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Gamma-ray emission from jet-clump interaction

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Abstract. Microquasars can produce gamma-rays through the interaction of a relativistic jet and matter of the wind from the stellar companion. The jet is ejected from the surroundings of the compact object and interacts with cold protons from the wind, producing pions that then quickly decay into gamma-rays. In the present contribution we calculate the spectral energy distribution and light curve produced by the interaction of a clumpy wind with the relativistic jet.

Resumen. Los microcuasares pueden producir rayos gama a través de la interacción del jet relativista con el viento de la estrella. El jet es eyectado de los alrededores del objeto compacto e interactúa con los protones fríos del viento estelar, produciendo piones que decaen rápidamente en rayos gama. En la presente contribución calculamos la distribución espectral de energía y la curva de luz producidas por la interacción de las inhomogeneidades del viento con el jet relativista.

1. Introduction

High-mass X-ray binaries are systems composed by a massive star and a compact object, such as a black hole or a neutron star. The interaction of the strong wind of the star with the jet of the compact object can produce gamma-rays. This high-energy emission is the result of the neutral pion-decay from inelastic proton-proton collisions. If the wind has a clumpy structure, then jet-clump interactions can produce rapid flares at gamma-rays which, if detected, could be used to probe the unknown parameters of wind inhomogeneties, such as their size, density, and velocity.

2. The general scenario

The basic scenario we are going to discuss in this work is shown in Fig. 1, left panel. A binary system is formed by a massive hot star and a compact object, which accretes matter from the star, either directly from the stellar wind or through the overflow of the Roche lobe. An accretion disk is formed and two jets are ejected perpendicularly to the orbital plane. We assume a radius $a = 2R_{\star}$ for

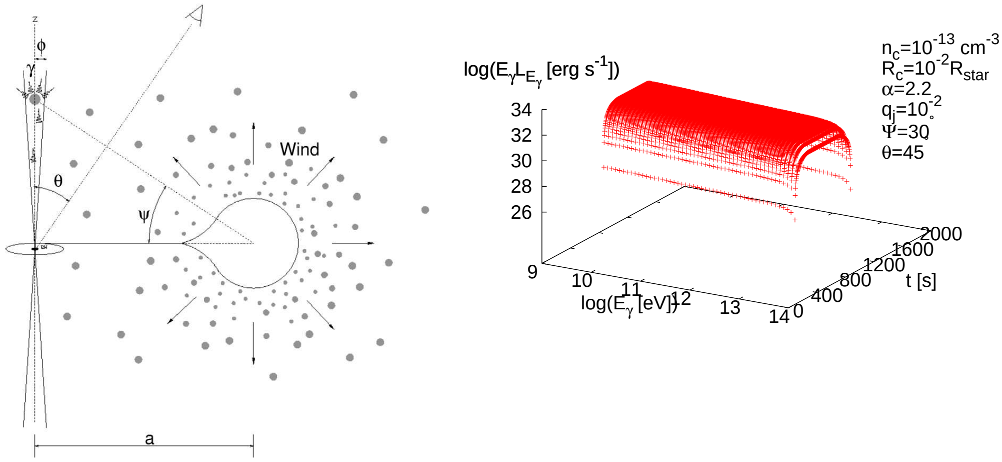

Figure 1. *Left panel*: Sketch of the scenario described in the text. *Right panel*: 3D-plot spectral energy distribution and light curve for a case with the parameters indicated in the labels.

the circular orbit of the system. The wind of the star has a clumped structure and individual clumps interact with the jet at different altitudes, forming an angle Ψ with the orbital radius.

For the jet, we shall adopt here the basic model proposed by Bosch-Ramon et al. (2006), where the beam is dynamically dominated by cold protons. Shocks produced by plasma collisions in the jet accelerate the supra-thermal tail of the particle population up to relativistic energies. These shocks convert part of the kinetic energy of the jet into internal energy of the relativistic gas, hence the beam should decelerate while particle acceleration is efficient. The result of diffusive shock acceleration in the inner jet will be a power-law distribution of relativistic particles in the co-moving frame: $N'_{e,\,p}(E'_{e,\,p}) = K_{e,\,p}\, E'^{-\alpha}_{e,\,p}$, valid for ${E'_{e,\,p}}^{\rm min} \leq E'_{e,\,p} \leq {E'_{e,\,p}}^{\rm max}$, in the jet frame. The corresponding particle flux will be $J'_{e,\,p}(E'_{e,\,p}) = (c/4\pi) N'_{e,\,p}(E'_{e,\,p})$. The total power of the jet is a significant fraction (~ 10 %) of the accretion power. Only a fraction $q_{\rm j}$ of this power goes to relativistic protons.

