Comparison of UHECR spectra from necklaces and vortons

Luis Masperi† and Milva Orsaria‡
Centro Latinoamericano de Física,
Av. Vencenslau Bráz 71 Fundos, 22290-140 Rio de Janeiro, Brazil

Abstract

Cosmic rays of energy higher than $10^{19}eV$ may be explained by topological defects produced in the early stages of universe. Two suitable alternatives are: necklaces formed by magnetic monopoles connected by strings, and vortons which are loops stabilized by superconducting currents. The former are uniformly distributed in the universe, may account for cosmic rays above the ankle, suffer a transient GZK cutoff with a subsequent recovery and isotropy of observations is expected. The latter are concentrated in the galactic halo, require an additional extragalactic contribution between the ankle and the GZK cutoff, beyond which give a harder component and predict anisotropy related to mass concentration.

PACS: 98.70.S, 98.80.C

1 Introduction

The ultra-high energy cosmic rays (UHECR) have an energy spectrum of their flux $F(E)$ that shows for $E^3 F(E)$ a minimum around $5 \times 10^{18}eV$ which

---

*Presented at the Chacaltaya Meeting on Cosmic Rays Physics, La Paz, 23-27 July 2000
†On leave of absence from Centro Atómico Bariloche, Argentina. E-mail: masperi@cbpf.br
‡E-mail: orsaria@cbpf.br
is called the ankle, then a maximum before the GZK cutoff\[1\] at $5 \times 10^{19}\,\text{eV}$ due to the interaction with the CBR and a recovery after it at $10^{20}\,\text{eV}$.

Whereas the cosmic rays below the ankle are most probably of galactic origin, it is not clear which is the explanation of the subsequent rise. The possibility that it is due to an extragalactic source seems to be supported by a partial GZK cutoff which would affect cosmic rays traveling at least 50 Mpc. But the subsequent observed spectrum up to the highest energy event of $3 \times 10^{20}\,\text{eV}$ indicates a hard component which may be or not related to that which appears above the ankle.

It is difficult to explain the observed events\[2\] beyond the GZK cutoff with ordinary astrophysical objects which are not identified if they are close to us, and that would require non standard messengers not interacting with CBR if they are very far away\[3\].

A solution may be the top-down mechanism where some type of superheavy microscopical object with mass of the order of the Grand Unification Theory (GUT) scale decays very slowly producing the observed UHECR. Since a general feature is a hard spectrum at emission $F(E_{em}) \propto 1/E_{em}$, these superheavy objects might be either condensed in the galactic halo or uniformly distributed in the universe.

The former case may correspond to closed cosmic strings stabilized by superconducting currents called vortons\[4\] or to superheavy particles whose interaction with the ordinary ones is of gravitational order generically denoted as cryptons\[5\]. Since they were presumably produced at the GUT scale, they behave afterwards as cold dark matter (CDM) and should have concentrated in the galactic halo.

The latter case may be instead represented by necklaces\[6\] where ordinary cosmic strings whose dynamics makes them evolve to a scaling solution, i.e. a uniform distribution in space, incorporate monopoles and antimonopoles that annihilate very slowly.

We will give a brief description of vortons and particularly show that if they represent a small fraction of the halo CDM, they may account for the apparent hard component of the UHECR spectrum above $10^{20}\,\text{eV}$. An additional extragalactic component would be necessary to explain the ankle feature.

Compared to this, an also small fraction of the critical density of universe represented by necklaces may give, with a reasonable law for the energy degrading due to interaction with CBR, the maximum of $E^3F(E)$ immediately below the GZK cutoff. The hard spectrum at emission allows a recovery.
above it at least up to the highest observed UHECR which would be impossible for extragalactic sources with the ordinary law $F(E_{em}) \propto 1/E_{em}^{3}$.

