Relativistic electron beams in IDV blazars

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Abstract. The observed variability of BL Lac objects and Quasars on timescales $\lesssim 1$ day (intraday variability, IDV) have revealed radio brightness temperatures up to $T_{\rm b} \sim 10^{16} - 10^{20}$ K. These values challenge the beaming model with isotropic comoving radio emission beyond its limits, requiring bulk relativistic motion with Lorentz factors $\Gamma \gtrsim 100$. We argue in favor of a model where an anisotropic distribution of relativistic electrons streams out along the field lines. When this relativistic beam is scattered in pitch angle and/or hits a magnetic field with components perpendicular to the beam velocity it starts to emit synchrotron radiation and redistribute in momentum space. The propagation of relativistic electrons with Lorentz factor $\gamma_0 \sim 10^2 - 10^4$ reduces the intrinsic variability timescale $\Delta t'$ to the observed value $\Delta t \sim \Delta t'/\gamma_0$ so that the intrinsic brightness temperature is reduced by a factor of order $\sim 1/\gamma_0^2$, easily below the Inverse Compton limit of $T_{\rm b} \lesssim 10^{12}$ K. When looking at a single event we expect the variability time scales Δt to be independent of frequency for a monoenergetic electron beam, whereas for a beam with a spread out distribution of energies (e.g. power-law) parallel to the magnetic field the timescales are shortened towards higher frequencies according to $\Delta t \propto \nu^{-0.5}$. The observations seem to favor monoenergetic relativistic electrons which explain several properties of variable blazar spectra. The production of variable X- and gamma-ray flux is briefly discussed.

Key words: acceleration of particles – plasmas – radiation mechanisms: non-thermal – BL Lacertae objects: general – galaxies: jets – galaxies: quasars: general

1. Introduction

It has become a reliable observational fact that active galactic nuclei are variable on all timescales throughout the whole electromagnetic spectrum from the radio range up to the gamma-ray-range (see Wagner and Witzel 1995 for a comprehensive review).

An especially interesting type of variability arises in the radio range on the timescales of less than one day, called intraday variability (IDV). IDV at radio frequencies has brought up significant difficulties with the standard picture of beamed intrinsically isotropic incoherent synchrotron emission. If the variability timescale Δt is used to calculate the source size by $l \sim c\Delta t$, where c is the velocity of light the resulting brightness temperatures reach up to the range $T_{\rm b} = 10^{16} - 10^{20}$ K, far in excess of the inverse Compton limit of $T_{\rm b} = 10^{12}$ K. The question arises: What is the physical nature of this very intense variable radio emission?

We first summarize the properties of the varying sources. They usually vary on the 5-10% level at cm wavelengths (Witzel 1992) but it may also be as high as 35% (Quirrenbach et al. 1992). The sources that show IDV of the total intensity generally also show IDV of the polarised flux and the polarisation angle, usually (anti-) correlated. The typical Blazar that is variable on such short timescales seems to have the following properties (Wegner 1994): 1.) it reveals a compact structure on VLBI scales (VLA compactness is not sufficient), 2.) associated variability of the polarisation, 3.) if the object is variable at radio frequencies, it is also variable in the optical, 4.) all BL Lac objects are variable, 5.) sources with a positive spectral index $\alpha_2^6 \approx 0.2$ between 2 and 6 cm ($I_\nu \propto \nu^\alpha$) show the largest variability amplitudes.

In the standard picture of beamed intrinsically isotropic emission it is found that a brightness temperature T' in the comoving frame will be seen as a variability brightness temperature of $T_{\rm b} \sim D^3 T'$, where $D = [\Gamma(1 - \beta\cos\theta)]^{-1}$ is the Doppler factor of the jet (Blandford et al. 1990). Here $\Gamma = (1 - \beta^2)^{-1/2}$ is the bulk Lorentz factor, βc the jet velocity in the observers frame and θ the angle between the jet and the line of sight. The Doppler factors calculated from the observed superluminal expansion are of the order of $D \lesssim 10$ (Cawthorne 1991). This is much too low to explain the extreme values of $T_{\rm b}$ found in sources with IDV which would require $D \gtrsim 100$. Begelmann et al. (1994) discuss the energetic constraints on highly relativistic jets ($\Gamma \sim 30 - 100$ to explain $T_{\rm b} \gtrsim 10^{16}$ K) and find that the jet must carry kinetic energy fluxes comparable to the total power of a luminous quasar ($L \gtrsim 10^{47}\,{\rm erg\,s^{-1}}$), whereas many objects with IDV are low luminosity AGN of the BL Lac type.

