RevMexAA (Serie de Conferencias), **26**, 145–146 (2006)

HADRONIC GAMMA-RAY PRODUCTION IN MICROQUASARS WITH EQUATORIAL WINDS

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RESUMEN

Los microcuasáres son sistemas binarios con emisión en rayos X vinculada a acreción, en los cuales se han detectado chorros de partículas relativistas (jets) a través de su emisión en bandas de radio. La transferencia de masa al objeto compacto puede darse a través del viento ecuatorial de la primaria, cuando ésta es de tipo espectral temprano, como es el caso del microcuásar LSI +61 303. En estos casos se dará inevitablemente una interacción entre el viento estelar y los jets, que puede resultar en la emisión de fotones con muy alta energía. El interés por este escenario resurge a partir de la confirmación de los microcuásares como fuentes detectadas a energías en el rango TeV. Presentamos un modelo para la emisión de rayos gamma que se origina en la interacción de protones relativistas del jet, con los protones fríos de un viento confinado en un disco circunestelar. Se calculó también, en forma simplificada, la emisión de los leptones secundarios. Teniendo en cuenta efectos de opacidad en la fostósfera, hemos podido estimar una curva de luz y un espectro que pueden ser contrastados con las mediciones de observatorios en altas energías como MAGIC o HESS.

ABSTRACT

Microquasars are accreting X-ray binary systems with non-thermal radio jets. When the primary is a high-mass early-type star, the compact object accretes from the stellar wind. In some cases, like LS I +61 303, the wind forms an equatorial disk and the secondary moves through it. In such a situation a strong interaction between the relativistic flow and the dense wind material is unavoidable and could result in the generation of high-energy emission. This is particularly interesting since microquasars have been recently confirmed to be high-energy γ-ray sources. We present here a hadronic model for gamma-ray production in this kind of systems, with a specific application to the case of LS I +61 303. We calculate the gamma-ray emission originated in *pp* interactions between relativistic protons in the jet and cold protons from the wind. The emission from secondary electron-positron pairs is estimated as well. After taking into account opacity effects on the gamma-rays introduced by the different photons fields, we present high-energy spectral predictions that can be tested with the new generation Cherenkov telescopes like MAGIC and HESS.

Key Words: **GAMMA-RAYS — STARS: INDIVIDUAL: LS I +61 303 — X-RAYS: BINARIES**

1. INTRODUCTION

The main characteristics of the microquasar LS I +61 303 can be found everywhere. In the present contribution we will assume that relativistic protons are part of the content of the observed jets in LS I +61 303 and we will develop a simple model for the high-energy gamma-ray production in this system, with specific predictions for Cherenkov telescopes like MAGIC. We emphasize that our model is not opposed, but rather complementary to pure leptonic models as those presented by Bosch-Ramon & Paredes (2004) and Bosch-Ramon et al. (2005), since the leptonic contribution might dominate at lower gamma-ray energies and after the periastron passage.

A hadronic model for the gamma-ray emission in microquasars with early-type companions has been already developed by Romero et al. (2003). This model, is limited to the simplifications of a spherically symmetric wind and a circular orbit. Here we will consider a B-type primary with a wind that forms a circumstellar outflowing disk of density $\rho_{\rm w}(r) = \rho_0(r/R_*)^{-n}$ (Gregory & Neish, 2002). We will consider that the wind remains mainly near to the equatorial plane, confined in a disk with half-opening angle $\phi = 15°$, with $n = 3.2$, $\rho_0 = 10^{-11}$ g cm^{-3}, and $v_0 = 5$ km s^{-1} (Martí & Paredes 1995).

