RELATIVISTIC PARTICLES IN MAGNETIZED MEDIA AROUND BLACK HOLES

Gustavo E. Romero* and Florencia L. Vieyro

Instituto Argentino de Radioastronomía (IAR, CCT La Plata, CONICET)
C.C.5, (1984) Villa Elisa, Buenos Aires, Argentina
**E-mail: romero@iar-conicet.gov.ar*

We study non-thermal processes produced by the injection of relativistic particles in a strongly magnetized corona around an accreting black hole. The spectral energy distribution produced in this component of X-ray binaries can be strongly affected by different interactions between locally injected relativistic particles and the different fields of the source. We compute in a self-consistent way the effects of relativistic Bremsstrahlung, inverse Compton scattering, synchrotron radiation, and pair-production/annihilation of leptons, as well as of hadronic interactions. Our goal is to determine the non-thermal broadband radiative output of the corona. The set of coupled kinetic equations for electrons, positrons, protons and photons are solved and the resulting particle distributions are computed self-consistently. We apply our model to Cygnus X-1 obtaining a good fit of the observational data.

Keywords: X-rays: binaries – radiation mechanisms: non-thermal – gamma-rays: general

1. Introduction

The complete X-ray spectrum of Galactic black holes can be explained through a geometrically thin and optically thick disk, and a *corona*, which is a hot plasma sorrounding the compact object (see Refs. 1 and 2). In this context, the soft photons emitted by the disk gain energy by successive Compton upscatterings in the corona.

Besides the X-ray spectra observed in X-ray binaries (XRBs), sources such as Cygnus X-1 –which is the most well-studied black hole candidate in the Galaxy– produce steady emission up to a few MeV[3] , that is indicative of a non-thermal contribution to the spectral energy distribution (SED).

In this work, we present a self-consistent treatment of photon and particle transport in a magnetized and static corona. We attempt to estimate the SED produced by relativistic particles, and to explain the origin of the non-thermal tail observed in some XRBs[3] .

2. Basic corona model

We study the system in the low-hard state, which is the state where the X-ray spectrum is dominated by the coronal emission.

The X-ray emission of the corona is characterized by a power law in photon energy and an exponential cut-off at high energies. The photon field of the accretion disk is modeled as a blackbody. Both the X-ray emission of the corona and the radiation field of the disk are considered as seed photon fields for Compton scattering and photomeson production in relativistic particle interactions.

To compute the SEDs of black hole coronae, we solve the kinetic equations (e.g., Refs. 4–6). We are interested in the injection of non-thermal particle distributions of electrons and protons in the system. The total power injected into relativistic particles, $L_{\rm rel}$, is assumed to be a fraction of the luminosity of the corona, $L_{\rm rel} = q_{\rm rel} L_{\rm c}$. We define the parameter a as $a = L_p/L_e$, where L_p is the luminosity in relativisic protons and L_e that corresponding to electrons. We consider models with $a = 1 - 100$.

Once protons are injected into the corona, they interact with both the photon and matter fields, producing pions. In addition, the charged pions decay producing muons, so we also take into account the presence of these transient particles.

We determine the relativistic particle and photon distributions solving the set of coupled transport equations in the steady state and assuming spatial homogeneity and isotropy. The set of kinetic equations are

$$\frac{\partial}{\partial E}\left(b_i(E)N_i(E)\right) + \frac{N_i(E)}{t_{\rm esc}} = Q_i(E), \tag{1}$$

where $i = e^+$, e^-, p,

$$\frac{\partial}{\partial E}\left(b_i(E)N_i(E)\right) + \frac{N_i(E)}{t_{\rm esc}} + \frac{N_i(E)}{t^i_{\rm dec}} = Q_i(E), \tag{2}$$

where $i = \pi^+$, π^-, μ^+, μ^-,

$$\begin{aligned} \frac{N_\gamma(E_\gamma)}{t^\gamma_{\rm esc}} = Q_\gamma(E_\gamma) + Q_{e^\pm\to\gamma}(N_{e^\pm}, E_\gamma) \\ - Q_{\gamma\gamma\to e^\pm}(N_\gamma, E_\gamma). \end{aligned} \tag{3}$$

In these equations, $N_i(E)$ represents the steady state of each particle distribution, $b(E)$ includes all radiative losses for a given type of particle, $t_{\rm esc}$ is the timescale over which relativistic particles escape from the system, and $Q_i(E)$ is the injection function. In Eq. (3), the term $Q_\gamma(E_\gamma)$ represents photon injection due to different radiative processes; $Q_{e^\pm}(N_\gamma, E_\gamma)$ is the injection of photons due to pair annihilation.