2 Vortons in halo

Considering sources that emit $n_X(t)$ GUT boson particles $X$ per unit space and time, each of them giving $N_c$ UHECR, the total flux on earth will be

$$F = \frac{1}{4\pi} \int_{t_{in}}^{t_0} dt \ N_c \ n_X(t) \left( \frac{a(t)}{a(t_0)} \right)^3,$$ \hspace{1cm} (1)

where $a$ is the scale parameter of universe, $t_0$ its age and $t_{in}$ the initial time of contributions.

For quasistable objects like vortons concentrated in halo with density $n(t)$ which emit by tunneling an $X$ with a lifetime $\tau$, $n_X = n/\tau$ and the total flux is

$$F_h = \frac{N_c}{4\pi} \ n_h(t_0) \frac{\Delta t}{\tau},$$ \hspace{1cm} (2)

where $\Delta t \sim 50kpc$ is the halo size.

The energy spectrum

$$F_h(E) = \frac{1}{4\pi} n_h(t_0) \frac{\Delta t}{\tau} \sum_{i=1}^{N_c} \delta(E - E_i)$$ \hspace{1cm} (3)

must be averaged on the intervals $\Delta E_i$ between produced particles to compare with observations

$$F_{h}(E_i) = \frac{1}{\Delta E_i} n_h(t_0) \frac{\Delta t}{4\pi} \frac{\Delta t}{\tau}. $$ \hspace{1cm} (4)

Since the production of UHECR comes from the hadronization of the very energetic quark into which the $X$ particle decays, by dimensional arguments there are no relevant ordinary mass parameters and we may expect

$$\Delta E_i \sim E_i, \hspace{0.5cm} F_{h}(E_i) \propto \frac{1}{E_i},$$ \hspace{1cm} (5)

i.e. a hard spectrum consistent with accurate QCD calculations\[7\] apart from energies close to $m_X$. 

3
It is interesting that according to Eq.(5) the average probability of UHECR production on energy intervals will be

\[
\frac{d\Gamma}{dE} \sim \frac{1}{\tau} \frac{1}{E},
\]

which integrated on the ultra-high energy range \(10^{19} - 10^{24} eV\) to agree with the total flux Eq.(2) must give

\[
\Gamma = \int \frac{d\Gamma}{dE} dE = \frac{N_c}{\tau},
\]

with \(N_c \sim 10\), that is a reasonably accepted value[8].

Therefore we may take the equally spaced particles in \(\log E\) according to \(E_1 \approx 10^{19} eV, E_2 \approx 10^{19.5} eV, E_3 \approx 10^{20} eV, E_4 \approx 10^{20.5} eV \ldots \ldots \ldots E_{10} \approx 10^{23.5} eV\)

so that \(\Delta E_i \approx 0.7 E_i\).

Since from eq.(4) the flux in each energy bin is the same, one may normalize it roughly at the expected value for \(10^{20} eV\)

\[
\frac{n_h(t_0)}{4\pi} \frac{\Delta t}{\tau} = \frac{1}{km^2 \text{ century}}.
\]

A vorton is a loop of ordinary cosmic string with an energy per unit length \(\mu \sim m_X^2\) stabilized by \(N\) massless fermionic carriers giving therefore a total energy

\[
E_v = \mu L + \frac{N^2}{L},
\]

which is minimized at \(E_v \sim 2Nm_X\) by a length \(L \sim N/m_X\). The decay of the vorton with emission of \(X\) by tunneling gives a lifetime \(\tau \sim t_0\) for \(N \sim 1000\). Therefore to satisfy Eq.(8) one only needs a fraction \(\sim 10^{-6}\) of the average energy density of the halo 0.3 GeV/cm\(^3\) represented by vortons. This small density may be the remnant of the collapse of most vortons at the electroweak phase transition[8].

This contribution of vortons to \(E^3 F(E)\) will be a hard component which reproduces the observed flux above the GZK cutoff as is seen in fig.1. One must therefore complement it with another possibly extragalactic component which may explain the spectrum between the ankle and GZK energy.

