

Clumping in Hot Star Winds

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Using gamma-rays to probe the clumped structure of stellar winds

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Gamma-rays can be produced by the interaction of a relativistic jet and the matter of the stellar wind in the subclass of massive X-ray binaries known as “microquasars”. The relativistic jet is ejected from the surroundings of the compact object and interacts with cold protons from the stellar wind, producing pions that then quickly decay into gamma-rays. Since the resulting gamma-ray emissivity depends on the target density, the detection of rapid variability in microquasars with GLAST and the new generation of Cherenkov imaging arrays could be used to probe the clumped structure of the stellar wind. In particular, we show here that the relative fluctuation in gamma rays may scale with the square root of the ratio of porosity length to binary separation, $\sqrt{h/a}$, implying for example a ca. 10% variation in gamma ray emission for a quite moderate porosity, $h/a \sim 0.01$.

1 Introduction

High-energy gamma-rays can be produced in accreting black holes with relativistic jets, as shown by the recent detection of a high-energy flare in the classical X-ray binary Cygnus X-1 (Albert et al. 2007). In this type of system the primary object is a hot, massive star with a strong stellar wind, and the secondary is usually an accreting black hole. Since the jet propagates through the wind and the radiation field of the star, gamma-rays can be produced by inverse Compton scattering with the radiation and/or pion-decays from inelastic proton-proton collisions with the stellar wind. If the wind has a clumpy structure, then jet-clump interactions can produce rapid flares of gamma-rays which, if detected, could be used to probe the size, density, and velocity of wind inhomogeneities.

2 Gamma-ray emission from jet-clump interaction

The basic model for hadronic gamma-ray production in a microquasar with an homogeneous wind has been developed by Romero et al. (2003). The reader is referred to this paper for the basic formulae. In the case of a clumped wind, the situation is illustrated in Figure 1. The compact object is assumed to be in a circular orbit of radius a , the clump crosses the jet forming an angle Ψ with the center of the star, and the viewing angle is θ .

The spectral gamma-ray intensity (photons per unit of time per unit of energy-band) produced by the injection of relativistic protons in the clump is

$$I_\gamma(E_\gamma, \theta) = \int_V n(\vec{r}') q_\gamma(\vec{r}') d^3 r', \quad (1)$$

where V is the interaction volume, $n(\vec{r}')$ is the clump density, and $q_\gamma(\vec{r}')$ is the gamma-ray emissivity, which depends on the proton spectrum and the interaction cross section. The spectral energy distribution is given by $L_\gamma^\pi(E_\gamma, \theta) = E_\gamma^2 I_\gamma(E_\gamma, \theta)$. Note that a change in the density of the target will be reflected in a variation of the gamma-ray luminosity. Figure 2 shows a 3D-plot of the evolution of the spectrum during the transit of a clump through the jet. For this specific calculation we have assumed the clump flow follows a typical β velocity law at an angle $\Psi = 5$ deg with the orbital plane, with a viewing angle of 45 deg. The clump density follow Gaussian profile with peak at $\sim 10^{13}$ cm⁻³ and a width of 0.01 R_* . The primary star is assumed to be similar to the primary in Cygnus X-1. The fraction of the accretion power that goes to relativistic protons in the jet is 10^{-3} .

From Fig. 2 we see that a gamma-ray flare with a power-law spectrum and a luminosity of $\sim 10^{35}$ erg s⁻¹ at 1 GeV is produced by the interaction. The flare duration is set by the clump crossing time, which here is a few hundred seconds. For clumps interacting at higher altitudes above the black hole, longer timescales are possible, but the luminosity de-

creases since the jet expands and hence the proton flux decreases.

