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Ultra high energy cosmic rays from extragalactic jets

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Abstract. A new mechanism for the acceleration of ultra high energy cosmic rays is presented. It is shown, that three dimensional reconnection in extragalactic jets is able to explain the highest observed particle energies, relevant loss effects included. In addition a possible source candidate is presented.

1 Introduction

Despite intense investigations in the last couple of years the origin of so called ”ultra high energy cosmic rays” (UHECR), particles with energies of up to $10^{20}\,\mathrm{eV}$, remains a mystery. So far no fully convincing acceleration mechanism or acceleration site has been proposed or found. Some models fail to explain the maximum observed energies (bottom up), others tend to give far too high energies or much too low fluxes (top down) (Bhattacharjee and Sigl, 2000). It is our aim to introduce a new acceleration process (bottom up) based on magnetic reconnection in extragalactic jets, which is in principle able to explain the existence of particles with energies up to the highest observed values. In addition we not only consider all relevant loss processes, but we can even show, that in fact these losses determine the energy cutoff observed (Bird et al., 1993) at $\approx 3.2 \cdot 10^{20}\,\mathrm{eV}$.

Extragalactic jets reveal themselves by synchrotron radiation from the radio to the optical and even the X-ray range (Biretta, 1996; Röser et al., 2000; Turner, 1997). The two latter frequency ranges present a clear proof for efficient continuous reacceleration of electrons up to energies of 1–100 TeV within the jets, since the synchrotron loss lengths for optical and X-ray radiation are many orders of magnitudes smaller than the observed jet lengths (Blackman, 1996; Lesch and Birk, 1998; Litvinenko, 1999; Birk and Lesch, 2000)

We have shown that three-dimensional magnetic reconnection plays an important role in the energization of electrons in such jets (Lesch and Birk, 1998; Birk and Lesch, 2000). Our approach differs from the two-dimensional stationary reconnection model (Parker, 1963; Biskamp, 1993) that concentrates in a highly idealized way on the plasma bulk flow perpendicular to the direction of the electric current. Rather the present study should be understood in the framework of general three-dimensional magnetic reconnection without magnetic null lines (Hesse and Schindler, 1988; Schindler at al., 1991). Fast particle acceleration along a guiding magnetic field component perpendicular to the plane where the reconnecting field component changes sign is the characteristic feature of the generalized reconnection process we dwell on in the present context. In the considered reconnection scenario magnetic field energy is converted to high energy particle acceleration. The violation of ideal Ohm's law, which is a necessary condition for the onset of reconnection, can be caused by particle inertia that is relevant in thin current filaments (Lesch and Birk, 1998; Birk and Lesch, 2000). Since our former investigations of three-dimensional reconnection have demonstrated that reconnection allows to solve the in situ re-acceleration problem in jets it is also worth to consider it as a promising mechanism for efficient proton acceleration. Especially since the protons do not suffer as heavily from synchrotron radiation losses as electrons do, the linear extragalactic jet accelerator is a perfect candidate for the origin of UHECR protons.

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

Extragalactic jet engines can be regarded as giant MHD generators filled with a magnetized relativistic plasma (Blandford, 1990). Continuous injection of magnetic helicity, i.e. free magnetic energy, caused by the plasma shear flow definitely associated with the rotating accretion disk that surrounds the massive black hole, is *the* energy source that can be tapped for the acceleration of charged particles. During the three-dimensional reconnection process magnetic free en-

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ergy can be converted to kinetic energy of electrons and protons as fast as it is built up by the shear flows. The question is to what energy levels protons can, in principle, be accelerated for typical jet parameters.

