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Radiation Emission and Absorption by Astrophysical Jets from XRBs

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Abstract High-energy particles and radiation such as protons, pions, muons, neutrinos and gamma-ray photons are known to emit from collimated outflows of magnetized astrophysical plasma known as jets. They are being ejected by Active Galactic Nuclei (i.e., AGNs) or X-ray binary systems (i.e., XRBs) consisting of a companion star accreting mass onto a black hole or a neutron star. Our work focuses on the calculation of the produced particle energy distributions and mainly on the intensity of gamma-rays. We apply a hadronic model to prominent examples of Black Hole X-ray Binary systems such as Cygnus X-1, SS 433, GRS 1915+105, etc. We also study and work on calculating the absorption of emitted gamma-rays by soft and hard X-ray radiation fields originating from the system's accretion disc, corona and companion star that could strongly affect the jet's gamma-ray intensity that finally reaches the Earth.

Keywords protons, gamma-rays, absorption, XRBs, astrophysical jets

INTRODUCTION

Some of the most exotic and interesting subjects of study in our galaxy are X-ray binary systems [1]. They were initially binary stellar systems where one of the star components transitioned to a neutron star or a black hole. Its excessive gravitational force pulls mass out of its respective companion star, turning it into a donor. The result is the formation of an accretion disk in rotation around the compact object. It consists of gas and matter of extreme temperatures due to friction. The system's magnetic field, due to the disk's charged rotating content, collects surrounding particles such as hadrons and leptons and ejects them in the form of two well-collimated and accelerated relativistic plasma jets. The twin jets are heading towards opposite directions perpendicular to their respective accretion disk.

Inside the jets, a portion of the particles, considered protons in this model [2, 3], are accelerated to even higher relativistic energies. Those collide with the rest of the cold protons engaging in p-p interactions that result in pion, muon, neutrino and gamma-ray production. Especially the latter emission is radiated from the jet regions and heads toward the Earth where they can be modeled [4, 5] and detected [6, 7]. A necessary condition though would be for them not to get annihilated by lower-energy ambient photons emitted by the system's accretion disk, donor star, corona, etc.

GAMMA-RAY PRODUCTION FROM PROTON COLLISIONS

Gamma-ray emissivity from neutral pions decay for energies below 100 GeV is given by [8]

$$Q_{\gamma}(E_{\gamma}, z) = 2 \int_{E_{min}}^{E_{max}} \frac{Q_{\pi^0}(E_{\pi}, z)}{\sqrt{E_{\pi}^2 - m_{\pi}^2 c^4}} dE_{\pi}, \quad (1)$$

where the pion and gamma-ray photon energies are E_{π} and E_{γ} , respectively. $E_{min} = E_{\gamma} + \frac{m_{\pi}^2 c^4}{4E_{\gamma}}$ and $E_{max} = K_{\pi}(E_p^{(max)} - m_p c^2)$ with $E_p^{(max)}$ determining the maximum proton energy inside the jet region. The inelasticity value that confirms the simulations is $K_{\pi} \approx 0.17$.

The neutral pion emissivity required is given by the δ -function approximation as

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$$Q_{\pi^0}(E_\pi, z) = \frac{cn(z)}{K_\pi} \bar{N}_{\pi^0} \sigma_{pp}^{(inel)}(E_p) N_p(E_p, z), \quad (2)$$

where $E_p = m_p c^2 + E_\pi/K_\pi$ and $\bar{N}_{\pi^0} = 1.1$ is the mean neutral pions produced per proton-proton collision. This value satisfies the continuity condition imposed by the respective emissivity for energies above 100 GeV. The cross-section employed is given in [8]. The proton distribution implemented in Eq. (2) is calculated through the solution to the transfer equation that we will discuss shortly. In addition, the cold proton density inside the jet is written as

$$n(z) = \frac{(1-q_r)L_k}{\Gamma m_p c^2 \pi r^2 v_b}, \quad (3)$$

where q_r denotes the ratio between the accelerated protons to the total number of jet protons, r the jet radius at distance z from the black hole and Γ the jet Lorentz factor. L_k is the kinetic luminosity carried by the jet, while v_b represents the respective bulk velocity associated with Γ .

