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Blazar jets: new clues and old challenges

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I will review some of the recent advancements in our understanding of blazar jets obtained from the combination of insights from observations, numerical simulations, particle acceleration physics and SED modelling. In particular, I will focus on 1) the clues on particle acceleration, magnetic fields and geometry of the emission region(s) offered by *IXPE* results and 2) the still open challenges to model the so-called extreme blazars.

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1. Introduction

Blazars, jetted active galactic nuclei with a jet pointing toward the observer, are ideal laboratories to explore the physical processes related to relativistic jets produced by supermassive black holes, from their dynamics (acceleration, collimation, propagation) to particle acceleration and emission mechanisms [1]. Despite several decades of efforts, a number of fundamental issues are still open. Particularly critical problems concern the understanding of the interlaced topics of jet composition and magnetization, the nature of the dissipation processes and the consequent acceleration of particles to ultra-relativistic energies (e.g., [2]). Diffusive shock acceleration (DSA) has been for a long time considered the favourite mechanism able to push particles up to the required relativistic energies. The focus on models of jet launching favouring highly magnetized flows [3], more recently shifts the attention to scenarios based on magnetic reconnection [4].

A basic division among blazars is between powerful FSRQ and weaker BL Lac objects, whose basic distinctive feature is the presence of strong (for FSRQ) or very weak (BL Lacs) emission lines. From the point of view of the electromagnetic output, the spectral energy distribution (SED) of these sources covers the entire spectrum, from radio waves up to very-high energy gamma rays, and displays two broad bumps, related to synchrotron and inverse Compton emission in the leptonic framework. In the following we will focus on blazars of the HBL type, low power BL Lac in which the two peaks have maxima at X-ray and TeV energies. In these kind of objects the X-rays trace the synchrotron emission from freshly accelerated electrons, allowing us to probe the close vicinity of the acceleration sites. Recent observations of HBL by the *IXPE* satellite, which provides unprecedented measurements of the polarization in the X-ray band [5], together with optical and radio polarimetric measurements, are best explained by DSA associated to a shock with *stratified* downstream region and challenge at the same time magnetic reconnection [6] (see Sect. 2). The issue of the mechanisms behind particle acceleration is particularly acute for so called extreme HBLs (EHBL), atypical blazars whose observational properties challenges all current views. Recent theoretical proposals for EHBL based on recollimation shocks and turbulence are discussed in Sect. 3.

2. New clues from X-ray polarization

High peak BL Lac (HBL) are characterized by the maximum of the synchrotron component in the X-ray band. Among blazars, they are the most efficient particle accelerators, with electrons exceeding TeV energies (or Lorentz factors of the order of $\gamma \sim 10^6$). The modeling of their multi-wavelength SED in the framework of one-zone leptonic models generally indicates low magnetic fields ($B \lesssim 0.1$ G), significantly below equipartition with the non-thermal electrons [7].

IXPE observations of representative HSP (e.g. Mkn 421 [8] and Mkn 501 [9]) during states characterized by quiescent/mid flux agree to indicate a relatively high degree of polarization (around 10-15%, up to $\sim 18\%$ in the extreme source 1ES0229+200), accompanied by (routinely observed, e.g. [10]) very small polarization in optical and in the radio band (2-3%). This result strongly supports a stratified shock scenario, in which particles are supposed to be accelerated at a shock and then advected downstream by the flow. Owing to the energy-dependent radiative lifetime of electrons, $t_{\rm cool} = 7.8 \times 10^4 B_{-1}^{-2} \gamma_6^{-1}$ s, it is naturally expected that high-energy emitting electrons

