High Energy Hadronic Acceleration in Extragalactic Radio Jets

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Abstract

Within an electric circuit description of extragalactic jets temporal variations of the electric currents are associated with finite collisionless conductivities and consequently magnetic-field aligned electric fields $E_\parallel$. The maximum field strengths depend on the efficiency of the jet MHD generator $E_\perp$ and the local conversion to the $E_\parallel$ component. The hadronic jet constituents can efficiently be accelerated in such fields all along the jets. To estimate the maximum energy the accelerated jet hadrons can achieve we consider energy loss processes as photon-pion and pair production as well as synchrotron and inverse Compton radiation. It turns out that for the strongest $E_\parallel$ possible the Centaurus A jet is a most promising candidate for the source of the highest energy component of cosmic rays.

Key words: High-Energy Particle Acceleration, Ultra High Energy Cosmic Rays, Extragalactic Jets

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1 Introduction

Extragalactic jets are nonthermal radiative and collimated magnetised plasma flows which predominantly consist of relativistic particles and magnetic fields. They originate from the very centres of active galaxies and dissipate most of their energies in hotspots and lobes far away from the host galaxy. Jet lengths

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range from a few kpc up to 100 kpc. The jet composition is not yet clear, since their nonthermal radiation (mainly synchrotron emission) provides information only about the leptonic constituents. The nonthermal radiation output of the jets extends from the radio even to the X-ray regime [1-3]. To emit X-rays via the synchrotron process, the radiating leptons must have energies of several TeV or Lorentz factors up to $10^{7-8}$ [4]. These remarkably high energy levels raise the problem of continuous re-acceleration simply because the particle's synchrotron loss lengths are orders of magnitudes smaller than the jet lengths along which the radiation is observed. Especially the almost constant radiation spectral index along the jets requires an almost constant lepton energy that closely follows the behaviour of the local magnetic energy density all along the jet [5].

The fact that nonthermal optical and X-ray emission is observed in jets means that the charged particles must experience a continuous energy gain up to TeV-energies. This is only possible by field aligned electric fields. Especially the constancy of the spectral index, varying only together with the local energy density of the magnetic field, give strong constraints for possible acceleration models. In particular, shock acceleration scenarios, in which also electric fields are the ultimate cause for particle acceleration, have serious problems explaining the astonishing continuous spectral index [5]. This constancy shows, that there is a need for an interplay of a very efficient electromagnetic energy gain and the radiative energy loss along the jets. For leptons to fulfil these requirements accelerating electric fields must be present all along the path of the radiating jet. This seems to be a trivial statement, however it has profound implications for the hadrons in the jets, which are not detectable by their radiational output.

This leads to the subject of the jet material: What kind of plasma is inside the extragalactic jets? Are they made up of protons and electrons, or electron-positron pairs, or a mixture of both? Discussing this important topic, Celotti & Fabian [6] argued in favour of proton-electron jets, whereas recently on the grounds of circular polarisation measurements of some bright quasars pure electron-positron jets [7, 8] have been suggested. Sikora and Madejski [9] derived strong constraints on the content of jets in quasars. Their conclusion was that the pair content of jets is high, but that dynamically the jets are dominated by protons. Especially they show that pure electron-positron jet models overpredict soft X-ray emission, whereas pure proton-electron jet models can be excluded since they predict too weak nonthermal X-radiation. Jets may dominantly consist leptons, but since the jets are supposed to be fed by accretion disks consisting of normal electron-proton-plasmas, there is always a hadronic component in extragalactic jets. However, in our context there is no need to precisely specify the relative abundance of the hadronic and leptonic jet components, because here we want to analyse the energisation of individual hadrons, only.
Before we dwell on the acceleration of individual particles within the jets, we first describe the possible origin of the jets. It is now generally agreed that there is a link between the central activity of an active galactic nucleus, the jets and the hotspots. The basic idea that underlies the jet models is that a jet is continuous collimated outflow which transports energy from the nucleus to the hotspot [e.g. 10]. Many jets exhibit superluminal motions, i.e. the plasma bulk speed in the jet has to be close to the velocity of light with minimal Lorentz factors between 2 and 10 [e.g. 11]. The only mechanism able to produce these relativistic jets is the magnetic sling effect in a rapidly rotating magnetosphere. The collimation of the outflow is provided by the pinching effect of the toroidal magnetic field. This would resolve the puzzle that some jets are not freely expanding and that an agent is necessary to confine them. Additionally, the dynamical effects of the magnetic field ranges from refocusing and knot formation to the possibility of electromagnetic interaction of the jets with their surroundings. One of the most important properties of jet production in rotating magnetospheres is that jets carry an electrical current which flows along the jet axis, a property which enhances their stability [12, 13]. The source of the jet current is the differential rotation of the magnetosphere in the innermost region of the galactic nucleus. In order to avoid charging up the nucleus a return current flowing in the surrounding plasma, must close the circuit. A current flow in and outside the jet requires current closure at the tip of the jet where Ohmic dissipation by nonlinear collisionless plasma processes may lead to particle acceleration and plasma heating in the hot spots [14].