Finally, the proton energy distribution $N_p(E_p, z)$ must be defined. It is calculated through the solution of the steady-state transfer equation given below

$$\frac{\partial N(E, z) b(E, z)}{\partial E} + t^{-1} N(E, z) = Q(E, z). \quad (4)$$

Here, $b(E, z) = -E t_{loss}^{-1}$ is the energy-loss rate that is due to the combination of several proton cooling mechanisms inside the jet region (i.e., emission of synchrotron radiation, proton-proton collisions, adiabatic jet expansion, etc.), $t_{loss}^{-1} = t_{sync}^{-1} + t_{pp}^{-1} + t_{ad}^{-1}$ [2, 9]. The particle reduction rate is defined as $t^{-1} = t_{esc}^{-1} + t_{dec}^{-1}$, where $t_{esc}^{-1} \approx c/(z_{max} - z)$ the particle escape rate from the jet region. The proton production rate is given in the observer's rest frame as

$$Q(E, z) = Q_0 \left(\frac{z_0}{z} \right)^3 \frac{\Gamma^{-1} (E - \beta_b \cos i \sqrt{E^2 - m^2 c^4})^{-2}}{\sqrt{\sin^2 i + \Gamma^2 (\cos i - \beta_b E / \sqrt{E^2 - m^2 c^4})^2}}, \quad (5)$$

where i is the system's angle to the line-of-sight (i.e., system inclination), Γ the jet bulk's Lorentz factor and z_0 the distance between the black hole and the initial point of the acceleration jet region that ends in z_{max} . The corresponding normalization constant is given by

$$Q_0 = \frac{8q_r L_k}{z_0 r_0^2 \ln(E_p^{(max)}/E_p^{(min)})}, \quad (6)$$

with the minimum and maximum proton energies being $E_p^{(min)} = 1.2 \text{ GeV}$ and $E_p^{(max)} \approx 10^7 \text{ GeV}$, respectively. The jet's radius corresponding to the injection point z_0 is denoted as r_0 .

The solution to the aforementioned differential equation is written as

$$N(E, z) = \frac{1}{|b(E)|} \int_E^{E_{max}} Q(E', z) e^{-\tau(E, E')} dE', \quad (7)$$

where it is

$\tau(E, E') = \int_E^{E'} \frac{dE'' t^{-1}}{|b(E'')|}$. Regarding the proton energy distribution, the integrated injection function is the one described in Eq. (5). We have conducted similar calculations regarding neutrino production in [10, 11].

EMISSION ABSORPTION

Hard and soft X-rays from the system's accretion disk and corona or/and UV emission from the donor star are the most common sources leading to the absorption of emitted gamma-rays.

Accretion disk

The disk is considered to begin at the last stable orbit radius (i.e., ISCO) dictated by the size and spin of the black hole. In the case of Schwarzschild black holes, it is $R_{in} = 6R_g = 6GM_{BH}/c^2$.

Each surface element of a horizontal and geometrically thin accretion disk with high optical thickness [12] emits soft X-ray radiation with a black-body spectrum given by

$$\frac{dn}{d\epsilon d\Omega} = \frac{2}{h^3 c^3} \frac{\epsilon^2}{e^{\mathcal{T}(R)} - 1}, \quad (8)$$

where $\mathcal{T}(R) = \epsilon/k_B T(R)$. The corresponding disk temperature profile is given below [13]

$$T(R) = T_g \left[\frac{\bar{r}-2/3}{\bar{r}(\bar{r}-2)^3} \left(1 - \frac{3^{3/2}(\bar{r}-2)}{2^{1/2}\bar{r}^{3/2}} \right) \right]^{1/4}, \quad (9)$$

with $\bar{r} = R/R_g$. The temperature of the inner disk regions is the following

$$T_g = \left(\frac{3GM_{BH}\dot{M}_{accr}}{8\pi\sigma_{SB}R_g^3} \right)^{1/4}. \quad (10)$$

Here, a very important system parameter is employed, the mass accretion rate \dot{M}_{accr} . It should be noted that the inner disk regions are capable of absorbing lower-energy gamma-ray photons compared to the equivalent outer regions.

