Spectral energy distribution, radio maps and polarization of Cygnus X-1: a lepto-hadronic model

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Resumen / El microcuásar Cygnus X-1 es uno de los objetos astrofísicos más estudiados. Existen varios modelos radiativos para la emisión no térmica de banda ancha de Cygnus X-1. Para la emisión del chorro (*jet*) en particular solo se han considerado modelos leptónicos, a pesar de la evidencia observacional de la presencia de hadrones en los chorros de otros microcuásares. En este trabajo se presenta un modelo de chorro lepto-hadrónico e inhomogéneo para la emisión no térmica de banda ancha de Cygnus X-1. Se calculan las contribuciones al espectro de protones y electrones relativistas, teniendo en cuenta su interacción con campos magnéticos, y campos de materia y de fotones internos y externos al chorro. Se obtienen ajustes al espectro desde radio a rayos gamma, incluida la emisión a energías de MeV cuyo origen está en discusión. También se presentan mapas sintéticos de la emisión en radio del chorro y se comparan con imágenes interferométricas de la fuente. Finalmente, se presentan resultados preliminares para el grado de polarización de la radiación del chorro en la banda de los MeV.

Abstract / The microquasar Cygnus X-1 is one of the most studied astrophysical sources. Several radiative models for the non-thermal broadband emission of Cygnus X-1 are available. For the jet emission in particular, only leptonic models have been considered despite the observational evidence of the presence of hadrons in the jets of other microquasars. In this work, we present an inhomogeneous, lepto-hadronic jet model for the non-thermal broadband emission of Cygnus X-1. We calculate the contribution to the spectrum of both relativistic electrons and protons, taking into account their interaction with the magnetic field, matter and photon fields internal and external to the jet. We obtain best-fit models for the spectrum that reproduce the observations from radio to gamma rays, including the MeV tail whose origin is still disputed. We also produce synthetic radio maps of the jet and compare them to actual interferometric observations of the source. Finally, we present preliminary results for the degree of polarization of the jet radiation in the MeV band.

Keywords / gamma rays: general — radiation mechanisms: non-thermal — X-rays: binaries — X-rays: individuals: Cygnus X-1

1. Introduction

Cygnus X-1 is a galactic microquasar (MQ) formed by an O9.7 star and a black hole of $\sim 14.8\,M_\odot$ (Orosz et al., 2011). This source has been extensively monitored at all wavelengths. In the radio band collimated jets have been resolved during the low-hard (LH) state (e.g. Stirling et al., 2001; Fender et al., 2006). Cygnus X-1 is one of the two microquasars known to be gamma-ray emitters. Soft gamma rays up to a few MeV were detected with *COMPTEL* (McConnell et al., 2002) and later with *INTEGRAL*. The *INTEGRAL* detections also revealed that the MeV emission during the LH state is significantly polarized (Laurent et al., 2011; Rodriguez et al., 2015). At higher energies the source is basically transient: in the 0.1–10 GeV band flares were detected with *AGILE* (Sabatini et al., 2010) and *Fermi* (Bodaghee et al., 2013), and above 100 GeV with the MAGIC Cherenkov telescopes (Albert et al., 2007).

The origin of the MeV emission from Cygnus X-1 is unclear, but its high degree of polarization suggests it is synchrotron radiation from the jets (but see Romero et al. 2014, who propose the MeV photons are produced in the corona). There is general agreement that the GeV–TeV radiation is emitted in the jets, although it is not yet settled whether it is of leptonic or hadronic origin. Presently, there is strong evidence of the presence of hadrons only in the jets of two MQs, but it is reasonable to assume that the composition of the outflows is similar to that of the accretion flow in all sources. Furthermore, the effects of the impact of the jets in the interstellar medium around Cygnus X-1 (e.g. Gallo et al., 2005) suggest that they carry a large amount of energy in baryons.

In this work we apply a lepto-hadronic, inhomogeneous jet model to analyse the spectral energy distribution (SED) of Cygnus X-1. The model is a refined and extended version of that by Romero & Vila (2008) and Vila et al. (2012). Here we also calculate synthetic maps of the radio emission from the jets that we compare with actual interferometric images. From the combined analysis of the SED and the radio maps we draw some conclusions on the hadronic content of the jet, the behaviour of the jet magnetic field, and the possible sites of particle (re-)acceleration in the outflows. Finally, we calculate the degree of polarization in the MeV band predicted by our best fits to the broadband SED.

