UHECRs from the Radio Lobes of AGNs

F. Fraschetti\textsuperscript{1,2, a}, and F. Melia\textsuperscript{3}

\textsuperscript{1} Laboratoire AIM, CEA/DSM - CNRS - Univ. Paris Diderot, Irfu/SAp, F-91191 Gif sur Yvette Cédez, France;
\textsuperscript{2} LUTH, Observatoire de Paris, CNRS-UMR8102 and Université Paris VII, 5 Place Jules Janssen, F-92195 Meudon Cédez, France;
\textsuperscript{3} Department of Physics and Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA

We report a stochastic mechanism of particle acceleration from first principles in an environment having properties like those of Radio Lobes in AGNs. We show that energies $\sim 10^{20}$ eV are reached in $\sim 10^6$ years for protons. Our results reopen the question regarding the nature of the high-energy cutoff in the observed spectrum: whether it is due solely to propagation effects, or whether it is also affected by the maximum energy permitted by the acceleration process itself.

1 Introduction

The search for the origin of the UHECRs still represents one the major challenges of theoretical astrophysics. Theoretical models may be divided into two classes: the so-called “bottom-up” scenarios, in which a specific process of acceleration in a particular astrophysical object leads to UHEs; and the so-called “top-down” prescription, in which UHE particles are produced through the decay of super-heavy dark matter particles or by collision among cosmic strings or by topological defects. The recent measurement by Auger, demonstrating a low fraction of high-energy photons in the CR distribution, rule out the top-down models, in which the UHECRs represent the decay products of high-mass particles created in the early Universe. The top-down models based on topological defects, however, are still compatible with the current data and could be constrained by future experiments.

Recently a steepening in the UHECR spectrum has been reported by both the HiRes\textsuperscript{4} and Auger\textsuperscript{5} collaborations. This result may be a strong confirmation of the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff due to photomeson interactions between the UHECRs and low-energy photons in the cosmic microwave background (CMB) radiation\textsuperscript{6,7}.

The most telling indicator for the possible origin of these UHECRs is the discovery by Auger of their clustering towards nearby ($\sim 75$ Mpc) AGNs along the supergalactic plane. However, the question remains open regarding the mechanism of acceleration to such high energies and on the origin of the observed cutoff in the spectrum, i.e., if it is due solely to the GZK effect, or whether it also points to an intrinsic limit to the acceleration efficiency.

UHECRs generation scenarios include the so-called first-order Fermi acceleration in GRBs, Pulsar Wind Bubbles, and also relativistic second order Fermi acceleration\textsuperscript{8,9}. We report here a treatment of particle acceleration in the lobes of radio-bright AGNs from first principles\textsuperscript{10}.

\textsuperscript{a}Corresponding author: federico.fraschetti@cea.fr
considering the acceleration of charged particles via random scatterings (a second-order process) with fluctuations in a turbulent magnetic field.

2 Model of magnetic turbulence

In our treatment, we follow the three-dimensional motion of individual particles within a time-varying field. By avoiding the use of equations describing statistical averages through the phase space distribution function of a given population of particles, we mitigate our dependence on unknown factors, such as the diffusion coefficient. We also avoid the need to use the Parker approximation in the transport equation. The remaining unknowns are the energy partition between turbulent and background fields, and the turbulent spectral distribution, though this may reasonably be assumed to be Kolmogorov. For simplicity, we assume that the magnetic energy is divided equally between the two components; the actual value of this fraction does not produce any significant qualitative differences in our results.

