RELATIVISTIC FLOWS IN BLAZARS

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ABSTRACT The radiation we observe from blazars is most likely the product of the transformation of bulk kinetic energy into random energy. This process must have a relatively small efficiency (e.g. 10%) if jets are to power the extended radio–structures. Recent results suggest that the average power reaching the extended radio regions and lobes is of the same order of that produced by accretion and illuminating the emission line clouds. Most of the radiative power is produced in a well localized region of the jet, and, at least during flares, is mainly emitted in the γ–ray band. A possible scenario qualitatively accounting for these facts is the internal shock model, in which the central engine produces a relativistic plasma flow in an intermittent way.

KEYWORDS: Jets, AGNs, blazars, radiation processes: synchrotron, inverse Compton, electron–positron pairs

1. INTRODUCTION

We believe that the continuum radiation we see from blazars comes from the transformation of bulk kinetic energy, and possibly Poynting flux, into random energy of particles, which quickly produce beamed emission through the synchrotron and the inverse Compton process. This is analogous to what we believe is happening in gamma–ray bursts, although the bulk Lorentz factor of their flow is initially larger.

Evidences for bulk motion in blazars with Lorentz factors between 5 and 20 have been accumulated along the years, especially through the monitoring of superluminally moving blobs on the VLBI scale (Vermeulen & Cohen 1994), and, more recently, through the detection of very large variable powers emitted above 100 MeV (see the third EGRET catalogue, Hartman et al., 1999), which require beaming for the source to be transparent to photon–photon absorption (e.g. Dondi & Ghisellini, 1995).

The explanation of intraday variations of the radio flux, leading to brightness temperatures in excess of $T_B = 10^{18}$ K (much exceeding the Compton limit) are instead still controversial (Wagner & Witzel 1995). Interstellar scintillation is surely involved, but it can work only if the angular diameter of the variable sources is so small to nevertheless lead to $T_B = 10^{15}$ K, which requires either a coherent process to be at work (e.g. Benford & Lesch 1998) or a Doppler factor of the order of a thousand.
Another controversial issue is the matter content of jets. We still do not know if they are dominated by electron–positron pairs or by normal electron–proton plasma (see the reviews by Celotti, 1997, 1998).

Part of our ignorance comes from the difficulty of estimating intrinsic quantities, such as the magnetic field and the particle densities, using the observed flux, which is strongly modified by the effects of relativistic aberration, time contraction and blueshift, all dependent on the unknown plasma bulk velocity and viewing angle. Furthermore it is now clear (especially thanks to multiwavelength campaigns) that the blazar phenomenon is complex.

On the optimistic side, we have for the first time a complete information of the blazar energy output, after the discovery of their $\gamma$–ray emission, and some hints on the acceleration process, through the behaviour of flux variability detected simultaneously in different bands (see the review by Ulrich, Maraschi & Urry 1996). Also, blazar research can now take advantage of the explosion of studies regarding gamma–ray bursts, which face the same problem of how to transform ordered to random energy to produce beamed radiation (for reviews: Piran 1999; Meszaros 1999).

2. ACCRETION = ROTATION?

Despite the prediction that jets carry plasma in relativistic motion dates back to 1966 (Rees, 1966), and intense studies over the last 20 years (Begelman, Blandford & Rees, 1984), quantitative estimates of the amount of power transported in jets have been done only relatively recently, following new observational results.

One important point is that the extended (or lobe) radio emission of radiogalaxies and quasars traces the energy content of the emitting region. Through minimum energy arguments and estimates of the lobe lifetime by spectral aging of the observed synchrotron emission and/or by dynamical arguments, Rawlings & Saunders (1991) found a nice correlation between the average power that must be supplied to the lobes and the power emitted by the narrow line region. Although one always expects some correlation between powers (they both scales with the square of the luminosity distance) it is the ratio of the two quantities to be interesting, being of order of 100. Since we also know that, on average, the total luminosity in narrow lines is of the order of one per cent of the ionizing luminosity, we have the remarkable indication that the power carried by the jet (supplying the extended regions of the radio–source) and the power produced by the accretion disk (illuminating the narrow line clouds) are of the same order.

