Acceleration of highest Energy ($> 10^{20}$ eV) Cosmic Rays by Superconducting Cosmic Strings

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Abstract

There are no known acceleration mechanisms to account for the observed highest energy cosmic rays (10^{20} to 10^{21} eV and perhaps beyond). The analogy between vortex lines in a Type II superconductor and conducting cosmic strings is used to calculate the electric field and critical current carried by such objects using the modified Ginburg-Landau theory. These quantities are related to the string tension. It is then shown that these objects can thus accelerate protons to about 10^{21} to 10^{22} eV and even higher. The spectrum has a rough E^{-3} form. A few such strings in a gigaparsec radius can account for the estimated observed flux in the highest energy cosmic rays.

1. Introduction

The highest energy cosmic rays are known to have energies $> 10^{20} eV$. Conventional supernova remnant models cannot accelerate CR particle to much above energies $\sim 10^{14} eV$. This is essentially because the interstellar magnetic field is only $\sim 5\mu G$. Pulsars are possible sources or sites for acceleration to higher energies. Even here there are limits ($\sim 10^{18} eV$) or at most $\sim 10^{19} eV$ for iron nuclei. Moreover acceleration near neutron stars is difficult because of the high energy loss rates of charges particles in intense magnetic fields. In short none of these processes can account for particles of $\sim$ 300 EeV energy like the 'falling brick' event. However, more compact objects like black holes can be considered. It was earlier showsn [1,2] that they are capable of accelerating charged particles to energies well above 10^{21} eV.

Again non-acceleration mechanisms were considered [2,3], i.e. it was shown that evaporating black holes in their terminal stages of decay as well as disintegrating cosmic strings (and other topological defects formed in the early universe) can spontaneously produce such UHE particles in situ, without any need for accelerating mechanisms.

2. Acceleration by Superconducting Cosmic Strings

Conducting cosmic strings are essentially topological line defects. As ususal they are characterized by a tension which depends on the energy scale (M) of the symmetry breaking phase transition producing them and given by:

$$T_s \approx \frac{c^2}{G} \left(\frac{M}{M_{pl}}\right)^2 \tag{1}$$

(M_{pl} being the Plank energy scale).

Further there are some nice analogies between vortex lines in a Type II superconductor (Carrying a quantized flux $\hbar/e$) and conducting cosmic strings. For instance, the field vanishes everywhere in a superconductor (Meissner effect), except along Abrikosov vortex lines carrying a confiened quantized flux $\hbar c/ze$. The vanishing of the field inside a superconductor is an effect of the Landau-Ginzburg theory. The Higgs field responsible for the above topological defects is described by a relativistic version of the Landau-Ginzburg model and consequently it can be shown that conducting strings also carry a flux [3,4,1]:

$$\phi = n\hbar c/e \tag{2}$$

The flux can be shown to give rise to an electric field [1,3,4]:

$$V \approx cT_s \; G \; M_{pl}^2/e\hbar$$

e is the electron charge.

$$\approx \frac{Gc}{e\hbar} \; T_s \; . \; M_{pl}^2 \tag{3}$$

Thus charged particles can be acelerated to a maximal energy given by: (corresponding to a critical current):

$$E \approx e\,c\; T_s^{1/2} \; G^{1/2} \tag{4}$$

For a string tension, corresponding to a GUT scale of $M \approx 10^{15}$ GeV (the corresponding tension being given by eq. (1)): eq. (4) gives:

$$E \approx 10^{21} eV \tag{5}$$

A higher string tension T_s give rise to a higher value of E. For a GUTs scale M $\sim 10^{16}$ GeV, E $\approx 10^{22} eV$.

It was shown in ref. (1) that the spectrum of the highest energy particles produced by the string has roughly a E^{-3} form.

Now the critical current carried by the conducting string is estimated from:

$$\mu_0 \; I_{crit} = 2\pi \; r \; B_{crit}$$

$$with \quad B_{crit} \approx \frac{m_s^2 c^3}{e} \hbar$$

$$This gives \quad I_{crit} \approx \frac{2\pi}{\mu_0} \frac{G^{12}}{e} \; T_s^{1/2} \; M_{pl} c^3 \qquad (6)$$

$$\approx 10^{22} amps$$

$$R_s \approx R_{vac} \approx 377 \quad ohms$$

$$I_{crit}^2 \; R \approx 5x10^{46} ergs/s$$

thus the total energy stored in the magnetic field of a conducting string of length $L_s \approx 10 kpc$ is given by:

$$E_{tot} \approx \pi \; B_{crit}^2 \; \frac{\hbar^2}{m_s^2 c^2} \; . \; L_s$$

$$\approx \pi \; L_s \; T_s \; G \; M_{pl}^2 \; c^2/e^2$$

$$\approx 10^{61} \; ergs$$

Hence the total number of UHE CR's which can be produced by a single 10 kpc long conducting string is $\approx 10^{47}$, implying a integalactic flux, consistent with that implied by the Fly's eye and other events.

References

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