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Magnetic reconnection in extragalactic jets

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Abstract. The extended nonthermal emission of extragalactic jets can only be explained by in situ particle acceleration. The only energy source in the entire jet region is the magnetic field. Magnetic reconnection can convert the free energy stored in the helical configuration to particle kinetic energy. In the collisionless magnetized jet plasma it is inertia driven reconnection operating in a highly filamentary magnetic flux rope that results in a continuous acceleration of high-energy particles.

1 Introduction

Extragalactic jets are characterized by continuous synchrotron radiation up to the X-ray range. Recently, observations by Chandra X-ray satellite indicate beyond all doubt that the X-ray emissions from Centaurus A and Pictor A stem from synchrotron radiating electrons. The radiating leptons have Lorentz factors up to $\gamma \sim 10^8$. The jets represent stable magnetohydrodynamic outflows collimated by helical (probably filamentary) current carrying magnetic flux rope configurations (see Benford (1978); Villata and Ferrari (1994)). Since the synchrotron spectra of the jets, e.g. of M87 (Meisenheimer et al., 1996). show astonishingly smooth variations of the optical and radio spectral indices and since the jet lengths (several kpc) largely exceed the electron loss lengths (~ 100 pc in the optical range) limited by the synchrotron losses, the problem of reacceleration of the electrons arises. Meisenheimer et al. summarized the necessary ingredients for an acceleration scenario based on the observations of 11 powerful radio galaxies (Meisenheimer et al., 1997). They argued that the interplay of local shock acceleration in the well defined knots and hot spots and a second unspecified acceleration mechanism which depends on the shear of the extended jets and should not be effective where shocks accelerate the electrons can explain the observed spectral index distribution. In a promising picture the necessary free energy for the in situ acceleration of leptons is supplied by the magnetic field and converted during reconnection events (Vekstein et al., 1994; Blackman, 1996; Lesch and Birk, 1998; Birk and Lesch, 2000). The energetic properties of reconnection in terms of achievable particle energies depend on the local violation of magnetic flux conservation. In the following we try to establish that field-aligned electric fields associated with the aforesaid reconnection mechanism are responsible for the acceleration of charged particles to very high energies which reveal themselves by synchrotron radiation detected even in the X-ray range.

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2 Particle Acceleration by Field-Aligned Electric Fields due to Inertia Mediated Reconnection

Extragalactic jet engines can be regarded as electric field generators that apply electric fields perpendicular to the jet flows. As a consequence of a toroidal magnetic field component associated with some plasma shear flow at the jet footpoints a mainly field-aligned electric current flows along the jet axis (e.g. Camenzind (1996) for a review on MHD models of cosmic jets). Some portion of the magnetic energy, i.e. injected magnetic helicity, can be converted to high energy particle acceleration via field-aligned electric fields during magnetic reconnection processes. We established (Lesch and Birk, 1998; Birk and Lesch, 2000) a parameterization for the efficiency α of the energy conversion

$$\alpha = \frac{cE_{||}}{v_A B} \tag{1}$$

where $E_{||}$, B, v_A, and c are the parallel component of the electric field, the magnetic field strength, the Alfvén velocity $v_A = B/(4\pi\rho)^{1/2}$ ($\rho = nm_p$ denotes the mass density, with the number density n and the proton mass m_p), and the speed of light. The necessary condition for the onset of magnetic reconnection is a localized violation of ideal Ohm's law

$$\boldsymbol{E} + \frac{1}{c}(\mathbf{v} \times \boldsymbol{B}) = \boldsymbol{R} \tag{2}$$

where $\boldsymbol{v}$ and $\boldsymbol{R} \neq 0$ are the plasma bulk velocity (which is the velocity of the jet flow, in our context) and some unspecified non-ideal term (see Schindler et al. (1991)). Since the relativistic plasma of extragalactic jets is highly collisionless the non-idealness is caused by particle inertia

