BOUNDARY SHEAR ACCELERATION IN THE JET OF MKN501

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ABSTRACT
The high resolution image of the jet of the BL Lac object MKN501 in radio, show a limb-brightened feature. An explanation of this feature as an outcome of differential Doppler boosting of jet spine and jet boundary due to transverse velocity structure of the jet requires large viewing angle. However this inference contradicts with the constraints derived from the high energy $\gamma$-ray studies unless the jets bends over a large angle immediately after the $\gamma$-ray zone (close to the central engine). In this letter we propose an alternate explanation to the limb-brightened feature of MKN501 by considering the diffusion of electrons accelerated at the boundary shear layer into the jet medium and this consideration does not require large viewing angle. Also the observed difference in the spectral index at the jet boundary and jet spine can be understood within the frame work of shear acceleration.

Key words: galaxies: active - galaxies: jets - BL Lacertae objects: individual(MKN501) - acceleration of particles - diffusion

1 INTRODUCTION
BL Lac objects are the extreme class of active galactic nuclei(AGN) with weak or no emission lines and are categorized along with flat spectrum radio quasars(FSRQ) as blazars. Their spectra cover a broad range of photon energies starting from radio to gamma rays with a few of them detected in TeV energies by ground based Air Cerenkov experiments[Krawczynski (2004); Katarzynski, Sol, & Kus (2001); Sambruna (2000) Costamante & Ghisellini (2002)]. These sources are found to be strongly variable with flare time scales ranging from days to less than an hour [Gardos et al. (1994); Coppi & Aharonian (1999); Sambruna (2000) Krawczynski et al. (2001)]. The short time variability and their detection at very high energies demand that the emission region should be moving down a jet at relativistic velocities close to the line of sight of the observer [Ghisellini et al. (1993); Dondi & Ghisellini (1993)]. The strong polarization detected in radio/optical energies and the non-thermal photon spectra indicates the radio to x-ray spectra is due to synchrotron radiation from a non-thermal electron distribution cooling in a magnetic field. However the gamma ray emission from these sources is still not well understood. Leptonic models explain the high emission as inverse Compton scattered synchrotron photons by the electron population responsible for the synchrotron process itself(SSC) [Maraschi, Ghisellini, & Celotti (1992); Bloom & Marscher (1996); Böttcher (2000)] where as in hadronic models it is due to the synchrotron proton emission and proton-photon interactions involving an external photon field (synchrotron proton blazar model(SPB)) [Mannheim (1998); Mücke et al. (2003)]. Under unification hypothesis of radio-loud AGN, BL Lac objects are considered to be aligned jet version of Fanaroff-Riley type I (FRI) radio galaxies [Urry & Padovani (1995)].

MKN501 is a nearby BL Lac object (z=0.034) and also the second extra galactic source detected in TeV photon energies by ground based Cherenkov Telescopes [Quinn et al. (1996)]. It was later detected in MeV photon energies by the satellite based experiment EGRET [Kataoka et al. (1994)]. The radio images of MKN501 show a jet emerging from a bright nucleus [Edwards et al. (2000); Giovannini et al. (1999); Aaron (1999); Giroletti et al. (2004)]. The high resolution (milli arc second) radio images show a transverse jet structure with the edges being brighter than the central spine commonly referred as "limb-brightened" structure [Edwards et al. (2000); Giovannini et al. (1999); Giroletti et al. (2004)]. This feature is usually explained by the "spine-sheath" model where the velocity at the jet spine is larger compared to the velocity at the boundary. Such a radial stratification of velocity across the jet arises when jet moves through the ambient medium and the viscosity involved will cause a shear at the boundary. Three-dimensional hydrodynamic simulations of relativistic jets...
boundary can also be accelerated via shear acceleration. In the present work, the acceleration of particles in a shear flow or by turbulence is well studied by various authors for both relativistic and non relativistic case [Earl, Jakipini, & Morfill (1988); Webb (1989); Ostrowski (1990); Stawarz & Ostrowski (2002); Rieger & Duffy (2006); Stawarz & Petrosian (2008); Virtanen & Vainio (2003)].

In this letter we explain the observed limb-brightened feature of MKN501 by considering the diffusion of electrons accelerated at the jet boundary via shear acceleration. In the next section we show the required condition for the shear acceleration to be dominant over turbulent acceleration and in §3 we consider the diffusion of particles accelerated at the boundary into the jet medium.

