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Models for Very Rapid High-Energy γ-Ray Variability in Blazars

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Abstract. We present a family of models for rapid γ-ray variability in blazars based on a two-component jet. Fast variability occurs when relativistic electron–positron pairs interact with small-scale perturbations in the inner jet. These perturbations are produced by Kelvin–Helmholtz instabilities. We fit the minute-scale strong variability displayed by the blazar PKS 2155−304 and present synthetic light-curves of the kind that might be observed with forthcoming instruments such as the Cherenkov telescope array.

Key words. Blazars—γ-rays: theory—jets—MHD-instabilities.

1. Introduction

Blazars display rapid variability across the entire electromagnetic spectrum. Variability at high energies on timescales of a few minutes has been observed for some of them, such as PKS 2155−304 (e.g., Aharonian *et al.* 2007). This discovery has led to the formulation of a large variety of models for non-thermal variability in relativistic jets. A quarter century ago, the discovery of the so-called intra-day variability at radio wavelengths led to a similar situation (see Wagner & Witzel 1995 for a review). Some of the ideas and models proposed then to explain the origin of phenomenon can be extended to cover the high-energy radiative regime of blazars.

Models based on shocks interacting with jet inhomogenetities and bends were developed in the early 1990s (e.g., Qian *et al.* 1991; Gopal-Krishna & Wiita 1992; Marscher 1992; see also the seminal papers by Blandford & Königl 1979; Königl 1981). Romero (1995) presented a unified model where bends and clumps develop in a magnetized jet when Kelvin–Helmholtz instabilities appear as the magnetization decreases. Here we revisit that model and explore the implications for the high-energy radiation, showing that it can explain rapid events as observed in PKS 2155−304.

2. Two-component jet model: Basic features

Structured jets have been frequently proposed to explain the diverse aspects of AGN physics (e.g., Sol *et al.* 1989; Romero 1995; Ghisellini *et al.* 2005; Boutelier *et al.*

2008). The structure usually consists of a fast and light inner relativistic flow ejected by the ergosphere of black hole. This 'spine' or 'beam' is thought to be formed by electron–positron pairs and electromagnetic fields. It starts as a Poynting-dominated flux, whose magnetic energy density decreases as the beam expands (e.g., Romero 1995, 1996). This beam is surrounded by a baryonic, slower, and much denser jet launched by the accretion disk (see Reynoso *et al.* 2011 for the physics of the heavy jet). The situation is shown in Fig. 1.

3. Kelvin–Helmholtz instabilities

The interface between beam and jet is a place prone to develop Kelvin–Helmholtz (KH) instabilities. These instabilities can be prevented, however, by large-scale axial magnetic fields. The critical value of the field is given by (Romero 1995)

$$B_{\rm c}^{\rm KH} = \frac{\sqrt{4\pi n_{\rm b} m_{\rm e} c^2 (\Gamma_{\rm b}^2 - 1)}}{\Gamma_{\rm b}}, \tag{1}$$

where $n_{\rm b}$ is the pair density in the beam, and $\Gamma_{\rm b}$ is its bulk Lorentz factor. If the field drops below this critical value, KH instabilities will develop and perturbations in the flows will appear. If the instabilities grow, the two components will eventually mix. In Fig. 2, we show the evolution of critical and actual fields along the jet-beam boundary layer. To implement calculations we have adopted values for the different parameters that are expected to be reasonable for a source such as PKS 2155−304 (see Reynoso *et al.* 2012).

From the figure we see that at a distance of $\sim 10^{16}$ cm from the black hole, the instabilities appear. It is in this region when the fast, unperturbed plasma will hit the slower, disturbed flow. A series of strong shocks will then form. These

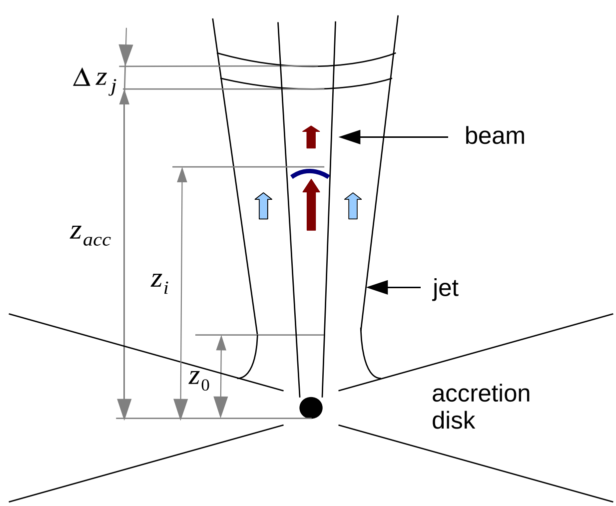

Figure 1. Sketch of a two-component jet. z_0 is the beam injection point. Particles are re-accelerated at a distance $z_{\rm acc}$ from the black hole, where shocks develop. The thickness of the shocked region is $\Delta z_{\rm j}$.