3. Hadronic interactions in the clump

The particle spectrum of relativistic protons is a power law in the jet reference frame with an index $\alpha = 2.2$. The number density of particles injected into the jet per unit of time can be determined as in Romero et al. (2003). The Lorentz transformation that relates the co-moving jet frame with the observer's frame introduces an angular dependence in the proton injected flux:

$$J_p(E_p,\theta) = \frac{cK_0}{4\pi}\Big(\frac{z_0}{z}\Big)^2 \frac{\Gamma^{-\alpha+1}\Big(E_p - \beta_{\rm b}\sqrt{E_p^2 - m_p^2c^4}\cos\theta\Big)^{-\alpha}}{\left[\sin^2\theta + \Gamma^2\left(\cos\theta - \frac{\beta_{\rm b}E_p}{\sqrt{E_p^2 - m_p^2c^4}}\right)^2\right]^{1/2}}$$

The constant K_0 normalizes the energy distribution of the proton flux in the jet's co-moving frame.
The maximum value of E_p obtained by balancing the acceleration and the energy loss rate by synchrotron, pp and $p\gamma$ interactions exceeds the energy constraints imposed by the size of the accelerator ($R_{\rm jet}(z) = \chi z$). In a model where the dependence of the magnetic field strength on z is inverse to that of $R_{\rm jet}(z)$, $E_p^{\rm max}$ is constant along the jet, i.e. $E_p^{\rm max} = 0.1eB_0R_0 \sim 100$ TeV, where B_0 and R_0 are the magnetic field and the jet radius taken at the base of the jet. This value is used to impose an exponential cut-off on the proton spectrum.
The δ-functional approximation (Aharonian & Atoyan 2000) and the new parametrization of the cross-section (Kelner et al. 2006) is used to estimate the production rate of π^0-mesons. The differential γ-ray emissivity generated through π^0-decays is

$$q_\gamma(E_\gamma) = 2\int_{E_\pi^{\rm min}(E_\gamma)}^{\infty} \frac{q_{\pi^0}(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}}\, dE_\pi, \tag{1}$$

where $E_\pi^{\rm min}(E_\gamma) = E_\gamma + \frac{m_\pi^2 c^4}{4E_\gamma}$. The pion emissivity is

$$\begin{aligned} q_{\pi^0}(E_\pi) &= 4\pi \int_{E_{\rm th}}^{\infty} \delta(E_\pi - \kappa E_{\rm kin}) J_p(E_p)\, \sigma_{pp}(E_p)\, dE_p \\ &= \frac{4\pi}{\kappa} J_p\left(m_p c^2 + \frac{E_\pi}{\kappa}\right) \sigma_{pp}\left(m_p c^2 + \frac{E_\pi}{\kappa}\right) \end{aligned} \tag{2}$$

Here, κ is the mean fraction of the kinetic energy $E_{\rm kin} = E_p - m_p c^2$ of the proton transferred to a secondary meson per collision. For a broad energy region (GeV to TeV) $\kappa \sim 0.17$.
The specific luminosity can then be estimated as:

$$E_\gamma L_{E_\gamma} = E_\gamma^2 \int q_\gamma(E_\gamma) n(\mathbf{r}) d\mathbf{r}, \tag{3}$$

where $n(\mathbf{r})$ is the clump particle density.
In the right panel of Fig. 1 we show an example of spectral energy distribution and light curve produced by the interaction of spherical clumps and a relativistic jet with a relativistic proton content characterized by a parameter $q_{\rm j} \sim 10^{-2}$. The clump velocity is assumed to follow a typical β-law (Lamers & Cassinelli 1999), with $\beta \sim 1$. We see that a gamma-ray flare with a luminosity $\sim 10^{33}$ erg s^{-1} can be produced. The luminosity depends on the parameters shown in the figure, especially the value of Ψ. The strongest flares result when a large clump crosses close to the base of the jet. The timescales are less than 1 hour.

4. Effects on the clump

The impact of the jet will inject energy into the clump at a rate:

$$\dot{E}_{\rm clump} \sim \pi \left(\frac{R_{\rm clump}}{z}\right)^2 L_p, \tag{4}$$

where $L_p \sim 10^{34} - 10^{35}$ erg s^{-1} is the luminosity in relativistic protons. Assuming that the clump radiate as a blackbody, we get a temperature

$$T \sim \left(\frac{\eta \dot{E}_{\rm clump}}{4\pi R^2_{\rm clump} \sigma_{\rm SB}} \right)^{1/4}. \quad (5)$$

Here η is the fraction of the injected energy that goes to heat the clump and $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant. Typically, $10^{-3} < \eta < 10^{-1}$ (Aharonian & Atoyan 1996). The thermal expansion of the clump will proceed with a velocity $v_{\rm s} \sim (kT/m_p)^{1/2}$. For standard values, $v_{\rm s} \sim 10^6$ cm s^{-1}, so the clump can expand significantly during the transit, producing an asymmetric light curve, with faster rise than decay time.
The magnetic field in the clump can be amplified by the proton flux to an equipartition value $B_{\rm clump} \sim \sqrt{8\pi nkT}$. For $T \sim 4.5 \times 10^4$ K and $n \sim 10^{13}$ cm^{-3}, we get $B_{\rm clump} \sim 40$ G. This means that electrons with energies $E_e < 1200(R_{\rm clump}/{\rm cm})$ eV will be trapped in the clump. If $R_{\rm clump} \sim 10^9$ cm, then $E_e \leq 1$ TeV. Hence synchrotron emission with a peak at hard X-rays will be produced after the transit.

5. Conclusions

According to the results presented in this paper and the statistical treatment developed in Owocki et al. (2007), gamma-ray fluctuation levels of order 10% are produced in a source with a luminosity of $\sim 10^{33-35}$ erg s^{-1}. These fluctuations could be detectable with GLAST and CTA opening a window to the study of clumpy winds.

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