2 SHEAR ACCELERATION AT MKN501 JET BOUNDARY

The particle acceleration process at the jet boundary can be described by the diffusion equation in momentum space. The evolution of an isotropic phase space distribution is given by (Melrose (1968))

\[ \frac{\partial f(p)}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D(p) \frac{\partial f(p)}{\partial p} \right) \]

where \( D(p) \) is the momentum diffusion coefficient. The characteristic acceleration timescale can be written as

\[ t_{acc} = p^3 \left( \frac{\partial}{\partial p} (p^2 D(p)) \right)^{-1} \]

If we consider a sheared flow, the electrons are scattered across different velocity layers by turbulent structures which are embedded in the shear flow. Berezhko (1981) showed in such case there will be a net gain of energy in the electrons getting scattered and this process is referred as shear acceleration. The momentum diffusion coefficient in case of a shear flow can be written as (Rieger & Duffy (2006; Rieger, Bosch-Ramon, & Duffy (2007))

\[ D_s(p) = \chi p^2 \tau \]

where \( \tau \) is the mean scattering time given by \( \tau \approx \lambda/c \) with \( \lambda \) the mean free path and \( \chi \) is the shear coefficient given for a relativistic flow as (Rieger & Duffy (2004))

\[ \chi = \frac{c^2}{15(\Gamma(r)^2 - 1)} \left( \frac{\partial \Gamma}{\partial r} \right)^2 \]

where \( \Gamma(r) \) is the bulk Lorentz factor of the flow and \( r \) is the radial coordinate of the jet cross section. Using (4), the shear acceleration timescale \( t_{acc}^{(s)} \) for \( \tau = \tau_0 p^5 \) will be

\[ t_{acc}^{(s)} = \frac{1}{(4 + \xi) \chi \tau} \]

In case of turbulent acceleration (stochastic), the particles are scattered off by randomly moving scattering centres and
gets energized by second order Fermi acceleration. The momentum diffusion coefficient in this case can be approximated as (Rieger, Bosch-Ramon, & Duffy (2007))

$$D_t(p) \approx \frac{n^2}{\lambda^3} \left( \frac{V_A}{c} \right)^2$$  \hspace{1cm} (6)

where the Alfvén velocity ($V_A$) is given by

$$V_A = \frac{B}{\sqrt{4\pi \rho}}$$  \hspace{1cm} (7)

Here $B$ is the magnetic field and $\rho$ the mass density of the jet. Hence the turbulent acceleration timescale ($t_{acc}(\xi)$) will be

$$t_{acc}(\xi) = \frac{3\pi}{(4-\xi)} \left( \frac{c}{V_A} \right)^2$$  \hspace{1cm} (8)

For shear acceleration to be dominant over turbulent acceleration $t_{acc}(\xi) < t_{acc}(\xi)$. If we consider Bohm diffusion ($\xi = 1$) then the mean free path of the electron aligned to the magnetic field ($\lambda_1$) scales as the gyro radius ($r_\gamma$) (Achterberg & Ball (1994)), $\lambda_1 \approx \eta \frac{m_e c^2}{eB^2}$, where $\eta$ is a numerical factor ($\eta > 1$ for magnetized particles) and $\gamma (\gg 1)$ is the Lorentz factor of the electron scattered. Since the magnetic field at the jet boundary of MKN501 is parallel to the jet axis (or toroidal) (Aaron (1999); Pushkarev et al. (2003); Gabuzda (1999)), we consider $\tau \approx \lambda_1/c$. Also if we consider

$$\frac{\partial r}{\partial r} \approx \frac{\Delta \Gamma}{\Delta r}$$  \hspace{1cm} (9)

where $\Delta \Gamma$ is the difference between the bulk Lorentz factor at the jet spine and the jet boundary and $\Delta r$ is the thickness of the shear layer, then the condition for shear acceleration to be dominant over turbulent acceleration will be

$$\Delta r < \frac{\eta \gamma m_e c^2 (\Delta \Gamma)}{eB^2} \left[ \frac{4\pi \rho}{3(1(\gamma^2 - 1))} \right]^{1/2}$$  \hspace{1cm} (10)