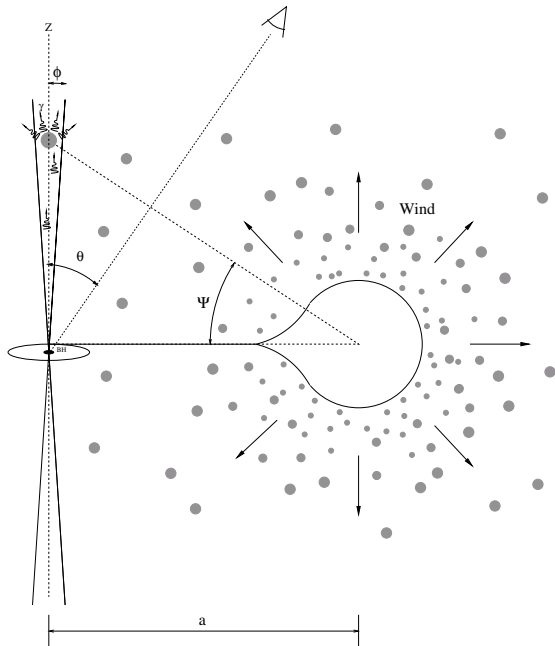


Figure 1: Sketch of a jet-clump interaction in a high-mass microquasar.

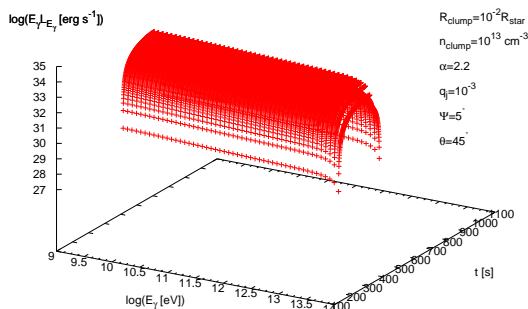


Figure 2: 3D-plot with the light curve and the spectral energy distribution resulting from a jet-clump interaction. The main parameters adopted are indicated in the figure. See text for details.

3 Porosity length scaling of gamma-ray fluctuation from multiple clumps

Individual jet-clump interactions should be observable only as rare, flaring events. But if the whole stellar wind is clumped, then integrated along the beam there will be clump interactions occurring all the time, leading to a flickering in the light curve, with the relative amplitude depending on the clump characteristics. In particular, while the mean gamma-ray emission will depend on the mean number of clumps intersected, the relative fluctuation should (following standard statistics) scale with the inverse square-root of this mean number. But, as we now demonstrate, this mean number itself scales with the same *porosity length* parameter that has been used, for example, by Owocki and Cohen (2006) to characterize the effect of wind clumps on absorption of X-ray line emission.

Let us first consider the *mean* gamma-ray emission integrated along the beam. Assuming a narrow beam with constant total energy along its length coordinate z , the mean total gamma ray emission scales as

$$\langle I_\gamma \rangle = I_b \sigma \int_0^\infty n(z) dz, \quad (2)$$

where $n(z)$ is the local mean wind density and σ represents an interaction cross-section for conversion of beam energy I_b to gamma-rays. For a steady wind with mass loss rate \dot{M} and constant speed v emanating from a star at binary separation a from the z -origin at the black hole, the integral in Eq. (2) gives

$$\langle I_\gamma \rangle = \frac{I_b \sigma \dot{M}_*}{8\mu v a}, \quad (3)$$

where μ is the mean wind mass per interacting particle (e.g., protons), and \dot{M}_* is the star mass loss rate.

The fluctuation in this mean emission depends on the properties of the wind clumps. A simple model assumes a wind consisting entirely of clumps of a characteristic length ℓ and volume filling factor f , for which the mean-free-path for any ray through the clumps is given by the porosity length $h \equiv \ell/f$. For a local interval along the beam Δz , the mean number of clumps intersected is thus $\Delta N_c = \Delta z/h$, whereas the mean gamma-ray production is given by

$$\Delta I_\gamma = I_b \sigma n \Delta z = I_b \sigma n \Delta N_c. \quad (4)$$

But by standard statistics for finite contributions from a discrete number N_c , the *variance* of this emission is

$$\langle \Delta I_\gamma^2 \rangle = \frac{I_b^2 \sigma^2 n^2 \Delta z^2}{\Delta N_c} = I_b^2 \sigma^2 n^2 h \Delta z. \quad (5)$$

