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PRESENTACIÓN ORAL

Lepto-hadronic models of high-energy radiation from microquasars: application to GX 339-4

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Abstract. In this work we apply a jet model to explain the observed broadband spectrum of GX 339-4 in the low-hard state, and make predictions for the emission in the gamma-ray domain. In our model, the electromagnetic emission is produced through the interaction of relativistic protons and electrons in the jet with local matter, radiation and magnetic fields. We expect to compare our predictions with the observations to be carried in the near future by instruments like the Fermi satellite and ground-based Cherenkov telescope arrays, in the GeV and TeV energy ranges, respectively.

Resumen. En este trabajo se intenta explicar el espectro de GX 339-4 en el estado *low-hard* aplicando un modelo de *jet*, y hacer predicciones para la emisión a altas energías. En nuestro modelo, la emisión electromagnética se origina en interacciones de protones y electrones relativistas en el *jet* con materia, radiación y campo magnético. Se espera poder comparar las predicciones del modelo con futuras observaciones de satélites como Fermi y telescopios Cherenkov terrestres, en energías en el rango de los GeV y TeV, respectivamente.

1. Introduction

The galactic black hole candidate GX 339-4 is an extensively studied X-ray binary. It has been observed in the canonical low-hard and high-soft states of X-ray binaries, as well as in the intermediate states. Many of the characteristics of the binary system have not been accurately determined yet. The type and mass of the companion star, and the orbital period are still unknown, although the latter has been calculated to be about 14.8 h (Callanan et al. 1992). The distance is not well constrained either, with estimates that range from 1.3 kpc to 15 kpc[1] (Zdziarski et al. 2004). Based on the lack of eclipses and the large secondary mass function, the inclination angle must be in the range $45^\circ \lesssim i \lesssim 80^\circ$ (Zdziarski et al. 2004).

The system GX 339-4 has been observed in all spectral states, sometimes simultaneously, along the electromagnetic spectrum, see for example Corbel & Fender (2002) and Nowak et al. (2002). In previous works, the origin of the broadband

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[1] The longer distances seem to be ruled out by energetic considerations.

spectrum of GX 339-4 has been explained in terms of a leptonic jet model. For example, Markoff et al. (2003, 2005) developed a model in which synchrotron radiation of relativistic electrons accelerated through shock waves at the base of a jet, can fit the radio and X-ray observations. The model also predicts a high-energy tail of the spectrum due to inverse Compton (IC) scattering by these electrons of synchrotron photons.

In the present work we also apply a jet model to the observed spectrum of GX 339-4, but taking into account the contribution of a component of relativistic protons in the outflow. As well as explaining the radio and X-ray data, our model leads to different predictions at gamma-ray energies from those of a purely leptonic model. This may be tested in the near future with observations carried out by new instruments operating in this energy range.

2. Jet model and radiative processes

We assume that the jets are launched at a distance $z_0 \sim 10^8$ cm from the compact object with an initial radius $r_0 = 0.1z_0$, and expand conically. The kinetic power of each jet is taken to be a fraction of the accretion power, $L_{\rm jet} = 0.1L_{\rm accr} \sim 10^{38}$ erg s^{-1}. This is in agreement with the estimates for the accretion rate of black hole X-ray binaries of Falcke & Biermann (1995) and Körding et al. (2006). Equipartition of energy among the magnetic energy density and the kinetic energy density of the outflow yields a magnetic field $B_0 \sim 10^7$ G at the base of the jet. The field decreases as $B(z) = B_0(z_0/z)^2$ as the jet expands. A certain fraction of $L_{\rm jet}$ must be in the form of relativistic particles; we fixed $L_{\rm rel} = 0.1L_{\rm jet}$. Both relativistic protons and electrons are present in the flow, and therefore $L_{\rm rel} = L_p + L_e$, with $L_p = a\,L_e$. The parameter a is a free parameter of the model.

Particles are accelerated by diffusion through shock waves. This process leads to an injection function that is a power-law in the energy of the particles, $Q_{e,p} \propto E_{e,p}^{-\alpha}$. Particles are accelerated until the acceleration rate equals the sum of the cooling rates, $t_{\rm acc}^{-1} = t_{\rm cool}^{-1}$; the size of the acceleration region does not add any constrain to the maximum particle energy. The value of the acceleration efficiency parameter is $\eta = 0.1$ (efficient accelerator). The maximum proton energy is $E^p_{\rm max} \sim 10^{16}$ eV, whereas for electrons $E^e_{\rm max}{\sim}10^{10}$ eV. Particles are accelerated up to these energies in time scales of $t_{\rm acc} = 10^{-3}$ s and $t_{\rm acc} = 10^{-9}$ s, respectively, shorter than any other characteristic temporal scale of the system. For the particle minimum energy we adopted $E_{\rm min} \sim mc^2$. The evolution of the particle distributions along the jet was calculated solving a transport equation that takes into account injection, cooling and particle escape (Khangulyan et al. 2007).