If we consider the mass density of the jet is dominated by cold protons and if the number of protons are equal to the number of non-thermal electrons, then the jet mass density can be written in terms of equipartition magnetic field ($B_{eq}$) as

$$\rho \approx \frac{m_p B_{eq}^2 (2\alpha - 1)}{16 \pi m_e c^2 \alpha \gamma_{min}}$$  \hspace{1cm} (11)

and (10) will be

$$\Delta r < 0.29 \frac{\eta \gamma c^2 (\Delta \Gamma)}{eB_{eq}} \left[ \frac{m_e m_p (2\alpha - 1)}{\alpha \gamma_{min} (\Gamma^2 - 1)} \right]^{1/2}$$  \hspace{1cm} (12)

where $\alpha$ is the observed photon spectral index, $m_e$ is the proton mass and $\gamma_{min}$ is the Lorentz factor of electron responsible for the minimum observed photon frequency $\nu_{min}$. The equipartition magnetic field can be expressed in terms of observed quantities as

$$B_{eq} \approx 9.62 \left( \frac{1}{\Gamma(r)} \left( m_e c^2 \nu_{min} \right) \right) ^{\frac{1}{2}} \left( \frac{d_T F (\nu_{min})}{V \sigma_T (2\alpha - 1)} \right) ^{\frac{1}{2}} G$$  \hspace{1cm} (13)

where $F (\nu_{min})$ is the flux at the minimum observed frequency $\nu_{min}$, $d_T$ is the luminosity distance, $V$ is the volume of the emission region and $\sigma_T$ is Thomson cross section. Hence, for $\Gamma(r)^2 \gg 1$ and $\alpha \approx 0.7$, shear acceleration will dominate the particle spectrum at the jet boundary of MKN501 if the thickness of the shear layer

$$\Delta r < 7.22 \times 10^{-9} \times \left( \frac{\eta}{10} \right) \left( \frac{\Delta \Gamma}{10} \right) \left( \frac{\nu_{obs}}{\nu_{min}} \right) ^{1/2} \left( \frac{\nu_{min}}{10 MHz} \right) ^{1/2} \times \left( \frac{B(10 MHz)}{6 \times 10^{-4} G} \right) ^{1/2} \left( \frac{\mu \nu}{1.5 \times 10^{-4}} \right) ^{1/2} \left( \frac{R}{910 \text{parsec}} \right) ^{1/4} \left( \frac{\gamma}{10} \right) ^{1/2} \left( \frac{\Gamma(r)}{5} \right) ^{1/2} \times$$

$$\left( \frac{\Gamma(r)}{10} \right) ^{-2}$$  \hspace{1cm} (14)

Where $R$ is the radius of the spherical region considered. (We assume $10 MHz \approx 10^{-4}$ as minimum observed frequency and the flux at $10 MHz$ is obtained from the flux at $1.6 GHz$ considering the same spectral index. The flux at $1.6 GHz$ and $R$ in (14) are obtained from a region around RA 10 mas and declination $-10$ mas from Fig.7 of Giroletti et al. (2004)). The corresponding equipartition magnetic field $B_{eq}$ for $\Gamma = 5$ is $1.2 \times 10^{-3} G$.

The electrons accelerated by shear acceleration cool via synchrotron radiation. The cooling time for synchrotron loss is given by

$$t_{cool} = \frac{6 \pi m_e c}{\eta \sigma_T B_{eq}^2}$$  \hspace{1cm} (15)

Using (15) and (16), we find

$$t_{cool} \approx 1.5 \times 10^{-12} \left( \frac{B}{1.2 \times 10^{-3} G} \right)^3 \left( \frac{\eta}{10} \right)^{-1} \left( \frac{\Gamma(r)}{5} \right)^2 \times$$

$$\left( \frac{\Delta r}{10^{-8} \text{parsec}} \right) ^{2} \left( \frac{\Delta \Gamma}{10} \right)^{-2}$$  \hspace{1cm} (16)

and since $t_{cool} \ll t_{cool}$, shear acceleration dominates over synchrotron cooling. It can be noted that (16) is independent of the electron energy and hence the maximum energy of the electron will be decided by the loss processes other than synchrotron loss (which are not considered in this simplistic treatment).

If we maintain the general form of mean scattering time $\tau = \tau_0^{\xi}$, then for shear acceleration to dominate over turbulent acceleration the thickness of the shear layer ($\Delta r$) should be

$$\Delta r < 1.7 \times 10^6 \frac{\tau_0^{\xi} (\Delta \Gamma)}{\Gamma(r)} \left( \frac{4 + \xi)(2\alpha - 1)}{16 \pi m_e c^2 \alpha (4 - \xi) \gamma_{min}} \right) ^{1/2} \text{cm}$$  \hspace{1cm} (17)

It can be noted that (10) is equal to (17) if we set in the latter $\xi = 1$ and $\tau_0^{\xi} = \eta r_\gamma/c$.