A completely different point of view involves coherent emission (Baker et al. 1988; Krishan and Wiita 1990; Benford 1984, 1992; Lesch and Pohl 1992). Coherent radiation easily accounts

for huge T_b, since the radiation intensity is due to collective emission of all particles within a coherent volume. The rather involved physics is well known from plasma laboratory experiments. The central argument against coherent radiation processes in AGN is the limitation of the brightness temperature by induced Compton scattering and/or Raman scattering (Coppi et al. 1993; Levinson and Blandford 1995). However, it was shown by Benford and Lesch (1998) that the saturation arguments are not valid for strong Langmuir turbulence excited by relativistic electron beams and radiated coherently via inverse Compton scattering.

In this contribution we would like to present an alternative scenario, which considers the possibility that the energy distribution function of the synchrotron emitting relativistic electrons is not isotropic in pitch angle throughout its propagation in the very center of an AGN. In other words we consider an electron beam, whose momentum parallel to the magnetic field is considerably higher than its momentum perpendicular to the field lines. The advantage of this model is that the synchrotron brightness temperature of a beam distribution has to be calculated with the square Lorentz factor of the particles (instead of the bulk Lorentz factor for an isotropic distribution), which can be of order $10^2 - 10^4$. Then the discrepancy of the inverse Compton limit of 10^{12}K with the observed values up to 10^{20}K is resolved.

In the next section we consider the formation and propagation of relativistic electron beams within the environment of active galactic nuclei. Here we especially investigate the conditions for isotropization by magnetohydrodynamic turbulence and how this redistribution towards larger pitch angles can be avoided in regions with high magnetic field strength. What follows is a calculation of the resulting synchrotron radiation of beams for two cases: for a beam with a narrow energy distribution (quasi-monoenergetic with a clearly defined low and high energy cutoff) and a beam with a broad energy distribution (power law). Finally we discuss our results and its implications for different parts of the electromagnetic spectrum from the radio up to the gamma-ray range.

2. Formation and propagation of a relativistic electron beam

In this section we consider the formation of a beam of relativistic particles near the central supermassive black hole in an active galactic nucleus and its propagation in the jet.

2.1. Acceleration of beam particles

We consider a spinning back hole with mass $M_{BH} = 10^8 M_\odot M_8$ and angular velocity Ω_{BH} with an accretion disk that brings in ionized gas and magnetic fields with strength $B_0 \sim 10^4 B_4$ G near the hole. The rotating magnetic field lines excert a torque and accelerate particles to high energies (Gangadhara and Lesch, 1997). The Lorentz factors obtained in this way are limited by the inverse Compton interaction of the relativistic particles with the ambient radiation field, basically UV

photons from the disk. This leads to the production of X- and γ-rays. The electrons will lose their energy perpendicular to the magnetic field very rapidly due to synchrotron radiation in a time

$$t_S = 5 \, 10^{-3} \gamma_{0,3}^{-1} B_4^{-2} \sin^{-2}\alpha \,\, \text{sec} \qquad (1)$$

where α is the angle between the particle velocity and the magnetic field and $\gamma_0 = 10^3 \gamma_{0,3}$ is the Lorentz factor of the relativistic electrons. The combined action of acceleration and inverse Compton losses results in a monoenergetic distribution of relativistic electrons propagating along the magnetic field. The particles accumulate at the energy where the timescales for gains and losses are equal and balance each other.

