J Geophys (1981) 50:70–72

Journal of Geophysics

Turbulent Acceleration of Electrons in Extended Extragalactic Radio Sources*

A. Ferrari[1] and E. Trussoni[2]

[1] Max-Planck-Institut für Extraterrestrische Physik, Garching bei München, Federal Republic of Germany
[2] Istituto di Cosmogeofisica del CNR, Corso Massimo d'Azeglio 46, I-10125 Torino, Italy

Key words: Stochastic acceleration of particles – MHD turbulence – Extragalactic radio sources

The physical properties and evolution of extended extragalactic radio sources (double, head-tail, jet) are supported energetically by the nuclear activity in the parent galaxies: accordingly, it is believed that the energy developed in the nuclei is transmitted to the extended radio components by supersonic (relativistic) beams or electromagnetic low frequency waves (Rees 1971; Scheuer 1974; Blandford and Rees 1974). The observed radio radiation is due to synchrotron emission, as shown by recent detailed observations, and for this process in situ acceleration of relativistic electrons is required.

Several theoretical papers have therefore been devoted to the problem of particle acceleration in physical conditions typical of radio sources (Pacholczyk and Scott 1976; Lacombe 1977; Eilek 1979; Ferrari et al. 1979). These are based on stochastic acceleration by magnetic inhomogeneities and shocks generated by magnetohydrodynamic (MHD) instabilities in supersonic flows. In particular a model may be envisaged in two steps:

(i) Resonant acceleration of electrons occurs by interaction with Alfvén waves of short wavelength λ: in this case we have a unique relation between the energy of the particle and wavelength: $\frac{2\pi}{\lambda_{\text{res}}} \simeq \frac{\Omega}{\gamma c} \frac{m_p}{m_e}$, where γ is the Lorentz factor, Ω the proton gyrofrequency, c the speed of light and m_p, m_e the proton and electron mass. Alfvén waves are assumed to reach a stationary spectral distribution with index ν and total energy $(\delta B)^2$, respect to the background magnetic field B_0, such that:

$$\left(\frac{\delta B}{B_0}\right)_A^2 \propto \int_{r_g}^{\lambda_0} \lambda^{\nu-2} d\lambda \tag{1}$$

where r_g is the proton gyroradius. As we need re-acceleration for frequencies $\gtrsim 10$ GHz, it is assumed that $\lambda_0 \gtrsim 10^{15}$ cm and $r_g \sim \frac{\Omega}{v_A} \sim 10^{10}$ cm (v_A is the Alfvén velocity). For the parameters of a typical radio source we assume (n_e is the number density):

$$\left.\begin{array}{l} B_0 \sim 10^{-(4-5)} G \\ n_e \sim 10^{-(4-5)} \text{cm}^{-3} \end{array}\right] \Rightarrow v_A \sim 10^{8-9} \text{cm s}^{-1}. \tag{2}$$

(ii) The energy lost by Alfvén waves during acceleration is supplied by an MHD Kelvin-Helmholtz instability which develops at the interface between the moving radio component and intra-cluster gas.

Although appealing, the previous model is based on two crucial assumptions:

(a) If we have a typical inhomogeneity scale length L in the problem (e.g. the diameter of the jet, or, for a shear layer with a gradient of velocity, the scale length $L^{-1} \sim \frac{u_0'}{u_0}$, u_0 is the beam velocity), the fastest growing mode has wavelength $\sim L$. In the extended sources it is reasonable to assume L not much lower than the component radius i.e. $\sim$several Kpc. Conversely, for resonant acceleration, $\lambda_{\text{res}} \lesssim \lambda_0 \sim 10^{15-16}$ cm are required.

(b) The unstable modes with frequencies $\omega_0 \simeq \frac{2\pi}{L} u_0$ for supersonic motion, are assumed to be compressive magnetic perturbations and not Alfvén waves.