The necessary condition for magnetic reconnection to operate is the violation of the ideal Ohm's law

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \mathbf{R}, \tag{1}$$

where $\mathbf{R} \neq 0$ is some unspecified nonideal term that gives rise to a nonvanishing electric field component parallel to the magnetic field. Since the plasma of extragalactic jets is highly collisionless, and of relativistic energies, no plasma fluctuations can contribute to $\mathbf{R}$ as in nonrelativistic plasmas. Only the particle inertia remains as a source of the nonidealness. Particle inertia operates on very small scales, i.e. the magnetic field has to be organized in a highly filamentary structure. Observations (Biretta, 1996; Meisenheimer et al., 1996) indicate that indeed the jets are characterized by highly filamentary current-carrying helical magnetic field configurations. The magnetic field-aligned electric fields in the reconnection regions are given (Lesch and Birk, 1998; Birk and Lesch, 2000) by

$$\begin{aligned} E_{\|} &= \alpha E_{\perp} = \frac{m_{\mathrm{e}}}{ne^2}\left|\frac{\partial \boldsymbol{j}}{\partial t} + \boldsymbol{\nabla}\cdot(\boldsymbol{v}\boldsymbol{j} + \boldsymbol{j}\boldsymbol{v})\right| \\ &\approx \frac{\lambda_{\mathrm{skin}}^2}{L_{\mathrm{shear}}^2}\frac{v}{c}B_{\perp}. \end{aligned} \tag{2}$$

Here, α denotes the efficiency of the conversion of the perpendicular (to the jet axis) electric field component $E_{\perp}$ caused by the MHD generator to the parallel component $E_{\|}$. m_{e}, e, n, $\boldsymbol{v}$, $\boldsymbol{j}$, $\lambda_{\mathrm{skin}} = c(m_{\mathrm{e}}/4\pi ne^2)^{1/2}$, L_{shear}, and $B_{\perp}$ denote the electron mass, the elementary charge, the particle density (quasi-neutrality is assumed), the plasma velocity, the current density, the electron skin length, the characteristic length scale of the the magnetic shear, and the strength of the toroidal magnetic field component, respectively. We consider the most efficient energy conversion by reconnection possible in a current filament. This case is given by the violation of ideal Ohm's law in current sheets as thin as the electron skin length, i.e. an efficiency of $\alpha = 1$, which implies for highly relativistic jets $E_{\|} = B_{\perp}$. We will show that such fields are strong enough to accelerate protons up to the highest energies measured (Bird et al., 1993) for UHECR particles $< 3.2 \cdot 10^{20}\,\mathrm{eV}$. The Lorentz factor Γ_{p} cosmic ray protons can gain in a linear jet accelerator is limited by

$$\Gamma_{\mathrm{p}} = \frac{eE_{\|}L_{\mathrm{acc}}}{m_{\mathrm{p}}c^2}, \tag{3}$$

where m_{p} and c are the proton mass and the speed of light. The acceleration length L_{acc} is given by $L_{\mathrm{acc}} = \min\{L_{\mathrm{Jet}}, L_{\mathrm{loss}}\}$ where L_{Jet} denotes the extension of the jet and the loss length L_{loss} depends on the governing loss mechanism, i.e. proton synchrotron radiation, inverse Compton scattering ($\mathrm{p} + \gamma \rightarrow \mathrm{p} + \gamma'$), pair production ($\mathrm{p} + \gamma \rightarrow \mathrm{p} + \mathrm{e}^+ + \mathrm{e}^-$) or photo pion production ($\mathrm{p} + \gamma \rightarrow \pi^+ + \mathrm{n}$; $\mathrm{p} + \gamma \rightarrow \pi^0 + \mathrm{p}$), respectively. The extension of the fast particle acceleration region should not be mixed up with the current width that is limited by mass conservation at least in the two-dimensional stationary reconnection scenario (Biskamp, 1993). However, we do not deal with this idealized and restricted process here (see introductory section). The loss lengths of the first two mentioned processes are identical, when $U_{\mathrm{Rad}} = B^2/8\pi$ (U_{Rad}: energy density of radiation), which just means equipartition between radiation and fields. The loss lengths then read (Rybicki and Lightman, 1979) $L_{\mathrm{loss}}^{\mathrm{syn}} = L_{\mathrm{loss}}^{\mathrm{ic}} = 6\pi m_{\mathrm{p}}^3 c^2/\sigma_{\mathrm{T}} m_{\mathrm{e}}^2 \Gamma_{\mathrm{p}} B^2$ where σ_{T} denotes the Thomson cross section. The loss lengths for pair and photo pion production are given by $L_{\mathrm{loss}}^{\mathrm{pair}} = (\kappa^{\mathrm{pair}}\sigma^{\mathrm{pair}}n_{\gamma})^{-1}$ and $L_{\mathrm{loss}}^{\mathrm{pion}} = (\kappa^{\mathrm{pion}}\sigma^{\mathrm{pion}}n_{\gamma})^{-1}$ where σ^{pair}, σ^{pion}, κ^{pair}, κ^{pion}, and n_{γ} 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 (Longair, 1981)