Now we have all the necessary ingredients for an electrodynamic model of extragalactic jets: There is a shear flow power supply which provides a current source associated with sheared magnetic fields in the jet. The jet itself represents the conductor along which the electric current flows. Finally, at least one well defined dissipation region can be identified- the hot spot and lobe region that corresponds to a resistance. However, the hotspot is not the only dissipative region. Since extragalactic jets show continuously distributed synchrotron emission continuous dissipation of particle kinetic energy into electromagnetic waves occurs in the completely collisionless jet plasma. The non-ideal current flow is associated (via Ohm’s law) with electric fields oriented along the current direction and in the context of extragalactic jets along the dominant poloidal magnetic field component. The behaviour of this electric field is a direct consequence of the self consistency of Ampère’s Law. Any variation in the current density must correspond to a change in the magnetic shear (the energy source) and the aligned electric field. It is this property of the magnetic field–current system to resist any disturbance given by radiative losses that provides the accelerating electric field.

Here we would like to address the question what it means for the hadronic jet component, if such magnetic field-aligned electric fields are present in the jet flows in the presence of the synchrotron radiation emitted by relativistic
leptons. Whereas leptons suffer synchrotron losses that limit their energy gain to a few TeV, protons undergo additionally energy losses by pair and pion production. Nevertheless, their equilibrium energy (where energy gain and energy loss processes are balanced) is significantly higher than the maximum energy of the leptons. We will show in this contribution that, in principle, field-aligned electric fields in extragalactic jets can accelerate protons even up to the highest energies measured for ultra-high-energy cosmic rays (UHECR) $10^{21}$ eV[15].

2 Acceleration of Cosmic Ray Protons in the Electric Fields of Extragalactic Jets

Jet engines in active galactic nuclei can be regarded as MHD generators filled with a magnetised relativistic plasma [16]. In a rather simple though highly instructive approach an extragalactic jet can be considered as giant manifestation of an electric circuit (Fig. 1). The AGN-MHD generator plays the role of the power/voltage supply. The hot spot region represents the load. The current must flow along the jet in not ideal conducting “wires”, since jets reveal themselves by the synchrotron emission from the radio to X-ray regime. The radiating electrons that carry the jet current suffer synchrotron energy losses and thus, need to be re-accelerated all along the jet. The re-acceleration must be caused by electric fields directed along the current flow. To be more specific in terms of an electric circuit description one deals with an electrical inductance, i.e. one faces time varying currents caused by the radiative dissipation. In collisionless plasmas a time varying current density is connected via Ohm’s law to a collisionless electrical conductivity due to particle inertia [17, 18]. It is this kind of conductivity $\Sigma$ that relates the field-aligned electric field to the field-aligned electric current density $j_\parallel$ in the case of extragalactic jets

$$E_\parallel = \frac{me}{ne^2} \left[ \frac{\partial j}{\partial t} + \nabla \cdot (vj + jv) \right]_\parallel = \Sigma j_\parallel = \frac{\lambda_{\text{skin}}^2}{L_{\text{shear}}^2} \frac{v_{\text{shear}}}{c} B_\perp$$