3 PARTICLE DIFFUSION AT THE JET BOUNDARY AND LIMB-BRIGHTENING

Particles accelerated at the shear layer of the jet boundary, diffuse into the jet medium before getting cooled off via synchrotron radiation. As the magnetic field at the jet boundary is parallel to the jet axis (or toroidal) (Aaron (1999); Pushkarev et al. (2003); Gabuzda (1999)), the radial diffusion of the electron into the jet medium is determined by cross field diffusion. The cross field diffusion coefficient can be approximated as (Axford (1965); Jokipii (1987); Achterberg & Ball (1994))

$$D_{\perp} \approx \frac{1}{3 \eta} r_\gamma c$$  \hspace{1cm} (18)

Where $\eta (\gg 1)$ is the scaling factor determining the field aligned mean free path (see (19)).
The radial distance $R_{diff}$ that the electron diffuse before getting cooled can then be approximated as

$$R_{diff} \approx \sqrt{\kappa_{\perp} \lambda_{cool}}$$  \hfill (19)$$

Using (15) and (18) and considering the equipartition magnetic field we get

$$R_{diff} \approx 2.9 \times 10^{-4} \left( \frac{\nu}{10^3} \right)^{-\frac{1}{2}} \left( \frac{B}{1.2 \times 10^{-4} G} \right)^{-\frac{1}{2}} \text{parsec}$$  \hfill (20)$$

Since the thickness of the shear layer $\Delta \tau \ll R_{diff}$ (refer [14] and [20]), the thickness of the limb brightened structure will be $\approx R_{diff}$. This corresponds to an angular distance of $4.7 \times 10^{-4} \text{mas}$ which is beyond the resolution of present day telescopes.

For $\tau = \tau_0 p^\xi$, the cross field diffusion coefficient will be

$$\kappa_{\perp} \approx \frac{1}{3\eta_0 r^2} \xi$$  \hfill (21)$$

Using (15) and (19) we get

$$R_{diff} \approx 5.2 \times 10^{15} B^{-2} \tau_0^{-\frac{1}{2}} \xi^{-\frac{1}{2}} \text{cm}$$  \hfill (22)$$

and hence the thickness of the limb brightened structure will be energy dependent for $\xi \neq 1$.

### 4 SPECTRAL INDEX

If we add mono-energetic particle injection term ($\delta(p-p_o)$) and particle escape term ($-1/\tau_{esc}$) in (1), then the steady state equation in case of shear acceleration for $p > p_o$ and $\xi = 1$ can be written as

$$p \frac{d^2 f_s}{dp^2} + 5p^2 \frac{df_s}{dp} - \frac{f_s}{\chi_{\perp} \nu_{esc}} = 0$$  \hfill (23)$$

and in case of turbulent acceleration it will be

$$p \frac{d^2 f_t}{dp^2} + 3p \frac{df_t}{dp} - \frac{f_t}{\psi_{esc}} = 0$$  \hfill (24)$$

where $\psi = \frac{\nu^2}{2\tau_0 \tau_a}$. If we substitute $p = 1/x$ in (23) we get

$$x \frac{d^2 f_s}{dx^2} - \frac{3f_s}{x} - \frac{f_s}{\chi_{\perp} \nu_{esc}} = 0$$  \hfill (25)$$

Equations (24) and (25) can be solved analytically (Kepinski (1993)) and the solutions are complex and are given by

$$f_s = \left( \frac{1}{\chi_{\perp} \nu_{esc}} \right)^2 \times \left[ a_s J_4 \left( 2i \sqrt{\frac{\psi_{esc}}{\chi_{\perp} \nu_{esc}}} \right) + b_s Y_4 \left( 2i \sqrt{\frac{\psi_{esc}}{\chi_{\perp} \nu_{esc}}} \right) \right]$$  \hfill (26)$$

and

$$f_t = \left( \frac{\psi_{esc}}{p} \right) \left[ a_t J_4 \left( 2i \sqrt{\frac{p}{\psi_{esc}}} \right) + b_t Y_4 \left( 2i \sqrt{\frac{p}{\psi_{esc}}} \right) \right]$$  \hfill (27)$$

