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STUDYING MICROQUASARS AT HIGH-ENERGIES

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RESUMEN

El estudio de la radiación gamma en fuentes galácticas ha experimentado un progreso radical durante los últimos años gracias a los resultados obtenidos por los telescopios Cherenkov y los aportes de misiones como Fermi. Entre tales fuentes, los sistemas binarios que se han detectado a energías mayores que $\sim$100 GeV albergan potentes aceleradores de partículas inmersos en regiones donde pueden operar múltiples procesos no térmicos de emisión y donde la propagación de los fotones energéticos da lugar al desarrollo de cascadas electromagnéticas. A su vez, desde un punto de vista hidrodinámico, también muestran un comportamiento fascinante, y cuya descripción aún no hemos alcanzado. Este tipo de ambiente, con condiciones regularmente variables, provee un excelente laboratorio de comparación para el desarrollo de modelos teóricos. Como último resultado de la combinación entre la acreción y la eyección de materia sobre un objeto compacto, los microcuasares, binarias de rayos X con radio jets, se manifiestan a lo largo de todo el espectro electromagnético. Esta charla presenta una breve puesta al día sobre nuestro conocimiento de estos sistemas, con énfasis en su emisión a muy altas energías.

ABSTRACT

The study of galactic gamma-ray sources has experienced an outstanding advance during the last years thanks to the results obtained by the atmospheric Cherenkov telescopes and satellites such as Fermi. Between those sources, the binary systems that have been detected at energies greater than $\sim$100 GeV, host powerful particle accelerators embedded into environments where multiple non-thermal emitting processes take place and where the propagation of high-energy photons trigger the development of electromagnetic cascades. The hydrodynamical description of the plasmas and flows within these systems also involves a complex, fascinating behavior which we have yet to fully understand. Moreover, the varying, but regularly repeating conditions make of them an excellent constraining laboratory for theoretical models concerning all these issues. The microquasars, X-ray binaries with radio jets, manifest all along the electromagnetic spectrum as the last result of the combined matter accretion and ejection by a compact object. Here I present a brief update on our knowledge about them, with focus on their high-energy emission.

Key Words: gamma-ray: observations — gamma-ray: theory — ISM: jets and outflows — stars: binaries

1. INTRODUCTION

Gamma-ray astronomy, embracing the photons with energies above $\sim$500 keV (the rest energy of an electron), has undergone an enormous progress during the last years. Successful observations in the MeV (10^6 eV), GeV (10^9 eV) and TeV (10^{12} eV) energy regions have been made recurring to different techniques. Satellites cover the energies below 100 GeV, the high-energy (HE) band, whereas at higher energies (very high: VHE, up to $\sim$100 TeV) the γ-rays start particle showers in the atmosphere. Those showers can be reconstructed thanks to the Cherenkov light emitted in the atmosphere by the yielded particles which move faster than light in the air.

The detections made by the Fermi-LAT (Large Area Telescope, 100 MeV to 100 GeV) during 11 months of operation form a First Catalog with 1451 sources above 4.1σ significance threshold (Abdo et al. 2010). Along with Fermi, INTEGRAL and AGILE are called to be the improved new generation of satellites after the revolutionary Compton Gamma-Ray Observatory (1991–2000, see e.g. Aharonian 2004). The ground-based detectors, with MAGIC and HESS as the most sounding present instruments, provide a lower number of detected sources in the TeV regime, i.e. 61 galactic sources by the end of 2010[3]. This is not surprising given the difficulties inherent to the technique, but the flux sensitivities and angular resolution need to be improved significantly in order to increase the ratio of identified-to-unidentified sources. There is a confidence that

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[3]See `http://www.mppmu.mpg.de/~rwagner/sources/` for an updated map of the sky at this energy range.

the new generation of stereoscopic arrays of Imaging Atmospheric Cherenkov Telescopes will do it. Good perspectives within Latin America for the installation of new γ-ray observatories are to be explored. A step in this direction is given with the ongoing construction of HAWC (see Gonzalez 2011).

2. BINARIES: HE AND VHE SOURCES

Gamma-ray binaries constitute a uniquely valuable, (still small) population of HE and VHE sources. There are three confirmed galactic High Mass X-ray Binaries (HMXBs) with persistent TeV emission: PSR B1259-63, LS 5039 and LSI +61 303 (Aharonian et al. 2005a; Albert et al. 2006; Aharonian et al. 2005b) plus a recently proposed candidate (HESS J0632+067, Hinton et al. 2009); and a flaring one at VHE: Cygnus X-1 (Albert et al. 2007). Cygnus X-3 has been detected in the HE band though not at VHE[4] (Tavani et al. 2009). They have all been detected by Fermi and/or AGILE satellites at $E > 100$ MeV, and have deserved extensive and individual studies. Paredes (2011) presents a summary on their properties and further references.

