

In order to calculate the neutrino and gamma-ray emissivities, we need, first, to calculate the distributions of protons, pions and muons. For these calculations we use a code written in the C programming language, mainly following the assumptions of Refs. [4, 5]. In the one-zone approximation [10], the particle distributions are independent of time (steady state approximation) and can be obtained from the solutions of the following transport equations

\[ \frac{\partial}{\partial E} \begin{pmatrix} N_{p}(E, z)b_{p}(E, z) \\ N_{\pi}(E, z)b_{\pi}(E, z) \\ N_{\mu}(E, z)b_{\mu}(E, z) \end{pmatrix} + \begin{pmatrix} t^{-1}_{esc}N_{p}(E, z) \\ t^{-1}_{esc}N_{\pi}(E, z) \\ t^{-1}_{esc}N_{\mu}(E, z) \end{pmatrix} = \begin{pmatrix} Q_{p}(E, z) \\ Q_{\pi}(E, z) \\ Q_{\mu}(E, z) \end{pmatrix} \]  (9)

where

\[ t^{-1}_{esc} \approx \frac{c}{z_{\text{max}} - z} \], \quad b(E, z) = \frac{dE}{dt} = -E t^{-1}_{loss}(E, z). \]  (10)

The first equation gives the escape rate and the second the energy loss rate. The energy loss rate for each particle is given by

\[ b_{p}(E, z) = -E(t^{-1}_{sync} + t^{-1}_{ad} + t^{-1}_{pp}), \quad b_{\pi}(E, z) = -E(t^{-1}_{sync} + t^{-1}_{ad} + t^{-1}_{pp}), \quad b_{\mu}(E, z) = -E(t^{-1}_{sync} + t^{-1}_{ad}) \]  (11)

For the \( \pi p \) interactions we consider

\[ t^{-1}_{\pi p}(E, z) \approx 0.5 n(z)c\sigma^{inel}_{\pi p}(E_{p}) \]  (12)

with \( \sigma_{\pi p}(E) \approx 2\sigma^{inel}_{pp}(E)/3 \), which is based on the fact that protons are made of three valence quarks, while the pions by only two quarks [14].

4.1. Proton distribution

The solution of the transport equation for protons is written as

\[ N_{p}(E, z) = \frac{1}{b_{p}(E)} \int_{E_{p}}^{E_{p}^{\text{max}}} Q_{p}(E', z)e^{-t^{-1}_{esc}r_{\pi}(E, E')}dE', \quad \tau(E, E') = \int_{E}^{E'} \frac{dE''}{b(E'')} \]  (13)

The quantity \( Q_{p}(E, z) \) corresponds to the injection function of protons [4], where \( \Gamma_{b} \) is the bulk Lorentz factor of the jet. The normalization constant \( Q_{0} \) is obtained by specifying the power in the relativistic protons [4]. The minimum energy of protons is \( E_{p}^{\text{min}} = 1.2 \text{ GeV} \) and the maximum energy is assumed to be \( E_{p}^{\text{max}} = 10^{7} \text{ GeV} \).
4.2. Pion and muon distributions

The steady state pion and muon distributions obey the transport equation with the replacement $t^{-1}_{esc} \rightarrow t^{-1}_\pi(E, z)$, for pions, and $t^{-1}_{esc} \rightarrow t^{-1}_\mu(E, z)$, for muons. The corresponding solutions are

$$N_\pi(E, z) = \frac{1}{|b_\pi(E)|} \int_{E}^{E_{\text{max}}} Q_\pi(E', z)e^{-\tau_{\pi}}dE'$$

$$N_\mu(E, z) = \frac{1}{|b_\mu(E)|} \int_{E}^{E_{\text{max}}} Q_\mu(E', z)e^{-\tau_{\mu}}dE'.$$

(14)

The rate of decay and escape (for pions or muons) is:

$$t^{-1}_{\pi,\mu}(E, z) = t^{-1}_{esc}(z) + t^{-1}_{\text{dec}}(E)$$

(15)

where $t^{-1}_{\text{dec}} = [(2.6 \times 10^{-8})\gamma_\pi]^{-1}$ s$^{-1}$, for pions, and $t^{-1}_{\text{dec}} = [(2.2 \times 10^{-6})\gamma_\mu]^{-1}$ s$^{-1}$, for muons.

The solution of the transport equation that corresponds to no energy-losses takes the simple form

$$\begin{pmatrix} N_{\pi,0}(E, z) \\ N_{\mu,0}(E, z) \end{pmatrix} = \begin{pmatrix} Q_\pi(E, z) \\ t^{-1}_{\pi}(E, z) \\ Q_\mu(E, z) \\ t^{-1}_{\mu}(E, z) \end{pmatrix}$$

(16)

In Ref. [6, 7] we have calculated the distributions of Eqs. (14) and (16).

4.2.1. Pion injection

The injection function of pions, produced by p-p interactions, is given by

$$Q_\pi(E, z) = n(z)c \int_{E_{\text{pp}}}^{1} N_p \left( \frac{E}{x}, z \right) F_\pi \left( x, \frac{E}{x} \right) \sigma^{\text{inel}}_{pp} \left( \frac{E}{x} \right) \frac{dx}{x}.$$  

(17)

where $x = E/E_p$ and $F_\pi$ denotes the distribution of pions produced per $p - p$ collision [12].

