Gamma-ray variability from wind clumping in HMXRB with jets

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ABSTRACT

In the subclass of high-mass X-ray binaries (HMXRB) known as “microquasars”, relativistic hadrons in the jet from the compact object can interact with cold protons from the star’s radiatively driven 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. We show here that the fluctuation in gamma rays can be modeled using a “porosity length” formalism that has been applied to characterize clumping effects in other contexts (e.g., reduction in bound-free absorption of X-ray emission from instability-generated wind shocks). In particular, for a porosity length set by $h \equiv \ell / f$, the ratio of the characteristic size $\ell$ of clumps to their volume filling factor $f$, we find that the relative fluctuation in gamma-ray emission in a binary with orbital separation $a$ scales as $\sqrt{\hbar/\pi a}$ in the “thin-jet” limit, and is reduced by a factor $1/\sqrt{1 + \phi a / 2 \ell}$ for a jet with a finite opening angle $\phi$. For a thin jet and quite moderate porosity length $\hbar \approx 0.03 \, a$, this implies a ca. 10% variation in the gamma-ray emission. Moreover, the illumination of individual large clumps might result in isolated flares, as has been recently observed in some massive gamma-ray binaries.

Key words: stars: binaries – stars: winds – gamma-rays: theory

1 INTRODUCTION

One of the most exciting achievements of high-energy astronomy in recent years has been to establish that high-mass X-ray binaries (HMXRB) and microquasars are variable gamma-ray sources (Aharonian et al. 2005, 2006b, Albert et al. 2006, 2007). The variability is modulated with the orbital period, but in addition short-timescale flares seem to be present (Albert et al. 2007, Paredes 2007). Since at least some of the massive gamma-ray binaries are known to have jets, interactions of relativistic particles with the stellar wind of the hot primary star seem unavoidable (Romero et al. 2003). At the same time, there are increasing reasons to think that the winds of hot stars have a clumped structure (e.g. Dessart & Owocki 2003, 2005; Puls et al. 2006, and references therein). The observational signatures of such clumping often just depend on the overall volume filling factor, with not much sensitivity to their scale. Here we argue that gamma-ray astronomy can provide new constraints on the clumped structure of stellar winds in massive binaries with jets. At the same time, our analysis provides a simple formalism for understanding the rapid flares and flickering in the light curves of these objects. Our basic hypothesis is that the jet produced close to the compact object in a microquasar will interact with the stellar wind, producing gamma-rays through inelastic pp interactions, and that the emerging gamma-ray emission will present a variability that is related to the structure of the wind. Thus the detection of rapid variability by satellites like GLAST and by Cherenkov arrays like MAGIC II, HESS II, and VERITAS can be used as a diagnosis of the structure of the wind itself.

2 JET-CLUMP INTERACTIONS

2.1 The general scenario

The basic scenario explored in this Letter is depicted in Fig. 1. A binary system consists of a compact object (e.g., a black hole) and a massive, hot star. The compact object accretes from the star, either directly from the stellar wind or through the overflow of the Roche lobe. Close to the accreting star, two jets are ejected. For simplicity, we shall assume that these jets are normal to the orbital plane and the accretion disk, but this assumption can be relaxed for specific systems (e.g. Romero & Orellana 2005). For simplicity, we also assume a circular orbit of radius $a$. The wind of the star has a clumped structure and individual clumps interact with the jet at different altitudes, forming an angle $\Psi$ with the orbital plane. The z-axis is taken along the jet, with the orbit thus in the xy-plane. The angle formed between the jet and the line of sight is $\theta$. The jet has
an opening angle $\phi$. To consider the effects of a single jet-clump interaction, we first adopt a model for the jet$^1$.

