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Gamma-Ray Variability from Stellar Wind Porosity in Microquasar Systems

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Abstract. In the subclass of high-mass X-ray binaries known as "microquasars", relativistic hadrons in the jets launched by 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. This paper summarizes recent analyses of how the "porosity length" of the stellar wind structure can set the level of fluctuation in gamma rays. A key result is that, for a porosity length defined by $h \equiv \ell/f$, i.e. as the ratio of the characteristic size ℓ of clumps to their volume filling factor f, the relative fluctuation in gamma-ray emission in a binary with orbital separation a scales as $\sqrt{h/\pi a}$ 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 ϕ. For a thin jet and quite moderate porosity length $h \approx 0.03\,a$, this implies a ca. 10% variation in the gamma-ray emission.

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 (HMXBs) and microquasars are variable gamma-ray sources (Aharonian et al. 2005, 2006; 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 2008). Since at least some of the massive gamma-ray binary systems 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 longstanding arguments that the winds of hot stars have a highly clumped structure, possibly arising from instrinic, strong instability in the wind driving by scattering of radiation in spectral lines (e.g. Dessart & Owocki 2003, 2005;

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Puls et al. 2006, and references therein). The present paper summarizes recent analyses on how gamma-ray variability arising from interaction of a microquasar jet with the massive-star companion's clumpy wind can be parameterized in terms of the wind's "porosity". Full details are given in Owocki et al. (2009).

The basic scenario explored is illustrated in figure 1. A binary system consists of a compact object (e.g., a black hole) and a massive, hot star with an outflowing stellar wind. The compact object accretes from the wind and produces two jets. For simplicity, the jets are assumed normal to the common xy-plane of the accretion disk and binary orbit, with the latter taken to be circular with a radius a. The z-axis is along the jet, which has an opening angle ϕ, with its axis at an angle θ to the line of sight. Individual clumps in the stellar wind interact with the jet at different altitudes, forming an angle Ψ with the orbital plane. We ignore any intrinsic variability in the jet itself.