We considered three processes of interaction of relativistic particles with the fields in the jet: synchrotron radiation of protons and electrons, proton-proton inelastic collisions (pp) and inverse Compton scattering (IC). The synchrotron and IC spectral energy distributions (SEDs) were calculated using the formulae given by Blumenthal & Gould (1970). In the case of IC interactions calculations were performed using the Klein-Nishina cross section when appropriate. The target photons for this process are those of the synchrotron radiation field of both protons and leptons. The synchrotron photon density was estimated in the *local approximation* of Ghisellini et al. (1985). High-energy photons are also produced via decay of neutral pions created in *pp* collisions. To estimate the spectrum from π^0 decay we followed the work of Kelner et al. (2006). All calculations, except those for interaction with matter, were carried out in the jet's co-moving reference frame, where the particle densities are isotropic. In the observer's reference frame the luminosities can then be obtained by applying an appropriate Doppler boost, that depends on the viewing angle θ and the bulk Lorentz factor of the jet $\Gamma_{\rm jet}$, see Bosch Ramon et al. (2006). For detailed formulae on the cooling rates, transport equation and radiative processes, see Romero & Vila (2008). We fixed here $\theta = 30^\circ$ and $\Gamma_{\rm jet} = 1.5$. For the rest of the relevant parameters, we used $d = 4$ kpc for the distance and $M_{BH} = 5M_\odot$ for the black hole mass.

3. Results and discussion

Figure 1 (a) shows the SEDs obtained applying the model described in the previous section, together with a set of data points from simultaneous observations in X-rays and radio wavelengths. The radio observations were performed with the Australian Telescope Compact Array (ATCA) and the Molongolo Observatory Synthesis Telescope (MOST) and the X-ray data were collected by the Rossi X-Ray Timing Explorer (RXTE), while the source was in the low-hard state in February 1997.

In our model, both the radio and X-ray data can be explained as being due to synchrotron radiation of relativistic electrons. To reproduce the slope of the observed X-ray luminosity ($L_X \propto E_\gamma^{0.4}$), a hard particle injection spectrum must be assumed, with $\alpha = 1.4$. To achieve the observed X-ray luminosity, $L_X \geq 10^{36}$ erg s^{-1}, a jet with a with a high leptonic content is required, so we fixed $a = 1$. Synchrotron radiation of protons and inelastic *pp* collisions contribute to the SED at high energies, whereas the IC luminosity is very small. However, as it can be seen in Figure 1 (b), all radiation above $E_\gamma \approx 10$ GeV is absorbed by photon-photon annihilation in the synchrotron field of electrons.

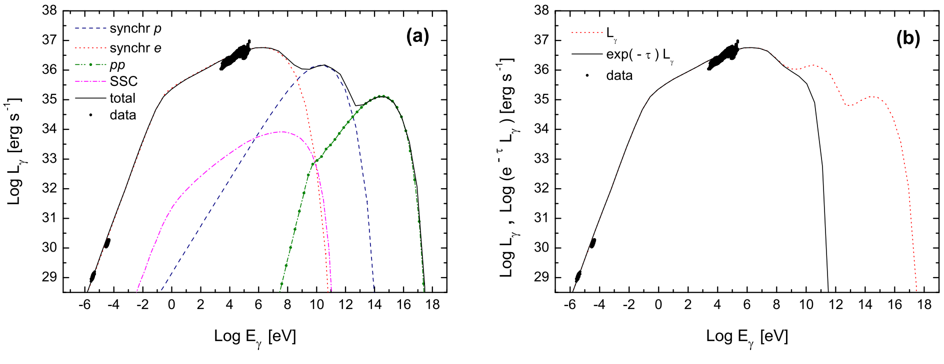

Figure 1. Calculated spectral energy distributions and observational data points for GX 339-4. (a) Emission spectrum, (b) spectrum modified by $\gamma - \gamma$ absorption.

Even if all very high-energy radiation is suppressed, the predictions in this energy range differ from those of a purely leptonic model. In Markoff et al. (2003), all emission above 10 MeV is due to IC scattering of synchrotron photons. The luminosity of this component is two orders of magnitude weaker than the electron synchrotron peak, and the spectrum is hard. In our model, absorption modifies the spectrum making it softer, but we still obtain luminosities of 10^{36-35} erg s^{-1} in the range 100 MeV - 10 GeV.

4. Conclusions

We have developed a lepto-hadronic jet model to fit the observed data of the galactic microquasar GX 339-4. In our model, the observed radio and X-ray emission is due to synchrotron radiation of relativistic electrons. We also consider the contribution to the spectrum of relativistic protons, through synchrotron radiation and *pp* collisions. Assuming equipartition of energy between protons and leptons in the jet, and a hard particle injection, this model explains the radio and X-ray data equally well as a purely leptonic model. However, predictions for the high energy emission differ. In our model all emission above $\sim$ 10 GeV is suppressed, we obtain significant luminosities and a soft spectrum between $\sim$ 100 MeV and 10 GeV, product of the proton synchrotron radiation spectrum modified by photon-photon absorption. We expect to improve our model by taking into account other radiative processes, such as proton-photon collisions, and also the contribution of secondary leptons created in hadronic interactions. In the near future detailed observations with the new gamma-ray instruments can provide information on the high-energy emission in GX 339-4, that can help to clarify its origin.

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