Donor star

The donor star, due to its temperature, emits thermal black body radiation that annihilates higher-energy gamma-ray photons. The respective radiation field density is given by

$$\frac{dn_{ph}}{d\epsilon} = \frac{15}{4c\pi^5} \frac{L_{star}\mathcal{T}^4}{\epsilon^2 D^2 (e^{\mathcal{T}} - 1)}, \quad (11)$$

where L_{star} corresponds to the stellar luminosity and $\mathcal{T} = \epsilon/k_B T_{eff}$ introduces the stellar effective surface temperature. Those two parameters are tied to the stellar type and evolution stage of the donor. Additionally, we define

$$D = [s^2 + l^2 + z^2 + 2l(z \cos i - s \sin i \cos \alpha)]^{1/2}, \quad (12)$$

as the distance between the donor star and the photon collision point with $\alpha = \alpha_0 + \frac{2\pi l}{cP_{orb}}$ [14]. Two more system parameters are introduced, P_{orb} the orbital period of the system and s that is called binary separation and describes the distance between the black hole and the donor star. It should be noted that this is the most dominant absorption source for the higher jet emission-regions, while the accretion disk emission mainly exterminates nearby photons from the lower jet parts.

Corona

Corona is defined as a spherical region outside the compact object that consists of high-energy electrons that emit hard X-ray radiation. The corresponding density is given by a power-law as

$$\frac{dn_{in}}{d\epsilon} = K_0 \epsilon^2 \text{ and } \frac{dn_{out}}{d\epsilon} = K_0 \left(\frac{R_c}{\rho} \right)^2 \epsilon^2. \quad (13)$$

As is evident, the X-ray density inside the corona is homogenous and isotropic and descends radially outside of it. The distance between the collision point and the black hole is declared as ρ . The relevant normalization constant is given by

$$K_0 = \frac{4L_c}{4\pi c(\epsilon_{max}^4 - \epsilon_{min}^4)R_c^2}, \quad (14)$$

with the hard X-ray photons having energies between 10-100 GeV [12].

RESULTS AND DISCUSSION

We implement the parameters listed in Table 1 in order to estimate the gamma-ray intensities emitted by the respective jets of the XRB systems Cygnus X-1, SS 433 and GRS 1915+105. In addition, we calculate the contribution of lower-energy emission sources including the accretion disk, donor star and corona of the system.

In Fig. 1, we present the optical depths for the three aforementioned absorption sources for the studied systems. Corona X-ray emission is negligible especially after crossing the corona radius. Regarding absorption due to the donor star's thermal emission, it is drastically more inefficient for

$E \leq 10 \text{ GeV}$ as seen in all graphs of Fig. 1. In comparison, SS 433 is far more vulnerable to gamma-ray absorption especially due to its accretion disk. The reason is the exceptionally high mass-accretion rate (Table 1) that surpasses the Eddington limit.

The gamma-ray intensities for distance $z = 10^{10} \text{ cm}$ from the black hole are demonstrated in Fig. 2. We can also see the damage inflicted upon the VHE emission heading towards the Earth by the various hard/soft X-ray or UV emissions discussed. Cygnus X-1 gamma-ray emission is mostly affected by thermal stellar photons. On the contrary, GRS 1915+105 is unaffected due to a much less luminous stellar component in comparison. As expected, SS 433 is the one impacted the most with approximately every gamma-ray photon engaging in annihilation processes with disk photons.