Celotti, Padovani and Ghisellini (1997) later confirmed this by calculating the kinetic power of the jet at the VLBI scale (see Celotti & Fabian 1993) and the broad line luminosity (assumed to reprocess $\sim 10\%$ of the ionizing luminosity).

A possible explanation involves the magnetic field being responsible for both the extraction of spin energy of a rotating black hole and the extraction of gravitational energy of the accreting matter. Assume in fact that the main mechanism to power
the jet is the Blandford–Znajek (1977) process:

\[ L_{\text{jet}} \simeq \left( \frac{a}{m} \right)^2 U_B(3R_s)^2c \]  

(1)

where \((a/m)\) is the specific black hole angular momentum (\(\sim 1\) for a maximally rotating Kerr hole), \(U_B\) is the magnetic energy density and \(R_s\) is the Schwarzchild radius. Note that Eq. 1 has the form of a Poynting flux. Assume now that most of the luminosity of the accretion disk is produced at \(3R_s\). The corresponding radiation energy density is then \(U_r = L_{\text{disk}}/(36\pi R_s^2c)\), leading to

\[ L_{\text{disk}} = U_r(3R_s)^2c \]  

(2)

Therefore a magnetic field in equipartition with the radiation energy density of the disk would lead to \(L_{\text{jet}} \sim L_{\text{disk}}\).

3. MASS OUTFLOWING RATE

We can estimate the ratio of the outflowing (in the jet) to the inflowing mass rate, since

\[ L_{\text{disk}} = \eta \dot{M}_\text{in}c^2; \quad L_{\text{jet}} = \Gamma \dot{M}_\text{out}c^2; \quad \rightarrow \quad \dot{M}_\text{out} = \frac{\eta L_{\text{disk}}}{\Gamma L_{\text{jet}}} \dot{M}_\text{in} \]  

(3)

If jets carry as much energy as the one produced by the accretion disk, we then obtain that the mass outflow rate is \(\sim 1\%\) of the accreting mass rate (if \(\eta = 10\%\) and \(\Gamma = 10\)).

4. THE BLAZAR DIVERSITY

BL Lac objects and Flat Spectrum Radio Quasars (FSRQ) are characterized by very rapid and large amplitude variability, power law spectra in restricted energy bands and strong \(\gamma\)-ray emission. These common properties justify their belonging to the same blazar class. However they differ in many other respects, such as the presence (in FSRQ) or absence (in BL Lacs) of broad emission lines, the radio to optical flux ratio, the relative importance of the \(\gamma\)-ray emission, the polarization degree, and the variability behavior. Within the BL Lac class, Giommi & Padovani (1994) have subdivided the objects according to where (i.e. at what frequency) the first broad (synchrotron) peak is located. Low energy peaked BL Lacs (LBL) show a peak in the IR–optical bands, while in High energy peaked BL Lacs (HBL) this is in the X–ray band (see, in this volume, the contributions of Costamante et al., Giommi et al., Pian et al., Tagliaferri et al., Tavecchio & Maraschi, Wolter et al.).

As the emission of all blazars is beamed towards us, so there must be a parent population of objects pointing in other directions. The parent populations of BL Lacs and FSRQs are believed to be FR I and more powerful FR II radio galaxies, respectively (see the review by Urry & Padovani 1995). The absence of broad emission lines in BL Lacs is shared by FR I radio galaxies, whose nuclei are well visible
by Hubble Space Telescope observations (Chiaberge, Capetti & Celotti 1999). This suggests that in FR I and BL Lac objects broad emission lines are intrinsically weaker than in more powerful objects.