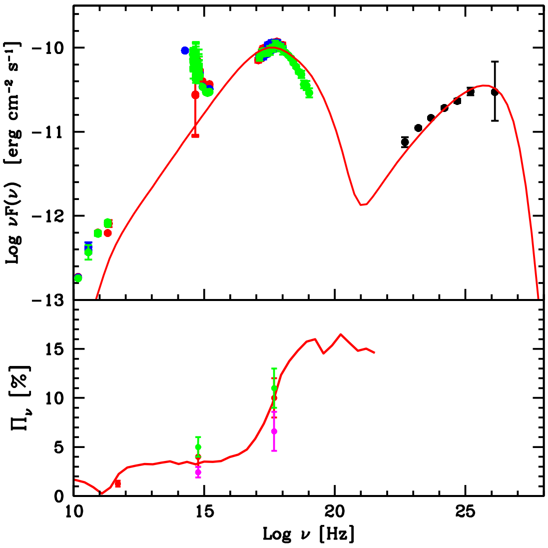

Figure 1: SED (upper panel) and degree of polarization at different frequencies (lower) of Mkn 501, reproduced with the stratified shock model described in the text. From Lisalda et al. in prep.

completely cool within a small distance from the shock (of the order of $ct_{\rm cool} \sim 10^{15}$ cm), while low energy electrons can travel further downstream. The synchrotron emission in the X-ray band thus carries the imprint of the magnetic field structure close to the shock front, while at lower frequencies the polarization properties are rather determined by average conditions in the downstream region [e.g. 11, 12]. The relatively large degree of polarization of the X-ray radiation therefore suggests a corresponding relatively organized magnetic field in the shock vicinity. On the contrary, the small polarization in the optical band indicates a somewhat smaller average organization. In this respect it is worth noting that the absence of rapid variations of the degree of polarization in current observations leaves little room for an important role of turbulence (and turbulent reconnection), at least during stationary quiescent states of activity [6, 13]. As pointed out above, these conclusions hold for low/medium activity phases of the sources. On the other hand, the rapid (~ 80 deg/day) rotations of the polarization angle displayed by Mkn 421 during a moderately active state (with a flux larger by a factor ~ 2 with respect to the first observations) points to a more complex situation during these phases [14].

The clues provided by the first *IXPE* observations of HSP sketched above naturally lead to reconsider our emission models of these sources, historically based on the one-zone paradigm, in which the bulk of the observed emission is assumed to originate in a unique, nearly homogeneous region containing electrons with isotropic distributions and tangled magnetic field [e.g. 15, 16]. A specific model for a stratified shock scenario has been presented in [12] and improved in Tavecchio (in prep). A key ingredient of this scenario is borrowed by particle-in-cell (PIC) simulations, which which display the formation of an intense perpendicular field just downstream of the front. This field is self-produced through beam-plasma instabilities by streaming accelerating particles [e.g.

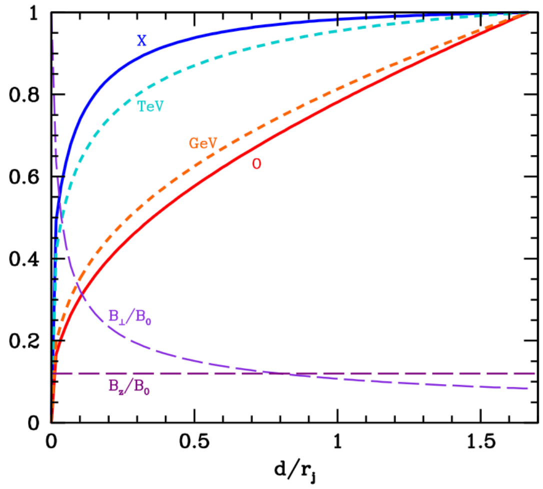

Figure 2: Cumulative emission profiles in different bands (*IXPE* band, solid blue; optical, solid red: 3 TeV, dashed cyan; 1 GeV, dashed orange) as a function of the normalized distance from the shock for the parameters of model 1. The dashed violet lines report the profiles of the orthogonal and parallel magnetic fields (normalized to the total magnetic field at the front).

17, 18] and rapidly decays in the downstream region, possibly due to collisionless dumping [e.g. 19].