The nature of the compact star can be crucial to establish the γ-ray production scenario in a binary. In the pulsar wind nebula case the massive star wind collides and confines the relativistic pulsar wind in a collimated outflow, a comet-like structure accompanying the pulsar along its orbit. Particles accelerated at the termination shock then produce the non-thermal emission (Maraschi & Treves 1981; Dubus 2006a). Such is case for PSR B1259-63, but the sketch is very different for microquasars (MQs) as are Cyg X-1 and Cyg X-3. LS 5039 and LS I +61 303 (Romero et al. 2007) are unclear in this sense.

In high-mass MQs the compact object accretes matter from the stellar wind, and redirects part of the accretion power to launch collimated (mildly) relativistic outflows. The matter content of those microquasars jets is unknown: a relativistic electron population is responsible for the synchrotron radio emission along the jets which is the peculiarity defining MQs (Mirabel & Rodríguez 1998), and, in the case of SS 433 the iron X-ray line observations have proved the presence of ions in the jets (Kotani et al. 1994).

Leptonic and hadronic relativistic populations may arise as the result of particle diffusive acceleration at shocks inside the jet itself, recollimating shocks or medium shocks (see e.g. Bosch-Ramon 2010), but other acceleration processes, related to

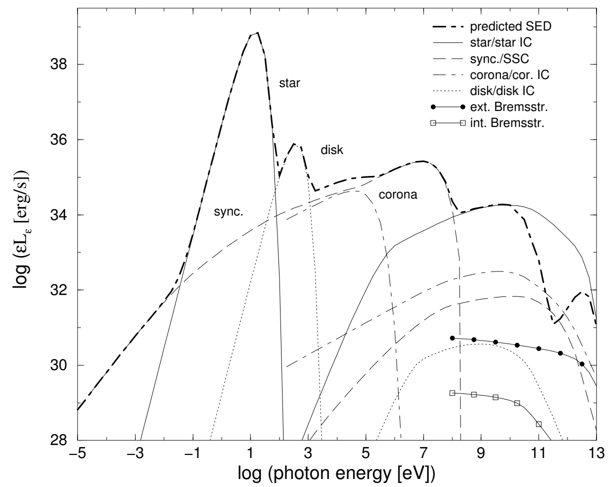

Fig. 1. Spectral energy distribution computed for a HMMQ (from Bosch-Ramon et al. 2006). The predicted total SED, summing up all the contributions is affected by absorption in the photon field of the star.

magnetic reconnection for instance, can be effective as well. Typically the injection of particles with a power-law distribution in energies can be expected, extending up to values many order of magnitude above the rest mass energy. More generally speaking, the cut-off depends on the competing processes that, together with the acceleration, simultaneously act making the particle to lose energy (i.e. radiative processes), or removing them from the acceleration region (i.e. diffusion and/or advection). The particles radiate by their interaction with the ambient fields: magnetic, matter field, soft photons. The output of any radiative process can be computed once the (time-dependent) distribution of particles is known, and such distribution is to be inferred from the injected one by solving the transport equation under appropriate assumptions (see e.g. Aharonian 2004; Bosch-Ramon et al. 2006, and references).

Many contributions, involving primarily injected and secondary particles, i.e. the byproduct of interactions or decaying primaries, collaborate the final Spectral Energy Distribution (SED), as shown in the example Figures 1 and 2. These predicted SEDs also illustrate (a) the broad extension in energies (at least 14 orders) that characterize γ-ray binaries, and (b) the strong influence of high-mass star, with its intense photon field, on the emerging SED. The reader is directed to Bosch-Ramon, Romero, & Paredes (2006) where the details on the calculation are properly discussed. It is worth to notice that a relatively large number of parameters are involved in this kind of models due to the many physical pro-

[4]Similar can be said about Eta Carinae, but this is a rather different case; a binary of massive stars.

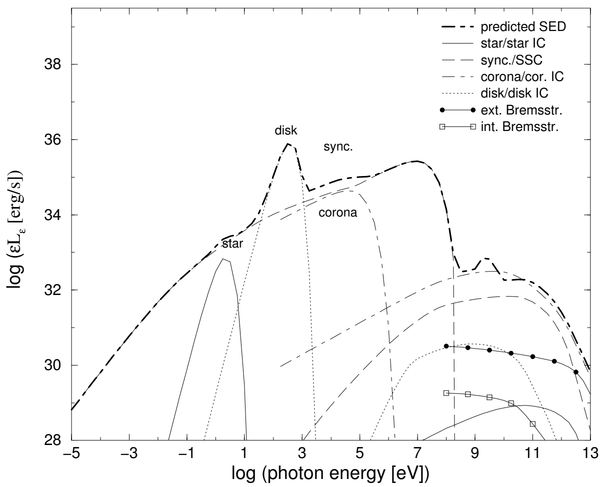

Fig. 2. Same for a low mass MQ. See also Vila & Romero (2010) for predicted HE features in the SED of the LMMQ GX 339-4.

cesses and effects, making then uneasy to estimate the properties of a source in unique way.