5. THE RE–UNITED BLAZARS

Fossati et al. (1998) found that the SED of all blazars is related to their observed luminosity. There is a rather well defined trend: low luminosity objects are HBL–like, and furthermore their high energy peak is in the GeV–TeV band. As the bolometric luminosity increases, both peaks shift to lower frequencies, and the high energy emission is increasingly more dominating the total output. Ghisellini et al. (1998), fitted the SED of all blazars detected in the γ–ray band for which the distance and some spectral information of the high energy radiation were available. They found a correlation between the energy $\gamma_{\text{peak}} m_e c^2$ of the electrons emitting at the peaks of the spectrum and the amount of energy density $U$ (both in radiation and in magnetic field), as measured in the comoving frame: $\gamma_{\text{peak}} \propto U^{-0.6}$. This indicates that, at $\gamma_{\text{peak}}$, the radiative cooling rate $\dot{\gamma}(\gamma_{\text{peak}}) \propto \gamma_{\text{peak}}^2 U \sim \text{const}$. It also suggests that this may be due to a “universal” acceleration mechanism, which must be nearly independent of $\gamma$ and $U$: in less powerful sources with weak magnetic field and weak lines the radiative cooling is less severe and electrons can be accelerated up to very high energies, producing a SED typical of a HBL. The paucity of photons produced externally to the jet leaves synchrotron self–Compton as the only channel to produce high energy radiation. At the other extreme, in the most powerful sources with strong emission lines, electrons cannot be accelerated to high energies because of severe cooling. Their spectrum is therefore peaked in the far IR and in the MeV band. In these sources the inverse Compton scattering off externally produced photons is the dominant cooling mechanism, producing a dominant γ–ray luminosity.

5.1. Powers

For the same sample of blazars fitted in Ghisellini et al. (1998) we can estimate the powers radiated and transported by jets in the form of cold protons, magnetic field and hot electrons and/or electron–positron pairs. Since the model allows to determine the bulk Lorentz factor, the dimension of the emitting region, the value of the magnetic field and the particle density, we can then determine

$$L_p = \pi R^2 \Gamma^2 \beta c n_p' m_p c^2; \quad L_e = \pi R^2 \Gamma^2 \beta c n_e' \langle \gamma \rangle m_e c^2; \quad L_B = \pi R^2 \Gamma^2 \beta c \frac{B^2}{8\pi} \quad (4)$$

where $n_p'$ and $n_e'$ are the comoving proton and lepton densities, respectively, $R$ is the cross section radius of the jet, and $\langle \gamma \rangle m_e c^2$ is the average lepton energy. These

\footnote{A note of caution: the limited sensitivity of EGRET (onboard CGRO) and ground based Cherenkov telescopes allows to detect sources which are in high states. Therefore the trend of more high energy dominated spectra as the total power increases strictly refers to high states.}
powers can be compared with the radiated one estimated in the same frame (in which the emitting blob is seen moving). The power radiated in the entire solid angle is thus \( \mathcal{L}_r = \mathcal{L}'_r \Gamma^2 \) (the same holds for the power \( \mathcal{L}_{\text{syn}} \) emitted by the synchrotron process). All these quantities are plotted in Fig. 2 (Celotti & Ghisellini 2000, in prep.). In this figure hatched areas correspond to BL Lac objects. Several facts are to be noted:

- If the jet is made by a pure electron–positron plasma, then the associated kinetic power is \( \mathcal{L}_e \). However, we note that \( \mathcal{L}_e \ll \mathcal{L}_r \) posing a serious energy budget problem.

- If there is a proton for each electron, the bulk kinetic power \( \mathcal{L}_p \sim 10 \mathcal{L}_r \). This corresponds to an efficiency of \( \sim 10\% \) in converting bulk into random energy. The remaining 90\% is therefore available to power the radio lobes, as required.

- The power in the Poynting flux, \( \mathcal{L}_B \), is of the same order of \( \mathcal{L}_e \), indicating that the magnetic field is close to equipartition with the electron energy density. This suggests that, on these scales, the magnetic field is not a prime energy carrier, but is a sub–product of the process transforming bulk into random energy.

6. INTERNAL SHOCKS

The central engine may well inject energy into the jet in a discontinuous way, with individual shells or blobs having different masses, bulk Lorentz factors and energies. If this occurs there will be collisions between shells, with a faster shell catching up a slower one. This idea has become the leading model to explain the emission of gamma–ray bursts, but it was born in the AGN field, due to Rees (1978) (see also Sikora 1994).