In the model non-thermal electrons are supposed to be injected at a mildly relativistic shock and advected by the downstream flow at speed $c/3$. Due to the energy-dependent radiative losses, high-energy electrons emitting X-ray synchrotron radiation (with Lorentz factor $\gamma \sim 10^5 - 10^6$) cool at a very small distance from the shock. When the jet is observed at a typical angle of the order of $1/\Gamma$ with respect to the jet axis (which transforms to 90 deg in the jet rest frame), the natural outcome of the partially ordered configuration of the self-produced field, coupled with the energy-dependent radiative lifetimes of emitting electrons, is a large polarization in the X-rays (Fig. 1). On the other hand, emission at lower frequencies is produced in large portion of the downstream flow and the resulting polarization is determined by the average structure of the magnetic field far from the shock. In the specific model used in Fig.1 we assume that the unshocked jet carries a weak field predominantly parallel to the jet axis (i.e. we consider a subluminal configuration, suitable for efficient acceleration, [20]). The interplay between this parallel field component and the self-produced orthogonal field determine a very small polarization at optical wavelength.

In Fig.1 we report the case of Mkn 501 for which the SED (upper panel) and the multifrequency degree of polarization are simultaneously reproduced. The model assumes the injection of electrons following a power law up to $\gamma_{\rm max} = 8 \times 10^5$ with slope $n = 2.2$. The strength of the self-produced (mostly orthogonal to the shock normal) field at the shock is $B_{\perp,0} = 0.27$ G, while the jet carries a field $B_z = 0.034$ G. The jet, assumed to have a cylindrical shape with radius $R = 4.3 \times 10^{15}$ cm. The self-produced field decay length is $\lambda = 5 \times 10^{13}$ cm. Finally, the bulk Lorentz factor of the downstream flow is $\Gamma = 22$, and the jet is observed at an angle $\theta_{\rm obs} = 1.3^\circ$. The last two parameters give a relativistic Doppler factor of $\delta = 35$.

Owing to the different cooling times $t_{\rm cool}$ (and the corresponding cooling lengths $l_{\rm cool}$, related by $l_{\rm cool} = v_{\rm adv} t_{\rm cool}$) characterizing electrons with different energies, emission at different positions along the synchrotron bump is produced in different volumes of the downstream region (Fig. 2). The short cooling distance of the particles at the highest energies (close to the cut-off around $\gamma \sim 10^6$), radiating in the X-ray band at the peak of the synchrotron component, allows the emission to occur only in a thin region after the shock, where the dominant field is the self-generated, orthogonal magnetic field. The radiation at lower frequencies is produced by electron with a relatively long cooling time, and it is thus emitted in a larger volume, where both the orthogonal and the parallel fields are important, determining the effective dilution of the emerging polarization. Indeed, Fig. 2 shows that a sizeable fraction of the optical emission originates in a region where the orthogonal and parallel fields are comparable. The result is a monotonically decreasing degree of polarization from high to low frequencies. Of course, the same stratification affects the inverse Compton emission, with the TeV radiation produced in a thin layer (comparable to that associated to the X-ray emission) and the GeV component produced in a larger volume.

In this model, a critical parameter for the predicted polarization degree is the angle $\theta_{\rm j}$ between the jet axis and the observer, as measured in the frame of the emitting plasma. An angle of $\theta'_{\rm j} = 90°$ maximizes the polarization in the X-ray band, since the projected self-generated field is fully orthogonal to the jet axis. For smaller viewing angles, both projected (randomly-distributed) B_x and B_y components contribute, resulting in a lower polarization. In the limiting case $\theta'_{\rm j} = 0°$, the effective polarization is zero, since an observer located exactly along the jet axis sees an equal contribution of the two random components of the magnetic field.

As mentioned above, this model is unable to explain the large rotation of the polarization angle displayed by Mkn 421 [14]. For possible explanation see [14].