We calculate the trajectory of a test particle with charge $e$ and mass $m$ in a magnetic field $B(t, r) = mc\Omega(t, r)/e$, where $c$ is the speed of light in vacuum. The particle motion is obtained as a solution of the Lorentz equation

$$\frac{du(t)}{dt} = \delta\mathcal{E}(t, r) + \frac{u(t) \times \Omega(t, r)}{c^2},$$

where $u$ is the three-space vector of the four-velocity $u^\mu = (\gamma, \gamma v/c)$, $t$ is the time in the rest frame of the source, and $\gamma$ is the Lorentz factor $\gamma = 1/\sqrt{1 - (v/c)^2}$. The quantity $\Omega$ in equation (1) is given by $\Omega(t, r) = \Omega_0 + \delta\Omega(t, r)$, where $\Omega_0 = e B_0/mc$ and $B_0$ is the background magnetic field. The time variation of the magnetic field, however, induces an electric field $\delta\mathcal{E}(t, r) = (e/mc)\mathcal{E}(t, r)$ according to Faraday’s law. We ignore any large-scale background electric fields; this is a reasonable assumption given that currents would quench any such fields within the radio lobes of AGNs.

We follow the Giacalone-Jokipii prescription for generating the turbulent magnetic field, including a time-dependent phase factor to allow for temporal variations. This procedure calls for the random generation of a given number $N$ of transverse waves $k$ at every point of physical space where the particle is found, each with a random direction defined by angles $\theta(k_i)$ and $\phi(k_i)$. This form of the fluctuation satisfies $\nabla \cdot B = 0$. We write

$$\delta\Omega(t, r) = \sum_{i=1}^{N} \Omega(k_i)[\cos \alpha(k_i) \mathbf{y}' \pm i \sin \alpha(k_i) \mathbf{z}'][e^{i(k_i \cdot x' - \omega t)}^{\pm}].$$

The primed reference system $(x', y', z')$ is related to the lab-frame coordinates $(x, y, z)$ via a rotation in terms of $\theta(k_i)$ and $\phi(k_i)$. For each $k_i$, there are 5 random numbers: $0 < \theta(k_i) < \pi$, $0 < \phi(k_i) < 2\pi$, $0 < \alpha(k_i) < 2\pi$, $0 < \beta(k_i) < 2\pi$ and the sign $\pm$ indicating the sense of polarization. We use the dispersion relation for transverse non-relativistic Alfven waves in the background plasma: $\omega(k_i) = v_A k_i \cos \theta(k_i)$, where $v_A = B_0/\sqrt{4\pi n m_p}$ is the non relativistic Alfven velocity in a medium with background magnetic field $B_0$ and number density $n$, being $m_p$ the proton mass, and $\theta(k_i)$ is the angle between the wavevector $k_i$ and $B_0$. The background plasma is assumed to have a background number density $n \sim 10^{-4} \text{ cm}^{-3}$, a reasonable value for the radio lobes of AGNs.

The amplitudes of the magnetic fluctuations are assumed to be generated by Kolmogorov turbulence, so

$$\Omega(k_i) = \Omega(k_{\text{min}}) \left( \frac{k_i}{k_{\text{min}}} \right)^{-\Gamma/2},$$

where $\Gamma$ is a constant. The remaining unknown factors, such as the diffusion coefficient, are avoided in this construction. We also avoid the need to use the Parker approximation in the transport equation. The remaining unknowns are the energy partition between turbulent and background fields, and the turbulent spectral distribution, though this may reasonably be assumed to be Kolmogorov. For simplicity, we assume that the magnetic energy is divided equally between the two components; the actual value of this fraction does not produce any significant qualitative differences in our results.
where $k_{\text{min}}$ corresponds to the longest wavelength of the fluctuations and $\Gamma = 5/3$. Finally, the quantity $\Omega(k_{\text{min}})$ is computed by requiring that the energy density of the magnetic fluctuations equals that of the background magnetic field: $B_0^2/8\pi$.

We choose $N=2400$ values of $k$ evenly spaced on a logarithmic scale; considering that the turbulence wavenumber $k$ is related to the turbulent length scale $l$ by $k = 2\pi/l$, we adopt a range of lengthscales from $l_{\text{min}} = 10^{-1} v_0/\Omega_0$ to $l_{\text{max}} = 10^9 v_0/\Omega_0$, where $v_0$ is the initial velocity of the particle and $\Omega_0$ is its gyrofrequency in the background magnetic field. Thus the dynamic range covered by $k$ is $k_{\text{max}}/k_{\text{min}} = l_{\text{max}}/l_{\text{min}} = 10^{10}$ and the interaction of particle with the turbulent waves is gyroresonant at all times. The particles passing through this region are released at a random position inside the acceleration zone, which for simplicity is chosen to be a sphere of radius $R$, with a fixed initial velocity $u_0$ pointed in a random direction. The initial value of the Lorentz factor $\gamma_0 = \sqrt{1 + u_0^2} = 1.015$ is chosen to avoid having to deal with ionization losses for the protons and ions.