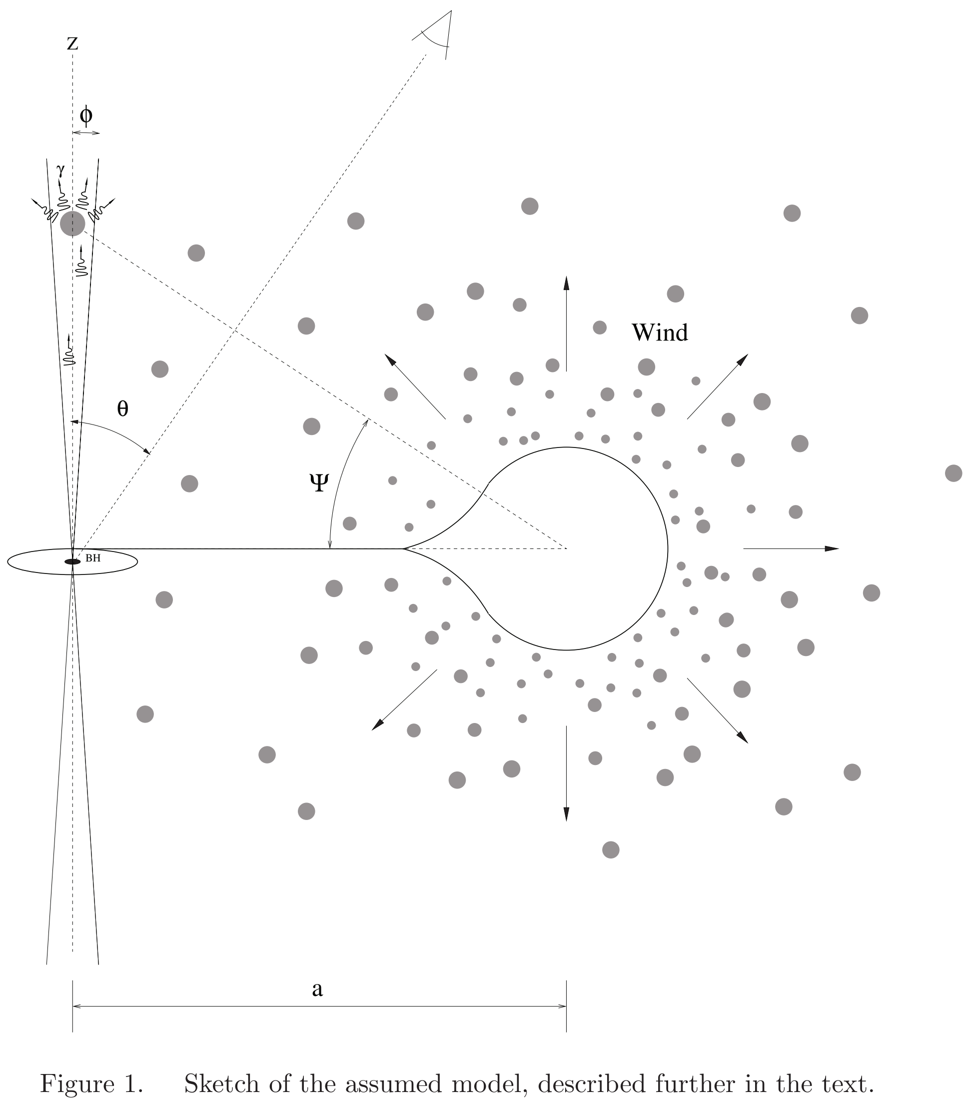

Figure 1. Sketch of the assumed model, described further in the text.

The interaction of relativistic hadrons in the jet with wind protons produces pions, which quickly decay to emit the observed gamma rays. The clumping of the stellar wind implies a variability in this gamma-ray emission. Individual jet-clump interactions should be observable only as rare, flaring events. But integrated along the jet there are clump interactions occurring all the time, leading to a flickering in the light curve, with the relative amplitude depending on the clump characteristics.

In the typical case that the overall jet attenuation is small, both cumulatively and by individual clumps, 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 & Cohen (2006) to characterize the effect of wind clumps on absorption of X-ray line emission (see also Oskinova, Feldmeier, & Hamann 2006).

2. Porosity-Length Scaling of Gamma-Ray Fluctuation from Multiple Clumps

To quantify this notion, let us first consider the gamma-ray emission integrated along the jet. Representing the relativistic particle component of the jet as a narrow beam with constant luminosity $L_b = q_j L_j$ along its length coordinate z, the total mean gamma-ray luminosity L_γ scales (in the small-attenuation limit $L_\gamma \ll L_b$) as

$$\langle L_\gamma \rangle = L_b \sigma \int_0^\infty n(z)\, dz \,, \tag{1}$$

where $n(z)$ is the local mean wind density (i.e. averaged over any small-scale clumped structure), and σ is the gamma-ray conversion cross-section defined above.

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

$$\langle \Delta L_\gamma \rangle = L_b \sigma n \Delta z = L_b \sigma n \Delta N_c h. \tag{2}$$

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

$$\left\langle \Delta L_\gamma^2 \right\rangle - \langle \Delta L_\gamma \rangle^2 = \frac{L_b^2 \sigma^2 n^2 \Delta z^2}{\Delta N_c} = L_b^2 \sigma^2 n^2 h \Delta z \,. \tag{3}$$

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 $\Delta z \to dz$. Taking the square-root of this yields an expression for the relative rms fluctuation of intensity,

$$\frac{\delta L_\gamma}{\langle L_\gamma \rangle} = \frac{\sqrt{\int_0^\infty n^2 h \, dz}}{\int_0^\infty n \, dz} \, . \tag{4}$$

Note that, in this linearized analysis based on the weak-attenuation model for the jet, the cross-section σ scales out of this fluctuation relative to the mean.

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

$$\frac{\delta L_\gamma}{\langle L_\gamma \rangle} = \sqrt{h/a} \, \frac{\sqrt{\int_0^\infty dx/(1+x^2)^2}}{\int_0^\infty dx/(1+x^2)} = \sqrt{h/\pi a} \, , \tag{5}$$

where the integration is now carried out in terms of the scaled length $x = z/a$. Typically, if, say $h \approx 0.03a$, then $\delta L_\gamma / L_\gamma \approx 0.1$. This implies an expected flickering at the level of 10% for a wind with such porosity parameters, occuring on a timescale of an hour or less.