The total variance is then just the integral that results from summing these individual variances as one allows $\Delta z \rightarrow dz$,

$$\delta I_\gamma^2 = I_b^2 \sigma^2 \int_0^\infty n^2 h dz. \quad (6)$$

Taking the square-root of this yields an expression for the relative rms fluctuation of intensity

$$\frac{\delta I_\gamma}{\langle I_\gamma \rangle} = \frac{\sqrt{\int_0^\infty n^2 h dz}}{\int_0^\infty n dz}. \quad (7)$$

As a simple example, for a wind with a constant velocity and constant porosity length h , the relative variation is just

$$\frac{\delta I_\gamma}{\langle I_\gamma \rangle} = \sqrt{h/a} \frac{\sqrt{\int_0^\infty dx/(1+x^2)^2}}{\int_0^\infty dx/(1+x^2)} = \sqrt{h/\pi a}. \quad (8)$$

On the other hand, for the Owocki & Cohen (2006) uniform expansion model with $v \sim r$ and $h = h'r$, we find $\rho \propto 1/r^3$ and thus,

$$\frac{\delta I_\gamma}{\langle I_\gamma \rangle} = \sqrt{h'} \frac{\sqrt{\int_0^\infty dx/(1+x^2)^{5/2}}}{\int_0^\infty dx/(1+x^{3/2})} = \sqrt{2h'/3}. \quad (9)$$

Typically then, if $h \sim 0.03a$,

$$\frac{\delta I_\gamma}{\langle I_\gamma \rangle} \approx 0.1.$$

This implies an expected flickering at the level of 10% for a wind with such porosity parameters. The

variability timescale will depend on the wind speed, the size of the clumps, and the width of the jet, with a typical value of \sim an hour.

4 Prospects

Fluctuations of 10% in a source with a luminosity of 10^{34-35} erg s $^{-1}$ on timescales of $\sim 10^3$ s could be detectable with GLAST and CTA if the source is located at a few kpc. This means that gamma-ray astronomy can be used to probe the structure of stellar winds through dedicated observations of microquasars with massive donor stars. If additional information on the wind can be obtained through X-ray observations (Owocki & Cohen 2006) and the source can be detected with neutrino km 3 -telescopes, we can also gain valuable insights in the relativistic proton content of the jets.

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References

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Puls: A couple of years ago it has been suggested that the winds themselves may be the source of γ -rays (second order Fermi acceleration between shock and final decay). May this process contaminate the scenario you have discussed?

Romero: I am a bit skeptic about γ -ray production in the stellar winds. Particles should be accelerated at shocks in the wind. In such an environment, losses should be very important for electrons (inverse Compton interactions with stellar photons) and for protons size constraints on the acceleration region should cut off the particle spectrum at low energies. In addition, the particle injection mechanism is unclear. So, I do not expect any contamination at high energies ($E > 10$ GeV).

Cassinelli: In the case of SS433: in $H\alpha$ one sees speeds of order $0.25c$ which is much smaller than the energy you are discussing. What are the relations? Secondly. The primary star provides the

disk. Does it also produce the clumps in the region you are considering?

Romero: The velocity of the order of $0.25c$ inferred for the jets of SS433 corresponds to the bulk velocity or the macroscopic outflow. In the model I am presenting, a small fraction of macroscopic kinetic energy is transformed into microscopic energy of some particles. These particles can be highly relativistic and generate the γ -rays when they interact with the clump material. Concerning the second question, yes, the clumps are produced by the same massive primary star that feeds the compact object through accretion.

O. Reimer: Are you considering heavier nuclei in the hadronic interactions than just pp for realistic modelling?

Romero: Yes. We introduce a phenomenological parameter that accounts for the presence of heavier nuclei in the jets.