Structured jets and VHE emission of blazars and radiogalaxies

Fabrizio Tavecchio and Gabriele Ghisellini

INAF–Osserv. Astron. di Brera, via E. Bianchi 46, 23807 Merate, LC, Italy

Abstract. Recent observations in the TeV band challenge the simplest models developed to describe the overall emission of blazars and radiogalaxies. In particular, the observation of variable TeV emission from M87 and the fast variability shown by PKS 2155-304 challenge the standard framework. We discuss how the existence of a radial structure in the sub-pc scale jet, with faster a component ("spine" or "needles") embedded in a slower layer can explain the basic phenomenology of these sources.

Keywords: gamma-rays: theory – galaxies: active

PACS: 95.30.Jx, 95.85.Pw, 98.54.Cm

INTRODUCTION: THE STRUCTURED JET MODEL

Several observational and theoretical clues suggest that jets in extragalactic sources can be structured, with a fast core (spine) surrounded by a slower layer. Among the evidences coming from observations we recall the direct radio imaging of structures in the innermost regions of the close-by BL Lac objects and radiogalaxies [1,2,3] and the two-velocity structure required to unify FRII radio galaxies and BL Lacs [4]. Theoretically, a structure in the jet alleviates some problems related to the models of TeV BL Lacs [5]. Recent simulations of jet formation support the existence of a spine–layer structure already in the initial phases of the jet propagation [6,7].

The existence of a velocity structure has a strong impact on the observed emission properties of jets. Specifically, the radiatively interplay between the layer and the spine amplifies the inverse Compton emission of both components [8,9]. Indeed, both components will see the emission of the other amplified because of the relative speed. This “external” radiation contributes to the total energy density, enhancing the emitted inverse Compton radiation. Depending on the parameters, this “external Compton” (EC) emission can dominate over the internal synchrotron self-Compton (SSC) component that, especially in TeV blazars, is depressed because scatterings mainly occur in the Klein-Nishina regime.

An important point to consider is that the emission from the layer is beamed within the angle $\theta_l \sim 1/\Gamma_l$ (where $\Gamma_l$ is the bulk Lorentz factor of the layer), larger than the corresponding angle for the spine, since $\Gamma_s > \Gamma_l$. This implies that the layer can be seen at relatively large viewing angles for which, instead, the emission from the spine is severely depressed. A direct prediction of this fact is that, besides blazars (dominated by the spine), also misaligned jets in radiogalaxies could be relatively strong $\gamma$-ray emitters, dominated by the layer [5].

In the following we use the spine-layer scenario to interpret the observed TeV emission from M87 and the challenging rapid variability (down to few minutes) recently observed from some TeV blazars.

TEV EMISSION OF M87

The nearby (16 Mpc) radiogalaxy M87 has been discovered as a TeV source by the HEGRA array [9]. Subsequent observations by H.E.S.S., VERITAS and MAGIC confirmed the emission and showed that the TeV flux is variable, both on short (~2 days) and long (years) timescales [10,11,12]. Though the limited spatial resolution of Cherenkov telescopes prevents to localize the emission region, the short variability timescale allows us to rule-out models predicting TeV emission from the kpc-scale jet [13].

Among the possible scenarios advanced to explain the observed emission, that considering the emission from the peculiar knot HST-1, located at 60 pc (projected) from the core [14,15] was supported by the apparent correlation of the measured TeV flux and the X-ray emission of HST-1 as measured by the monitoring of Chandra. X-ray measures are difficult, since the separation of the core and HST-1 is at the limit of the capabilities of Chandra. Recent observations, showing an increase of the TeV flux not accompanied by a corresponding increase of the X-ray brightness of HST-1 [11] though not completely ruling out the connection between TeV emission and HST-1, open the possibility that the VHE emission originates in the core. Moreover, the short variability timescales seem difficult to reconcile with the size of HST-1 without invoking some special geometry at the shock [15,16].
Models in which the emission region is located close to the core do not have problems in explaining the short timescale variability. Neronov & Aharonian [17] proposed that the TeV emission comes from relativistic particles accelerated by magnetic fields close the central supermassive black hole. A more direct possibility is that the emission comes from the slightly misaligned ($\theta \simeq 20$ deg) inner jet [18]. However, it can be shown that a simple homogeneous synchrotron-SSC model fails in reproducing the entire spectral energy distribution of the core of M87, mainly because of the large separation of the synchrotron and SSC peaks in the SED [19,20], requiring unreasonably large Doppler factors ($\delta \sim 500$).

The spine-layer scenario can easily overcome this problem [20]. In our model (Fig.1) the emission from the spine (with bulk Lorentz factor $\Gamma_s = 12$) accounts for the low-energy emission, from radio to the GeV band, while the VHE component is produced by the layer (with bulk Lorentz factor $\Gamma_l = 4$). To produce TeV photons we have to assume that electrons in the layer are highly relativistic and thus the corresponding synchrotron radiation peaks at relatively high frequency, above the X-ray band, where the SSC radiation of the spine dominates. The SSC emission in the layer occurs mainly in the KN regime and thus is strongly suppressed. The high-energy peak of the layer is thus largely dominated by the EC component.

An important constrain that such a model has to satisfy is that the SED seen by an observer located at small angle should display a shape similar to that of known blazars. For comparison, in Fig.1 the filled symbols report the observational data for the prototype of BL Lac objects, BL Lac itself. The upper solid line is the SED of M87 measured by an observer locate at 6 deg with respect to the jet axis. At small angles the jet is dominated by the beamed emission of the spine, while the less amplified layer component provides a negligible contribution. Though we do not intend to exactly reproduce the SED of this particular blazar, one can see that the model follows quite well the observed data.

