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Neutrino flares from black hole coronae

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Abstract

We present a model for neutrino flares in accreting black holes based on the injection of a non-thermal population of relativistic particles in a magnetized corona. The most important products of hadronic and photohadronic interactions at high energies are pions. Charged pions decay into muons and neutrinos; muons also decay yielding neutrinos. Taking into account these effects, coupled transport equations are solved for all species of particles and the neutrino production is estimated for the case of accreting galactic black holes.

Keywords: Black hole; Neutrino; High-energy

1. Introduction

The existence of a broad-band X-ray/soft gamma-ray spectrum of accreting black holes in binary systems strongly suggests the presence of a very hot plasma (corona) around the central object. This plasma comptonizes the soft X-ray photons produced in the inner accretion disk (Shakura and Sunyaev, 1973) generating a power-law, high-energy feature in the spectrum. A wide variety of stable two-temperature corona models have been developed since (Shapiro et al., 1976) introduced a temperature differentiation for ions and electrons in the inner accretion flow of Cygnus X-1 (see, for instance, the review by Poutanen, 1998).

Galactic black holes are found in different spectral states. The most typical are the *high-soft*, in which the spectrum is dominated by thermal emission of the disk, and the *low-hard*, characterized by the presence of a hot corona around the compact object and steady jets. The existence of these jets is supported by observational evidence of radio emission in almost every black hole binary in the hard state (Corbel et al., 2000; Fender and Belloni, 2004). The radio emission is generally too bright to be produced by thermal electrons in the accretion flow.

A strong correlation has been found between the radio and X-ray luminosity in the hard state (Corbel et al., 2003). This suggests that the X-ray emission is strongly coupled to that of the jets (e.g., Falcke et al., 2004). Since the jets flow out of the corona and are thus tightly associated to it, a model in which the X-ray emission is mostly from the disk + corona and radio is from the jets is compatible with the observations (Narayan and McClintock, 2008). Other possibilities are discussed, for instance, by Markoff et al. (2003).

In two-temperature magnetized plasmas around black holes it is reasonable to expect significant deviations from purely Maxwellian distributions for the particles. Such deviations are the result of the injection of non-thermal populations of particles. Recently, Vurm and Poutanen (2009) have presented a model for time-dependent non-thermal (purely leptonic) emission from magnetized coronae. Romero et al. (2010) have studied the case of a steady state magnetized corona with injection of both relativistic electrons and protons. In the present work we extend the latter study to time-dependent injection and calculate, by first time, the neutrino output of a hot magnetized corona around a galactic black hole.

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2. Static corona model

2.1. Basic scenario

The model considered here represents a static corona with a component of relativistic particles that can be removed by diffusion (see Romero et al., 2010 for details). In the Bohm regime, the diffusion coefficient is $D(E) = r_g c/3$, where $r_g = E/(eB)$ is the gyro-radius of the particles. The diffusion rate is

$$t_{\rm diff}^{-1} = \frac{2D(E)}{R_{\rm c}^2}. \quad (1)$$

Relativistic particles injected in the corona can have a local origin. Strong shocks resulting from fast magnetic reconnection events and converging magnetic mirrors can in principle accelerate particles up to relativistic energies through first-order Fermi mechanism (e.g., Tsuneta and Naito, 1998; de Gouveia Dal Pino et al., 2010). More complicated processes resulting in second-order Fermi acceleration are plausible in a turbulent corona (e.g., Dermer et al., 1996). In the present work we assume first-order Fermi acceleration. In such a case, the acceleration rate for a particle of energy E in a magnetic field B is given by

$$t_{\rm acc}^{-1} = \frac{\eta ecB}{E}, \quad (2)$$

where $\eta \leqslant 1$ is a parameter that characterizes the efficiency of the acceleration. We fix $\eta = 10^{-2}$, which describes the efficient acceleration by shocks with $v_s \sim 0.1c$ in the Bohm regime.

We consider a two-temperature corona in steady state, with a thermal emission characterized by a power-law with an exponential cutoff at high energies, as observed in several X-ray binaries in the low-hard state (e.g., Romero et al., 2002). Since the corona is in steady state, the assumption of equipartition between the different component allows to estimate the mean value of the main parameters in the model. Table 1 summarizes these values.

In a corona characterized by such parameters, it is expected that relativistic electrons and muons lose energy mainly because of synchrotron radiation and inverse compton scattering, whereas for protons and charged pions the relevant cooling processes are synchrotron radiation, inellastic proton-proton collisions, and photomeson production. Fig. 1 shows the cooling time for the different radiative processes under the conditions of Table 1.

Table 1
Model parameters.

Parameter	Value
$M_{\rm BH}$: black hole mass [$M_\odot$]	10[a]
R_c: corona radius [cm]	5.2×10^7[a,b]
T_e: electron temperature [K]	10^9
T_i: ion temperature [K]	10^{12}
E_c: X-ray spectrum cutoff [keV]	150
α: X-ray spectrum power-law index	1.6
η: acceleration efficiency	10^{-2}
B_c: magnetic field [G]	5.7×10^5
n_i, n_e: plasma density [cm^{-3}]	6.2×10^{13}
a: hadron-to-lepton energy ratio	100
kT: disk characteristic temperature [keV]	0.1

[a] Typical value for Cygnus X-1 in the low-hard state.
[b] $35R_G, R_G = \frac{GM}{c^2}$.

2.2. Spectral energy distributions

We study the effect of the injection of a power-law distribution of relativistic electrons and protons. The main products of hadronic interactions are charged pions, which quickly decay producing muons and neutrinos. Neutral pions yield gamma-rays, that are a source of secondary pairs. Therefore, we also include the effect of all these secondary particles in our treatment.

We solve the transport equation in steady state obtaining particle distributions for the different species. Then, the spectral energy distributions (SEDs) of all radiative processes are estimated. The results are shown in Fig. 2.

Gamma-rays produced in the corona can be absorbed by different mechanisms. The most relevant one is photon–photon annihilation. The absorption can be quantified by the absorption coefficient or opacity τ. In Fig. 3 we show the opacity due to the interaction between gamma-rays and thermal X-ray photons from the corona, which are by far the dominant electromagnetic component at low energies.

Because of the high values of the opacity, it is expected a large number of secondary pairs. The effects of internal absorption and the radiation emitted by secondary pairs are also include in the final SED, which is shown in Fig. 4. This figure also shows the spectrum of the well-known source Cygnus X-1, detected by COMPTEL (McConnell et al., 2000) and *INTEGRAL* (Cadolle Bel et al., 2006), and the radio emission from the jet. As it can be seen, the emission of the corona at low energy is negligible compared to that of the jet, in accordance with the idea that both components are present in the *low-hard* state.

2.3. Mass scaling

Currently, the best evidence for the existence of a common mechanism operating in both X-ray binaries and Active Galactic Nuclei (AGNs) is given by the detection of steady jets in accretion regimes with low rates on all scales (Markoff, 2005). It is thought that most black holes spend a significant amount of time in this low-luminosity regime on their way in and out of the quiescent ground state. For galactic black holes this corresponds to the hard state. In AGNs this would correspond to the class of low-luminosity AGNs (LLAGNs; e.g., Ho, 1999) which includes most nearby AGNs such as M81, NGC 4258 and M31.

The latest results strongly support that accretion at low rates is similar across the entire range of black hole masses. It seems that the same physical model, in which all