In this paper we want to discuss how interaction of particles with long wavelength perturbations can lead to efficient electron acceleration. It can in fact be shown that the counteracting effect of large wavelength modes (which leads to anisotropy in the electron pitch-angle distribution) and Alfvén waves (which tend to remove such anisotropy) can lead to an equilibrium state of production of Alfvén waves and acceleration of particles. We shall discuss the phenomenon in terms of the time scales of the relevant processes, i.e. acceleration (t_{acc}) and scattering (t_{sc}) of particles, growth (t_{inst}) and absorption (t_{abs}) of MHD modes and Alfvén waves.

We start by considering the influence of a slowly varying magnetic field (associated with long wavelength MHD modes) on the particles, following a procedure similar to that applied by Melrose (1969; 1974).

An isotropic distribution function, under the effect of a time varying magnetic field $\left(\left(\frac{\delta B}{B_0}\right)_L^2\right.$ is the energy density of the long wavelength MHD perturbations$\Big)$

$$B = B_0 \left[1 + \left(\frac{\delta B}{B_0}\right)_L \cos(\omega_0 t)\right] \tag{3}$$

* Paper presented at the Workshop on Acceleration of Particles by Shock Waves, 7–9 October, 1980, Max-Planck-Institut für Aeronomie, Lindau, Federal Republic of Germany.

0340-062X/81/0050/0070/$01.00

develops anisotropy at a rate (a pitch angle of electrons)

$$\frac{d\varepsilon}{dt} \sim \omega_0 \left(\frac{\delta B}{B_0}\right)_L, \quad \varepsilon \approx \frac{f(p, a=\frac{\pi}{2}) - f(p, a=0)}{f(p, a=\frac{\pi}{2}) + f(p, a=0)} \tag{4}$$

with $f(p, a)$ the electron distribution function.

On the other hand for $\varepsilon \gtrsim \frac{v_A}{c}$, Alfvén waves grow and lead to acceleration and scattering of particles at a rate (Lacombe 1977):

$$t_{sc} \sim \frac{1.2 \cdot 10^{-10}}{\pi^2} \lambda_0 \left(\frac{B_0}{\delta B}\right)_L^2 F(\lambda_0, v)$$

$$t_{acc}^A \sim \left(\frac{c}{v_A}\right)^2 t_{sc}, \quad F(\lambda_0, v) = \frac{1}{v-1} \left(\frac{\lambda_0}{\lambda_{ris}}\right)^{v-2}. \tag{5}$$

A quasi equilibrium situation (for $\omega_0 t_{sc} \ll 1$) can be reached when

$$\frac{\varepsilon}{t_{sc}} \sim \omega_0 \left(\frac{\delta B}{B_0}\right)_L, \quad \varepsilon \cong \frac{v_A}{c}. \tag{6}$$

Taking into account that we are dealing with a resonant process and that we have a power law distribution of electrons, we can have Alfvén waves with wavelengths from $\sim r_g$ up to $\lambda_0(\sim 10^{15}$ cm). From (5) and (6) it is possible to derive a relationship between $\left(\frac{\delta B}{B_0}\right)_L$ and $\left(\frac{\delta B}{B_0}\right)_A$

$$\left(\frac{\delta B}{B_0}\right)_L \sim 1.4 \cdot 10^6 \frac{\pi}{F(\lambda_0, v)} \frac{v_A}{u_0} \frac{L_{21}}{\lambda_{015}} \left(\frac{\delta B}{B_0}\right)_A^2,$$

$$\lambda_{015} = \frac{\lambda_0}{10^{15}\,\text{cm}}, \quad L_{21} = \frac{L}{10^{21}\,\text{cm}} \tag{7}$$

As we are dealing with perturbations, $\left(\frac{\delta B}{B_0}\right)_L < 1$, from (7) and the condition $\omega_0 t_{sc} < 1$ we have the following limits for $\left(\frac{\delta B}{B_0}\right)_A$

$$\left(\frac{\delta B}{B_0}\right)_A^2 > \frac{2.4 \cdot 10^{-8}}{\pi} u_{08} \frac{\lambda_{015}}{L_{21}} F(\lambda_0, v), \quad u_{08} = \frac{u_0}{10^8\,\text{cm/s}}$$

$$\left(\frac{\delta B}{B_0}\right)_A^2 < \frac{7.2 \cdot 10^{-7}}{\pi} \frac{u_{08}}{v_A} \frac{\lambda_{015}}{L_{21}} F(\lambda_0, v), \quad v_{A8} = \frac{v_A}{10^8\,\text{cm/s}}. \tag{8}$$

