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An analysis of the broadband electromagnetic emission of the microquasar GX 339-4

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Abstract. The source GX 339-4 is an extensively studied galactic X-ray binary. Radio observations have revealed the presence of relativistic jets. In this work we present a jet model that provides good fits to a set of simultaneous radio and X-ray observations of GX 339-4. We assume that relativistic electrons and protons are present in the jets, and calculate both the leptonic and hadronic contributions to the radiation produced by several types of particle interactions. We also calculate the electromagnetic emission of secondary particles (pions, muons and electron-positron pairs) created in hadronic and electromagnetic interactions, and assess the relevance of photon self-absorption in the jet. Finally, we estimate the pair production rate in order to investigate the possible connection between microquasars and the observed anti-matter annihilation line flux at 511 keV. Our predictions may be tested in the near future with data collected by the gamma-ray satellite Fermi and the Cherenkov telescope array HESS II.

Resumen. La fuente GX 339-4 es una binaria de rayos X galáctica extensamente estudiada. Observaciones en radio revelaron la presencia de jets relativistas en el sistema, lo que la convierte en un microquasar confirmado. En este trabajo se presenta un modelo de jet que permite ajustar observaciones simultáneas en radio y rayos X de GX 339-4. Se supone que en el jet existen electrones y protones relativistas, y se calcula su contribución radiativa debido a diversos procesos de interacción de partículas relativistas. Se calculan también las contribuciones radiativas de las partículas secundarias (piones, muones y pares electrón-positrón) creadas en interacciones hadrónicas y electromagnéticas, y se evalúan los efectos de la auto-absorción de los fotones emitidos en el jet. Finalmente, se estima la tasa de producción de pares electrón-positrón para investigar la posible conexión entre los microquasares y el flujo galáctico difuso observado en 511 keV. Las predicciones del modelo podrán ser comparadas en el futuro cercano con datos obtenidos por el satélite de rayos gamma Fermi y el arreglo de telescopios Cherenkov HESS II.

1. Introduction

The galactic microquasar GX 339-4 has been the target of frequent simultaneous broadband observations. Radio and X-ray data collected during the low-hard state (LHS) reveal that the emission in both bands is tightly correlated (Corbel et al. 2003). This strongly indicates a common origin related to synchrotron emission from the jet. As an alternative to existent purely leptonic models (e.g. Markoff et al. 2003), we present a lepto-hadronic model to fit the broadband spectrum of GX 339-4 that also allows us to make predictions for the high-energy emission.

Recently, Wednespointer et al. (2008) claimed that there exists a correlation between the spatial distribution of galactic low-mass X-ray binaries (LMXRBs) and the line emission at 511 keV due to electron-positron annihilation above the galactic plane. This suggests that LMXRBs could be the production site of the electron-positron pairs. The total pair production rate required to account for the observed flux is $\sim 10^{41}$ s^{-1}. To asses this possibility, we also calculate the pair production rate predicted by our model for GX 339-4.

2. Model

The jet model applied here is presented in detail in Romero & Vila (2008) and Reynoso & Romero (2009). We assume a conical jet that expands with a half-opening angle of $\sim 6^{\rm o}$, injected at a distance $z_0 \sim 50 R_{\rm g}$ from a black hole of $M = 6 M_{\odot}$ (Muñoz-Darias et al. 2008); $R_{\rm g} = GM/c^2$ is the gravitational radius of the black hole. The jet advances with a bulk Lorentz factor $\Gamma_{\rm jet} = 2$ (Gallo et al. 2004).

The magnetic field at the jet base is estimated by equipartition between the magnetic energy density and the kinetic energy density of the jet. For a jet power $L_{\rm jet} \sim 10^{38}$ erg s^{-1} (see below) this yields $B_0 \sim 5 \times 10^7$ G. The magnetic field strength is assumed to decay as $B \propto z^{-m}$, with $m > 1$.

In a thin region located at a certain distance $z_{\rm acc}$ from the compact object, we assume that a fraction ~ 0.1 of the jet power is transferred to relativistic protons and leptons through diffusive shock acceleration. These particles are injected with a hard power-law spectrum $\propto E^{-1.5}$ (consistent with a relativistic shock acceleration scenario, see Stecker et al. 2007), and then suffer radiative and non-radiative (adiabatic) losses until their energy distribution reaches the steady state. Under these assumptions, the steady-state energy distributions can be calculated solving the transport equation in the one-zone approximation, as in Khangulyan et al. (2007).

We calculate the electromagnetic emission from relativistic primary (p and e^-) and secondary ($\pi^{\pm}$, $\mu^{\pm}$ and $e^{\pm}$ pairs) particles due to several processes: synchrotron radiation, inverse Compton scattering against the synchrotron photon field (synchrotron self Compton, SSC), relativistic Bremstrahlung, proton-proton (pp) and proton-photon ($p\gamma$) interactions; see Reynoso & Romero (2009) for the relevant formulae. Finally, we estimate the $e^{\pm}$ pair flux leaving the source following Heinz (2008).