$$E_{||} = \frac{m_e}{ne^2}\left|\frac{\partial \boldsymbol{j}}{\partial t} + \nabla\cdot(\boldsymbol{vj}+\boldsymbol{jv})\right| \approx \kappa \frac{\lambda_{skin}^2}{L_{shear}^2}\frac{v_A}{c}B \tag{3}$$

where L_{shear} and $\lambda_{skin} = c(m_e/4\pi ne^2)^{1/2}$ (m_e and n are the electron mass and particle density) denote the spatial scale of the magnetic field inhomogeneity, i.e. thickness of the current sheets of the filamentary current carrying magnetic field configuration that represents the jet, and the electron skin length. The ratio of the bulk velocity and the Alfvén velocity is denoted by $\kappa = v/v_A$. Thus, the efficiency of energy conversion is given by $\alpha = \kappa\lambda_{skin}^2/L_{shear}^2$ in the case of inertia driven magnetic reconnection. The right-hand side of Eq.(3) represents the one-fluid description of the non-ideal effect of electron inertia which is identified to be responsible for collisionless reconnection in a rigorous two-fluid approach (Biskamp et al., 1997). On the considered scales one deals with electron magnetohydrodynamics. As discussed in the context of solar flares (see Somov and Kosugi (1997) and references therein) Eq.(3) describes the collisionless transformation of free magnetic energy into particle acceleration via inductive electric fields along the main magnetic field component.

The acceleration length L_{acc} and thereby the energies the particles can gain are limited by synchrotron losses (Burns et al., 1983; Israel, 1998) $L_{syn} = ct_{syn} = 4\pi m_e c^2/\sigma_T\gamma B^2$ (where σ_T is the Thomson cross section), and, thus, we assume $L_{acc} = L_{syn} = L$. In the following we apply our model, e.g., to the case of the Centaurus A X-ray jet. In order to accelerate electrons up to a Lorentz factor of $\gamma \approx 8\cdot 10^7$ (Burns et al., 1983)

$$\gamma = 8\cdot 10^7 = \frac{eE_{||}L}{m_e c^2} \tag{4}$$

we obtain with the help of equation(1) and the expression for the synchrotron losses for the efficiency of the reconnection process

$$\alpha = \frac{c\sigma_T}{4\pi e}\gamma^2(4\pi\rho)^{1/2} \approx 0.01\left(\frac{n}{10^{-2}\mathrm{cm}^{-3}}\right)^{1/2}. \tag{5}$$

For synchrotron losses the efficiency α is independent of the magnetic field strength. Such an efficiency implies a thickness of the current filaments of $L_{shear} \approx 10\kappa^{1/2}\lambda_{skin}$. If collisionless reconnection is the dominant process responsible for electron re-acceleration in Centaurus A the magnetic energy must be converted in very thin filamentary current sheets of widths of $L_{shear} \approx 500\kappa^{1/2}$km for particle densities of $n = 0.01\mathrm{cm}^{-3}$. A highly filamentary configuration is natural for MHD flows under the influence of external forces. The electric currents flow parallel to the poloidal magnetic field and will evolve into a filamentary structure by inducing local toroidal magnetic fields which isolate one filament from the other (Wiechen et al., 1998). Some shear of current carrying filaments cannot be opposed by resistivity since the particles do not collide. The current filaments shrink to spatial scales where the particle inertia becomes important. The overall structure of the jet is given by a force-free magnetic configuration that represents the lowest state of magnetic energy (Taylor, 1986).

With equations(1) and (4) the achievable Lorentz factor is given by

$$\gamma = \left(\frac{4\pi}{m_p}\right)^{1/4}\left(\frac{e}{\sigma_T c}\right)^{1/2}\frac{\alpha^{1/2}}{n^{1/4}}. \tag{6}$$