These two inequalities are consistent independently of the wave spectrum if

$$v_{A8} < 30. \tag{9}$$

Scattering of particles controls the process of acceleration by long wavelength modes: following the quasi-linear theory (Kulsrud and Ferrari 1971), the rate of acceleration is fixed by the conditions $\left(k_0 = \frac{2\pi}{\lambda_0}\right)$

$$\left.\begin{matrix} k_0 c t_{sc} \\ \omega_0 t_{sc} \end{matrix}\right] \gg \text{or} \ll 1. \tag{10}$$

Taking into account (5) and (8) together with the fact that previously we assumed $\omega_0 t_{sc} < 1$ in (10) we have $k_0 c t_{sc} > 1$ with the condition

$$u_{08} \lesssim 10\, v_{A8}. \tag{11}$$

In this case the time scale of acceleration is given by

$$t_{acc}^L \sim \frac{10^8}{\pi^2} \frac{L_{21}}{(u_{08})^2} \left(\frac{B_0}{\delta B}\right)_L^2 \text{yr}. \tag{12}$$

In the mean time Alfvén waves accelerate particles at a rate (taking into account Eq. (11))

$$t_{acc}^A \sim \frac{5 \cdot 10^7}{\pi} \frac{L_{21}}{v_{A8} u_{08}} \left(\frac{B_0}{\delta B}\right)_L \text{yr}. \tag{13}$$

It is interesting that in our picture the acceleration times do not depend on the details of the Alfvén spectrum $F(\lambda_0, v)$ but only on the mechanism of the Kelvin-Helmholtz instabilities and therefore on the parameters $\left(\frac{B_0}{\delta B}\right)_L$, L_{21}, u_{08}, v_{A8}, which are strictly related to the physical conditions in the radio sources. Observational data suggest that both $v_{A8}, u_{08} \sim 1$–10 (we remember that relativistic motions lead to stabilization of modes). The values of L_{21} and $\left(\frac{B_0}{\delta B}\right)_L$ are more uncertain and can be estimated only roughly. The time scale of unstable modes is (Ferrari et al. 1978)

$$t_{inst} \sim \frac{1.7 \cdot 10^5}{\pi} \frac{M L_{21}}{\Phi u_{08}} \text{yr}, \quad \Phi < 1 \tag{14}$$

where M is the Mach number and ϕ is determined from the dispersion relation. For consistency $t_{inst} \ll t_{rs}$ (t_{rs} is the age of the radio source $\sim 10^7$ yr) so we have an upper limit for L:

$$L_{21} < 60\pi \frac{\Phi u_{08}}{M}. \tag{15}$$

Referring to $\left(\frac{\delta B}{B_0}\right)_L$ we can again assume an equilibrium situation between the growth rate of modes and their dissipation by interaction with particles.

For a power law spectrum of relativistic electrons, we know that the energy E is lost by the MHD modes during the process of acceleration at a rate

$$\frac{dE}{dt} = \int_{\gamma_{min}}^{\infty} \frac{d\gamma}{dt} dn(\gamma) \sim$$

$$3.3 \cdot 10^{-16}\ \pi^2 \zeta \frac{u_{08}^2}{L_{21}} \left(\frac{\delta B}{B_0}\right)_L^2 \varepsilon_{rel}\,\text{erg cm}^{-3}\,\text{s}^{-1} \tag{16}$$

$$\zeta = \frac{\Gamma - 1}{\Gamma - 2} \gtrsim 1$$

where ε_{rel} and $n(\gamma)(\alpha \gamma^{-\Gamma})$ are the energy density and number density of relativistic particles. In a steady equilibrium state