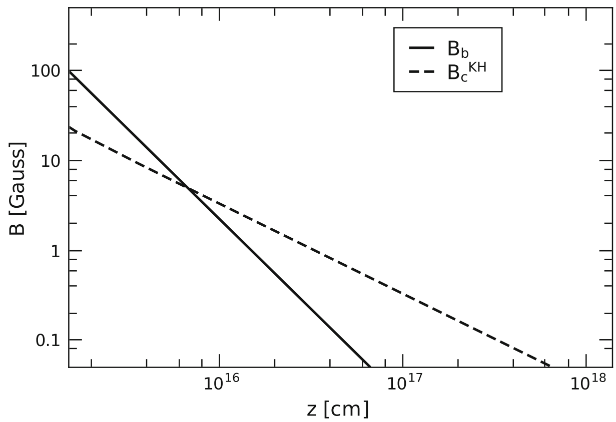

Figure 2. Evolution of the magnetic field and the critical limit for development of KH-instabilities along the inner jet. Parameters as in Reynoso *et al.* (2012).

shocks are expected to re-accelerate the pairs of beam, which will cool in the post-shock region very quickly mainly through the synchrotron self-Compton radiation (Reynoso *et al.* 2012), producing a rapid succession of short γ-ray flares, as originally suggested by Romero (1995).

4. Applications

We have applied the model outlined above to PKS 2155−304. In Fig. 3 we show a fit of the observational data obtained by HESS telescopes at energies $E > 200$ GeV.

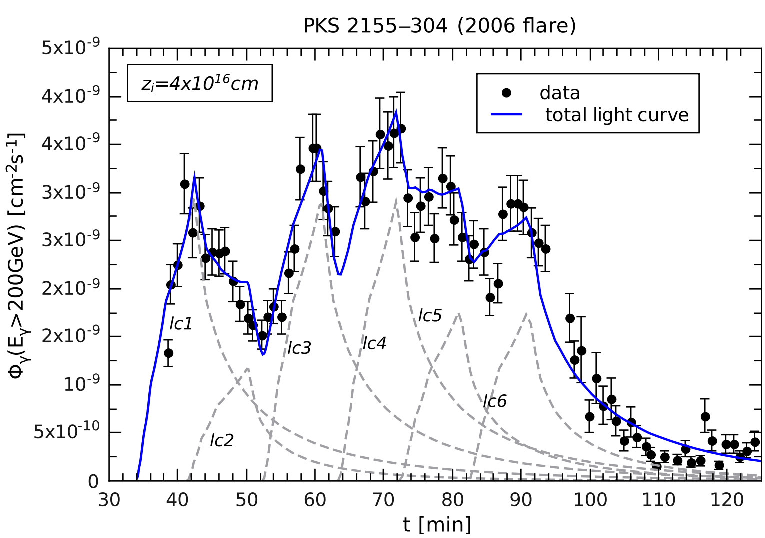

Figure 3. Fit of the two-component jet model with multiple shocks of HESS variability data of outburst of PKS 2155−304.

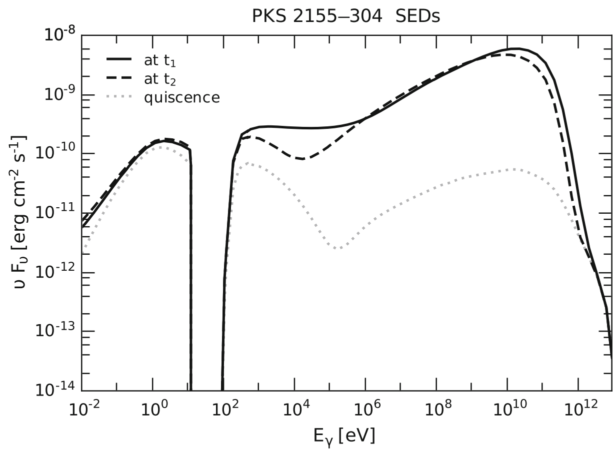

Figure 4. Spectral energy distributions at different moments during a flare. The γ-ray variability is far more dramatic than the radio intra-day variability. Instant t_1 is 40 min after the beginning of the flare. Instant t_2 is 10 min after t_1.