Another possibility for the formation of relativistic particle beams along the magnetic field is by means of reconnecting magnetic fields in the inner part of the accretion disks and their coronal environments. Schopper et al. (1998) have clearly shown that acceleration by magnetic reconnection and energy losses via synchrotron radiation and/or inverse Compton scattering leads to beam-like energy distributions. Their test-particle simulations use realistic magnetohydrodynamical magnetic field structures originating in sheared, magnetized gas flows as the back stage for the acceleration process. Keplerian shear of the field lines leads to the build up of strong magnetic gradients, corresponding to high current densities, which finally are dissipated by localized three-dimensional magnetic reconnection structures with a length d. Three-dimensional magnetic reconnection is equivalent to the presence of magnetic field aligned electric fields $E_\parallel$ along which particles are efficiently accelerated on very small time scales (Schindler et al. 1991). Thus, the maximum energy $eE_\parallel d$ is reached by almost all particles, only a few particles are influenced by energy losses. Finally a quasi-monoenergetic electron distribution function results.

We note that in the central 50 pc and the inner 10^{13} cm of the Milky Way several locations (Arc and Sgr A*) reveal inverted radio spectra, in which the flux increases with frequency with an exponent 1/3, which is easily interpreted as optically thin synchrotron radiation of quasi-monoenergetic electron distributions (Lesch and Reich 1992; Duschl and Lesch 1994). Such a spectrum has also been observed in M81, which is classified as a "dead" Seyfert nucleus (Reuter and Lesch 1996; Böttcher et al. 1997).

Obviously central regions of galactic nuclei are preferred physical environments for the formation of beams. The main reason is that both mechanisms, centrifugal acceleration and magnetic reconnection are natural constituents of a rotating magnetized system, including turbulent gas motions and directed flows (jets), which are all supposed to be necessary ingredients of models for active galactic nuclei (e.g. Blandford et al. 1990 for a general review)

2.2. Stability of the beam

The question arises if these streaming particles can excite Alfvén waves and if they are scattered in pitch angle, which would lead to isotropisation. It is generally believed that this occurs

throughout the whole jet. Instead we will argue now that this can not be the case for the innermost part considered here. The phase velocity v_ϕ of Alfvén waves with frequency ω and wavenumber k propagating at an angle θ with respect to the magnetic field is given by (Krall and Trivelpiece 1973)

$$v_\phi^2 = \frac{\omega^2}{k^2} = V_A^2 \, \cos^2 \theta \left(\frac{1 + V_A^2}{c^2} \right)^{-1} . \tag{2}$$

Here the parameter called the Alfvén velocity is

$$V_A = B / \sqrt{4 \pi m_p n_p} \tag{3}$$

where m_p is the mass and n_p is the number density of the protons constituting the background plasma that carries the waves. The numerical value is given by $V_A = 2.2 \, 10^{11} n_p^{-1/2} B$ cm/s. Near the black hole this is larger than the speed of light for $n_p < 5.3 \, 10^9 B_4^2$ cm^{-3}. If one asssumes that the total kinetic power of the jet is in thermal material this is just about the maximum average gas density in the jet (Celotti et el., 1998). Since it is much more likely that the gas is confined in filamentary structures (probably on the rim of the jet), the density of gas that can carry Alfvén waves in the central regions of the jet is much lower. In fact from the lack of significant Faraday rotation in BL Lac objects Celotti et al. (1998) derived $n_p f_V \lesssim 10^6$ cm^{-3} at the base of the jet (with radius $R_0 = 10^{14}$ cm) where f_V is the volume filling factor of the thermal material. So either the density or the the volume filling factor is low. They concluded that most of the energy in the jet is carried by the relativistic particles and the magnetic field in BL Lac objects.

The relativistic electrons can generate and interact with the waves when the resonance condition

$$\omega - s\Omega - k_\parallel v_\parallel = 0 \tag{4}$$

is fulfilled. Here $k_\parallel = k \cos \theta$ and $v_\parallel = v \cos \alpha$ are the components of the wave vector and the particle velocity along the magnetic field, respectively, with α being the pitch angle. Further, s is the harmonic number of the gyromagnetic interaction and $\Omega = \Omega_e / \gamma_0$, with $\Omega_e = eB/mc$, is the relativistic gyrofrequency of the electrons. The case of resonant scattering of Alfvén waves occurs when (Melrose, 1986)

$$|k_\parallel v_\parallel| \approx |s\Omega| \gg \omega . \tag{5}$$

From Eqs. (4) and (5) it follows that resonance is only possible when

$$\frac{c}{V_A} \left(1 + \frac{V_A^2}{c^2} \right)^{1/2} \beta \cos \alpha \gg 1 \tag{6}$$