(1)

with $\lambda_{\text{skin}} = c(m_e/4\pi ne^2)^{1/2}$ ($m_e$ and $n$ are the electron mass and particle density), $L_{\text{shear}}$ and $B_\perp$ denoting the electron skin length, the characteristic length scale of the the magnetic shear, and the strength of the toroidal magnetic field component caused by the generator shear flow $v_{\text{shear}}$, respectively. Recently, we have shown that in this scenario the in situ acceleration of electrons up to TeV energies is possible provided that magnetic reconnection taps the jet magnetic field as the relevant energy source [19, 20] (for a discussion of magnetic reconnection in the context of jets see also [21, 22]). Since particle inertia operates on relatively small spatial scales the jet magnetic field has to be organised in a highly filamentary structure. Observations indicate [e.g. 5, 23]
that indeed the jets are characterised by highly filamentary current-carrying helical magnetic field configurations. A characteristic feature of current filamentation is the local reversal of the average current direction. Thus, besides leptons, in magnetic field-aligned electric fields \( E \parallel \) caused by particle inertia protons should be efficiently accelerated towards the hot spots.

The main question that concerns us here is to what maximum energies part of the jet protons can be accelerated. The \( E \parallel \) can be estimated from Eq. (2) as a fraction \( \alpha = \frac{\lambda_{\text{2-shear}} v_{\text{shear}}}{c} \) of the toroidal magnetic field. The maximum \( E \parallel \) appears in thin current filaments of the order of the electron skin length which implies \( \alpha = 1 \). The following calculations are performed for \( \alpha = 1 \) and can be re-scaled straightforward for weaker electric fields. The Lorentz factor \( \Gamma_p \) cosmic ray protons can gain in a linear jet accelerator is limited by

\[
\Gamma_p = \frac{eE_{\parallel} L_{\text{acc}}}{m_p c^2},
\]

where \( m_p \) and \( c \) are the proton mass and the speed of light. The above estimation is highly idealised, since in real jets the twisted and tangled magnetic fields give an equally distributed \( E \parallel \) and even local field reversals. The net energy gain is given by the average of a stochastic acceleration within the jet. However, the randomness should only influence the flux of the accelerated hadrons and not their maximum energy achievable.

The acceleration length \( L_{\text{acc}} \) is given by

\[
L_{\text{acc}} = \min\{L_{\text{jet}}, L_{\text{loss}}\}
\]

where \( L_{\text{jet}} \) denotes the extension of the jet and the loss length \( L_{\text{loss}} \) depends on the governing loss mechanism, i.e. proton synchrotron radiation, inverse Compton scattering \( (p + \gamma \rightarrow p + \gamma') \), pair production \( (p + \gamma \rightarrow p + e^+ + e^-) \) or photo pion production \( (p + \gamma \rightarrow \pi^+ + n; p + \gamma \rightarrow \pi^0 + p) \), respectively. The loss lengths of the first two mentioned processes are comparable, if \( U_{\text{Rad}} = B^2/8\pi \) \( (U_{\text{Rad}}: \) energy density of radiation), which just means equipartition between radiation and fields. The loss lengths then read [24]

\[
L_{\text{loss}}^{\text{syn}} = L_{\text{loss}}^{\text{ic}} = 6\pi m_p^3 c^2 / \sigma_T m_e^2 \Gamma_p B^2
\]

where \( \sigma_T \) is the Thomson cross section. The loss lengths for pair and photo pion production are given by

\[
L_{\text{loss}}^{\text{pair}} = (\kappa_{\text{pair}} \sigma_{\text{pair}} n_\gamma)^{-1} \quad \text{and} \quad L_{\text{loss}}^{\text{pion}} = (\kappa_{\text{pion}} \sigma_{\text{pion}} n_\gamma)^{-1}
\]

where \( \sigma_{\text{pair}}, \sigma_{\text{pion}}, \kappa_{\text{pair}}, \kappa_{\text{pion}} \), and \( n_\gamma \) represent the cross sections against pair and photo pion production the fractional proton energy losses during one interaction process, and the densities of the involved photons. The cross section and fractional energy loss per collision are given by [25]

\[
\sigma_{\text{pair}} = a r_0^2 \left[ \frac{28}{9} \ln \left( \frac{2e_{\gamma}^{\text{pair}}}{m_e c^2} \right) - \frac{218}{27} \right]
\]

\[
\kappa_{\text{pair}} = \frac{2m_e}{m_p},
\]