4.2.2. Muon injection

In order to take the muon energy loss into account [14], it is necessary to consider the production of left handed and right handed muons separately because they have different decay spectra. The injection functions of the left handed and right handed muons are [15]:

$$Q_{\mu^-_L} \rightarrow \pi^+(E_\mu, z) = \int_{E_\mu}^{E_{\text{max}}} dE_\pi t^{-1}_{\pi,\text{dec}}(E_\pi) N_\pi(E_\pi, z) \frac{r_\pi(1-x)}{E_\pi x(1-r_\pi)^2} \Theta(x-r_\pi),$$

$$Q_{\mu^-_R} \rightarrow \pi^+(E_\mu, z) = \int_{E_\mu}^{E_{\text{max}}} dE_\pi t^{-1}_{\pi,\text{dec}}(E_\pi) N_\pi(E_\pi, z) \frac{(x-r_\pi)}{E_\pi x(1-r_\pi)^2} \Theta(x-r_\pi),$$

(18)

with $x = E_\mu/E_\pi$ and $r_\pi = (m_\mu/m_\pi)^2$.

4.3. Gamma-ray emission from the p-p interaction mechanism

The p-p collision mechanism in the jets, produce secondary $\gamma$-rays. For $E_\gamma \geq 100$ GeV, we consider the $\gamma$-ray emissivity at a height $z$ along the jets (in units $\text{GeV}^{-1}\text{s}^{-1}$) as

$$Q_\gamma = \int_{E_{\gamma}}^{1} \sigma^{\text{inel}}_{pp} \left( \frac{E_\gamma}{x} \right) cN_p \left( \frac{E_\gamma}{x}, z \right) F_\gamma \left( x, \frac{E_\gamma}{x} \right) \frac{dx}{x}.$$  

(19)
The spectral intensity of $\gamma$-rays emitted from the jets, can be obtained from the following expression

$$I_\gamma(E_\gamma) = \int_V Q_\gamma(E_\gamma, z) d^3r = \pi \tan^2 \xi \int_{z_0}^{z_{max}} Q_\gamma(E_\gamma, z) z^2 dz,$$

where $F_\gamma$ is the spectrum of the produced $\gamma$-rays \[12\] with energy $x = E_\gamma / E_p$ for a primary proton energy $E_p$.

5. Results and discussion

Figure 1 shows the cooling rates of protons, pions and muons for the extragalactic binary system M33 X-7 (up) at the base of the jets. For comparison, the corresponding results of the Galactic binary system SS 433 (bottom). The plots of the cooling rates of protons show the synchrotron emission (solid lines), the adiabatic cooling (dotted lines), and the p-p collision (dashed lines). The plots for pions show respectively the synchrotron emission (solid lines), the pion-proton collision (dashed lines), the adiabatic cooling (dotted lines), and the decay rates of pions (dot-dashed lines). Finally the plots of the cooling rates of muons show the synchrotron emission (solid lines), the adiabatic cooling (dotted lines), and the decay rates of muons (dot-dashed lines).

**Figure 1.** Cooling rates for protons, pions and muons for M33 X-7 (top) and SS433 (bottom) at the base of the jets

From Fig. 1 it becomes obvious that, the particle synchrotron losses dominate the high energy region. In the case of protons, due to their mass, synchrotron losses are not dominant up to very high energies. For pions and muons, the decay losses dominate for lower energies, due to their decay rates. The main difference for these two MQs systems concerns the synchrotron cooling rates. For wide half-opening angles (M33 X-7, $\xi = 7^\circ$), the magnetic energy density is lower than that for narrow ones (SS433, $\xi = 0.6^\circ$), and, hence, the magnetic field is also lower. This leads to a lower synchrotron loss rate for the M33 X-7 system.

After obtaining the distributions for protons, pions and muons, the neutrino and $\gamma$-ray intensities may be calculated. Extensive results for $\gamma$-ray and neutrino production in various half-opening angles $\xi$ of the M33 X-7 will be discussed elsewhere.
6. Summary and Conclusions

In this work we address radiative and neutrino emission from microquasars and X-ray binary stars (XRBs). These consist of a compact object (a stellar mass black hole or a neutron star) and a donor star. The strong gravitational field of the compact object is attracting the companion’s star mass and an accretion disc in the equatorial region is formed which emits radiation and produces relativistic plasma jets all along the axis of rotation of the black hole. The neutrino and $\gamma - ray$ emissions originate from decay and scattering processes of the secondary particles produced by the $p - p$ scattering mechanism, i.e. the collision of relativistic protons of the jet with the thermal ones.

In this work we performed detailed calculations for the cooling rates of various processes taking place in hadronic jets of the extragalactic system M33 X-7. These cooling rates enter the proton, pion and muon distributions through which one obtains neutrino and $\gamma - ray$ intensities. The results obtained depend crucially on the half-opening angle $\xi$ of the employed model.

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