Table 1. System parameters

	M_{BH}	M_{don}	d	i	P_{orb}	\dot{M}_{accr}	L_{star}	T_{eff}	s	u_b	ξ	Refs.
Cyg X-1	14.8	19.2	1.86	27.1	5.6	10^{-8}	3.5×10^5	31000	2.82×10^{12}	0.6	1.5	[15], [16], [17]
SS 433	15	21	5.5	78.8	13.1	10^{-4}	3.16×10^4	8000	5.3×10^{12}	0.26	0.6	[18], [19], [20]
GRS 1915+105	12.4	0.5	8.6	66.0	33.8	10^{-8}	1×10^2	5000	1×10^{13}	0.81	5	[21], [22]
Units	M_{\odot}	M_{\odot}	kpc	$^{\circ}$	days	$M_{\odot} \text{yr}^{-1}$	L_{\odot}	K	cm	c	$^{\circ}$	

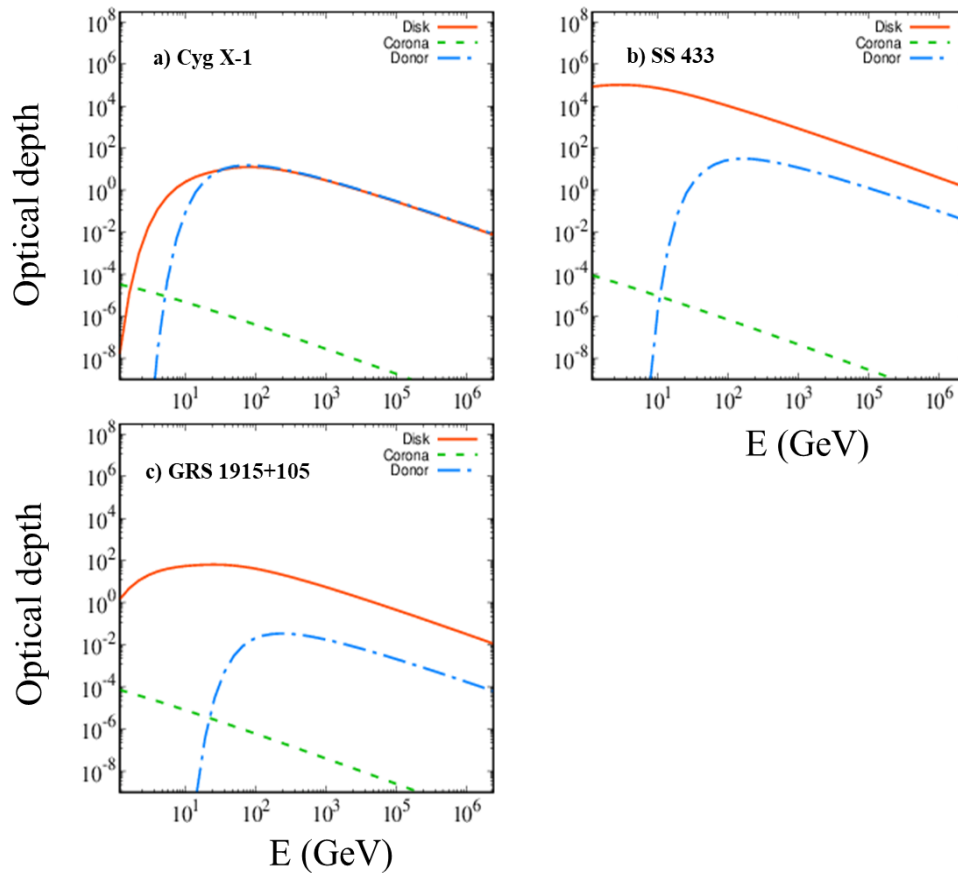


Figure 1. Optical depths for gamma-ray absorption due to accretion disk, donor star and corona emission for XRB systems **a)** Cygnus X-1, **b)** SS 433 and **c)** GRS 1915+105