(3)
where \( r_0 \), \( a \), and \( \epsilon^{p.r.}_\gamma \) are the classical electron radius, the fine-structure constant, and the photon energies in the proton rest frame. The asymptotic value for the cross section for very high \( \epsilon^{p.r.}_\gamma \) is given by \( \sigma^{\text{pair}} \sim 10^{-26} \text{ cm}^2 \). Depending on the magnetic field strength and the frequency of the involved photons at very high proton energies the photo pion losses may become important [26].

\[
\sigma^{\text{pion}} = 7 \cdot 10^{-36} \text{ cm}^2 \text{ eV}^{-1} (\epsilon^{p.r.}_\gamma - 160 \text{ MeV})
\]

\[
\kappa^{\text{pion}} = \frac{\epsilon^{p.r.}_\gamma}{m_p c^2} \frac{1 + m_{\text{pion}}^2 c^2 / 2e^{p.r.} m_p}{1 + 2e^{p.r.} / m_p c^2}
\]

and the asymptotic value for the cross section \( \sigma^{\text{pion}} \sim 10^{-28} \text{ cm}^2 \) for very high \( \epsilon^{p.r.}_\gamma \).

In absence of nearby powerful external photon sources, the loss processes have to be examined for the microwave background photons and, more important, for the observed radio, optical and X-ray synchrotron photons emitted by the electrons re-accelerated in the jets. The thermal relic photons do not hinder UHECR acceleration in extragalactic jets. For the relevant energy ranges \( E_p \approx 10^{18} - 10^{21} \text{ eV} \) (at lower eV’s the energy of the relic photons \( \epsilon^{p.r.}_\gamma \) is not sufficient for pair production) the proton mean free path is \( L_{\text{loss}} = \min\{ (\sigma^{\text{pair}} \kappa^{\text{pair}} n_\gamma)^{-1}, (\sigma^{\text{pion}} \kappa^{\text{pion}} n_\gamma)^{-1} \} \geq 15 \text{ Mpc} \) given [26, 27] a relic photon density of \( n_\gamma \approx 400 \text{ cm}^{-3} \). Thus, the proton mean free paths against pair and photo pion production via thermal background photons largely exceed typical jet lengths (synchrotron as well as inverse Compton losses are negligible in this case). On the other hand, if protons can be accelerated in extragalactic jets up to the highest observed cosmic ray energies, the jets should not be further away than \( \sim 15 \text{ Mpc} \) in order to contribute significantly to the UHECR-flux detected on earth.

Equipartition of the magnetic energy density and the photon energy density photons is a consequence of the synchrotron emission of the jet leptons. The number density of the synchrotron photons that reveal the existence of the relativistic extragalactic jets is given as a function of the Lorentz factor of the radiating electrons and the magnetic field strength \( n_\gamma = B^2 / 4h \Gamma_e^2 \omega_e \) where \( h \) and \( \omega_e = eB / m_e c \) are the Planck constant and the electron gyro frequency. Making use of the relation between the frequency \( \nu \) of the observed synchrotron emission and the electron Lorentz factor \( \nu = \Gamma_e^2 eB / 2\pi m_e c \) one can determine \( \Gamma_e \) and therefore \( n_\gamma = B^2 / 8\pi h \nu \). The observationally determined magnetic field strengths in jets are of the order [5, 23] of some \( 1 - 10 \mu \text{G} \). The synchrotron radiation is caused by electrons with Lorentz factors \( \Gamma_e \sim 10^3 - 10^5 \).