3. Old challenges: extreme blazars

Among blazars, the so-called extreme blazars (EHBL, [22]) play a unique role [23]. Their extremely hard GeV-TeV spectra extending unbroken up to several TeV is very difficult to explain in standard leptonic models. This, coupled with the small variability at all wavelength, suggests physical conditions quite different from those characterizing standard blazars (e.g. a rather small jet magnetization). Considering only leptonic scenarios, the unusual phenomenology of EHBL has been explained invoking an hard electron distribution with a large minimum energy [24], a maxwellian-like electron distribution [25], internal absorption [26] or emission from a large-scale jet [27].

The tiny magnetization inferred for the jet of EHBL limits the potential role of magnetic reconnection and supports DSA. However, standard electron energy distributions obtained in the framework of DSA for mildly relativistic shocks (i.e. power laws with slopes $\gtrsim 2$) are not suitable to adequately reproduce the SED of EHBL. An interesting proposal [29] invokes the idea of multiple acceleration steps in recollimation shocks. Oblique standing shocks are formed when expanding jets are recollimated by the pressure of an external medium [30]. In this case, classical 2D simulations display the development of a series of compression/expansion phases resulting in the formation of a chain of recollimation/reflection shocks (see, e.g. [31]) In this situation particles can undergo several successive acceleration steps, eventually reaching the hard distribution required by the SED modelling. However, as demonstrated by recent three-dimensional simulations [32], the

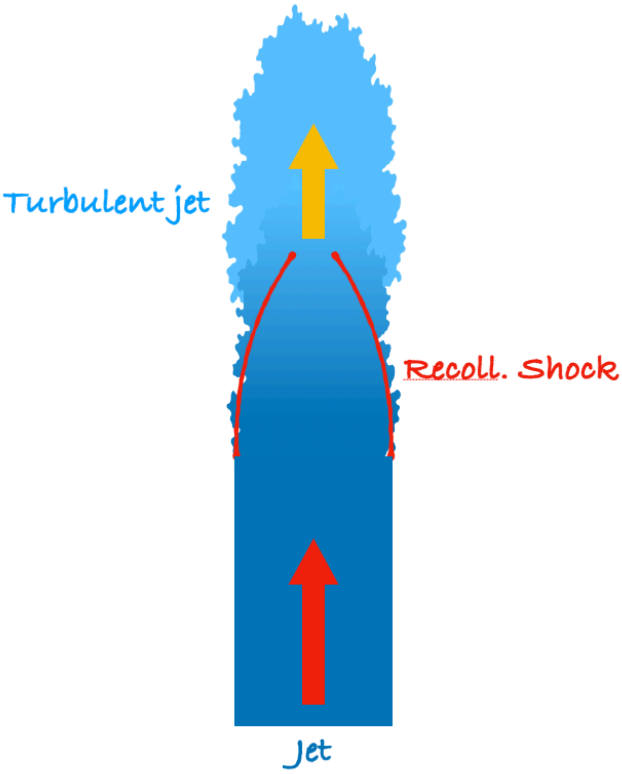

Figure 3: Cartoon of the new scenario proposed for EHBL in [21]. Due to the pressure of an external medium the jet recollimates, triggering the onset of the centrifugal instability recently revealed by 3D simulations. Downstream of the oblique standing shock, the non-linear development of the instability results in a highly turbulent decelerating flow. Relativistic electrons are accelerated at the shock front and, subsequently, in the turbulent flow through stochastic acceleration, reaching a hard equilibrium distribution.

recollimation excites unstable non-axisimmetric modes (involving the interplay of several instability mechanisms, e.g. [33]) that have a strong impact on the jet. The resulting flow includes the first recollimation shock, followed by a decelerated turbulent region (and, for low power jet, by the complete disruption of the jet, [33]). Instabilities could be dumped by a sufficiently large magnetic field (of suitable geometry) [32], but simple estimates suggest magnetization values far in excess of what inferred for EHBL ($\lesssim 10^{-3}$).