For reasonable particle densities and a relatively high efficiency of the reconnection process the acceleration in the reconnection regions can result in Lorentz factors high enough to contribute, e.g., to the observed X-ray luminosity in the Centaurus A jet. The particles are accelerated in generalized electric potential structures $U = -\int_L E_{||}ds$ (Schindler et al., 1991) where the integral is extended along the magnetic field line element ds. The strengths of the field-aligned electric fields $E_{||}$ can be estimated for a given magnetic field strength. Taking $B \approx 60\mu$G from minimum pressure calculations (Burns et al., 1983) we find from equations(3) and (5)

$$\begin{aligned} E_{||} &= \frac{\alpha}{c}\frac{B^2}{(4\pi n m_p)^{1/2}} \\ &\approx 3\cdot 10^{-9}\left(\frac{B}{60\mu\mathrm{G}}\right)^2\left(\frac{n}{10^{-2}\mathrm{cm}^{-3}}\right)^{-1/2}\frac{\mathrm{statvolt}}{\mathrm{cm}}. \end{aligned} \tag{7}$$

3 Time scales

In order to get a feeling for the timescales involved in the inertia-driven reconnection processes it is helpful to find the growth rate of the tearing mode, which can be regarded as a generic reconnection mechanism. Different from the resistive tearing instability the electron inertia term plays the dominant role in the resonant layer of the unstable mode. In a two-dimensional treatment (say $\partial/\partial z = 0$) the dispersion relation can be found as a solution of the boundary layer problem (Lesch and Birk, 1998)

$$q\nabla\cdot(\rho_0\nabla u_1) - \left(\boldsymbol{B}_0\cdot\nabla\triangle + \frac{dj_0}{dA_0}\boldsymbol{B}_0\cdot\nabla\right)A_1 = 0 \tag{8}$$

$$\boldsymbol{B}_0\cdot\nabla u_1 + (\alpha\triangle - 1)qA_1 = 0 \tag{9}$$

where the indices 0 and 1 denote equilibrium and perturbed quantities, respectively, and $\boldsymbol{B} = \nabla A\times\boldsymbol{e}_z$ as well as $\boldsymbol{v} = \nabla u\times\boldsymbol{e}_z$ have been used. The solution is obtained as

$$\frac{\pi\rho_0^{1/4}}{\alpha^{3/4}}\sqrt{q}\frac{\Gamma\left(\frac{\Lambda+3}{4}\right)}{\Gamma\left(\frac{\Lambda+1}{4}\right)}\frac{1}{1-\Lambda^2} = \frac{1-k^2}{\sqrt{k}} \tag{10}$$

where q and k denote the (complex) growth rate and the wave number and $\Lambda = q\rho_0^{1/2}/k\alpha^{1/2}$. Figure 1 shows solutions of

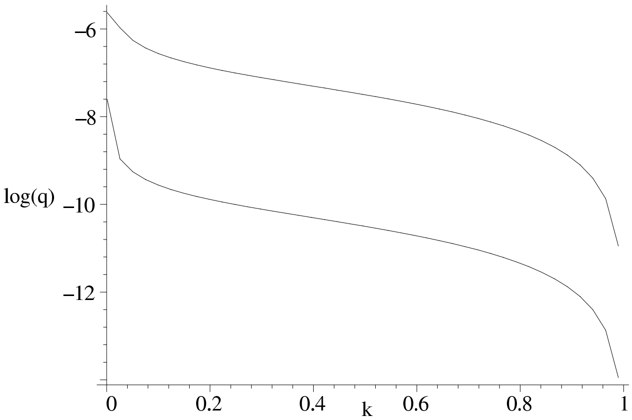

Fig. 1. The normalized real growth rate log(q) of the inertia driven tearing mode in logarithmic representation is plotted against the normalized wave number k for $\alpha = 10^{-5}$ (upper curve) and $\alpha = 10^{-7}$ (lower curve).

the dispersion relation for the efficiencies $\alpha = 10^{-5}$ (upper curve) and $\alpha = 10^{-7}$ (lower curve). For a magnetic field strength of $B = 10^{-5}$G and a particle density of $n = 10^{-2}\mathrm{cm}^{-3}$ a normalized real growth rate of $q = 10^{-7}$ corresponds to a reconnection time scale of $\tau_{rec} = 16$yr. This means that synchrotron loss processes can easily be compensated by reconnection events. One should have in mind that the linear tearing growth time gives an upper limit of the time scale of the actual dynamic reconnection process.