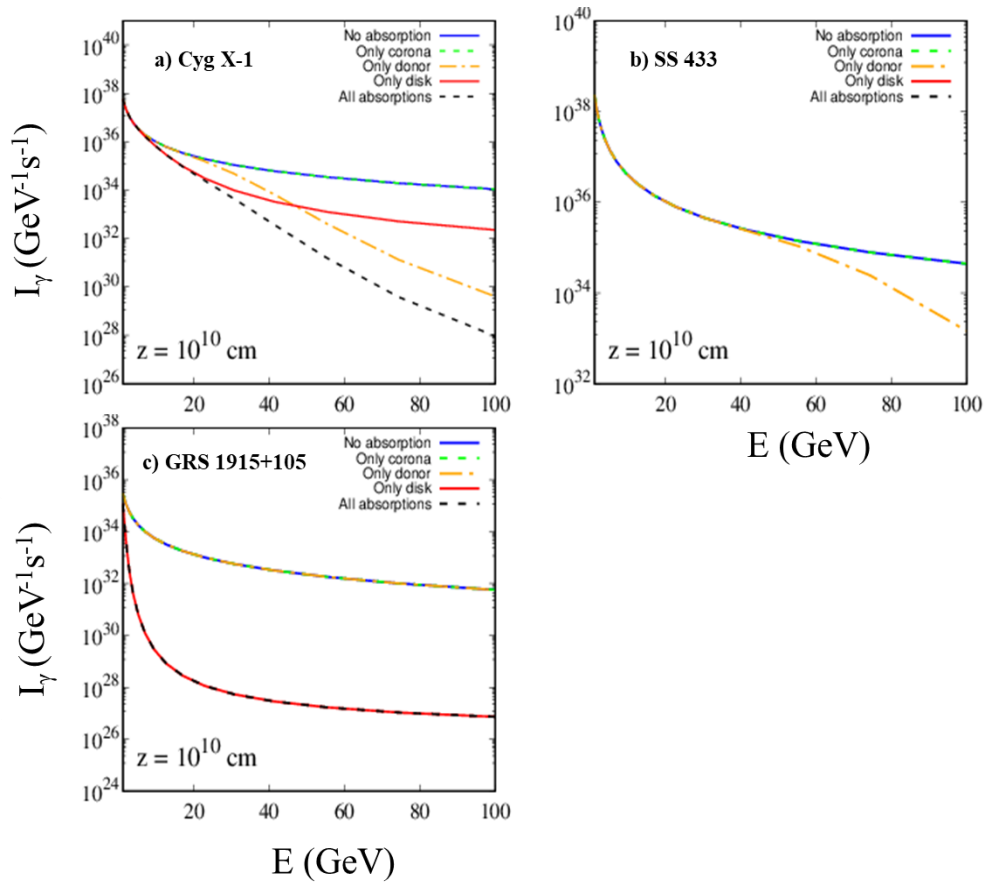


Figure 2. Gamma-ray intensities emitted by jet-regions with distance $z = 10^{10}$ cm from the black hole for XRB systems **a)** Cygnus X-1, **b)** SS 433 and **c)** GRS 1915+105

CONCLUSIONS

Relativistic magnetohydrodynamic jets are launched by black hole X-ray binary systems. Their particle content (i.e, leptons and/or hadrons) engage in interactions that result in secondary particles and gamma-ray photons. We focus on the proton-proton interaction mechanism and calculate the corresponding produced gamma-ray emission for three separate systems: Cygnus X-1, SS 433 and GRS 1915+105. Absorption due to surrounding emissions is also taken into account.

We conclude that Cygnus X-1 presents the greatest probability for gamma-ray detection among the studied systems while the donor star contributes the most to gamma-ray absorption for $E \leq 100$ GeV. Moreover, the super-Eddington accretion limit of SS 433 makes difficult the detection of high-energy emissions originating in its jets. Finally, the less-luminous donor star of GRS 1915+105 is advantageous towards gamma-ray detection even though the larger accretion disk further eradicates higher-energy emitted photons.

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