Where $J_n(z)$ and $Y_n(z)$ are the Bessel functions of first and second kind and $as$, $bs$, $at$ and $bt$ are constants. For negligible escape ($\tau_{esc} \to \infty$), using the limiting forms of Bessel functions (Abramowitz & Stegun (1972)), the solutions (26) and (27) approaches a power law $f_s \propto p^{-4}$ and $f_t \propto p^{-2}$. The shear accelerated particle number density will then be $n_s(p) \propto p^{-2}$ and the corresponding synchrotron photon flux will be $S_{\nu, shear} \propto \nu^{-1/2}$. For turbulent acceleration the number density will be independent of $p$ ($n_t(p) \propto p^0$) and hence the observed synchrotron photon flux will be a flat one $S_{\nu, turb} \propto \nu^{1/3}$. The spectral index map of MKN501 jet indicates a steep photon spectra at the boundary and flat spectra at the spine (Giroletti et al. (2004)). Hence it can be argued that the shear acceleration may be dominant at the jet boundary of MKN501 and turbulent acceleration at the jet spine. However $\xi$ is usually related to the turbulent spectral index (Biermann & Strittmatter (1982)) which may be different at the jet boundary and jet spine.

### 5 DISCUSSION

As the AGN jet moves through the ambient medium the viscosity involved will cause a shear at the jet boundary and hence acceleration of particles in these shear layer is unavoidable. If the shear gradient $\partial \tau / \partial r$ is very steep or if the shear layer is very thin (14), then shear acceleration can dominate over the turbulent acceleration initiated by the instabilities at the jet boundary (Eilek (1982)). Turbulent acceleration may play an important role at the interior regions of the jet (Virtanen & Vainio (2005)) and can provide an alternative to explain the emission from the inner knot regions of AGN jets (Macchetto (1996), Jester et al. (2001)). The observed hard spectra at the jet spine (Giroletti et al. (2004)) also supports this inference since turbulent acceleration can produce a hard particle spectra (Virtanen & Vainio (2005)) (also shown in section §4). The electrons accelerated by the turbulence can be reacelerated by shocks and can form a broken power law electron spectrum. This can possibly explain the break in the radio-to-x-ray spectra of the knots of FRI jets (Sahayanathan (2008)).

Giroletti et al. (2004) calculated the jet viewing angle ($\theta$) using the correlation between the core power and the total power (Giovannini et al. (2001)). They estimated the jet viewing angle to be within $10^\circ < \theta < 27^\circ$ by comparing the observed core radio power and the expected intrinsic core power derived from the correlation. However this estimation may vary if the core flux density variability is more than factor 2. Also considering the variation of the parameter values in the correlation with increase number of samples, this may not provide a strong constrain on the jet viewing angle. The estimate of $\theta$ based on the adiabatically expanding relativistic jet model (Baum et al. (1997)) may not be a strong constraint as it considers a simplified situation. Also the constrain is less severe in case of perpendicular magnetic fields and observed polarisation studies have indicated the presence of perpendicular magnetic fields at jet spine (Pushkarev et al. (2005); Aaron (1994)).

Stawarz & Ostrowski (2002) proposed a model similar to the present one, however their aim was to show the observational implications of the two-component particle spectrum (power law distribution with high energy pile-up) formed at the boundary shear layer and the complex beaming pattern.

### 6 CONCLUSION

The observed limb brightened structure seen in the radio maps of MKN501 jet can be explained if we consider the...
shear acceleration of particles at the boundary due to velocity stratification and their diffusion into the jet medium. This inference does not demand large viewing angle which is required otherwise for the explanation via differential Doppler boosting of the jet spine and boundary. We have shown that shear acceleration dominates over turbulent acceleration at the boundary if we consider thin shear layer or a sharp velocity gradient. Also for the estimated set of parameters, shear acceleration timescale is much smaller than synchrotron cooling timescale allowing acceleration of electrons to be possible. The thickness of the limb brightened structure will be decided by the distance electrons have diffused into the jet medium before losing its energy via synchrotron cooling timescale. The radio spectral index map of MKN501 jet is also observed to have steep spectra at the boundary supporting the presence of shear acceleration.

The author is grateful to the anonymous referee for his useful comments which helped in clearing many of the ignorances and a better understanding. The author acknowledges the useful discussions with S. Bhattacharyya, N. Bhatt, M. Choudhury and A. Mitra. The author is grateful to L. Stawarz and F. M. Rieger for enlightening information on various topics related to shear acceleration.

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