where β is the velocity of the particles normalized by c. In the case $V_A \gg c$ this condition reads $\beta \cos \alpha \gg 1$, which cannot be fulfilled. When the phase velocity of the Alfvén waves along the field is close to c the waves that propagate in the medium are almost purely electromagnetic; these are ineffective in pitch angle scattering. Achatz and Schlickeiser (1993) find that an electron-positron beam is completely stable for

$$\frac{\omega_p}{\Omega_e} < \left(\frac{2}{\gamma_0 - 1} \right)^{1/2} \tag{7}$$

where $\omega_p = (4 \pi n_e e^2 / m_e)^{1/2}$ is the plasma frequency. This can be compared with the condition as discussed above, since we can write $V_A / c = (m_e / m_p)^{1/2} \Omega_e / \omega_p \gtrsim (\gamma_0 m_e / m_p)^{1/2} \sim 1$. So for the Lorentz factors considered here both are essentially the same.

It seems that in the acceleration region near the black hole anisotropy is favored and a quasi monoenergetic and one-dimensional beam of relativistic particles can propagate along the magnetic field.

2.3. Disruption of the beam

The relativistic beam distribution of electrons with number density N_0 and

$$N(\gamma) = N_0 \, \delta(\gamma - \gamma_0) \tag{8}$$

and the background plasma carry a current that produces a toroidal component $B_\perp$ of the magnetic field near the rim of the jet. The strength scales with the radius R of the jet as

$$B_\perp = B_{\perp,0} \left(\frac{R}{R_0} \right)^{-1} \tag{9}$$

and confines it magnetically. The poloidal magnetic field in the central part of the jet falls off as

$$B_\parallel = B_{\parallel,0} \left(\frac{R}{R_0} \right)^{-2} . \tag{10}$$

As the jet widens in radius the parallel field ceases to be important.

It is now interesting to ask when the Alfvén velocity V_A becomes less than c. The scaling (9) for the toroidal magnetic field gives a constant value of V_A when the particle density scales according to

$$n_p = n_0 \left(\frac{R}{R_0} \right)^{-2} . \tag{11}$$

But since the internally dominating poloidal field falls off more rapidly we find that the Alfvén velocity is below the velocity of light for $B / n_p^{1/2} \lesssim 0.1$ or

$$\frac{R}{R_0} \gtrsim 10^2 \, B_{0,4} n_{0,6}^{-1/2} \tag{12}$$

with $n_0 = 10^6 n_{0,6}$ cm^{-3}. This means that the beam of relativistic electrons will not be scattered in pitch angle as long as the jet has not expanded enough. When condition (12) is fulfilled, i.e. when $R \gtrsim 10^{16}$ cm and consequently $B_\perp \sim 10^2$ G the beam will rapidly start to excite Alfvén waves which scatter the particles in pitch angle leading to isotropisation. The flow of the particles becomes unstable and turbulent as the relativistic beam particles couple to the background medium. A standing shock will develop some distance L away from the black hole, which can be identified with the VLBI core. The relativistic electrons then run into a shock compressed magnetic field with large perpendicular components and impulsively start to radiate.

3. Emission from the relativistic electron beam

The radiation will be dominated by the perpendicular magnetic field component. The relativistic particle beam hits the magnetic field with a Lorentz factor γ_0 and starts to emit synchrotron radiation. Although the individual electron will have its emission confined to an angle of the order of $1/\gamma_0$, the overall emisson of the jet will be spread over an angle $\varphi \sim 0.1$, the opening angle of the jet. The spectrum reaches up to the frequency (e.g., Longair 1981)

$$\nu_c = \frac{3}{2}\gamma_0^2 \nu_e \sin\alpha = 4.2\,10^{14}\gamma_{0,3}^2 B_2 \sin\alpha \text{ Hz} \qquad (13)$$

where $\nu_e = \Omega_e/2\pi$ is the nonrelativistic gyrofrequency. Thus we have emission from radio frequencies up to the optical. The intensity I_ν is proportional to $\nu^{1/3}$ for frequencies $\nu \ll \nu_c$ and falls off exponentially for $\nu \gg \nu_c$. This naturally gives the observed inverted spectra of compact radio sources in Blazars. Self-absorption effects may become important at lower radio-frequencies.