3. Results and discussion

Figure 1 shows two least-squares fits to the low-hard state spectrum of GX 339-4 obtained with our model. The data correspond to observations carried out in February 1997 (Nowak et al. 2002).

Two different values of the magnetic field decay index where considered, $m = 1.5$ and $m = 1.8$. For the diffusive shock acceleration mechanism to be efficient, the outflow must be matter-dominated. Therefore, to determine the position $z_{\rm acc}$ of the acceleration region we imposed that the magnetic energy density was a fraction of the bulk kinetic energy density of the jet, $U_{\rm B} = \chi U_{\rm kin}$, $\chi < 1$. The parameter χ was left free during the fitting. In the model with $m = 1.5$, $z_{\rm acc} \approx 10^2 R_{\rm g}$, whereas for $m = 1.8$, $z_{\rm acc} \approx 10^4 R_{\rm g}$.

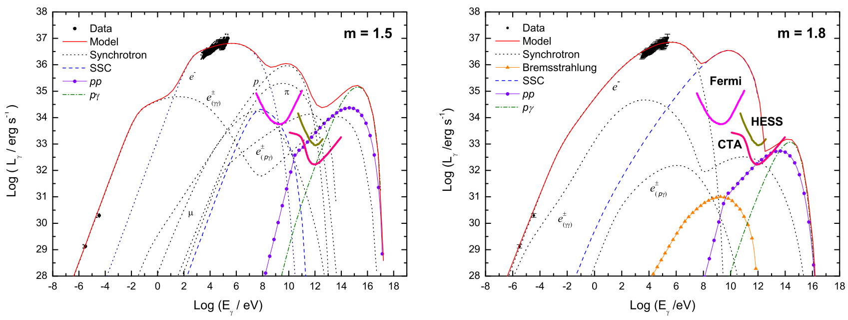

Figure 1. Model fits to the observed low-hard state spectrum of GX 339-4 in February 1997. The value of the magnetic field decay index m is indicated. Also shown are the sensitivity curves of the Fermi satellite and the Cherenkov arrays HESS and the future CTA.

In all cases a very powerful jet is required to account for the X-ray observations, $L_{\rm jet} \gtrsim 10^{38}$ erg s^{-1}, what means that the accretion rate must be near the Eddington limit (similar results have been previously found by, for example, Markoff et al. 2003, and Homan et al. 2005). The X-ray data is always explained as synchrotron radiation of primary electrons. Depending on the case, radio emission is due to synchrotron radiation of primary ($m = 1.8$) or secondary leptons ($m = 1.5$). Between ~ 100 MeV and ~ 1 TeV, for $m = 1.5$ the dominant contribution is proton synchrotron radiation. In the model with $m = 1.8$, the magnetic field in the acceleration region is lower and SSC emission dominates at these energies. The most relevant hadronic contributions above ~ 1 TeV are due to pp and $p\gamma$ interactions. Electromagnetic radiation of secondary charged pions and muons is not significant; synchrotron emission from electron-positron pairs is relevant in models where the acceleration region is nearer to the base of the jet and the magnetic field is higher.

High-energy photons can be absorbed in the jet photon field before escaping, modifying the shape of the production spectrum. The main process of absorption is pair production due to photon-photon annihilation, $\gamma + \gamma \rightarrow e^+ + e^-$. Gamma-rays mostly annihilate against the low-energy photons of the electron synchrotron field. Although this field is intense, the acceleration region is far enough from the jet base for the photon density to be low. Therefore, the opacity is small and the primary spectrum of Figure 1 is not strongly modified.

In the model with $m = 1.5$, the hadronic contribution at high-energies is undetectable with present gamma-ray instruments. In the model with $m = 1.8$, proton synchrotron radiation and the contribution of inelastic pp collisions could be detectable by Fermi and HESS II.

Along with $\gamma\gamma$ annihilation, muon decay and direct pair production in $p\gamma$ collisions also inject electron-positron pairs. The total pair production rate is $\dot{N}_e \sim 10^{38} - 10^{40}$ s^{-1}. According to the latest available cathalogue (Liu et al. 2007) the number of low-mass X-ray binaries in our Galaxy is 186. Therefore, the values of $\dot{N}_e$ we obtain are of the order of the minimum value estimated by Wednespointer et al. (2008) to explain the observed flux at 511 keV.

4. Conclusions

We have developed a model for electromagnetic emission in microquasar jets that allows to fit the observed spectrum of the low-mass microquasar GX 339-4. The emission in radio to X-rays is due to electron synchrotron radiation, but above $\sim$ 100 MeV, the contribution due to hadronic interactions dominates. Depending on the model, this high-energy emission may be detectable by the gamma-ray satellite Fermi and the Cherenkov arrays HESS and the future CTA and HESS II. These observations may provide important information about the hadronic content of microquasar jets.

The pair production rate predicted by the model is large enough to account for the pair injection rate required to produce the observed annihilation line flux at 511 keV, according to the estimations of Wednespointer et al. (2008). This supports, at least in energetic terms, the association between LMXRBs and annihilation line emission suggested by the correlation in their spatial distribution. In this way, other proposed explanations such as annihilation of dark matter may turn unnecessary.

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