Frascati Physics Series Vol. XLV (2007) pp.265-272
Science with the New Generation of High Energy Experiments
Frascati, 18-20 June, 2007

FOSSIL AGN AS COSMIC PARTICLE ACCELERATORS

R.J. Protheroe [a], Gregory Benford [b]

[a] *Department of Physics, School of Chemistry & Physics, University of Adelaide, Adelaide, SA 5005, Australia*

[b] *Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA*

Abstract

Remnants of active galactic nucleus (AGN) jets and their surrounding cocoons leave colossal magnetohydrodynamic (MHD) fossil structures storing total energies $\sim 10^{60}$ erg. The original active galacic nucleus (AGN) may be dead but the fossil will retain its stable magnetic configuration resembling the reversed-field pinch (RFP) encountered in laboratory MHD experiments. Slow decay of the large-scale RFP field induces electric fields which can accelerate cosmic rays with an E^{-2} power-law up to ultra-high energies. A similar mechanism, operting for fossil microquasars could contribute to Galactic cosmic rays and be responsible for some unidentified GeV and TeV gamma-ray sources.

1 Introduction

The energy spectrum of cosmic rays (CR) extends from below 1 GeV up to at least 10^{20}eV, and at the highest energies is almost certainly extragalactic. Possible acceleration sites of these ultra-high energy (UHE) CR include hotspots of giant radio galaxies, the intergalactic medium, gamma ray bursts and blazar jets. UHE CR are subject to interaction with the cosmic microwave background radiation (CMBR) by pion photoproduction as was first noted by Greisen [1]

and Zatsepin & Kuzmin [2], and the cut-off they predicted is referred to as the "GZK cut-off". See ref. [3] for a recent review of UHE CR.

Remnants of AGN jets and their surrounding cocoons may persist long after their parent AGN fade from view. These colossal MHD structures decay slowly and yet may retain their relatively stable self-organized configurations. Decay depends on the structure circuit resistance, and lifetimes could be quite long, given the large inductance of the circuit, an initial outward current along the jet and a return current back along an outer sheath or cocoon around the jet. On the immense scale of these fossil jets, the decay time from instability can be billions of years. However, decay of these colossal MHD structures on such time-scales result in electric fields capable of accelerating existing populations of lower energy cosmic rays up to ultra high energies with a flat spectrum extending from some minimum rigidity (momentum/charge) determined by fossil dimensions, magnetic field and decay time. A more extensive discussion and full details of our present work are given in ref. [4].

2 Evolution of AGN Fossil Magnetic Structures

Helical structures are common in AGN jets, arising during jet formation from rotation of magnetized plasma accreting toward the central black hole – this could be enhanced in the case of binary black hole systems. Azimuthal electric currents are therefore likely, yielding a magnetic field component along the jet direction. Laboratory MHD experiments show that reversed-field pinches are fairly stable, and are therefore likely configurations of "fossil jets", and Benford [7] has proved that for jet-built RFP structures, the same simple MHD stability conditions for a jet guarantee stability, even after the jet turns off. We discuss elsewhere [4] further details the stability of MHD structures, but here we concentrate on radio and X-ray observations of fossil jets. Recent detections of several ghost cavities in galaxy clusters [5] – often, but not always, radio-emitting – suggest that the cluster hot plasma stays well separated from the bulk of the relativistic plasma on a timescale of $\sim$100 Myr. This means that magnetic structures made stable while a jet is on can evolve into fossils that persist long after the building jet current has died away. These may be the relic radio "fossils", "ghost bubbles" or "magnetic balloons" found in clusters and made visible by contrast against the X-ray emission as seen in Hydra A [8]. Giant radio galaxies such as Cyg A are building such structures now. Such fossils have a massive inventory of magnetic energy that can be $\sim 10^{60}$ erg [6]. Such enormous amounts of energy can only come from the gravitational infall energy of a supermassive black hole, when jets convey a few percent of the energy outward.