These results led [21] to explore the possibility that electrons, after a first acceleration step in the recollimation shock, are further energized through stochastic acceleration in the downstream region, where turbulence is effectively injected by the growing instabilities (see Fig. 3). With a simple approach based on the Fokker-Planck equation for the description of the evolution of the electron distribution, [21] show that the model can satisfactorily reproduce the SED of the prototypical source 1ES 0229+200 assuming physically plausible parameters (see Fig.4). Even better agreement with the data (in particular with the gamma-ray spectrum) is obtained if the back-reaction of the accelerating particles on the turbulence spectrum is considered [28].

Since the emission is thought to occur in a turbulent environment, it seems that a natural

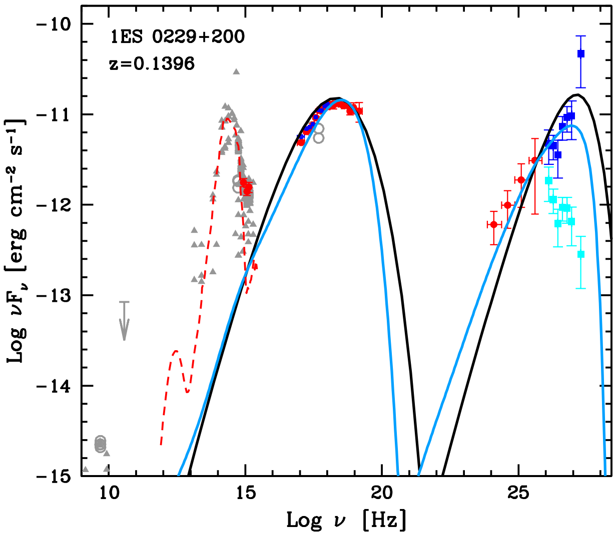

Figure 4: SED of the extreme BL Lac 1ES 0229+200 reproduced with the stochastic acceleration model described in the text. The black line shows the result for stationary turbulence [21], while the cyan line reports the result if the time-dependent dumping of the turbulent energy by the accelerating electrons is taken into account [28].

prediction of the model is a low level of polarization. 1ES 0229+200 has been recently detected by *IXPE* with a degree of polarization about 18% [34]. Although at face value this result seems to challenge our scenario, a careful analysis reveals that this degree of polarization is fully compatible with a relatively high level of turbulence. Following the phenomenological approach of [13], the mean polarization degree of a turbulent emitting region can be estimated as:

$$\langle P\rangle \approx 0.75[f_{\rm ord}^2 + (1-f_{\rm ord})^2 N_{\rm cell}^{-1}]^{\frac{1}{2}}, \tag{1}$$

where $f_{\rm ord} = B/(B+\delta B)$ (with B and δB the ordered and the turbulent magnetic field component) and $N_{\rm cell}$ is the number of turbulent cells. Fixing $f_{\rm ord}$, the minimum is reached when $N_{\rm cell} \to \infty$, therefore the maximum value of $f_{\rm ord}$ necessary to obtain the polarization degree derived by *IXPE* is given by $f_{\rm ord,max} = \langle P\rangle/0.75 \approx 0.24$, which implies $\delta B/B \gtrsim 3$, a value much beyond that assumed in our model (and beyond the scope of the standard quasi-linear theory at the base of the classical treatment of stochastic acceleration). This simplified calculation demonstrates that polarization measured by *IXPE* is compatible with a high level of turbulence, even higher than that required by our scenario.

4. Conclusions

Despite past and current efforts, several fundamental issues concerning the structure and the functioning of relativistic jets escape a complete description. In particular, among the most fundamental topics is how energy is dissipated and through which mechanisms an important fraction of it is conveyed to non-thermal particles. Significant advancements in these topics will require an approach able to combine simulations at macro (MHD) and micro (PIC) scales with phenomenological modelization. As the recent advances I discusses here demonstrate, particularly fruitful is the investigation of the role of the several instabilities potentially disturbing the flow and promoting particles acceleration.

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