In addition to wind clumping, there can also be intrinsic variability associated with the jet. This includes periodic orbital modulation, as observed in LS 5039 or LS I 61 303 (e.g., Aharonian et al. 2006b; Albert et al. 2006), and periodic precession of steady jets (e.g., Kaufman-Brown et al. 2002). Both these long-term, periodic variations would be quite distinct from the rapid, stochastic variations from wind clumps. But intrinsic disturbances and shocks in jets can produce aperiodic variability that might be confused with variability associated with jet-clump interactions.

However, in microquasars such intrinsic fluctuations are expected to arise from jet-disk coupling, as proposed by Falcke & Biermann (1995) for the case of AGNs, and observationally demonstrated for a galactic microquasar by Mirabel et al. (1998). The latter observed how the rapidly variable X-ray emission went to a minimum, followed immediately by a synchrotron flare at optical, IR and then radio wavelengths. This is interpreted as the effect of the disappearance of the innermost part of the accretion disc followed by a plasma ejection into the jet that creates a shock that accelerates particles to produce non-thermal emission. The same effect has been observed in AGNs (Marscher et al. 2002). Thus intrinsic variability in the jet would likely be preceded by a drop in the X-ray activity, whereas in the case of a jet-clump interaction, the effect would be the opposite: first the gamma-ray flare would appear, and then, an X-ray flare produced by the secondary electrons and positrons as well as the primary electrons injected into the clump. Depending on the magnetic field and the clump density, the X-ray radiation could be synchrotron, inverse-Compton, or Bremsstrahlung. In summary, simultaneous X-ray observations with gamma-ray observations could be used to differentiate jet-clump events from intrinsic variability produced by the propagation of shocks in the jets.

### 2.2 Basics of the jet model and jet-clump interaction

The matter content of the jets produced by microquasars is not well-known. However, the large perturbations these jets cause in the interstellar medium imply a significant barion load (Galotto et al. 2005, Heinz 2006). The presence of relativistic hadrons in the jet of SS433 has been directly inferred from iron X-ray line observations (e.g. Kotani et al. 1994, 1996; Migliari et al. 2002). The fact that the jets are usually well-collimated also favors a content with cold protons that provide confinement to the relativistic gas. We adopt here the basic jet model proposed by Bosch-Ramon et al. (2006), where the jet is dynamically dominated by cold protons. The jet is inhomogeneous since the gas expands laterally with the sound speed of the cold plasma. The magnetic field is assumed to be in equipartition with the particle energy density, since it is likely that the launching mechanism is related to magneto-centrifugal effects (e.g., Blandford & Payne 1982). Shocks produced by plasma collisions in the jet accelerate the supra-thermal tail of the particle population to relativistic energies. Electrons cool efficiently through synchrotron and inverse Compton losses in the inner jet. Adiabatic losses become important only at distances beyond the size of the binary system (Bosch-Ramon et al. 2006; Perucho & Bosch-Ramon 2008). Proton cooling is radiatively inefficient, unless very high densities of matter are involved. The shocks convert part of the kinematic energy of the jet into internal energy of the relativistic gas, hence the jet should decelerate while particle acceleration is efficient. The macroscopic Lorentz factor of the outflow will thus change with the distance to the compact object.

The result of diffusive shock acceleration in the inner jet will be a power-law distribution of relativistic particles in the co-moving frame. For electrons, this is confirmed through the detection of synchrotron radiation in all microquasars. The maximum energy is determined by the local balance between radiative losses and particle energy gain due to the acceleration process, as far as size constraints are satisfied.