- **Location** — The \( \gamma \)-ray emission of blazars and its rapid variability imply that there must be a preferred location where dissipation of the bulk motion energy occurs. If it were at the base of the jet, and hence close to the accretion disk, the produced \( \gamma \)-rays would be inevitably absorbed by photon–photon collisions, with associated copious pair production, reprocessing the original power from the \( \gamma \)-ray to the X–ray part of the spectrum (contrary to observations). If it were far away, in a large region of the jet, it becomes difficult to explain the observed fast variability, even accounting for the time–shortening due to the Doppler effect. The region where the radiation is produced is then most likely located at a few hundreds of Schwarzschild radii (\( \sim 10^{17} \) cm) from the base of the jet, within the broad line region (see Ghisellini & Madau 1996 for more details). The extra seed photons provided by emission lines enhance the efficiency of the Compton process responsible for the \( \gamma \)-ray emission. This is indeed the typical distance at which two shells, initially separated by \( R_0 \sim 10^{15} \) cm (comparable to a few Schwarzschild radii) and moving with \( \Gamma \sim 10 \) and \( \Gamma \sim 20 \) would collide.
FIGURE 1. Histograms of the powers carried by the jet in protons, total radiation, synchrotron radiation, magnetic field and relativistic electrons, from top to bottom. Hatched areas correspond to BL Lac objects. The electron distribution was assumed to extend down to $\gamma_{\text{min}} \sim 1$. From Celotti & Ghisellini (2000, in prep.)
FIGURE 2. Cartoon illustrating the internal shock scenario. The intermittent activity of the central engine produces two shells, initially separated by $R_0$. The faster one will catch up the slower one at $R \sim \Gamma^2 R_0$.

- **Variability timescales** — In fact if the initial separation of the two shells is $R_0$ and if they have Lorentz factors $\Gamma_1, \Gamma_2$, they will collide at

$$R = \frac{2\Gamma_1^2}{1 - (\Gamma_1/\Gamma_2)^2} R_0 \quad (5)$$

If the shell widths are of the same order of their initial separation the time needed to cross each other is of the order of $R/c$. The observer at a viewing angle $\theta \sim 1/\Gamma$ will see this time Doppler contracted by the factor $(1-\beta \cos \theta) \sim \Gamma^{-2}$. The typical variability timescale is therefore of the same order of the initial shell separation. If the mechanism powering GRB and blazar emission is the same, we should expect a similar light curve from both systems, but with times appropriately scaled by the different $R_0$, i.e. the different masses of the involved black holes.

- **Efficiencies** — As most of the power transported by the jet must reach the radio lobes, only a small fraction can be radiatively dissipated. The efficiency $\eta$ of two blobs/shells for converting ordered into random energy depends on their masses $m_1, m_2$ and bulk Lorentz factors $\Gamma_1, \Gamma_2$, as

$$\eta = 1 - \Gamma_f \frac{m_1 + m_2}{\Gamma_1 m_1 + \Gamma_2 m_2} \quad (6)$$
where $\Gamma_f = (1 - \beta_f^2)^{-1/2}$ is the bulk Lorentz factor after the interaction and is given by (see e.g. Lazzati, Ghisellini & Celotti 1999)

$$\beta_f = \frac{\beta_1 m_1 + \beta_2 m_2}{\Gamma_1 m_1 + \Gamma_2 m_2}$$

(7)

The above relations imply, for shells of equal masses and $\Gamma_2 = 2\Gamma_1 = 20$, $\Gamma_f = 14.15$ and $\eta = 5.7\%$.

Efficiencies $\eta$ around $5\text{–}10\%$ are just what needed for blazar jets.

- **Peak energies?** — In the rest frame of the fast shell, the bulk kinetic energy of each proton of the slower shell is $\sim (\Gamma' - 1)m_pc^2$, where $\Gamma' \sim 2$. This is what can be transformed into random energy. Assume now that the electrons share this available energy (through an unspecified acceleration mechanism). In the comoving frame, the acceleration rate can be written as $\dot{E}_{\text{heat}} \sim (\Gamma' - 1)m_pc^2/t_{\text{heat}}'$. The typical heating timescale may correspond to the time needed for the two shells to cross, i.e. $t_{\text{heat}}' \sim \Delta R'/c \sim R/(c\Gamma)$, where $\Delta R'$ is the shell width (measured in the same frame). The heating and the radiative cooling rates will balance for some value of the random electron Lorentz factor $\gamma_{\text{peak}}$:

$$\dot{E}_{\text{heat}} = \dot{E}_{\text{cool}} \rightarrow \frac{\Gamma m_pc^3}{R} = \frac{4}{3}\sigma_T cU\gamma_{\text{peak}}^2 \rightarrow \gamma_{\text{peak}} = \left(\frac{3\Gamma m_pc^2}{4\sigma_TRU}\right)^{1/2}$$

(8)

The agreement of the above simple relation with what can be derived from model fitting the SED of blazars is surprisingly good (see Ghisellini 2000).