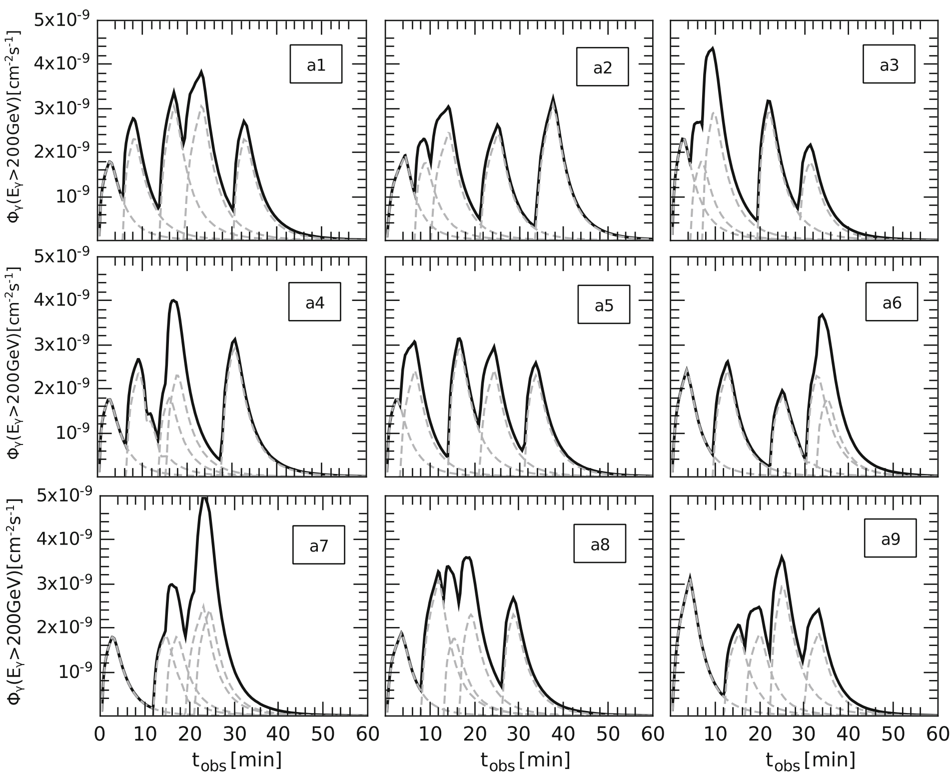

Figure 5. Synthetic light curves showing rapid γ-ray variability of a blazar modelled with a two-component jet.

Six different shocks are formed at a distance of 4×10^{16} cm from the black hole. Lorentz factors of these shocks are in the range 15–20. Of course, since we are dealing with a complex inverse problem, the solution is not unique. The model however, allows us to infer the kind of physical conditions that should exist in the source to generate the observed phenomenology (see Reynoso *et al.* 2012 for details).

It is quite interesting to investigate the behaviour of the whole spectral energy distribution of the source during the flaring state. In Fig. 4 we show the entire spectrum at three different moments: before the variability (i.e. the quiescent state), 40 min after the outset of the first flare, and after 10 min. It is remarkable that at a later time, the flux increases significantly at 10 KeV than at 200 GeV. This is likely produced by the energy redistribution due to pair-cascading, which are computed by solving the coupled transport equations in our model. This means that, under some conditions, a source can display an X-ray flare, without important activity in the γ-ray domain. Another interesting feature is that the overall variability has far larger amplitudes at multi-GeV energies than in radio and optical variabilities, i.e. the rapid γ-ray variability is faster than the intra-day radio/optical variability, which is of synchrotron origin.

Finally, we show a wide variety of light curves that are attainable in our model by changing within a reasonable range of values, the parameters related to different shocks. In Fig. 5, we present 9 different light curves obtained with 5 shocks, where we have just changed the instant of injection and the Lorentz factor within the range 17–19.

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