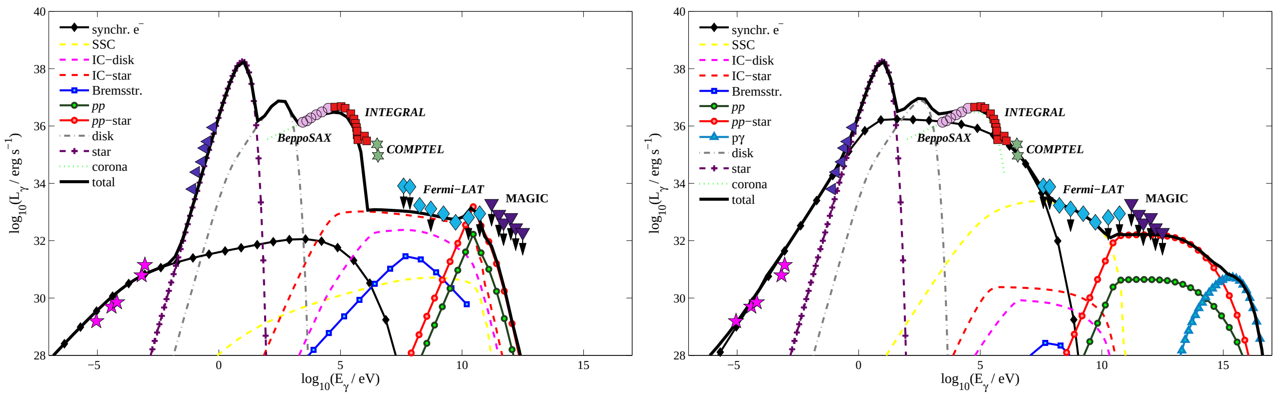

Figure 1: Model fits to the observed LH state broadband SED of Cygnus X-1. Model A (left): $p = 2.4$, $m = 1.9$, $\eta = 6\times10^{-4}$, $E_{\rm min} = 95m_{(p,e)}c^2$, $a = 39$, $z_{\rm max} = 2\times10^{12}$ cm. Model B (right): $p = 2.0$, $m = 1.0$, $\eta = 3\times10^{-3}$, $E_{\rm min} = 120m_{(p,e)}c^2$, $a = 0.07$, $z_{\rm max} = 9\times10^{11}$ cm.

2. Model

We assume a pair of conical jets of semi-aperture angle 2° (Stirling et al., 2001) are injected at a distance $z_0 = 50R_{\rm grav}$ from a black hole of mass $M = 14.8\,{\rm M}_\odot$; here $R_{\rm grav} = GM/c^2$ is the gravitational radius of the black hole and the z-axis is parallel to the symmetry axis of the jets. All model parameters depend only on the coordinate z. The outflows propagate with constant Lorentz factor $\Gamma = 1.25$ up to $z_{\rm end} = 10^{15}$ cm. This value is chosen to match the extent of the radio jets inferred from the observations of Stirling et al. (2001).

We estimate the magnetic field at the jet base assuming that equipartition between kinetic and magnetic energy densities holds at $z = z_0$; this yields $B_0 = B(z_0) \sim 10^7$ G. We model the decay of the magnetic field along the jet as $B \propto z^{-m}$ with $m = 1$–2. In the region $z_{\rm acc} \leq z \leq z_{\rm max}$ a fraction of the electrons and protons in the jet is accelerated to relativistic energies. A 10% of the jet power is transferred to relativistic particles, i.e. $L_{\rm rel} = 0.1L_{\rm jet}$. The jet power is in the range $L_{\rm jet} = 10^{37-38}$ erg s^{-1}, in agreement with the estimates of Gallo et al. (2005). We define the ratio $a \equiv L_{\rm p}/L_{\rm e}$, where $L_{\rm p}$ and $L_{\rm e}$ are the powers in relativistic protons an electrons, respectively. These particles are injected with a power-law spectrum $\propto E^{-p}$ with $p = 2.0$–2.4 (consistent with a diffusive acceleration mechanism) in the energy range $E_{\rm min} \leq E \leq E_{\rm max}$, and then suffer radiative and non-radiative energy losses. The maximum energy $E_{\rm max}$ is estimated balancing the total energy loss rate and the acceleration rate $t_{\rm acc}^{-1} = \eta ecB/E$, where $\eta < 1$ is the acceleration efficiency. We compute the energy distributions of relativistic particles in steady state numerically solving a transport equation that accounts for particle injection, cooling and convection, see for example Khangulyan et al. (2008).

We calculate the electromagnetic emission from relativistic particles due to several processes: synchrotron and inverse Compton (IC) radiation, proton-proton (pp) and proton-photon ($p\gamma$) interactions. The targets for pp collisions are the thermal protons in the wind of the companion star (pp-star, $\dot{M}_{\rm star} = 10^{-5}\,{\rm M}_\odot$ yr^{-1}) and the internal matter field of the jet (pp). The target photons for IC scattering are provided by the thermal radiation of the star (IC-star, $T_{\rm star} \sim 3\times10^4$ K) and the accretion disk (IC-disk, $T_{\rm disk} \sim 10^6$ K), and by the internal synchrotron field of the jet (synchrotron self-Compton). The intrinsic luminosity is corrected for absorption caused by photon-photon annihilation into electron-positron pairs, that affects mainly the gamma-ray band. We assume that the binary is in the superior conjunction.