Only a fraction $q_j$ of the accretion power goes into relativistic protons. The gamma-ray emissivity can be calculated as in Romero et al. (2003) and Orellana et al. (2007), transforming the expressions of the relativistic proton flux to the lab frame. Then, the spectral energy distribution is obtained by integrating the emissivity times the target particle density over the interaction volume. For the cross section we have adopted the recent parametrizations of Kelner et al. (2006) and we work in the $\delta$-function approximation (Aharonian & Atoyan 2000, Kelner et al. 2006). In Fig. 2 we show the result of the interaction of a large clump with a size 1% of the stellar radius (the star is assumed to be an O9, similar to that in Cygnus X-1) with a jet with $q_j = 10^{-3}$. The interaction occurs at $\Psi = 5^\circ$ above the base of the jet, and the viewing angle is assumed to be small, as could be the case of Cygnus X-1: $\theta = 1.5^\circ$ (Albert et al. 2007, Romero et al. 2002). The profile of the clump is Gaussian, which is reflected in the light curve. The peak density is $10^{13}$ protons cm$^{-3}$. The jet Lorentz factor is assumed to be about 1.5, and thus beaming effects are not dramatic for moderate changes in the viewing angle (see Orellana et al. 2007 for more details on beaming in this scenario).

The timescale of the resulting gamma-ray flare depends on the clump size and its velocity. For the latter we have adopted a standard $\beta$-law (Lamer & Cassinelli 1999) with $\beta = 1$ and a terminal wind velocity of $v_{\infty} = 2500$ km s$^{-1}$. From this simple example we see that gamma-ray flares with luminosities $\sim 10^{44}$ erg s$^{-1}$ can be...
produced depending on the parameters, especially the value of $\Psi$, i.e. the impact angle. The strongest flares result when a large clump crosses close to the base of the jet. Typical timescales are of less than 1 hour for a fast wind. While this is quite short, it is comparable to the variability already detected in Cygnus X-1 by MAGIC (Albert et al. 2007e). Variability on day timescales has been detected by HESS in extragalactic sources, for example for the active galaxy M87 (Aharonian et al. 2006a). HESS II and MAGIC II will have a much higher sensitivity, so these instruments should be able to detect variability from galactic sources like LS 5039, LS I +61 303 and Cygnus X-1 on timescales below an hour. And future instruments like CTA and AGIS will have roughly a hundred times the collecting area to HESS-class telescopes. Overall then, if a microquasar is observed in an active state (i.e. when the jet is powerful), then satellite instruments like GLAST and ground-based Cherenkov telescopes should be able to detect variability down to timescales of 10 minutes or so, sufficient to measure variations associated with jet interactions with wind clumps.

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 jet 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, under the reasonable assumption that the overall jet attenuation is small, both cumulatively and by individual clumps, then the mean gamma-ray emission should depend on the mean number of clumps intersected, while 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 (see also Oskinova, Hamman, and Feldmeier 2006).

Let us first consider the mean gamma-ray emission integrated along the jet. For a total interaction cross section $\sigma$ between jet and wind particles, then from the black hole origin along a coordinate $z$ tracing the jet, the total “collision depth” is

$$
\tau = \sigma \int_0^\infty n(z) \, dz = \frac{\sigma M_*}{8 \mu \nu a}.
$$

(1)

where $n$ is local wind particle number density. The latter equality evaluates the integral assuming a steady wind with mass loss rate $M_*$ and constant speed $v$ emanating from a star at a distance $a$ from the $z$-origin at the black hole, with $\mu$ the mean wind mass per interacting particle (e.g., protons). A key assumption of our “particle interaction” approach is that $\tau \ll 1$ for all possible interaction processes. Note that this quite opposite from the collision-dominated assumption, $\tau \gg 1$, inherent in hydrodynamical treatments, such as often used to model jet interactions with an ambient interstellar medium over a much larger length scale of many parsecs (e.g., Aloy et al. 2003). In the present case, the jet luminosity $L_j$ is only marginally reduced by interaction with the wind over the much smaller, AU scale of the binary separation $a$. Indeed, if we next identify the specific cross section $\sigma_\gamma$ for interactions that lead to production of gamma rays, then we can write a simple expression for the resulting gamma-ray luminosity,

$$
L_{\gamma} \approx \tau_\gamma L_j ,
$$

(2)

where $\tau_\gamma \ll 1$ is the interaction probability associated with just gamma-producing interactions.