$$\frac{dE}{dt} \sim \frac{d\left(\frac{\delta B^2}{8\pi}\right)_L}{dt} \sim 2 \frac{\left(\frac{\delta B^2}{8\pi}\right)_L}{t_{inst}} \tag{17}$$

from which we get (see (14))

$$\left(\frac{\delta B}{B_0}\right)_L \sim \frac{4 \cdot 10^2 \phi}{M u_{08} \eta \zeta} \quad \eta = \frac{\varepsilon_{rel}}{\left(\frac{\delta B^2}{8\pi}\right)_L}. \tag{18}$$

From (18) we conclude that the process of acceleration in the weak turbulence limit is possible only for supersonic flows and for $\eta \sim 1$.

From (12), (13), and (18) we draw the main conclusion of the model. First of all we notice that long wavelength modes and Alfvén waves accelerate at almost the same rate:

$$\frac{t_{\mathrm{acc}}^{L}}{t_{\mathrm{acc}}^{A}} \sim \frac{2}{\pi} \frac{v_{A8}}{u_{08}} \left(\frac{B_0}{\delta B}\right)_L \tag{19}$$

Regarding the efficiency of the process (i.e., $t_{\mathrm{acc}} < t_{\mathrm{rs}}$) we can envisage two limiting cases (assuming δB less but of the order of B_0):

(i) For fast motion (u_{08}, possibly $v_{A8} \sim 10$) acceleration is effective even with smooth boundaries ($L_{21} \lesssim 1$). In this case the main difference from previous papers (Lacombe 1977; Eilek 1979; Ferrari et al. 1979) is that two different MHD perturbations can contribute to the acceleration.

(ii) For slow motion ($u_{08}, v_{A8} \sim 1$) the process is critically dependent on L_{21}. Again for very sharp boundaries ($L_{21} \lesssim 10^{-2}$) we have an efficient acceleration, but in the mean time the MHD modes evolve non linearly, unless they are well supersonic (see (18)). Conversely, for smooth boundaries we expect only nonlinear evolution of instabilities and no effective acceleration.

References

Blandford, R.D., Rees, M.J.: A 'Twin-Exhaust' model for double radio sources. Mon. Not. R. Astron. Soc. **169**, 395–415, 1974

Eilek, J.A.: Particle reacceleration in radio galaxies. Astrophys. J. **230**, 373–385, 1979

Ferrari, A., Trussoni, E., Zaninetti, L.: Relativistic Kelvin-Helmholtz instabilities in extragalactic radio sources. Astron. Astrophys. **64**, 43–52, 1978

Ferrari, A., Trussoni, E., Zaninetti, L.: Magnetohydrodynamic instabilities and electron acceleration in extended extragalactic radio sources. Astron. Astrophys. **79**, 190–196, 1979

Kulsrud, R., Ferrari, A.. The relativistic quasilinear theory of particle acceleration by hydromagnetic turbulence. Astrophys. Space Sci. **12**, 302–318, 1971

Lacombe, C.. Acceleration of particles and plasma heating by turbulent Alfvén waves. Astron. Astrophys. **54**, 1–16, 1977

Melrose, D.B.. Acceleration of ultrarelativistic electrons in the Crab Nebula. Astrophys. Space Sci. **4**, 165–181, 1969

Melrose, D.B.: Resonant scattering of particles and second phase acceleration in the solar corona. Sol. Phys. **37**, 353–365, 1974

Pacholczyk, A.G., Scott, J.S.: In situ particle acceleration and physical conditions in radio tail galaxies. Astrophys. J. **203**, 313–322, 1976

Rees, M.J.: New interpretation of extragalactic radio sources. Nature **229**, 312–317, 1971

Scheuer, P.A.G.: Models of extragalactic radio sources with a continuous energy supply from a central object. Mon. Not. R. Astron. Soc. **166**, 513–528, 1974

Received January 22, 1981, Revised Version June 1, 1981

Accepted June 4, 1981