$$\begin{aligned} \sigma^{\mathrm{pair}} &= ar_0^2\left[\frac{28}{9}\ln\left(\frac{2\epsilon_{\gamma}^{\mathrm{p.r.}}}{m_{\mathrm{e}}c^2}\right) - \frac{218}{27}\right] \\ \kappa^{\mathrm{pair}} &= \frac{2m_{\mathrm{e}}}{m_{\mathrm{p}}}, \end{aligned} \tag{4}$$

where r_0, a, and $\epsilon_{\gamma}^{\mathrm{p.r.}}$ 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 $\epsilon_{\gamma}^{\mathrm{p.r.}}$ is given by $\sigma^{\mathrm{pair}} \sim 10^{-26}\,\mathrm{cm}^2$. 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 (Berezinsky and Grigor'eva, 1988)

$$\begin{aligned} \sigma^{\mathrm{pion}} &= 7 \cdot 10^{-36}\,\mathrm{cm}^2\,\mathrm{eV}^{-1}(\epsilon_{\gamma}^{\mathrm{p.r.}} - 160\,\mathrm{MeV}) \\ \kappa^{\mathrm{pion}} &= \frac{\epsilon_{\gamma}^{\mathrm{p.r.}}}{m_{\mathrm{p}}c^2}\,\frac{1 + m_{\mathrm{pion}}^2 c^2 2\epsilon_{\gamma}^{\mathrm{p.r.}} m_{\mathrm{p}}}{1 + 2\epsilon_{\gamma}^{\mathrm{p.r.}} m_{\mathrm{p}}c^2}. \end{aligned} \tag{5}$$

For very high $\epsilon_{\gamma}^{\mathrm{p.r.}}$ the asymptotic value for the cross section is $\sigma^{\mathrm{pion}} \sim 10^{-28}\,\mathrm{cm}^2$.

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 $E_{\mathrm{p}} \approx 10^{18} - 10^{21}\,\mathrm{eV}$ (at lower eV's the energy of the relic photons $\epsilon_{\gamma}^{\mathrm{p.r.}}$ is not sufficient for pair production) the proton mean free path is $L_{\mathrm{loss}} = \min\{(\sigma^{\mathrm{pair}}\kappa^{\mathrm{pair}}n_{\gamma})^{-1}, (\sigma^{\mathrm{pion}}\kappa^{\mathrm{pion}}n_{\gamma})^{-1}\} \geq 15\,\mathrm{Mpc}$ (see (Blumenthal, 1970; Berezinsky and Grigor'eva, 1988)) given a relic photon density of $n_{\gamma} \approx 400\,\mathrm{cm}^{-3}$. 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 $\sim 15\,\mathrm{Mpc}$ in order to contribute significantly to the UHECR-flux detected on earth.