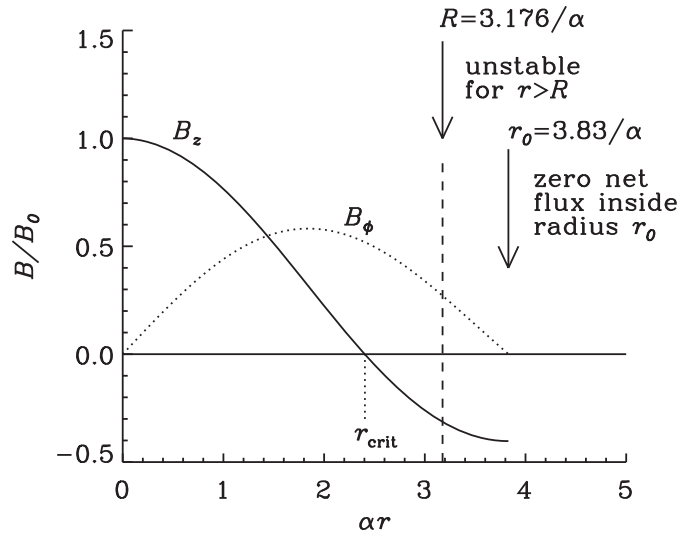

Figure 1: Magnetic field components of an RFP.

3 Particle acceleration in a reversed field pinch

The simplest idealization would be for an infinite cylindrical jet where the magnetic field in cylindrical coordinates (r, ϕ, z) is [9]

$$B_r = 0, \quad B_\phi(r) = B_0 J_1(\alpha r), \quad B_z(r) = B_0 J_0(\alpha r), \tag{1}$$

and this has been shown [10] to be stable for $\alpha r < 3.176$. This radius for stability which we take to be $R \equiv 3.176/\alpha$ is where a conducting wall with a large inertial mass would be present in an experimental situation, and provide part of the circuit along which a return current could flow, which we assume here to be the cocoon. The magnetic field is shown in Fig. 1. Notice the longitudinal field changes sign at $r_{\rm crit} = 2.405/\alpha$, the first zero of $J_0(\alpha r)$.

The current density and vector potential are everywhere proportional to the magnetic field,

$$\vec{j}(r) \quad = \quad \frac{\vec{B}(r)\alpha}{\mu_0} \quad (\mathrm{A\ m^{-2}}), \quad \vec{A}(r, \phi, z) = \frac{1}{\alpha}\vec{B}(r, \phi, z). \tag{2}$$

Electric fields from reconnection are *emf*s induced according to Faraday's law, and so the electric field will be more extensive. The cold plasma (pressure is low) responsible for currents which maintain the magnetic structure cannot short out these electric fields, since they are inductively driven everywhere in the structure, allowing acceleration outside the reconnection zone. Assuming a flow of flux lines toward the reconnection region, the field will be changing everywhere and will induce an electric field. The simplest way of estimating

this global electric field is by assuming an exponential decay of the magnetic field,

$$\vec{B}(t) \quad = \quad B_0 e^{-t/t_{\rm dec}}[J_1(\alpha r)\hat{\phi} + J_0(\alpha r)\hat{z}]. \tag{3}$$

Then,

$$\vec{\mathcal{E}} = -\frac{\partial \vec{A}}{\partial t} \quad = \quad 3.18 \times 10^{-5} \left(\frac{B_0}{10\ \mu\mathrm{G}}\right)\left(\frac{R}{100\ \mathrm{kpc}}\right)\left(\frac{t_{\rm dec}}{\mathrm{Gyr}}\right)^{-1} \times [J_1(\alpha r)\hat{\phi} + J_0(\alpha r)\hat{z}]e^{-t/t_{\rm dec}} \quad (\mathrm{V\ m^{-1}}) \tag{4}$$

We have simulated charged particle trajectories in the RFP magnetic field including the effect of energy change in the induced electric field. We inject particles uniformly and isotropically over the surfaces of disks of radius R at both ends of the fossil jet of length L, and follow their motion until they escape. A typical example is shown in Fig. 2(a).