The fluctuation in this mean gamma-ray emission depends on the properties of the wind clumps. A simple model assumes a wind consisting entirely of clumps of a characteristic length $\ell$ 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 jet $\Delta z$, the mean number of clumps intersected is thus $\Delta N_c = \Delta z / h$, whereas the associated mean gamma-ray production is given by

$$
L_j \sigma_\gamma n \Delta z = L_j \sigma_\gamma n \Delta N_c h.
$$

(3)

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

$$
\frac{\Delta L_j^2 \sigma_\gamma^2 n^2 \Delta z^2}{\Delta N_c} = \frac{L_j^2 \sigma_\gamma^2 n^2 h \Delta z}{\Delta z} .
$$

(4)

Each clump-jet interaction is an independent process; thus, the variance of an ensemble of interactions is just the sum of the variances of the individual interactions. The total variance is then just the integral that results from summing these individual variances as one allows $\Delta z \to dz$.

$$
\delta L_\gamma^2 = L_j^2 \sigma_\gamma^2 \int_0^\infty n^2 h dz .
$$

(5)

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

$$
\frac{\delta L_\gamma}{L_\gamma} = \sqrt{\frac{\int_0^\infty n^2 h \, dz}{\int_0^\infty n \, dz}} .
$$

(6)

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

2 In this initial analysis, we ignore here any feedback of the jet interaction on the wind or clump structure, e.g. through heating and associated expansion.

**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. We have assumed $R_{\text{star}} = 35 R_\odot$ and an orbital radius $a = 2 R_{\text{star}}$. 

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Thus, \( \frac{\delta \gamma}{\gamma} = \frac{\sqrt{h/a}}{\delta L} \frac{\sqrt{\int_0^\infty dx/(1 + x^2) \delta z}}{\int_0^\infty dx/(1 + x^2)} = \frac{\sqrt{h/a}}{\delta L} \). 

(7)

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

\[
\frac{\delta \gamma}{\gamma} = \frac{\sqrt{h^3}}{\delta L} \frac{\sqrt{\int_0^\infty dx/(1 + x^2)^{3/2}}}{\int_0^\infty dx/(1 + x^2)^{3/2}} = \sqrt{2h^3/3}.
\]

(8)

Typically, if, say \( h \approx 0.03a \),

\[
\frac{\delta \gamma}{\gamma} \approx 0.1.
\]

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 order an hour.

4 GAMMA-RAY FLUCTUATIONS FROM A FINITE-CONE JET

Let us now consider how to generalize this analysis to take account of a small but finite opening angle \( \phi \) for the jet cone. The key is to consider now the total number of clumps intersecting the jet of solid angle \( \Omega \approx \phi^2 \). At a given distance \( z \) from the black hole origin, the cone area is \( \Omega z^2 \approx (\phi z)^2 \). For clumps of size \( \ell \) and mean separation \( L \), the number of clumps intercepted by the volume \( \Omega z^2 \Delta z \) is

\[
\Delta N_c = \Delta z \frac{\ell^2 + \Omega z^2}{L^2} = \frac{\Delta z}{h} \left[ 1 + (\phi z/\ell)^2 \right],
\]

(9)

where the latter equality uses the definition of the porosity length \( h \approx \ell/f \) in terms of clump size \( \ell \) and volume filling factor \( f = \ell^3/L^2 \).

Note that the term “intercepted” is chosen purposefully here, to be distinct from, e.g., “contained”. As the jet area becomes small compared to the clump size, the average number of clumps contained in the volume would fractionally approach zero, whereas the number of clumps intercepted approaches the finite, thin-jet value, set by the number of porosity lengths \( h \) crossed in the thickness \( \Delta z \). As such, for \( \phi z \ll \ell \), this more-general expression naturally recovers the thin-jet scaling, \( \Delta N_c = \Delta z/h \), used in the previous section.

