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A model for gamma-ray sources in the galactic halo

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Abstract. Among the galactic gamma-ray sources detected by the EGRET instrument there exists a group located at moderate galactic latitudes, distributed as a halo around the galactic centre. These sources are X-ray quiet with soft spectra in gamma-rays. Their variability on short time scales indicate the presence of a compact object. In this work we present a model for gamma-ray halo sources based on hadronic processes in the jet of a low-mass microquasar. Several interaction mechanisms between relativistic protons and local fields are taken into account. We also estimate the contribution to the spectrum of primary leptons. Finally, we compare our results with the general properties of the halo gamma-ray sources and make some predictions for the forthcoming satellite-borne gamma-ray telescopes.

Resumen. Entre las fuentes de rayos gamma galácticas detectadas por el instrumento EGRET existe un grupo ubicado a latitudes galácticas medias, distribuidas en una especie de halo alrededor del centro de la galaxia. Estas fuentes son poco luminosas en rayos X y presentan espectros blandos en rayos gamma. Su variabilidad sobre escalas de tiempo cortas indica la presencia de un objeto compacto. En este trabajo se presenta un modelo para las fuentes de rayos gamma del halo galáctico basado en interacciones hadrónicas en el jet de un microquasar de baja masa. Se consideran distintos procesos de interacción entre los protones relativistas y los campos en el jet. Se estima también la contribución al espectro de leptones primarios. Finalmente, se comparan los resultados con las características generales de las fuentes gamma del halo y se realizan predicciones para la próxima generación de telescopios espaciales de rayos gamma.

1. Introduction

Variable gamma-ray sources in the galactic halo are located at moderate galactic latitudes ($|b| > 3^{\rm o}$) and distributed over a scale-height of $z_H \sim 2.0$ kpc above the galactic plane. They have a radial distribution similar to that of globular clusters, but there is no positional coincidence between these sources and the clusters. They show luminosities of $L_\gamma \sim 10^{33-36}$ erg s^{-1} above 100 MeV and they are much more luminous in gamma-rays than in X-rays, with typical ratios $L_\gamma/L_X \sim 100$. Their gamma-ray spectra are soft, with average spectral indices of ~ 2.5. Among the probable counterparts of the halo sources are low-mass microquasars. Microquasars can accelerate particles up to energies high enough to produce gamma-rays, as demostrated by the detection of three microquasars by ground-based Cherenkov telescopes (Aharonian et al. 2005; Albert et al. 2006; Albert et al. 2007). Furthermore, the presence of a compact object would account for the observed variability. Previous works on low-mass microquasars have considered a scenario where gamma-rays are produced by inverse Compton (IC) up-scattering of stellar photons in the jet (Grenier et al. 2005). However, because of the paucity of the seed photons the predicted luminosities are too low. Here we propose a model in which relativistic particles in the jet interact with locally generated magnetic and radiation fields, and not with external fields, to produce high-energy emission. Also, in contrast to previous works, our model is mainly based on hadronic interactions. The low-mass X-ray binary XTE J1118+480, the firmest black hole candidate in the halo, is the archetype of the class of objects studied here. We adopted the values of the relevant physical parameters of this source as input in our model. Our primary goal is to develop a model that could be able to reproduce the required luminosity and spectra of variable gamma-ray sources located at distances 2-10 kpc. Since our model is quite general, we express, as usual, the radiative output in terms of intrinsic luminosity of the sources.

2. Jet model and radiative processes

We assumed that the jets are launched at a distance $z_0 \sim 10^8$ cm from the compact object with an initial radius $r_0 = 0.1 z_0$, and expand conically up to a given $z_{\rm max}$. The kinetic power of each jet is taken to be a fraction of the accretion power, $L_{\rm jet} = 0.1 L_{\rm acc} \sim 10^{38}$ erg/s. Equipartition of energy among the magnetic energy density and the kinetic energy density of the outflow yields a magnetic field $B_0 \sim 2 \times 10^7$ G at the base of the jet. It then 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 $L_{\rm rel} = 0.1 L_{\rm jet}$. Both relativistic protons and electrons are present in the flow, and therefore $L_{\rm rel} = L_p + L_e$, with $L_p = a L_e$. We considered here values of $a > 1$ (hadronic jet) as well as the case $a = 1$ (equipartition of energy between both species). 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 $Q_{e,p} \propto E_{e,p}^{-l}$ (s^{-1}cm^{-3}erg^{-1}); we fixed $l = 2.2$. Particles are accelerated until the acceleration rate equals the synchrotron cooling rate, $t_{\rm acc}^{-1} = t_{\rm sy}^{-1}$. Expressions for both rates can be found in Begelman et al. (1990). It should be noticed that proton losses are weaker, and for z larger than a certain value the maximum energy becomes contrained by the condition that the gyroradius $R_{\rm g} = E/eB(z)$ does not exceed the radius of the jet. This results in a fixed maximum energy, $E_{\rm max}^p = eB_0 r_0 \sim 7 \times 10^{16}$ eV. For the minimum energy we adopted $E_{\rm min} = 100 m_{e,p} c^2$. The evolution of the particle distributions $n_{p,e}(E, z)$ along the jet was calculated solving a transport equation that takes into account injection, cooling and particle escape (Khangulyan et al. 2006). This yields in the case of leptons $n_e(E_e, z) \propto E_e^{-(l+1)}$. The spectral index l of the injection function is changed to $l+1$ due to synchrotron losses. Only the most energetic protons suffer strong losses, and in this case the distribution is a broken power-law: $n_p(E_p, z) \propto E_p^{-l}$ for $E_p < E_p^b$ whereas $n_p(E_p, z) \propto E_p^{-(l+1)}$ for $E_p^b < E_p$. The break energy $E_b(z)$ is such that the characteristic cooling time equals the escape time, $t_{\rm sy}(E, z) \approx v_{\rm esc}/z_{\rm max}$.