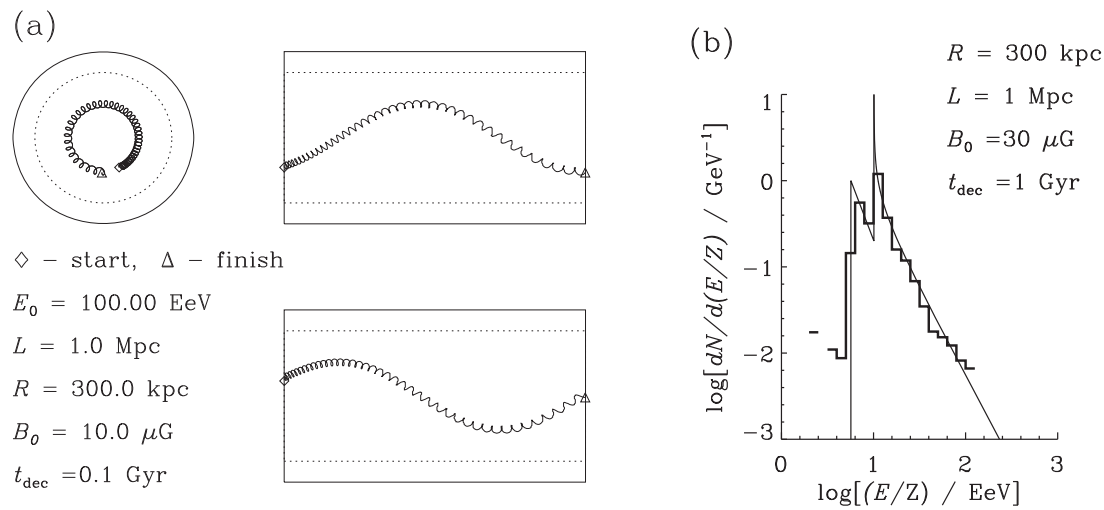

Figure 2: (a) Three orthogonal views showing a typical trajectory in the RFP fields, and critical radius (dashed). (b) Histogram: output spectrum for monoenergetic injection at $E_0/Z = 10^{18}$ eV, and fossil jet parameters as specified, and following particle trajectories as they undergo helical motion along field lines. Solid curve: shows analytic result from Fig. 3(b).

Ultra-relativistic particles of charge Ze are injected with energy E_0 and their final energies are binned as shown in Fig. 2(b). Since the induced electric field is in the same direction as the magnetic field, energy is gained as particles move *along* field lines. Since the induced electric field is proportional to the magnetic field according to Eq. 4, positively charged particles will gain energy for pitch angles less than 90° and lose energy if their pitch angles are greater than 90°.

The energy gain on traversing the fossil jet length L will actually depend on the pitch angle ψ *of the helical magnetic field line* acting as the guiding centre. So, positive particles injected into the RFP with $r < r_{\rm crit}$ will gain energy while moving in the positive z direction, and those injected with $r_{\rm crit} < r < R$ will gain energy while moving in the negative z direction. The increase in energy of ultra-relativistic particles of charge Ze is

$$E_{\rm gain} \quad = \quad E^0_{\rm gain} \, \frac{J_0(\alpha r)^2 + J_1(\alpha r)^2}{J_0(\alpha r)} \tag{5}$$

where

$$E^0_{\rm gain} \quad \approx \quad (10^{18} Z \text{ eV }) \left(\frac{B_0}{10\ \mu\text{G}}\right) \left(\frac{L}{\text{Mpc}}\right) \left(\frac{R}{100 \text{ kpc}}\right) \left(\frac{t_{\rm dec}}{\text{Gyr}}\right)^{-1} \tag{6}$$

and this is plotted in Fig. 3(a). Note that as $r \to r_{\rm crit}$, $p_{\rm gain} \to \infty$.