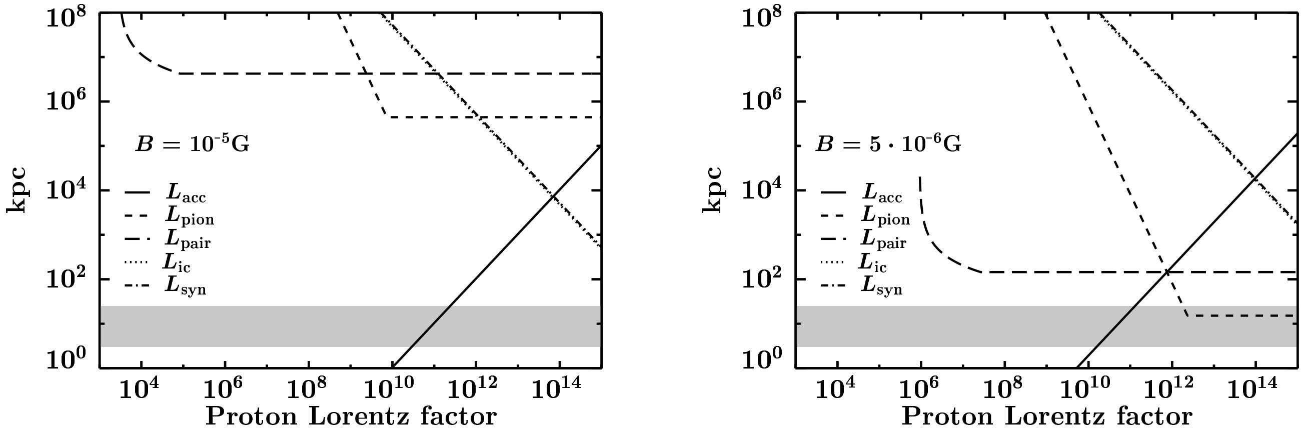

Fig. 1. The dependence of the loss lengths and the acceleration length on the proton Lorentz factor is displayed. The hatched area represents the range of typical jet lengths. In Fig. 1a the influence of optical synchrotron photons is shown, whereas Fig. 1b represents the effect of radio synchrotron emission. The displayed lengths depend on the magnetic field strength also (see Fig. 1). Here, $B = 10\,\mu$G (Fig. 1a) and $B = 5\,\mu$G (Fig. 1b) have been chosen, for example.

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 $n_\gamma = B^2/4h\Gamma_{\rm e}^2\omega_{\rm c}$ where h and $\omega_{\rm c} = eB/m_{\rm e}c$ are the Planck constant and the electron gyro frequency. Making use of the relation between the frequency ν of the observed synchrotron emission and the electron Lorentz factor $\nu = \Gamma_{\rm e}^2 eB/2\pi m_{\rm e}c$ one can determine $\Gamma_{\rm e}$ and therefore $n_\gamma = B^2/8\pi h\nu$. The observationally determined magnetic field strengths in jets are of the order (Biretta, 1996; Meisenheimer et al., 1996) of some $1 - 10\,\mu$G. The synchrotron radiation is caused by electrons with Lorentz factors $\Gamma_{\rm e} \sim 10^3 - 10^8$.

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. (3) and the expression for the photon density n_γ. When pair and photo pion production dominate synchrotron/inverse Compton losses, we receive

$$\Gamma_{\rm p} = \frac{8\pi e h}{m_{\rm p}c^2\kappa\sigma}\,\frac{\nu}{B}. \tag{6}$$

Here κ and σ denote the transfered energy rates per collision and cross sections for either the pair or the photo pion production process, respectively. It should be noted, that κ and σ might depend on B due to $\epsilon_\gamma^{\rm p.r.}$. For the second case, when pair and photo pion production losses are negligible against synchrotron/inverse Compton losses, one finds

$$\Gamma_{\rm p} = \frac{m_{\rm p}}{m_{\rm e}}\sqrt{\frac{6\pi e c}{\sigma_{\rm T} B}}. \tag{7}$$