Applying now this more-general scaling, the emission variance of this layer is given by

\[
\frac{L^3 \sigma^2 n^2 \Delta z^2}{\Delta N_c} = \frac{L^2 \sigma^2 n^2 h \Delta z}{1 + \phi^2 z^2/\ell^2}.
\]

(10)

Obtaining the total variance again by letting the sum become an integral, the relative rms fluctuation of intensity thus now has the corrected general form,

\[
\frac{\delta \gamma}{\gamma} = \frac{\sqrt{\int_0^\infty n^2 dx/(1 + \phi^2 z^2/\ell^2) \delta z}}{n \int_0^\infty dx/(1 + x^2)}. \]

(11)

For the simple example that both the porosity length \( h \) and clump size \( \ell \) are fixed constants, the integral forms for the relative variation becomes

\[
\frac{\delta \gamma}{\gamma} = \frac{\sqrt{h/a}}{\delta L} \frac{\sqrt{\int_0^\infty dx/(1 + p^2 x^2)/(1 + x^2)^{3/2}}}{\int_0^\infty dx/(1 + x^2)^{3/2}}.
\]

(12)

where we have defined here a “jet-to-clump” size parameter, evaluated at the binary separation radius \( a \),

\[
p \equiv \frac{\phi a}{\ell}.
\]

(13)

Carrying out the integrals, we find the fluctuation from the thin-jet limit given above must now be corrected by a factor

\[
C_p = \sqrt{\frac{1 + 2p}{1 + p}} \approx \frac{1}{\sqrt{1 + p/2}},
\]

(14)

where the latter simplification is accurate to within 6% over the full range of \( p \).

In the thin-jet limit \( p \equiv \phi a/\ell \ll 1 \), the correction approaches unity, as required. But in the thick-jet limit, it scales as

\[
C_p \approx \sqrt{\frac{2}{p}} = \sqrt{\frac{2\ell}{\phi a}}; \quad \phi \gg \ell/a.
\]

(15)

When combined with the above thin-jet results, the general scaling of the fluctuation takes the approximate overall form

\[
\frac{\delta \gamma}{\gamma} \approx \frac{h/\pi a}{1 + p/2} \approx \sqrt{\frac{h/\pi a}{1 + \phi a/2\ell}},
\]

(16)

wherein the numerator in both forms represent the thin-jet scaling, while the denominators correct for the finite jet size.

If the jet has an opening of one degree, then \( \phi = (\pi/180) \approx 1.7 \times 10^{-2} \) radian. If we assume a clump filling factor of say, \( f = 1/10 \), then the previous section’s example of a fixed porosity length \( h = 0.03a \) implies a clump size \( \ell = 0.003a \), and so a moderately large jet-to-clump size ratio of \( p \approx 6 \). But even this gives only a quite modest reduction factor \( C_p \approx 0.5 \), yielding now a relative gamma-ray fluctuation of about 5%.

For the Owocki & Cohen (2006) uniform expansion model with \( v \approx r \), \( h = \ell r \), and \( \ell = \ell r \), we find \( n \propto 1/r^3 \) and thus,

\[
\frac{\delta \gamma}{\gamma} \approx \frac{\sqrt{h^3}}{\delta L} \frac{\sqrt{\int_0^\infty dx/[1 + (1 + p^2 x^2)/(1 + x^2)^{3/2}]}}{\int_0^\infty dx/(1 + x^2)^{3/2}},
\]

(17)

where now the jet-to-clump size parameter is given in terms of the angle ratio

\[
p \equiv \frac{\phi}{\ell}.
\]

(18)

The integrations for this case lead to a general correction factor of the form

\[
C_p = \sqrt{\frac{1 + p^2}{2p^3/3}} \approx \frac{1}{\sqrt{1 + 4p/3\pi}}.
\]