A direct prediction of the structured jet model is that Fermi (and possibly Cherenkov telescopes) should detect other radiogalaxies, probably those with the (inner) jet only slightly misaligned with respect to the line of sight.
Other possibilities to produce detectable fluxes of $\gamma$-rays from radiogalaxies, not critically dependent on the viewing angle, include the emission of the kpc scale jet [13], of the hotspots [21] or of the lobes. The most direct way to distinguish the origin of the high-energy emission is through the variability. Fast ($\sim$ days) variability would directly exclude possibilities involving large scale regions, indicating that the emission originates in the most compact regions of the radiogalaxy (jet or BH).

RAPID TEV VARIABILITY OF PKS 2155-304

In summer 2006 the TeV BL Lac PKS 2155-304 showed a period of extreme variability in the TeV band [22]. During the night of July 28 well resolved flares varying on timescales of 200 seconds were observed (similar variations have been also observed in Mkn 501, [23]). In this phase the source was very active at VHE, reaching observed luminosities of $10^{47}$ erg/s (to be compared with more typical luminosities of $\sim 10^{45}$ erg/s). Such short variability timescales are difficult to explain in the standard framework [24]. Indeed, in the widely assumed internal shock scenario variations should last for times larger than the timescale associated to the black hole, $t_{\text{var}} > R_s/c \sim 1.4 M_9$ h, where $R_s$ is the Schwarzschild radius of the BH. On the other hand, if the source is a moving sphere, Doppler factor as large as $\delta = 50 - 100$ are required in order to keep the compactness of the source to acceptable values [25,26].

Also in this case a structured jet offers a good way to reproduce these states [27] without a radical change of the theoretical framework (Fig.2). In this version the role of the spine is played by a “needle”, a very compact (size $\sim 3 \times 10^{14}$ cm) region inside the ten times bigger “normal” jet, responsible for the emission observed during most of the time. Though the needle is characterized by a high bulk Lorentz factor, $\Gamma = 50$, the total power needed to reproduce the observed emission does not exceed that carried by the normal jet.

As in the model for M87, a crucial role is played by the radiative interplay between the needle and the normal jet. As can be seen in Fig.2 the bulk of the IC emission from the needle is produced through the scattering of the photons emitted by the jet, whose energy density is amplified by the high relative speed. Note that the contribution of the needle at other frequencies is minor, consistently with the small variability observed during the active phases, especially at X-ray frequencies (e.g. Costamante, these proceedings). Such a scenario could
thus easily explain the so-called “orphan flares”, TeV flares without a counterpart in the X-ray band [28]. This also offers an effective way to test our scenario through multifrequency observations, especially in the crucial X-ray and UV bands. If ultrafast variations on the TeV band are not accompanied by corresponding variations at lower frequencies, then the “needle-jet” model (or, more generally, any model considering more than an emission region) is preferred.

A consequence of the “needle-jet” model is that the power of the jet is dominated by the electrons (and protons) carried by the “normal” flow, while the magnetic field provides a negligible role (contrary the conclusions of [24]).

ACKNOWLEDGMENTS

We thank Laura Maraschi for useful comments

REFERENCES

1. Giroletti, M., et al. 2004, ApJ, 600, 127
2. Giroletti, M. et al. 2008, A&A, 488, 905
3. Kovalev, Y.Y. et al. 2007, ApJ, 668, L27
4. Chiaberge, M., Celotti, A., Capetti, A., & Ghisellini, G. 2000, A&A, 358, 104
5. Ghisellini, G., Tavecchio, F., Chiaberge, M., 2005, A&A, 432, 401
6. Aloy, M.-A. et al. 2000, ApJL, 528, L85
7. McKinney, J. C. 2006, MNRAS, 368, 1561
8. Georganopoulos, M., & Kazanas, D. 2003, ApJL, 594, L27
9. Aharonian, F., et al., 2003, A&A, 403, L1
10. Aharonian, F., et al., 2006, Science, 314, 1424
11. Acciari, V. A., et al. 2008, ApJ, 679, 397
12. Albert, J., et al. 2008, ApJL, 685, L23
13. Stawarz, L., Sikora, M., & Ostrowski, M. 2003, ApJ, 597, 186
14. Stawarz, L., et al. 2006, MNRAS, 370, 981
15. Cheung, C. C., Harris, D. E., Stawarz, L., 2007, ApJ, 663, L65
16. Levinson, A., Bromberg, O., 2007, Proceedings of “High Energy Phenomena in Relativistic Outflows”, held in Dublin, Ireland, September 24-28, 2007 [arXiv:0712.2664]
17. Neronov, A., & Aharonian, F. A. 2007, ApJ, 671, 85
18. Bai, J. M., Lee, M. G., 2001, ApJ, 549, L173
19. Georganopoulos, M., Perlman, E. S., Kazanas, D., 2005, ApJ, 634, L33
20. Tavecchio, F., Ghisellini, G., 2008, MNRAS, 385, L98
21. Mannheim, K., Biermann, P. L., & Kruells, W. M. 1991, A&A, 251, 723
22. Aharonian, F., et al., 2007, ApJL, 664, L71
23. Albert, J., et al. 2007, ApJ, 669, 862
24. Begelman, M.C., Fabian, A.C., Rees, M.J., 2008, MNRAS, 384, L19
25. Finke, J. et al. 2008, ApJ, in press [arXiv:0802.1529]
26. Foschini, L., et al. 2008, A&A, 484, L35
27. Ghisellini, G., Tavecchio, F., 2008, MNRAS, 386, L28
28. Krawczynski, H., et al. 2004, ApJ, 601, 151