The reader is referred to Ref. 7 for a detailed description of the model.

3. Application to the low-hard state of Cygnus X-1

We apply our corona model to the well studied black hole candidate Cygnus X-1. The value of the magnetic field is $B = 5.7 \times 10^5$ G and the plasma density is $n_i, ne = 6.2 \times 10^{13}$ cm^{-3}. We adopted a disk characteristic temperature of 0.1 keV.

In Fig. 1, we show the total photon flux produced in the corona. The different pannels in the figure correspond to two different values of the parameter a. We compare our results with observations of Cygnus X-1 made by COMPTEL[3] , obtaining good agreement. The best-fit model was achieved with $q_{\rm rel} = 0.02$ for a corona dominated by protons ($a = 100$) and $q_{\rm rel} = 0.03$ for $a = 1$.

The gap observed in the energy range $10^5 < E < 10^8$ keV is produced by the internal photon absorption in the corona and accretion disk fields.

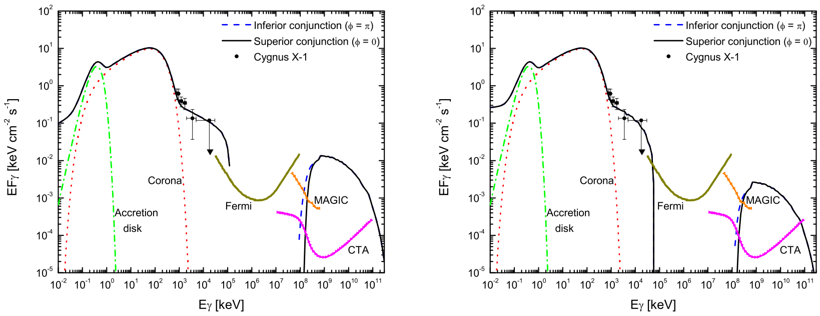

Fig. 1. Final flux in a corona + disk characterized by the parameters of Table 1. We include the 5σ sensitivities for different instruments (50 hours of direct exposure for MAGIC and CTA and 1 yr survey mode for Fermi). (a) $a = 100$. (b) $a = 1$.

4. Conclusions

We have developed a model to deal self-consistently with the non-thermal emission from a magnetized corona.

Since the synchrotron emission of the corona is self-absorbed, all radio emission of the source comes from the jet[8] . The absorption in the stellar field partially suppresses the high-energy bump at $E \sim 10^{10-11}$ eV, which makes difficult to detect this source using either the MAGIC or VERITAS Cherenkov telescopes. The high-energy emission may be detectable by future instruments with higher sensitivity and wider energy ranges, such as the Cherenkov Telescope Array (CTA).

5. Acknowledgments

This work was partially supported by the Argentine Agencies CONICET (PIP 0078) and ANPCyT (PICT 2007-00848), as well as by Spanish Ministerio de Ciencia e Innovación (MICINN) under grant AYA2010-21782-C03-01. We thank Prof. Bisnovatyi-Kogan for useful comments.

References

1. J. B. Dove, J. Wilms, M. Maisack and M. C. Begelman, *ApJ* **487**, p. 759 (1997).
2. G. S. Bisnovatyi-Kogan and S. I. Blinnikov, *A&A* **59**, 111 (1977).
3. M. L. McConnell, J. M. Ryan, W. Collmar, V. Schönfelder, H. Steinle, A. W. Strong, H. Bloemen, W. Hermsen, L. Kuiper, K. Bennett, B. F. Phlips and J. C. Ling, *ApJ* **543**, 928 (2000).
4. P. S. Coppi and R. D. Blandford, *MNRAS* **245**, 453 (1990).
5. F. A. Aharonian and A. V. Plyasheshnikov, *Astroparticle Physics* **19**, 525 (2003).
6. I. Vurm and J. Poutanen, *ApJ* **698**, 293 (2009).
7. F. L. Vieyro and G. E. Romero, *A&A* **542**, 1 (2012).
8. A. M. Stirling, R. E. Spencer, C. J. de la Force, M. A. Garrett, R. P. Fender and R. N. Ogley, *MNRAS* **327**, 1273 (2001).