- **Radio flares** — Collisions between shells may (and should) happen in a hierarchical way. As an illustrative example, assume that one pair of shells after the collision moves with a final Lorentz factor $\Gamma_1 = 14$ (this number corresponds to $\Gamma = 10$ and 20 for the two shells before the interaction). The collision produces a flare –say– in the optical and $\gamma$–ray bands. After some observed time $\Delta t$ two other shells collide and another flare is produced. Assume that the final Lorentz factor is now $\Gamma_2 = 17$ (corresponding to an initial $\Gamma = 10$ and 30 before collision). Since the second pair is faster, it will catch up the first one after a distance (from eq. 5) $R \sim 1200c\Delta t$. A time separation of $\Delta t \sim 1$ day between the two flares then corresponds to $R \sim 1$ pc, i.e. the region of the radio emission of the core. Due again to Doppler contraction, this radio flare will be observed only a few days after the second optical flare. Since the ratio $\Gamma_2/\Gamma_1$ is small, the efficiency is also small (at least a factor 10 smaller than the firsts shocks). There is then the intriguing possibility of explaining the birth of radio blobs after intense activity (i.e. more than one flare) of the higher energy flux. Radio light–curves should have some memory of what has happened days–weeks earlier at higher frequencies.

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7. CONCLUSIONS

Here I will dare to assemble different pieces of information gathered in recent years in a coherent, albeit still preliminary, picture.

There is a link between the extraction of gravitational energy in an accretion disk and the formation and acceleration of jets, since both have the same power. Objects of low luminosity accretion disks also lack strong emission lines, suggesting that it is the paucity of ionizing photons, not of gas, the reason for the lack of strong lines in BL Lacs. Correspondingly, this implies that, if FR I are the parents of BL Lacs, they also have intrinsically weak line emission (i.e. no need for an obscuring torus). Despite the fact that the jet power in blazars spans at least four orders of magnitude, the average bulk Lorentz factor is almost the same, suggesting a link between the power and the mass outflowing rate: their ratio is constant. In the region where most of the radiation is produced, the jet is heavy, in the sense that protons carry most of the bulk kinetic energy. There the jet dissipates $\sim 10\%$ of its power and produces beamed radiation. The power dissipated at larger distances is much less, and therefore the jet can transport $\sim 90\%$ of its original power to the radio extended regions. One way to achieve this is through internal shocks, which can explain why the major dissipation occurs at a few hundreds Schwarzschild radii, why the efficiency is of the order of 10%, and give clues on the observed variability timescales and even on why electrons are accelerated at a preferred energy. The spectral energy distribution of blazars depends on where shell–shell collisions take place, and on the amount of seed photons present there. Even in a single source it is possible that the separation of two consecutive shells is sometimes large, resulting in a collision occurring outside the broad line region. In this case the corresponding spectrum should be produced by the synchrotron self–Compton process only, without the contribution of external photons: we then expect a simultaneous optical–$\gamma$–ray flare of roughly equal powers (but with the self–Compton flux varying quadratically, see Ghisellini & Maraschi 1966). This is what should always happen in lineless BL Lac objects. On the other hand, if the initial separation of the two shells is small (or the $\Gamma$–factor of the slower one is small), the collision takes place close to the disk. X–rays produced by the disk would then absorb all the produced $\gamma$–rays and a pair cascade would develop, reprocessing the power originally in the $\gamma$–ray band mainly into the X–ray band. We should therefore see an X–ray flare without accompanying emission above $\Gamma m_e c^2$.

Pairs of shells which have already collided can interact again between themselves, at distances appropriate for the radio emission. This offers the interesting possibility to explain why the radio luminosity is related with the $\gamma$–ray one, and why radio flares are associated with flares at higher frequencies. Work is in progress in order to quantitatively test this idea against observations.

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