(19)

where the latter simplification is accurate to within about 10% over the full range of \( p \). The correction again approaches unity in the thin-jet limit \( \phi \ll \ell \), for which \( p \to 0 \). But for a thick jet it scales as

\[
C_p \approx \sqrt{\frac{3\pi}{4p}} = \sqrt{\frac{3\pi \ell}{4\phi}}; \quad \phi \gg \ell.
\]

(20)

When combined with the previous thin-jet results, the general scaling of the fluctuation in this case is

\[
\frac{\delta \gamma}{\gamma} \approx \frac{2h/3}{1 + 4p/3\pi} \approx \sqrt{\frac{2h/3}{1 + 4\phi/3\pi \ell}},
\]

(21)

wherein again the numerator represents the thin-jet scaling, and the denominators correct for the finite jet size.
In analogy with the above example for the fixed porosity case, typical clumping parameters might be $h^\prime = 0.03$ and $f = 0.1$, which implies $\ell^\prime = 0.003$. For a cone-angle of one degree, we thus again find a moderately large jet-to-clump size ratio $\rho \approx 6$, but only a modest reduction factor, still about $C_p \approx 0.5$. Moreover, since the thin-jet fluctuation in this model is higher by roughly a factor $\sqrt 2$, the net gamma-ray fluctuation is now about 7%.

5 CONCLUSION

The bottom line here is thus that the correction for finite cone size seems likely to give only a modest (typically a factor two) reduction in the previously predicted gamma-ray fluctuation levels of order 10%. This holds for clump scales of order a few thousands of the binary separation, and for jet cone angles of about 1 degree. But as the ratio between these two parameters decreases (still keeping a fixed porosity length), the fluctuation level should decrease in proportion to the square root of that ratio, i.e. $\delta L_\gamma \propto \sqrt{h/\phi} \propto 1/\sqrt{\rho}$.

Overall, the general model has just two free parameters, namely a suitably scaled porosity length (either $h/\alpha$ or $h^\prime$), and the jet-to-clump size ratio (given either by $p = \phi\alpha/\ell$ or $p = \phi/\ell^\prime$.) Within factors of order unity, the relative gamma-ray fluctuation in both types of model is predicted to scale as

$$\frac{\delta L_\gamma}{L_\gamma} \approx \sqrt{\frac{h/3}{1 + p/2}}$$

where here $h$ represents a suitably scaled, dimensionless porosity length. The canonical sample case cited above has $h = 0.03$ and $p = 6$, giving a relative gamma-ray fluctuation of about 5%.

Note however, that the formalism here is based on a simple model in which all the wind mass is assumed to be contained in clumps of a single, common scale $\ell$, with the regions between the clumps effectively taken to be completely empty. More realistically, the wind structure can be expected to contain clumps with a range of length scales, superposed perhaps on the background smooth medium that contains some nonzero fraction of the wind mass. For such a medium, the level of gamma-ray fluctuation would likely be modified from that derived here, perhaps generally to a lower net level, but further analysis and modelling will be required to quantify this.

One potential approach might be to adapt the “power-law porosity” formalism developed to model the effect of such a clump distribution on continuum driven mass loss (Owocki, Gayley, and Shaviv 2004). This would introduce an additional dependence on the distribution power index $\alpha_p$, with smaller values $\alpha_p \rightarrow 0$ tending to the smooth flow limit. But for moderate power indices in the range $0.5 < \alpha_p < 1$, we can anticipate that the above scalings might still roughly apply, with some reduction that depends on the power index $\alpha_p$, if one identifies the assumed porosity length $h$ with the strongest clumps.

Thus while there remains much further work to determine the likely nature of wind clumping from hydrodynamical models, the basic porosity formalism developed here does seem a promising way to characterize its broad effect on key observational diagnostics, including the relative level of fluctuation in the gamma-ray emission of HMXRB microquasar systems.

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REFERENCES

Albert, J. et al. ( MAGIC coll.), 2006, Science, 312, 1771