3. INTERACTING WITH A HIGH-MASS DONOR STAR

The detected γ-ray binaries are all of the high-mass kind. Two important ingredients are then provided by the star beside the matter supply for accretion: a dense soft radiation field and the strong wind where the jets propagate. Relativistic electrons upscatter the stellar photons to VHE through Inverse Compton (IC) interactions. Low-energy synchrotron photons radiated by the same electrons can also act as seeds for IC scattering, and then we speak of Synchrotron Self Compton (SSC). See e.g. Aharonian (2004) for a review on all the γ-ray production and absorption mechanisms.

The stellar radiation field can absorb gamma-rays by pair creation within the binary system. The optical depth is strongly dependent on the location of the γ-ray emission region if it is close to the compact object, and on the orientation of the system as seen by the observer. The attenuation has been found to be relevant for photon energies $\sim$10 GeV to 10 TeV, well within the observational range. Its study may help to set constraints on the location of the emission region (e.g. Dubus 2006b). In fact, this can be done for Cygnus X-1, which was detected in a configuration with the black hole behind the companion star, when the absorption of gamma-ray photons is expected to be highest (Romero, Del Valle, & Orellana 2010). At large optical depths, if the magnetic is low enough, electromagnetic cascades develop through a combination of pair creation and IC scattering, decreasing the effective opacity and considerably changing the spectrum (e.g. Bednarek 1997). Under a stronger ambient magnetic field in the region of gamma-ray absorption the energy of the pairs is channeled by the synchrotron radiation, and the cascade is suppressed (Khangulyan et al. 2008). As the pairs diffuse over the whole system, an extended broadband non-thermal emitter can arise (Bosch-Ramon, Khangulyan, & Aharonian 2008). Finally, a tunned magnetic field of intermediate strength can lead to a spatially extended cascade (e.g. Zdiarski et al. 2009) which needs of a careful treatment, i.e through 3D numerical simulations (e.g. Pellizza et al. 2010).

Stellar wind-jet interactions can also enhance the VHE emission: matter from the wind can penetrate the jet from the side, continuously diffusing into it as assumed by Romero et al. (2003), with the incoming (cold) nuclei acting as targets for inelastic hadronic collisions with the relativistic protons in the jet. The neutral pions created at such interactions decay emitting γ-ray photons, whereas the charged ones lead to the creation of energetic leptons and neutrinos (e.g. Reynoso, Romero, & Christianse 2008).

The jet propagation and integrity might be dynamically affected by the wind. Perucho et al. (2008, 2010) have found limiting conditions under which the jet can be disrupted by the growth of instabilities or suffer significant bending at the binary spatial scales. Concerning the wind structure, observational evidence supports the idea that winds of hot stars are formed by clumps. These inhomogeneities may interact with the jets producing a flaring activity at HE and VHE (e.g. Araudo et al. 2009). When the system contains a Be star, the presence of a dense equatorial outflow in addition to the tenuous stellar wind can strongly influence the matter accretion rate and therefore the lightcurve at HE (Romero et al. 2007).

The termination region of high-mass microquasar jets, or farther away, the dense and cold shocked ISM shell can be strongly modified by the jet impact. Large scale structures act as calorimeters, as in the case of SS 433 and Cyg X-1. The interaction of an SS 433-like jet with its external medium has been detected even in a nearby galaxy (Pakull et al. 2010). Bosch-Ramon et al. (2011) have studied the non-thermal emission related to this large spatial scales and found that hard X-rays and VHE photons may be the best probes to unveil the presence of microquasar jets interacting with their environment.

At much smaller scales, close to the compact object, an inflated accretion flow with a corona-like structure could also be a potential gamma-ray emission zone. Romero, Vieyro, & Vila (2010), have explored this scenario in the context of coronae around galactic black holes, such as Cyg X-1 (see also Vieyro & Romero 2011).

4. CHALLENGES

The discovery of HE and VHE gamma-ray emitting X-ray binaries has triggered an intense effort to better understand the particle acceleration, absorption, and emission mechanisms in compact binary systems. Some of the physical processes involved, in particular, those related with the presence of the jets, share a common problematic with Young Stellar Objects and AGNs. But the context of gamma-ray binaries which provide variable conditions along eccentric orbits and the jet/wind interaction possibility is truly unique at the same time that the complexity brought by a massive star makes HMMQ phenomenology difficult to interpret. Analogies between sources are then to be treated with care, and deeper comprehensive studies are desired from both theoretical and multiwavelength observational grounds. The new instrumentation in gamma-rays is crucial to carry out refined studies and to find more sources, allowing to speak in statistical terms of a real population.

Refined models/simulations including variability, acceleration prescriptions, absorption and secondary emission may help constrain the acceleration and radiation mechanisms, and disentangle the location and contributions from different emitting regions.

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