INTERNAL SHOCKS AND THE BLAZAR SEQUENCE

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We consider the internal shock model as the dissipation mechanism responsible for the emission in blazars. It has been shown that this model is successful in reproducing the observed spectral energy distribution and the variability properties of a powerful blazar like 3C 279. However, the blazar family covers a wide range of spectral characteristics which appear to be correlated and the whole class can be seen as a sequence: the frequency and the intensity of the low energy versus high energy peak intensity increase with decreasing luminosity. We show that the internal shock model can satisfactorily account also for the properties of the low power blazars like BL Lac and Mkn 421 and it is successful in reproducing the blazar sequence.

1 Introduction

The discovery that blazars are strong $\gamma$-ray emitters together with the results from the multiwavelength campaigns of these sources have allowed to deepen our knowledge on these objects. We know that the Spectral Energy Distribution (SED) of blazars is characterized by two broad emission peaks strongly variable on different timescales. Two main radiation processes produce these peaks, i.e. the synchrotron at low frequencies and the inverse Compton at high energies (see e.g. [1] for a review). The relative importance of the two peaks and their location in frequency appear to be a function of the total power of blazars leading to a blazar sequence. The blazar emission is variable on different timescales, which are typically weekes-months for the radio emission of the order of a day for the $\gamma$-ray.

Several studies, mainly based on the fitting of the observed SED, have allowed us to consistently derive the physical parameters in the emitting region of these sources, however many aspects in the understanding of relativistic jets remain open, most notably the jet energetics and particle acceleration. In order to explore these issues and their relationship we have considered a
scenario where the plasma characteristics are not treated as free parameters, but are the result of the jet dynamics, thus relating the observed emission properties to the transport of energy along the jet. We have achieved that by quantitatively considering a dissipation mechanism within the jet responsible for the emission of blazars analogous to the standard mechanism proposed to explain gamma–ray bursts: the internal shock model. This model was actually originally proposed for blazars more than two decades ago. The most important assumption of the model is that the central power engine produces energy which is channeled into jets in an intermittent way, though such a time dependent process cannot be easily inferred from first principles. The model assumes that different parts of the jet (shells), moving at different speeds can collide producing shocks, giving rise to the non-thermal radiation we see. This mechanism has a limited efficiency because only a small fraction of the bulk energy can be converted into radiation (unless the contrast between the two initial Lorentz factor is huge, see Beloborodov 2000, Guetta et al. 2001, but also Ghisellini 2002). In blazars, on the other hand, the radiative output has to be a small fraction of the energy transported by the jet (less than 10%), since most of the bulk energy has to go un–dissipated to the outer radio–lobes. The low efficiency required for blazars is a characteristic of the model, moreover the internal shock model can naturally explain other properties of these sources: a minimum dimension for the $\gamma$–ray source is required, as well as a minimum distance from the accretion disk, in order to avoid pair production. The internal shock model can naturally account for this, since the jet becomes radiative at ($\gtrsim10^{16} - 10^{17}$ cm) from the black hole. The observed large amplitude variability must be explained by a non steady state model: we believe that the shell–shell collision scenario is the simplest among them. The shells that have already collided once can collide again, at larger distances from the black hole with reduced efficiency, since the Lorentz factor contrast of the colliding shells decreases. This can explain why the luminosity of jets decrease with distance. Fig. 1 shows the efficiency as a function of distance for a simulation we have done for Mkn 421. A detail study via numerical simulations of the predictions of this model in blazars has been carried out by for powerful objects (like 3C279). However the SED of this object does not represent the whole of the blazar family, which covers a wide range of spectral characteristics (luminosity, frequency of the peaks of emission and their relative intensity). We have applied our model to Mkn 421 and BL Lac itself which, besides being among the best studied BL Lac objects, are representative of the extremely blue and intermediate blazar class, respectively. Our aim is to see if the proposed scenario can explain the difference of the SED along the blazar sequence, more than to explain every detail of a particular spectrum of
2 Internal shocks and spectrum

2.1 Generalities

In this work we use the approximate model of the unsteady wind described in detail in Spada et al. (2001) and in the following we report only its most relevant assumptions. We consider a compact source, of typical dimension $R_0 \sim 10^{14}$ cm, which produces an unstable relativistic wind characterized by an average luminosity $L_{\text{jet}}$. The emission from the jet is obtained by adding pulses radiated in a series of internal shocks that occur in the wind. The wind flow is described as a sequence of $N = t_w/t_v$ shells, where $t_w$ is the overall duration of the emission of the wind and $t_v \ll t_w$ is the average interval between two consecutive shells. Each shell is characterized by four parameters (the subscript $j$ denotes the $j$th shell): the ejection time $t_j$, randomly extracted from a uniform distribution with an average value of $t_v$; the Lorentz factor $\Gamma_j$ that is randomly extracted from a distribution between $\Gamma_m$ and $\Gamma_M$; the mass $M_j$ also randomly extracted; the width $\Delta_j \sim R_0$. The dynamics of the wind expansion is characterized by a series of two–shell collisions in which the faster shells catch up with the slower ones in the outer parts of the ejecta. The energy released in each shock is assumed to be distributed among electrons and magnetic field with fractions $\epsilon_e$ and $\epsilon_B$, respectively. In this way we can determine the magnetic field strength needed to evaluate the synchrotron and the inverse Compton emission. Electrons are assumed to be accelerated at relativistic energies with a power law spectrum.