If the loss lengths are shorter than the length of the jets, the achievable Lorentz factors for the protons accelerated within extragalactic jets can be calculated from Eq. (2) and the expression for the photon density \( n_\gamma \). When pair and
photo pion production dominate synchrotron/inverse Compton losses, we receive

\[ \Gamma_p = \frac{8\pi e h \nu}{m_p c^2 \kappa \sigma B}. \]  

(5)

Here \( \kappa \) and \( \sigma \) denote the transferred energy rates per collision and cross sections for either the pair or the photo pion production process, respectively. It should be noted, that \( \kappa \) and \( \sigma \) might depend on \( B \) due to \( \epsilon^\gamma_{\gamma^\gamma^\gamma} \). For the second case, when pair and photo pion production losses are negligible against synchrotron/inverse Compton losses, one finds

\[ \Gamma_p = \frac{m_p}{m_e} \sqrt{\frac{6\pi e c}{\sigma T B}}. \]  

(6)

If we assume \( B \approx 10 \mu G \), the high frequency X-ray photons (\( \sim \) keV) result in proton energy losses via pair production starting from \( \Gamma_p \approx 10^3 \). Given a threshold energy for the \( p + \gamma \rightarrow \pi^+ + n \) process of \( \epsilon_0 = 160 \) MeV proton energy losses by photo pion production start from \( \Gamma_p \approx 10^5 \). However, the number density of the non-thermal photons available for the proton energy loss processes depend on \( \Gamma^{-2} \). The density of these high energy photons is too small to effectively slow down the protons via photo pion production. We can state that the X-ray photons do not limit the proton acceleration.

In Fig. 2 the loss lengths and the acceleration lengths (see Eq. (2)) are displayed in double-logarithmic representation as functions of the proton Lorentz factors for optical (Fig. 2a, \( \nu = 10^{14} \) Hz), and radio (Fig. 2b, \( \nu = 10^{9} \) Hz) synchrotron photons. The grey areas show typical jet lengths for comparison. In Fig. 2a the magnetic field strength is chosen as \( B = 10 \mu G \) and in Fig. 2b as \( B = 5 \mu G \), for example. As for the x-ray photons the optical synchrotron radiation does not limit the proton acceleration, i.e. the principal acceleration length \( L_{acc} \) is limited, in this case by the synchrotron/inverse Compton loss length \( L_{syn,ic} \), far beyond the extension lengths of extragalactic jets \( L_{Jet} \). In the case of the radio emission for a magnetic field strength of \( B = 5 \mu G \) the loss lengths for pair and photo pion production and the acceleration length meet at the same Lorentz factor of \( \Gamma_p \approx 8 \cdot 10^{11} \). In fact, protons could be accelerated up to this energy in unusually long jets (for the longest known extragalactic jet, Pictor A at a distance of 140 Mpc, one finds \( L_{Jet} \approx 300 \) kpc).

The stronger the magnetic fields are the smaller are the loss lengths. This is due to the strong dependence \( n_\gamma \sim B^2 \). On the other hand, stronger fields imply higher field strengths available for particle acceleration, which leads to a higher energy gain per unit length. The maximum Lorentz factor, protons can be accelerated to, depends on the magnetic field strength as shown in Fig. 3 for \( L_{Jet} = 3 \) kpc to \( L_{Jet} = 300 \) kpc and \( \nu = 10^{9} \) Hz. For relatively weak
magnetic fields the proton energy is limited by only the jet lengths (solid line). Photo pion production (short dashed line) gets important for very long jets (upper plot). It is pair production that effectively limits the achievable Lorentz factor of UHECR protons in typical extragalactic jets. For example, for $L_{\text{jet}} = 25\,\text{kpc}$, which, in fact, is the extension of the Centaurs A jet and a field strength of $B \approx 10\,\mu\text{G}$ the pair production allows for $\Gamma_p \approx 3 \cdot 10^{11}$. It should be stressed that observations indicate that, indeed, the Centaurus A jet has a magnetic field [4] of some $10\,\mu\text{G}$. Given an isotropic proton distribution injected in the jet only a small fraction of protons with can gain the highest energies observed in the UHECR population (a quantitative analysis of this point is possible in the framework of collisionless magnetic reconnection [28]).