4 Luminosity

The total radiation power is released in a huge number of relatively small scale reconnection events in the highly filamentary current system of the jet. The luminosity emitted in a reconnection flux tube filament is

$$\mathcal{L}_{fil} = \frac{B^2}{8\pi} \frac{L L_{shear} w}{\tau_{rec}} \tag{11}$$

where w is the width of the current filament. By τ_{rec} the time scale of the reconnection process is denoted, i.e. the tearing growth time as a first (and linear) guess. An upper limit of the luminosity is given by

$$\begin{aligned}\mathcal{L}_{fil} &= \frac{m_e c^2}{2\sigma_T \gamma} \frac{\tau_A}{\tau_{rec}} v_A w \\ &\leq \frac{1}{2} \frac{m_e c^{5/2}}{(4\pi)^{3/4} m_p^{1/4} (\sigma_T e)^{1/2}} \frac{B w}{n^{1/4} \alpha^{1/2}}\end{aligned} \tag{12}$$

where $\tau_A = L_{shear}/v_A$ is the Alfvénic transit time. The inequality arises from the fact that the reconnection process cannot work faster than the Alfvénic time scale ($\tau_{rec} \geq \tau_A$).

If we consider $\tau_{rec} \approx \tau_A$, current filaments with comparable widths and thicknesses $w = L_{shear}$, which means a lower limit for the cross section of the reconnection flux tube, and the slightly super-Alfvénic jet flow with $v \approx 5000 \mathrm{km\ s}^{-1}$ (Burns et al., 1983; Israel, 1998) we find

$$\begin{aligned}\mathcal{L}_{fil} &= \frac{1}{2} \frac{m_e c^{5/2}}{(4\pi)^{3/4} m_p^{1/4} (\sigma_T e)^{1/2}} \frac{B \kappa^{1/2} \lambda_{skin}}{n^{1/4} \alpha} \\ &\approx 10^{26} \left(\frac{B}{60\mu\mathrm{G}}\right) \left(\frac{n}{0.01\mathrm{cm}^{-3}}\right)^{-5/4} \mathrm{erg\ s}^{-1}.\end{aligned} \tag{13}$$

In order to account for the observed X-ray luminosity of the Centaurus A jet $\mathcal{L}_X \approx 10^{39} \mathrm{erg\ s}^{-1}$ (Turner et al., 1997; Israel, 1998) at least a total volume of a diameter of ~ 167pc and a elongation of $L \approx 17$pc must radiate with a filling factor of 1 for the current filaments, which means that the considered jet segment is penetrated by numerous current sheets all along its width. In fact, the total luminosity is caused by numerous subsequent acceleration regions along the jet with therefore considerably smaller necessary diameters. Lower filling factors demand for larger radiating volumes powered by individual reconnection processes.

5 Discussion

In a highly filamentary jet configuration due to particle inertia alone the magnetic energy supplied by the jet engine can be efficiently converted to particle acceleration. A longitudinal magnetic field is crucial for the electron acceleration. In the considered filamentary current configuration relatively weak electric fields are sufficient to accelerate electrons up to Lorentz factors of some 10^7. It should be noted that during the nonlinear dynamics of the reconnection process even stronger field-aligned electric fields may form (Litvinenko, 1999). In the proposed scenario the acceleration process is not limited by the reconnection time τ_{rec}, because magnetic energy (helicity) is continuously injected into the jet by shear MHD flows stemming from the central engine. This allows for reconnection all along the jet in a quasistationary way. It bears mentioning that current filamentation in a helical jet configuration is in agreement with the somewhat puzzling emptiness of extragalactic jets that are observed head-on.

In the proposed scenario ions also can be accelerated up to very high energies. Compared to the electrons they do not suffer from severe loss processes. Ions accelerated in extragalactic jets may contribute to the ultra high energy cosmic ray population. Details about the acceleration of ultra high energy cosmic rays in the framework of the suggested reconnection model can be found in (Schopper et al., 2001a,b).

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