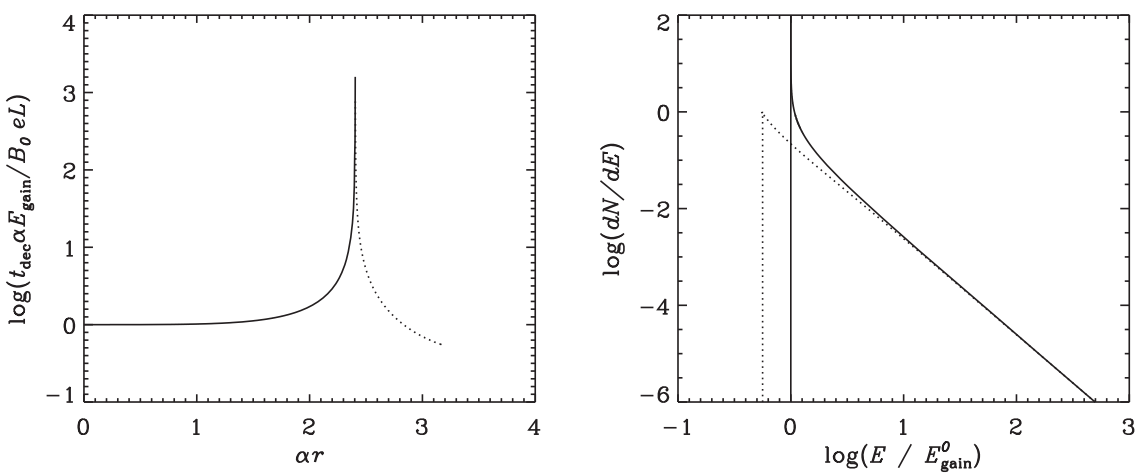

Figure 3: (a) Energy gain of particles injected at one end of the RFP of length L and exiting at the other – solid curve for positive particles traveling in positive z direction, dotted for positive particles traveling in negative z direction. (b) Spectrum of accelerated particles – curves have same meaning as in part (a)

We can work out the energy spectrum as follows,

$$\frac{dN}{dE_{\rm gain}} = \frac{dN}{dr} \left[\frac{dE_{\rm gain}}{dr}\right]^{-1} \tag{7}$$

where dN/dr is the distribution in radius of the injection points. For injection at one end of the RFP we would have uniform injection over the disk of radius R, giving

$$\frac{dN}{dr} = \frac{2r}{R^2} \qquad \text{for } 0 < r < R, \tag{8}$$

Differentiating Eq. 5 gives $dE_{\rm gain}c/dr$.

Thus, from Eqn. 7 we have $dN/dE_{\rm gain}$ as a function of the parameter r, and from Eqn. 5 we have $E_{\rm gain}$ as a function of the parameter r, and so we can plot $dN/dE_{\rm gain}$ vs. $E_{\rm gain}$, and this is shown in in Fig. 3(b). In Fig. 2(b) we have added the analytical spectrum and compared it with that obtained by following particle trajectories. The analytic slope, which asymptotically is E^{-2}, is consistent with the histogram. Note that the "double peaked" structure is due to separate contributions from injection at $r < r_{\rm crit}$ and $r > r_{\rm crit}$. The shape of the spectrum reflects a geometric property of the acceleration mechanism, as particles near $r_{\rm crit}$ being preferentially accelerated to become UHE CRs.

4 Discussion

For an extragalactic source distribution producing an E^{-2} spectrum of protons, Lipari [11] estimates the local power requirement to be $\sim 10^{50}$ erg Mpc^{-3} y^{-1}. Decaying magnetic fields with local filling factor η_B lose energy at a rate

$$\dot{u}_B \quad \sim \quad 10^{53}\eta_B \left(\frac{B_0}{10\ \mu\mathrm{G}}\right)^2 \left(\frac{t_{\rm dec}}{\mathrm{Gyr}}\right)^{-1} \quad \mathrm{erg\ Mpc^{-3}\ y^{-1}}$$

Magnetic fields from quasars can fill up to 5–20% of the intergalactic medium [12] – probably higher locally since our Galaxy is in a "Wall". Indeed, Gopal-Krishna & Wiita [13] estimate the fractional relevant volume that radio lobes born during the quasar era cumulatively cover is ∼0.5. Hence, our crude energetics arguments show fossil AGN structure decay could well be responsible for the observed UHE CR.

The spectrum of accelerated particles will cut off at some maximum momentum determined by either the finite thickness of the reconnection zone (recall that in the analytic approximation as $r \to r_{\rm crit}$, $E_{\rm gain} \to \infty$), or by the gyroradius increasing so that it is no longer much less than the radius of the fossil. From Fig. 1, we see that for $r < R$ the magnetic field is in the range $0.4B_0 < B < B_0$. Hence, the condition $r_L \ll R$ implies

$$E_{\rm gain}^{\rm max} \quad \ll \quad (10^{21} Z\ \mathrm{eV}\ ) \left(\frac{B_0}{10\ \mu\mathrm{G}}\right) \left(\frac{R}{100\ \mathrm{kpc}}\right). \tag{9}$$

The spectrum of UHE CR observed at Earth would have contributions from nearby fossil jets at different distances, with different powers and each having different dimensions and magnetic fields, and hence a range of $E_{\rm gain}^0$ and $E_{\rm gain}^{\rm max}$. Given that several percent of the universe's volume may house such slowly decaying structures, these fossils may even re-energize ultra-high energy cosmic rays from distant/old sources, offsetting the GZK-losses due to

interactions with photons of the cosmic microwave background radiation and giving evidence of otherwise undetectable fossils.