The duration of a radiation event at a fixed location in the observers frame is given by

$$\Delta t = \frac{\Delta t'}{\gamma_0} \approx \frac{l'}{c}\gamma_0^{-1} \qquad (14)$$

where $\Delta t'$ is the corresponding time interval in the beam frame and l' is the intrinsic length scale of the beam. In the case of ~ 10 hrs variability from a $\gamma_0 = 10^3$ beam the length scale is given by $l' \sim 10^{18}$ cm. The brightness temperature that is calculated from light travel time arguments is then overestimated by a factor γ_0^2 since

$$T_B \propto (c\Delta t)^{-2} = (c\Delta t'/\gamma_0)^{-2} = l'^{-2}\gamma_0^2 \qquad (15)$$

and l' is the comoving size of the emitting region. The variability timescale is the same at every frequency, from the optical down to the radio. The observed variability timescale will be given by (14) as long as it is larger than the radiative loss time, see Eq. (1). If the latter becomes larger it smears out the first, because then the whole beam seems to flare up with the synchrotron life time of the particles. From Eqs. (1) and (9) we find the condition

$$\frac{R}{R_0} \lesssim 3\,10^3 \gamma_{0,3}^{1/2} B_{0,4} \left(\frac{\Delta t}{10 \text{ hrs}}\right)^{1/2} \qquad (16)$$

assuming $B_\perp$ to be dominant during the emission, according to what is seen in BL Lac objects. As long as the radius is limited in such a way, variability is dominated by Doppler boosting. Indeed jet formation models yield fairly constant radii over large distances (Camenzind 1996).

If we assume the energy distribution of the beam to be a power-law (still with zero perpendicular momentum)

$$N(\gamma) \propto \gamma^{-s} \qquad (17)$$

the emission of synchrotron radiation at a certain frequency will be dominated by the particles with a Lorentz factor given by relation (13). The variability timescale then depends on the frequency. Using (13) and (14) the dependence is found to be

$$\Delta t \propto \gamma^{-1} \propto \nu^{-1/2}. \qquad (18)$$

This means that for a spread in the energy distribution of the radiating particles the spectral emission will be variable on a shorter timescale at higher frequencies.

4. Further evolution of the spectrum

When the beam starts to dissipate its energy into radiation the distribution of the particles in energy space will change. If mono-energetic electrons (8) are injected quasi-continuously and are confined in the radiating volume for a time long compared to the synchrotron loss timescale ($\sim 10^5$ sec to allow cooling down to $\gamma \sim 1$ with the parameters considered here), the particle distribution will become

$$N(\gamma) \propto |\dot{\gamma}|^{-1} \propto \gamma^{-2}. \qquad (19)$$

This produces a radiation spectrum $I_\nu \propto \nu^{-0.5}$ which is very flat. This is rather stable because the particles now are isotropic in the comoving jet frame and do not have the large beaming factor as before but only the one from the bulk plasma motion, namely Γ. Together with the beam radiation one has a highly variable polarised $\nu^{0.3}$ component and a less variable or constant $\nu^{-0.5}$ power-law component with a different degree and angle of polarisation. This combination seems to fit to the observations quite well. A two-component model was already suggested by Qian et al. (1991) to explain the drastic variations in the linear polarisation.

Assuming that the beam is quasi-steady we also have to consider the inverse Compton scattering of the power-law component from the background jet by high energy beam particles. Since the secondary component radiates isotropically in the jet frame (also backwards), the beam electrons will have head-on collisions with those photons (radio to optical). The photons scattered in the observer's direction will be boosted in frequency by a factor of order γ_0^2, thus producing a power-law radiation component from the optical, over the X-ray to the gamma-ray part of the spectrum. This emission is beamed towards an observer who also receives the radio to optical radiation, probably with a time lag. The timescale for the variability of this high frequency radiation is also determined by fluctuations in the beam structure and should therefore be given by Eq. (14), i.e., it is of the same order of magnitude as for the variations in the radio-optical part. In fact this is seen in IDV-blazars (Wagner and Witzel 1995). Since the variability time-scale depends on the high Lorentz factor of the beam electrons and not on the bulk Lorentz factor of the background jet plasma, the constraints on the compactness of the emitting region are much less stringent.