Assuming that both the radio and CMB intensity fields are isotropic, we take these energy losses into account using the following angle-integrated power-loss rate:

$$\frac{-dE}{dt} = \frac{4}{3} \sigma_T(m)c^2 \left( \frac{B^2}{8\pi} + U_R + U_{\text{CMB}} \right),$$  

(4)

where $\sigma_T(m) = 6.6524 \times (m_e/m)^2 10^{-25}$ cm$^2$ is the Thomson cross section for a particle of mass $m$, $B^2/(8\pi) = (2B_0^2)/(8\pi)$ is the total energy density of the magnetic field, and $U_R$ is the photon energy density inside a typical Radio Lobe, for which we assume a standard luminosity density corresponding to the Fanaroff-Riley class II of galaxies (with a luminosity $L = 5 \times 10^{25}$ W Hz$^{-1}$ sr$^{-1}$ at 178 MHz), and a radius $R = 30$ kpc, the size of our spherical acceleration zone. For the CMB, we use $U_{\text{CMB}} = aT^4 = 4.2 \times 10^{-13}$ erg cm$^{-3}$.

In a region where magnetic turbulence is absent or static, a given test particle propagates by “bouncing” randomly off the inhomogeneities in $B$, but its energy remains constant. The field we are modeling here, however, is comprised of transverse plane waves (see equation 2), and collisions between the test particle and these waves produces (on balance) a net acceleration as viewed in the lab frame.

In Figure 1 (left), we plot the time evolution of the particle Lorentz factor $\gamma$ for three representative values of the background field $B_0$: $10^{-7}$, $10^{-8}$, and $10^{-9}$ gauss. We see the particle undergoing various phases of acceleration and deceleration as it encounters fluctuations in $B$. In Figure 1 (right), we compare a differential injection spectrum for a population of 500 protons for energy $E > 4 \times 10^{18}$ eV. The observed spectrum may be affected by the cosmological evolution in source density. However, a likelihood analysis of the dependence of the observed distribution on input parameters has already shown that, in the case of pure proton-fluxes of primaries, for $\alpha \sim 0$, where $\alpha$ is the evolution index in the source density, the HiRes observations are compatible with a power-law injection spectrum with index $-2.6$.

From our sampling of the various physical parameters, we infer that $B_0$ should lie in the range $(0.5, 5) \times 10^{-8}$ gauss in order to produce UHECRs with the observed distribution. We note, however, that the particle distribution calculated for energies above 50 EeV does not include the GZK effect, which becomes progressively more important as the energy approaches $10^{20}$ eV.

3 Conclusion

In view of the very good match between our theoretical simulation and the Auger observations, it is worth emphasizing that this calculation was carried out without the use of several unknown factors often required in approaches involving a hybrid Boltzmann equation to obtain the phase-space particle distribution. In addition, we point out that the acceleration mechanism we have invoked here is sustained over 10 orders of magnitude in particle energy, and the UHECRs
therefore emerge naturally—without the introduction of any additional exotic physics—from the physical conditions thought to be prevalent within AGN giant radio lobes.

As the Auger observatory gathers more data and improves the statistics, our UHECR source identification will continue to get better. Eventually, we should be able to tell how significant the GZK effect really is, and whether the cutoff in the CR distribution is indeed due to propagation effects, or whether it is primarily the result of limitations in the acceleration itself. Given the fact that energies as high as $\sim 10^{20}$ eV may be reached within typical radio lobes, it is possible that both of these factors must be considered in future refinements of this work.

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