3. Gamma-ray Fluctuations from a Finite-Cone Jet

This analysis can also be readily generalized to take account of a small but *finite opening angle* ϕ 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 $\Omega z^2 = (\phi z)^2$. For clumps of size ℓ and mean separation L, the number of clumps *intercepted* by the volume $\Omega z^2 \Delta z$ is

$$\Delta N_c = \Delta z \frac{\ell^2 + \Omega z^2}{L^3} = \frac{\Delta z}{h} \left[1 + (\phi z/\ell)^2 \right] \, , \tag{6}$$

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

The term "intercepted" is chosen purposefully, 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 Δz. 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 subsection.

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

$$\frac{L_b^2 \sigma^2 n^2 \Delta z^2}{\Delta N_c} = \frac{L_b^2 \sigma^2 n^2 h \Delta z}{1 + \phi^2 z^2/\ell^2} \, . \tag{7}$$

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,

$$\frac{\delta L_\gamma}{\langle L_\gamma \rangle} = \frac{\sqrt{\int_0^\infty n^2 h \, dz/(1 + \phi^2 z^2/\ell^2)}}{\int_0^\infty n \, dz} \, . \tag{8}$$

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

$$\frac{\delta L_\gamma}{\langle L_\gamma \rangle} = \sqrt{h/a}\, \frac{\sqrt{\int_0^\infty dx/[(1+p^2x^2)(1+x^2)^2]}}{\int_0^\infty dx/(1+x^2)} \,, \tag{9}$$

where $p \equiv \phi a/\ell$ defines a "jet-to-clump" size parameter, evaluated at the binary separation radius a. Carrying out the integrals, we find the fluctuation from the thin-jet limit given above must now be corrected by a factor

$$C_p = \frac{\sqrt{1+2p}}{1+p} \approx \frac{1}{\sqrt{1+p/2}} \,, \tag{10}$$

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

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

$$C_p \approx \sqrt{\frac{2}{p}} = \sqrt{\frac{2\ell}{\phi a}} \quad ; \quad \phi \gg \ell/a \,. \tag{11}$$

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

$$\frac{\delta L_\gamma}{\langle L_\gamma \rangle} \approx \sqrt{\frac{h/\pi a}{1+\phi a/2\ell}} \tag{12}$$

wherein the numerator represents the thin-jet scaling, while the denominator corrects 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 example of the previous section for a fixed porosity length $h = 0.03\,a$ implies a clump size $\ell = 0.003\,a$, 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%.

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 thousandths of the binary separation, and for jet cone angles of about 1 degree. 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. $\delta L_\gamma \propto \sqrt{l/\phi} \propto 1/\sqrt{p}$.

4. Conclusion

Overall, for a given binary separation scale a, our general model for gamma-ray fluctuation due to jet interaction with clumped wind has just two free parameters, namely the porosity length ratio h/a, and the jet-to-clump size ratio $p = \phi a/\ell$. Given these parameters, then, within factors of order unity, the predicted relative gamma-ray fluctuation is given by eqn. (12). For reasonable clump properties with $h \approx 10\ell \approx 0.03a$, the fluctuation amplitude would be a few percent.

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 ℓ, 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 modeling will be required to quantify this.

One potential approach might be to adopt the "power law porosity" formalism developed to model the effect of such a clump distribution on continuum driven mass loss (Owocki, Gayley & Shaviv 2004). This would introduce an additional dependence on the distribution power index α_p, with smaller values $\alpha_p \to 0$ 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 should still roughly apply, with some reduction that depends on the power index α_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 HMXB microquasar systems.

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References

Aharonian, F. A. et al. (HESS Coll.), 2005, Sci, 309, 746
Aharonian, F. A. et al. (HESS Coll.), 2006, Sci, 314, 1424
Albert, J. et al. (MAGIC coll.), 2006, Sci, 312, 1771
Albert, J. et al. (MAGIC coll.), 2007, ApJ, 665, L51
Dessart, L., & Owocki, S.P., 2003, A&A, 406, L1
Dessart, L., & Owocki, S.P., 2005, A&A, 437, 657
Oskinova, L. M., Feldmeier, A., & Hamann, W.-R. 2006, MNRAS, 372, 313
Owocki, S.P., & Cohen, D.H. 2006, ApJ, 648, 565
Owocki, S.P., Gayley, K.G., & Shaviv, N. 2004, ApJ, 616, 525
Owocki, S.P. et al. 2009, ApJ, 696, 690.
Puls, J. et al. 2006, A&A, 454, 625
Paredes, J. M. 2008, Int. Journal of Modern Physics D, 17, 1849
Romero, G.E., et al., 2003, A&A, 410, L1