Gamma-Ray Emission from Microquasars: Leptonic vs. Hadronic Models

G.E. Romero[1], V. Bosch-Ramon[2], J.M. Paredes[2], and M. Orellana[1]

[1] Instituto Argentino de Radioastronomia, C.C.5, (1894) Villa Elisa, Buenos Aires, Argentina, `romero@irma.iar.unlp.edu.ar`
[2] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain, `vbosch@am.ub.es`

Summary. In this work we discuss two different types of models for the high-energy gamma-ray production in microquasars. On the one hand, we introduce a new leptonic model where the emission arises from inverse Compton interactions with both internal (synchrotron) and external photon fields, and relativistic Bremsstrahlung from interactions with cold protons in the jet and the stellar wind material. On the other hand, we introduce a hadronic model where the gamma rays are the result of interactions between relativistic protons in the jet and cold protons from the anisotropic stellar wind. Spectral differences and similarities between both types of models are briefly discussed.

1 Introduction

Microquasars are characterized by the ejection of jets formed by relativistic plasma. These jets are detected at radio wavelengths as non-thermal synchrotron sources, indicating the presence of relativistic leptons. Synchrotron emission has been found in the extended jets of sources like XTE 1550-564 at X-rays, strongly suggesting the acceleration of electrons up to TeV energies (e.g. Corbel et al. 2002 [1]). The presence of such energetic particles in an environment with strong photon fields provided by the stellar companion, the accretion disk, and the hot inner corona around the compact object will result in the production of high-energy gamma rays [2, 3].

The matter content of the jets is not well established, but the large perturbations they produce in the interstellar medium suggest that they should have a large baryonic load (e.g. Heinz 2005 [4]). If particles are accelerated by shocks, we can expect that not only electrons, but also protons could reach relativistic energies. These protons might interact with the ambient medium inside the binary system, producing high-energy gamma rays through the decay of neutral pions created in pp collisions [5].

The recent detection of high-energy gamma rays from the microquasar LS 5039 by HESS telescopes [6] shows that relativistic particles reach multi-TeV energies in these objects. In what follows we outline both leptonic and hadronic models for gamma-ray production in microquasars and we compare the expected spectral energy distributions.

2 A Leptonic Model for Microquasars

We have developed a new model based on a freely expanding magnetized jet, whose internal energy is dominated by a cold proton plasma extracted from the accretion disk [7]. The cold proton plasma and its attached magnetic field, that is frozen to matter and similar to or below equipartition, provides a framework where internal shocks accelerate a fraction of the leptons up to very high energies. These accelerated leptons radiate by synchrotron, Bremsstrahlung and inverse Compton (IC) processes. In this model, the seed photons that interact with the jet leptons by IC scattering come from the star, the disk and the corona. A blackbody spectrum is assumed for the star and the disk, and a power-law plus and exponential cut-off spectrum for the corona. The synchrotron self-Compton radiation is also computed as well as the Bremsstrahlung and Compton self-Compton emission, where the radiation contribution of the latter two mechanisms is negligible.

The dissipated shock kinetic energy that goes to relativistic particles comes from the mean bulk motion kinetic energy, directly related to the kinetic energy carried by shocks in the plasma. The number of relativistic particles that can be produced along the jet is constrained by the limited capability of transferring energy from the shock itself to the particles, and by the fact that the relativistic particle pressure must be kept below the cold proton pressure. Their maximum energy is limited by the acceleration mechanism properties: strong shock, trans-relativistic velocities, almost parallel shock geometry, and diffusion coefficient.

We have applied the model to a high-mass microquasar with efficient acceleration, a compact object of 3 solar masses, macroscopic Lorentz factor around 1.5 (this factor actually evolves as the bulk energy is transferred to particles), and a jet viewing angle of 45 degress (see Ref. [7], Model A, for additional details). At high energies the spectral energy distribution (SED) is dominated by the inverse Compton upscattering of the stellar photons. There is significant absorption of gamma rays in the stellar photon field between 10 GeV and a few TeV, which results in a broad “valley” in the spectrum. The maximum luminosity is around a few times 10^{34} erg s^{-1} at $\sim$ 10 GeV.

3 A Hadronic Model for Microquasars

In microquasars with high-mass stars, the stellar wind can provide a matter field for interactions with relativistic protons from the jet [5]. We have developed a model for a system similar to LSI +61 303, where the stellar companion is a Be star with a dense and slow equatorial wind and the compact object is in an eccentric orbit. The matter from the wind partially penetrates the jet from the side and pp interactions result in the production of neutral pions, which decay producing gamma-rays. Since the star is bright, at the periastron passage the opacity effects of the stellar photon field to the propagation of the high-energy gamma-rays can be important. At energies around 100 GeV the system is transparent only beyond distances $> 10^{12}$ cm, i.e. gamma-ray radiation is strongly absorbed inside the binary. The resulting gamma-ray SED from neutral pion decays mimics the proton spectrum at a few GeV, where absorption is unimportant, but then steepens showing a minimum around 100 GeV during the periastron. At high energies the spectrum hardens again, as the absorption decreases. For additional details we refer the reader to Ref. [8].

4 Discussion

Both leptonic and hadronic processes can produce significant gamma-ray emission in the inner part of microquasar jets when the companion star is of an early-type. In general, the intrinsic emission is higher in the case of IC scattering. The general shape of the SED is similar. As noted by Romero et al. [5] and Aharonian et al. [9], neutrino emission, associated with the charged pion decays in the hadronic scenario, can be used to differentiate the mechanism responsible for the radiation. Rapid variability at high energies could be used as well, since protons are expected to reach higher energies in the inner jet, where they do not suffer as strong losses as leptons. In particular, variability observations of objects with dense winds like LSI +61 303 which might be performed with the MAGIC telescope) might be very useful to shed light on the gamma-ray production in microquasars. In the case of systems with low-mass stars, gamma rays could be the result of interactions of relativistic particles (both leptons and hadrons) with the photon field of the putative corona around the compact object or produced by synchrotron self-Compton mechanism [10]. Such emission has yet to be found with Cherenkov telescopes.

References

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