3. Results

We fit the observed broadband observed SED of Cygnus X-1 by a least-squares method with free parameters $z_{\rm max}, m, a, p, \eta$ and $E_{\rm min}$. Fig. 1 shows two equally good fits already corrected by absorption. Model A corresponds to a proton-dominated jet ($a = 39$) with a fast decaying magnetic field ($m = 1.9$); for Model B, $a = 0.07$ and $m = 1.0$. The main difference between the two models is that in the former the MeV tail (*COMPTEL* observations) cannot be fit simultaneously with the rest of the data, whereas in the latter it is well explained as the cutoff region of the jet synchrotron spectrum. In both models the gamma-ray emission up to ~ 100 GeV is of leptonic origin. The emission above ~ 1 TeV is dominated by hadronic processes: in Model A there are practically no photons above ~ 100 GeV, but in Model B the very high energy part of the SED extends up to ~ 100 TeV and is just below the upper limits of *MAGIC*, and might be detectable by future arrays with higher sensitivity like the Cherenkov Telescope Array. It is worth noting here that other jet models for the non-thermal SED of Cygnus X-1 predict a synchrotron origin of the MeV tail, the most developed among them being that of Zdziarski et al. (2014). These authors, however, are not able to fit simultaneously the data at GeV energies.

In Fig. 2 we show the spatial distribution of the jet emission at 8.4 GHz for Model B, convolved with a 2D Gaussian of full width at half maximum 2.25×0.86 mas^2 to mimic the effect of an array with a beam as that in the observations with the Very Long Baseline Array by

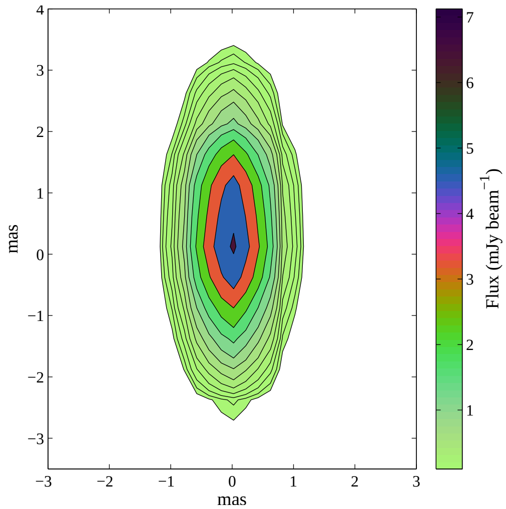

Figure 2: Synthetic map of the jet radio emission at 8.4 GHz corresponding to the SED of Model B.

Stirling et al. (2001). We obtain flux levels in excellent agreement with the observations; the extension of the synthetic jet at this frequency, however, is smaller than the ~ 15 mas of the extended radio source mapped by these authors. The cause is that in our model most of the synchrotron emission is concentrated in a thin region compared to the length of the jet. This suggests that particle acceleration sites may exist farther from the black hole and/or the behaviour of the jet magnetic field is substantially different from that assumed here. Suitable conditions for particle acceleration in the jets may develop at the sites of recollimation shocks – such as those observed in extragalactic sources and also predicted by numerical simulations, see e.g. Perucho et al. (2010), or because of the impact of the stellar wind in the jet (e.g. Perucho & Bosch-Ramon, 2012; Araudo et al., 2009).

Finally, we calculate the degree of polarization of the MeV emission for Model B. To compute the Stokes parameters we follow the general expressions given in Korchakov & Sirovat-skii (1962). We assumed two different geometries for the magnetic field: a magnetic field purely in the z-direction and a purely azimuthal magnetic field. For both configurations the magnetic field strength decays as $|\mathbf{B}| = B_0(z_0/z)^m$ with $m = 1$ as in Model B. We obtain degrees of polarization at 1 MeV of $\sim 80\,\%$ and $\sim 75\,\%$ for the cases of purely vertical and purely azimuthal magnetic fields, respectively. These results, although quite crude estimates, are consistent with the degrees of polarization of $(75 \pm 32)\,\%$ in the energy range 400 keV – 2 MeV measured with *INTEGRAL* during the LH state of Cygnus X-1 (Rodriguez et al., 2015).

4. Conclusions

Applying an inhomogeneous, lepto-hadronic radiative jet model to study the broadband emission of Cygnus X-1, we obtain two SEDs that fit the available observational data and upper limits from radio wavelengths to TeV energies. One of these best-fit models explains the MeV tail as jet synchrotron emission, and simultaneously fits the GeV data. Considering a toy model for the magnetic field geometry, for this model we estimate a degree of polarization at MeV energies in agreement with that measured by *INTEGRAL*. We also investigate the morphology of the jet at radio wavelengths predicted by our model and we find that the synthetic jet is much more compact than the observed radio source. This result suggests that a more detailed modeling of the magnetic field and/or the acceleration region(s) in the outflows is necessary, since these are the main factors that determine the properties of the electron distribution and their synchrotron emission along the jet. We aim at tackling these issues in future works by considering more realistic magnetic field configurations and assessing the existence of sites of particle (re-)acceleration further away from the black hole. Reproducing the morphology of the source and its polarization properties may provide valuable information about the conditions in the jets beyond what can be extracted from only fitting the non-thermal SED, further helping to remove the intrinsic degeneracy of radiative jet models.

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