5. Summary and discussion

We consider a model for BL Lac objects and quasars that show variabiliy on timescales less than a day. The basic ingredient is

a monoenergetic relativistic electron beam. We discuss the formation and stability of such an anisotropic distribution and find that it is stable as long as the magnetic field along the jet is strong enough. The beam can propagate along the field lines without being scattered. When the phase velocity of the Alfvén waves starts to depart significantly from the velocity of light the beam will excite magneto-hydrodynamic waves. The particles will be scattered in pitch angle and start to emit synchrotron radiation at radio to optical frequencies. The electrons in the beam are then coupled to the background plasma of the jet. The spectrum of the monoenergetic particles which are injected quasi-continuously evolves to a power-law. This gives rise to a second component in the radiation spectrum. Concerning the high brightness temperatures derived from variability arguments in IDV blazars, the upper limit on the compactness of the emitting region is relaxed by the Lorentz factor of the beam, which can be much larger than the bulk Lorentz factor of the jet.

It seems even possible, when the Lorentz factor of the beam particles is of the order of $\gamma_0 \sim 10^6$, that also highly variable emission in the TeV range observed in several AGN (e.g. Mkn 421; Gaidos et al. 1996) can be produced this way. There the observed timescales go down to 0.5 hours. This is beyond the capabilities of models involving bulk relativistic beaming of intrinsically isotropic distributions of particles and radiation with particle acceleration at shocks. When the TeV emission comes from an anisotropic beam distribution the intrinsic length is only restricted to $l' \lesssim 10^{20}(\Delta t/1\,\mathrm{hr})(\gamma_0/10^6)$ cm. This reduces the opacity of $\gamma - \gamma$ interactions below its critical value.

For the objects considered here the Lorentz factor of the monoenergetic electron beam is in the range $10^2 - 10^4$. This is the basic input parameter. The model presented in this paper can account for several features observed in IDV blazars:

1.) the high variability brightness temperatures by relativistic effects

2.) synchrotron radiation from the monoenergetic beams has an inverted spectral index as observed in the most variable sources

3.) the dominant timescale is quasi-stable, which can be understood in terms of the distance from the black hole where the standing shock develops

4.) together with the radiation from the reprocessed beam, a two-component model can be constructed, to explain drastic changes in the polarisation and its angle

5.) in such a combination $I_\nu \propto a\nu^{0.3} + b\nu^{-0.5}$ one also expects the radio variations to be more pronounced at higher frequencies, which is seen in the modulation index

6.) since the synchrotron radiation of the beam reaches from the radio up to the optical, correlated variability (with the same timescale) is obviously explained

7.) a larger variability amplitude at optical frequencies compared to the radio is expected (and observed)

8.) correlations of the radio spectral-index with optical flux (flatter spectrum when optical flux rises) without any measurable time lag can be understood in terms of the varying $\nu^{1/3}$ emission, which gives the simultaneous fluctuations at radio and optical frequencies and also a spectral flattening (increase of spectral index) of the summed components

9.) because the degree of polarisation of synchrotron radiation from a monoenergetic distribution depends on the frequency (contrary to a power-law distribution) this also gives a key to the observed variations and the frequency dependence of the polarisation and its angle

10.) if the emission of the two components are polarised (nearly) orthogonal to each other, this goes along with anticorrelated variations of the total and the polarised flux (this is the case for BL Lac objects, where the magnetic field is perpendicular to the jet)

11.) if the polarisation of the two components is parallel, correlated variability of the total and polarised flux is expected (this is the case for quasars, where the magnetic field is oriented parallel to the jet)

12.) time lags between total and polarised emission may be attributed to the reprocession of beam particles into the power-law distribution

13.) variability at X-ray and gamma-ray wavelengths (with timescales comparable to the radio/optical) can be accounted for in head-on collisions of photons radiated backwards from the power-law component (comoving with the background jet) off beam electrons by inverse Compton scattering.

This model seems to be compatible with many properties of IDV blazars. It is now necessary to work out the details of the acceleration and radiation processes and to compare them with specific objects.

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