For an individual fossil, the cut-off is expected to be rigidity dependent, implying the observed composition would change from light to heavy close to the cut-off if one or two nearby AGN fossils dominate. However, if distant sources dominate nuclei will be photo-disintegrated by interactions with CMBR photons, and in this case the composition would remain light to the highest energies if distant sources or fossils dominated. Otherwise the composition could be mixed near the observed cut off.

We expect most of the fossil jets to be below the sensitivity of current radio telescopes, based on the work of Blundell & Rawlings [14], and it is impossible at the present time to make firm predictions for the expected UHE CR intensity at Earth. However, this may well change when the SKA (www.skatelescope.org/) is commissioned. Nevertheless, we have demonstrated that it is possible for this process to accelerate protons to UHE, and nuclei to a Z times higher energy, and shown that the power requirements may reasonably be achieved given plausible volume filling factors.

In conclusion, remnants of jets and their surrounding cocoons may still be present around or close to galaxies which contain AGN which are now no longer active. These fossil jets are colossal MHD structures and may have total energies $\sim 10^{60}$ erg. We have shown that decay of such structures over timescales of $\sim$Gyr induces large-scale electric fields which accelerate cosmic rays an E^{-2} power-law up to ultra-high energies. Energetics arguments show that this provides a plausible mechanism for the origin of the UHE CR.

Finally, Heinz & Sunyaev [15] have shown that particles should be accelerated at the reverse shock of a micro-quasar jet colliding with the interstellar medium, and that this may give a contribution to the galactic cosmic rays up to about $\sim$10 GeV. We mention here the possibility of particle acceleration by induced electric fields in a micro-quasar's decaying remnant magnetic bubbles after the micro-quasar's jets have switched off, as in the case of fossil AGN, if they form self organized magnetic structures such as the RFP. The minimum energy of accelerated particles would the be

$$E^0_{\rm gain} \quad = \quad (10^{12} Z \text{ eV }) \left(\frac{B_0}{0.1 \text{ mG}}\right) \left(\frac{L}{1 \text{ pc}}\right) \left(\frac{R}{1 \text{ pc}}\right) \left(\frac{t_{\rm dec}}{\text{Myr}}\right)^{-1} . \qquad (10)$$

Such a mechanism might also apply to decaying pulsar wind nebulae, as well as fossil micro-quasars, and could be responsible for emission in unidentified EGRET and TeV gamma-ray sources, as well as contributing to galactic CR up to $\sim 10^{12} Z$ eV.

Acknowledgements

We thank Garang Yodh and Roger Blandford for stimulating discussions, and KIPAC and SLAC for hospitality in May 2007. RJP thanks the Australian Research Council for support through a Discovery Project grant.

References

[1] K. Greisen, 1966, Phys. Rev. Letters, 16, 748

[2] G.T. Zatsepin, V.A Kuzmin, 1966, JETP Lett., 4, 78

[3] R.J. Protheroe and R.W. Clay, 2004, PASA, 21, 1

[4] G. Benford& R.J. Protheroe, arXiv:0706.4419

[5] T. Clarke et al., arXiv:astro-ph/0612595

[6] P.P. Kronberg et al., 2004, ApJL, 604, L77

[7] G. Benford, 2006, Mon. Not. R. Astron. Soc. 369, 77

[8] M.W. Wise et al., 2007, ApJ, 659, 1153

[9] S. Lundquist, 1951, Phys. Rev., 83, 30

[10] D. Voslamber & D.K. Callebaut, 1962, Phys. Rev., 128, 2016

[11] P. Lipari, 29th International Cosmic Ray Conference, Pune, vol. 6, 381, 2005

[12] S.R. Furlanetto, & A. Loeb, 2001, ApJ, 556, 619

[13] Gopal-Krishna & P.J. Wiita, 2001, ApJ, 560, L115

[14] K.M. Blundell, & S. Rawlings, 2000, AJ. 119, 1111

[15] Heinz, S., & Sunyaev, R. 2002, Astron.Astroph., 390, 751