3 Discussion

The observed high energy synchrotron emission of extragalactic radio jets in the optical and X-ray-regime clearly indicates the presence of magnetic field-aligned electric fields along the whole jet lengths. The leptons need such electric field to be continuously re-accelerated, otherwise they would loose their TeV energies on length scales that are orders of magnitudes smaller than the observed jet lengths.

The hadronic jet components should be accelerated in these magnetic field-aligned electric fields caused by the temporal variations of the electric current density which flows along the jet axis. Such current driven jets are produced by the rotating magnetospheres of supermassive accreting black holes in the central regions of active galactic nuclei. The differential rotation of the accretion disk induces currents along the rotation axis and in the ideal magnetohydrodynamical case, where the electrical conductivity is infinitely high, an electric field which is perpendicular to the magnetic field is the consequence. However, such a fully ideal MHD-jet cannot explain any kind of dissipation like the observed particle acceleration. Some deviation from idealness, i.e. a localised finite electrical conductivity, is required on order to explain the nonthermal jet radiation. It is a well-known fact, that nonideal processes in plasmas are always related to field-aligned electric fields which, of course, are perfect particle accelerators. In other words some part of the perpendicular electric fields generated by the AGN-disk interaction can be tapped for direct particle acceleration along the jet depending on the plasma conductivity. In the proposed scenario it is particle inertia that gives rise to the violation of ideal Ohm’s law. Since the inertia effect only becomes important on relatively small spatial scales, filamentary currents are indispensable for the suggested model. Also, in thin current filaments only relatively strong field-aligned electric fields are reasonably to be expected. In fact, one should bear in mind that for our calculations we used that strongest $E_\parallel$ possible, namely $E_\parallel = \alpha B_\perp$ with $\alpha = 1$. 

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Our findings have to be re-scaled accordingly for $\alpha < 1$. The Lorentz factors the protons can gain in these electric fields are mainly determined in a quite complex way by the strength of the jet magnetic field and the synchrotron photon background. For typical jet parameters protons, in principle, can be energised up to $\approx 10^{20}$ eV. Our model considers all relevant loss processes and therefore clearly shows its own limitations. The balance of the suggested acceleration mechanism and the respective dominant loss process that gives an upper limit for the proton energy may help to explain the observed energy range of the measured highest energy UHECR particles in a promising manner. This means it seems understandable not only how, why and under what circumstances protons can gain the measured energies, but also why we do not see particles with higher energies.

The magnetic field strength is the strongest constraint for possible UHECR source candidates. Magnetic fields significantly lower than $\approx 10 \mu$G are not sufficient to accelerate hadrons to the highest observed energies. On the other hand, if magnetic fields are significantly stronger than some $10 \mu$G the synchrotron photon densities and thus the losses are too high to allow for extremely high Lorentz factors. We find, that efficient acceleration is limited to magnetic fields very close to $\approx 10 \mu$G, for the typical jet lengths of 3–25 kpc found within a distance of 15 Mpc. Consequently, we feel that the Centaurus A jet, located 3.4 Mpc away, should significantly contribute to the observed UHECR population at the highest energy levels. According to our calculations Centaurus A may even be able to produce cosmic rays with energies up to the presently still unique Fly’s Eye event [15] of $3.2 \cdot 10^{20}$ eV.

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Fig. 1. Illustration of the electric circuit that is equivalent to an extragalactic jet. The current source $I$ stands for the permanent magnetic shear injection of the Keplerian accretion disk surrounding the central supermassive black hole. The underlying 6 cm radio image shows, for example, the Quasar 3C175 (©1996 by NRAO).

Fig. 2. The dependence of the loss lengths and the acceleration length on the proton Lorentz factor is displayed. The hatched area represents the range of typical jet lengths. In Fig. 2a the influence of optical synchrotron photons is shown, whereas Fig. 2b represents the effect of radio synchrotron emission. The displayed lengths depend on the magnetic field strength also. Here, $B = 10 \mu G$ (Fig. 2a) and $B = 5 \mu G$ (Fig. 2b) have been chosen, for example.

Fig. 3. The maximum achievable Lorentz factor of UHECR protons as a function of the jet magnetic field strength ($B$) for different jet lengths ($L_{\text{Jet}}$) and GHz radio synchrotron emission.