2.2 Local spectra

We refer the reader to Spada et al. (2001) for a detailed description of the derivation of the spectra that is obtained considering the synchrotron, the synchrotron self-Compton (SSC) and the external Compton radiation mechanisms. The only thing we would like to point out is that even in the case of low power BL Lacs we consider the presence of a source of soft photons external to the jet, which we identified with the emission reprocessed in the broad line region (BLR). We consider a luminosity $L_{\text{ext}} = a L_{\text{disk}}$ (with $a \sim 0.1$) produced within $R_{\text{BLR}}$, corresponding to a radiation energy density (as measured in the frame comoving with the shell) $U_{\text{ext}} = (17/12) a L_{\text{disk}} \Gamma^2 / (4\pi R_{\text{BLR}}^2 c)$. (e.g. [4]). For simplicity, this seed photon component is considered to abruptly vanish beyond $R_{\text{BLR}}$. High and low power blazars have different line luminosities (and different photoionizing disk continua). According to Kaspi et al. (2000)
Figure 1: The result of a simulation of the internal shock model for Mkn 421. The average local radiative efficiency and the cumulative efficiency versus the distance from the black hole. The first “peak” in the efficiency corresponds to the first collisions between shells, while the “tail” at larger distances corresponds to second, third (and so on) collisions. The top of the plot shows a schematic representation of the jet, with grey levels proportional to the local efficiency. From Guetta et al. (2002), in prep.
4. $R_{\text{BLR}}$ and $L_{\text{disk}}$ are related by $R_{\text{BLR}} \propto L_{\text{disk}}^b$ with $b \sim 0.7$. This implies that blazars with weaker broad emission lines should have smaller broad line regions. In turn, this implies that, in low power BL Lacs, the first collisions between shells can occur preferentially outside $R_{\text{BLR}}$.

3 Results and Discussion

We applied our model to Mkn 421 and BL Lac itself. In Tab. 1 we list the input parameters used for the model, and for comparison we also report the same parameters for 3C 279. Via the numerical simulations the full time–resolved spectral behavior of the sources can be determined. The full time–dependent behavior of the simulated sources can be also examined through animations (see [http://ares.merate.mi.astro.it/~gabriele/421/index.html](http://ares.merate.mi.astro.it/~gabriele/421/index.html)) in which the temporal and spectral evolutions are simultaneously shown.

The results of this work show that the internal shock model can satisfactorily account also for the properties of the low power blazars. We find that the key model parameters that need to be changed in order to reconstruct the sequence in the frame of the internal shock scenario, are indeed the broad lines intensity and the power carried in the jet which is proportional to the radiative luminosity. These parameters in turn regulate the SED shape, as they control the cooling efficiency of the emitting particles. The internal shock scenario in fact determines a characteristic time interval for the injection of relativistic electrons during each shell–shell collision, of the order of the dynamical timescale $t_{\text{cross}}$. The intensity of the spectrum out of each collision is maximized at the end of this particular timescale. Two regimes are relevant: fast and slow cooling, corresponding to whether electrons of energy $\gamma_b (\gamma_b m_e c^2$ is the minimum energy of the injected electrons) can (fast cooling) or not (slow cooling) radiatively cool in $t_{\text{cross}}$. In highly powerful blazars the fast cooling regime applies in the inner regions (within the BLR) where also most of the power is dissipated. Consequently the peak frequencies are produced by the electrons of energy $\gamma_b m_e c^2$ (as even these electrons can cool in $t_{\text{cross}}$). In the lowest powerful blazars instead the slow cooling regime applies to all collisions. Consequently only the electrons with the highest energy can cool in $t_{\text{cross}}$ (even for the most powerful collisions): the peak frequencies thus shift to very high values. Between these two extremes there is the possibility of BL Lac objects with broad lines of intermediate intensity originating at a distance from the accretion disc within which very few (but not zero) shell–shell collisions can occasionally take place. This is the case of BL Lac itself and all the blazars of intermediate luminosity. Observationally this corresponds to a SED produced by internal shocks of moderate Compton to synchrotron luminosity ratio as
the seed photons for Compton scattering are provided only by the synchrotron photons (collisions outside the BLR). The rare collisions within the BLR will give rise to a dramatic change in the SED characterized by a large increase of the Compton component as in the case of BL Lac itself.

One can conclude that the internal shock scenario explains the blazar sequence and the main characteristics of the blazar behaviour. While observationally we were able to see that the important quantity is the ratio between the observed luminosity in the jet and the disc (thus BLR), the internal shock scenario allows to i) directly connect the radiated jet luminosity with the effective power carried by the jet and ii) account for the preferred distance at which most of the jet luminosity is produced. While the latter distance is qualitatively the same for high and low power blazars, the BLR is instead located at very different distances in the two sub-classes of objects, as determined by the ionizing luminosity.

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| Source     | $\langle L_{\text{jet}} \rangle$ | $\Gamma_m - \Gamma_M$ | $t_v$ | $\epsilon_e$ | $\epsilon_B$ | $L_{\text{BLR}}$ | $R_{\text{BLR}}$ |
|------------|-------------------------------|-----------------------|------|-------------|-------------|----------------|----------------|
| Mkn 421    | 8e45                          | 10–25                 | 1.3e4| 0.5         | 6e-4        | 1e42           | 1e16           |
| BL Lac     | 4e46                          | 10–25                 | 1.6e4| 0.5         | 1e-2        | 8e42           | 7e16           |
| 3C 279     | 1e48                          | 10–25                 | 1.0e4| 0.5         | 4e-3        | 1e45           | 5e17           |

Table 1: Input parameters of the model for the 3 blazars.
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