We considered three processes of interaction of relativistic particles with the fields in the jet: synchrotron radiation of protons and electrons, proton-photon inelastic collisions ($p\gamma$) and inverse Compton scattering (IC). The synchrotron and IC spectral energy distributions (SEDs) were calculated using the formulae given by Blumenthal & Gould (1970). The target photons for the latter process are provided by the synchrotron radiation fields. High-energy photons are also produced via decay of neutral pions created in $p\gamma$ collisions. To estimate the spectrum from π^0 decay we followed the work of Atoyan & Dermer (2003). All the calculations 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 details. We fixed here $\theta = 30^{\rm o}$ and $\Gamma_{\rm jet} = 1.5$.

3. Results and discussion

The SEDs obtained for different values of the model parameters are shown in Figure 1. These share some general features. At low energies, the main contribution to the spectra is due to synchrotron radiation of leptons, whereas in the range 10^8 eV $\lesssim E_\gamma \lesssim 10^{10}$ eV the spectra are dominated by proton synchrotron radiation. It is also seen that as the value $z_{\rm max}$ is reduced, the proton synchrotron contribution becomes more important but the lepton synchrotron spectrum is hardly affected. This is due to the fact that protons are constrained to radiate their energy budget in a region of stronger B and therefore suffer stronger losses, whereas leptons always radiate all their available energy very near the base of the jet, and the spectrum is insensitive to the length of the outer jet. Photons product of the decay of neutral pions created in $p\gamma$ collisions yield a hard high-energy tail to the SEDs, with a maximum $p\gamma$ luminosity that decreases as the lepton synchrotron luminosity decreases with increasing a. In any case the IC contribution is important.

Depending on the values of the parameters, these SEDs reproduce some of the characteristics observed in the spectra of the halo sources, but fail to explain others. For example, a large ratio L_γ/L_X is obtained in a strongly proton dominated ($a = 10^3$) and compact jet, but the spectrum is hard and does not reproduce the soft spectral indices found in halo sources. The cases with $a = 10$ and $z_{\rm max} = 10^{11-12}$ cm do predict soft spectra and luminosities $L_\gamma \sim 10^{35}$ erg s^{-1} around 10^9 eV. However, the luminosity in X-rays is very high and L_γ/L_X does not match the observed values.

4. Conclusions

We have developed a model for gamma-ray sources in the galactic halo based on hadronic interactions in the jet of a low mass microquasar. In this scenario, high-energy emission is produced by interactions of relativistic protons with the magnetic field and the radiation field inside the jet. Depending on the value of the parameters the calculated SEDs account for some of the observed characteristics of these sources, but cannot explain all of them. If the jet is hadronic, the gamma-ray region of the spectrum is very hard. On the other hand, if the leptonic content is relatively high, too much radiation is produced at low energies. It is possible that the excess of radiation at low energies may be

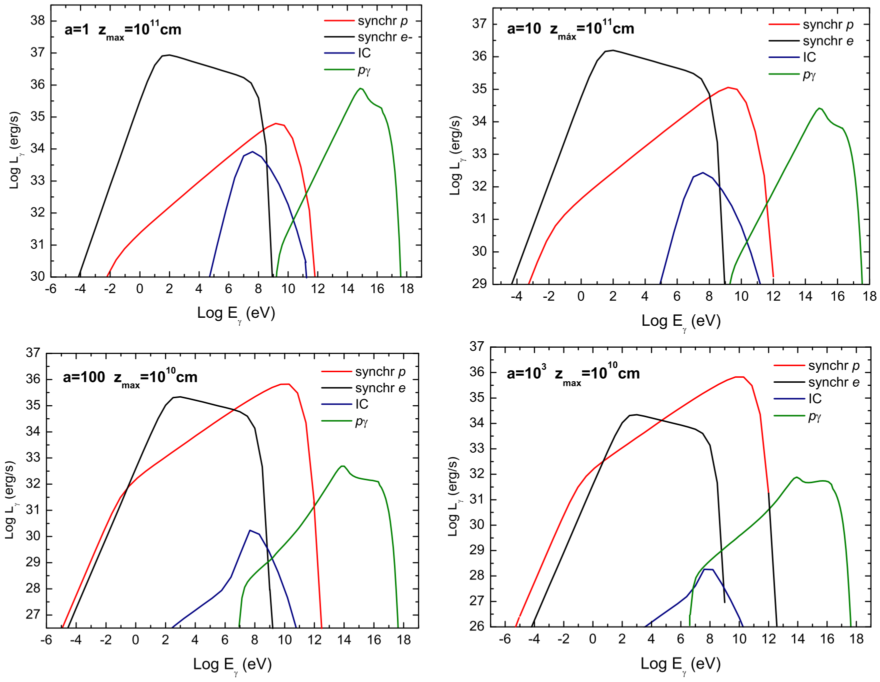

Figure 1. Spectral energy distributions obtained for different values of the parameters.

absorbed, but this does not seem likely in the enviroment of the galactic halo, where the density es very low. In spite of this, our results make the very clear prediction that low-mass microquasars can be gamma-ray sources. Presently, the only instrument capable of detecting radiation above 100 MeV is the gamma-ray satellite AGILE, but its sensitivity is no significantly better than that of EGRET. The next generation of satellite-borne telescopes (GLAST) should be capable of detecting these sources and to provide more detailed spectral data, that might help to shed light on the origin of the high energy emission.

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