2. GAMMA-RAY EMISSION

The wind accretion rate onto the compact object of mass $M_{\rm c}$ can be estimated when knowing the relative velocity between the neutron star and the circumstellar wind, assumed to be flowing radially on the equatorial plane. We will assume that the accretion rate is coupled to the kinetic jet power. Most of this power will consist of cool protons that are

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ejected with a macroscopic Lorentz factor $\Gamma \sim 1.25$ (Massi et al. 2001). Only a small fraction ($\sim 10^{-3}$) is assumed to be in the form of relativistic hadrons. The jet is modeled as conical, and the relativistic proton spectrum will be a power law in the jet frame, with index $\alpha = 2.2$ and extending up to ${E'}_p^{\max} = 100$ TeV. It can be calculated in the lab (observer) frame through the corresponding Lorentz transformation. We will make all calculations in the lab frame, where the cross sections for pp interactions have suitable parametrizations. The matter from the wind can penetrate the jet from the side, diffusing into it as long as the particle gyro-radius is smaller than the radius of the jet. Some effects, like shock formation on the boundary layers, could prevent some particles from entering into the jet. Given our ignorance of the microphysics involved, we adopt a parameter $f_{\rm p}$ that takes into account particle rejection from the boundary in a phenomenological way. In a conservative approach, we will adopt $f_{\rm p} \sim 0.1$, then the particle density of the wind that penetrates the jet is $n(r) \approx f_{\rm p}\rho_w(r)/m_p$. In our calculations, we adopt a viewing angle of $\theta = 30°$ in accordance with the average value given by Casares et al. (2005).

Relativistic protons in the jet will interact with target protons in the wind leading to π-meson production. Then pion decay chains will lead to gamma-ray and neutrino emission. The differential gamma-ray emissivity $q_\gamma(E_\gamma, \theta)$ from π^0-decays can be expressed as (e.g. Aharonian & Atoyan 1996). To obtain the luminosity one integrates over the the interaction volume between the jet and the circumstellar disk.

3. OPACITY

Once generated, the gamma-ray photon has to pass though the radiation a field formed by two components, one from the Be star and the other from the hot accreting matter impacting onto the neutron star. The optical depth for a photon with energy E_γ, in this case depends upon the direction observed. We find that for photons of $E_\gamma = 100$ GeV significant absorption occurs mostly between $\psi = 0.1$ and $\psi = 0.5$ (where ψ is the orbital phase, with $\psi = 0.23$ at the periastron passage). The optical depth remains well below the unity along the whole orbit for photons of energies $E_\gamma \lesssim 30$ GeV and $E_\gamma \gtrsim 2$ TeV.

4. SECONDARY SYNCHROTRON EMISSION

Secondary pairs are produced by the decays of charged pions and muons, as well as by photon–photon interactions. The presence of a magnetic field in the jet will imply that all the secondary pairs will produce synchrotron emission. To calculate the synchrotron luminosity we estimate the specific emission and absorption coefficients from the secondary particle distribution (see Pacholczyk 1970 for the detailed formulae). To calculate the specific emission we adopt different values of the magnetic field at the base of the jet $B_0 = 1$, 10, and 100 Gauss (Bosch-Ramon & Paredes 2004). The radio emission results quite negligible in comparison to the observed values, which at the minimum imply a luminosity of $\sim 10^{31}$ erg s^{-1} (e.g. Ribó et al. 2005).

5. CONCLUSIONS

We have presented a hadronic model for the high-energy gamma-ray production in the microquasar LS I +61 303. An extensive version of this work is given in Romero, Christiansen and Orellana (2005). The model is based on the interaction of a mildly relativistic jet with a small content of relativistic hadrons with the dense equatorial disk of the companion B0 V star. Gamma-rays are the result of the decay of neutral pions produced by pp collisions. The model takes into account the opacity of the ambient photon fields to the propagation of the gamma-rays. The predictions include a peak of gamma-ray flux in the periastron passage, with a secondary maximum at phase $\psi \sim 0.65$. The spectral energy distribution presents a minimum around 100 GeV due to absorption. The spectral features should be detectable by an instrument like MAGIC through exposures ~ 50 hr, integrated along different periastron passages.

M.O. thanks to LARIM 2005 organization, and IAU for financial support to attend the meeting.

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