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 $\Gamma_{\rm p} \approx 10^3$. Given a threshold energy for the $p + \gamma \rightarrow \pi^+ + n$ process of $\epsilon_0 = 160\,{\rm MeV}$ proton energy losses by photo pion production start from $\Gamma_{\rm p} \approx 10^5$. However, the number density of the non-thermal photons available for the proton energy loss processes depend on $\Gamma_{\rm e}^{-2}$. 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. 1 the loss lengths and the acceleration length (see Eq. (3)) are displayed in double-logarithmic representation as functions of the proton Lorentz factors for optical (Fig. 1a, $\nu = 10^{14}\,{\rm Hz}$), and radio (Fig. 1b, $\nu = 10^9\,{\rm Hz}$) synchrotron photons. The grey areas show typical jet lengths for comparison. In Fig. 1a the magnetic field strength is chosen as $B = 10\,\mu$G and in Fig. 1b 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 $L_{\rm acc}$ is limited, in this case by the synchrotron/inverse Compton loss length $L_{\rm syn,ic}$, far beyond the extension lengths of extragalactic jets $L_{\rm Jet}$. 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 $\Gamma_{\rm p} \approx 8 \cdot 10^{11}$. 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 $140\,{\rm Mpc}$, one finds $L_{\rm Jet} \approx 300\,{\rm kpc}$).

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. 2 for $\rm L_{Jet} = 3\,{\rm kpc}$ to $L_{\rm Jet} = 300\,{\rm kpc}$ and $\nu = 10^9\,{\rm Hz}$. 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 $L_{\rm Jet} = 25\,{\rm kpc}$, which, in fact, is the extension of the

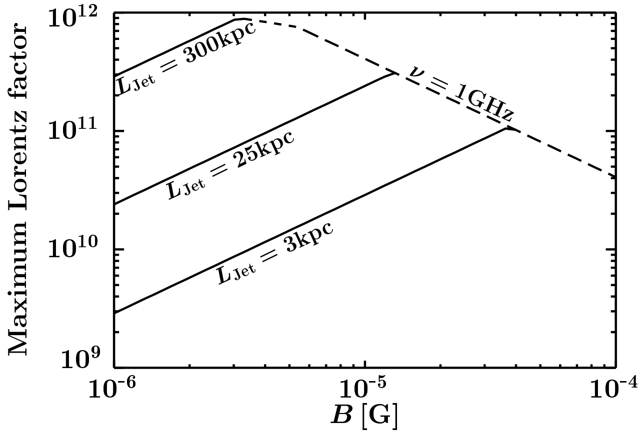

Fig. 2. The maximum achievable Lorentz factor of UHECR protons as a function of the jet magnetic field strength (B) for different jet lengths ($L_{\rm Jet}$) and GHz radio synchrotron emission.

Centaurs A jet and a field strength of $B \approx 10\,\mu$G the pair production allows for $\Gamma_{\rm p} \approx 3 \cdot 10^{11}$. It should be stressed that observations indicate that, indeed, the Centaurus A jet has a magnetic field (Burns et al., 1983) of some $10\,\mu$G.

3 Discussion

A characteristic feature of current filamentation is the local reversal of the average current direction. Thus, in magnetic field-aligned electric fields in localized reconnection regions protons can be accelerated along extragalactic jets in the direction of the hot spots and can contribute to the observed UHECR population. The Lorentz factors the protons can gain in the proposed scenario are mainly determined in a quite complex way by the strengths of the jet magnetic fields and the synchrotron photon background. For typical parameter the linear jet accelerator can, in principle, accelerate protons up to $\approx 10^{20}$ eV. It should be stressed that the balance of the suggested acceleration mechanism and the respective dominant loss process giving 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, that our new model for the acceleration of UHECR particles (it's not limited to protons) not only explains how, why and under what circumstances protons can gain the measured energies, it is also able to explain why we do not see particles with higher energies. This might be the most promising feature of this acceleration mechanism. Our model considers all relevant loss processes and therefore clearly shows its own limitations. Especially the magnetic field is the strongest constraint for possible UHECR source candidates. Magnetic fields significantly lower than $\approx 10\,\mu$G give too little free magnetic energy to reach the highest energies. On the other hand in scenarios with magnetic fields significantly larger than that the synchrotron photon densities and thus the losses are too large in order to get very 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.

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 is even able to produce cosmic rays with energies up to the now unique Fly's Eye event (Bird et al., 1993) of $3.2 \cdot 10^{20}$ eV. In fact, it is the authors opinion, that Centaurus A might well be responsible for *all* observed ultra high energy cosmic rays above $\approx 10^{18.5}$ eV.

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