A similar analysis may be done for cryptons being necessary to explain their required density.
3 Necklaces in universe

These hybrid topological defects may be formed by a sequence of GUT symmetry breakings

\[ G \rightarrow H \times U(1) \rightarrow H \times Z_2, \]

where in the first monopoles would be produced and then would be attached to the ordinary strings which appear in the second one as beads of a necklace.

The relevant parameter for the necklace dynamics is \( r = m/(\mu d) \) where \( m \) is the monopole mass, \( d \) its separation from the antimonopole in the string and \( \mu \) the tension of the latter. For \( r \sim 10^6 \) the distance between strings at present is small \( \sim 3 \text{Mpc} \).

The evolution of the necklace networks is scale invariant, i.e. they would be distributed uniformly in the universe and represent a constant fraction of its energy. Monopoles and antimonopoles trapped in the necklaces at the end would annihilate producing \( X \) particles with a rate

\[ \dot{n}_X(t) \sim \frac{r^2 \mu}{t^3 m_X} = \frac{\alpha}{t^3}. \]

Therefore the expression for the UHECR flux eq.(1) would apply but with an early \( t_{in} \) compatible with avoiding their redshift below \( 10^{19} \text{eV} \) which is roughly of the order of the matter-radiation equivalence time. \( r^2 \mu \) cannot be larger than \( 10^{28} \text{GeV}^2 \) to avoid a diffuse gamma radiation above the experimental bound. The total flux will be

\[ F_u = N_c \frac{\alpha}{t_0^2} \ln \left( \frac{t_0}{t_{in}} \right). \]

Even though at emission the UHECR produced by an \( X \) are equally spaced in \( \log E_{em} \) as discussed in Sec.2, their redshift would cause a softening of the law \( 1/E \) for the flux spectrum on earth.

But more important than this effect is the interaction of cosmic rays with CBR. The \( p\gamma \) total cross-section at the highest energy is \( \sim 0.2 \text{ mb} \), and rises up to \( \sim 0.6 \text{ mb} \) for the \( \Delta \) resonance mass.

Then to evaluate the flux spectrum, we may proceed as follows. Instead of taking one cosmic ray in each bin as in the case of vortons in halo, we will consider \( N_i \) to account for the degrading of energy so that

\[ F_U(E_i) = \frac{\alpha}{t_0^2} \ln \left( \frac{t_0}{t_{in}} \right) \frac{N_i}{\Delta E_i}. \]
Therefore we may parameterize for all cases

$$\log \left[ E_i^3 T(E_i) \right] = \log J + \log N_i + 2 \log \left( \frac{E_i}{10^{19} \text{eV}} \right), \quad (14)$$

where $J$, related to the properties of sources, will be adjusted to fit the observed events. For the case of vortons all $N_i = 1$.

For necklaces to determine the effective $N_i$ and considering the mean free path associated to the quoted $\sigma_{p\gamma}$ and the density of $3K$ photons, we will take 1% of probability that the cosmic ray for $\Delta$ production keeps its energy. This is consistent with the fact that the sources of non degrading protons are concentrated in a radius $\sim 50\text{Mpc}$ out a whole space $\sim 100$ times larger. For higher $E_i$ this probability will increase to 3% following $\sigma_{p\gamma}$. We will assume that the missing events are transferred in equal parts to the two immediate lower bins. According to the bins defined in Sec.2, that of $E_3$ is particularly affected by the resonant scattering. The immediate lower one has only the upper 10% of the bin in the resonance region so that $\sim 90\%$ of its events keep their energy and the rest is transferred to the bin of $E_1$.

In this way it turns out

$N_1 = 4.09 \quad N_2 = 5.15 \quad N_3 = 0.05 \quad N_4 = 0.14 \quad N_5 = 0.12$

$N_6 = 0.10 \; N_7 = 0.08 \; N_8 = 0.06 \; N_9 = 0.04 \; N_{10} = 0.03$

and the flux spectrum eq.(14) is shown in fig.2.

We see that the existence of an ankle and the recovery after a transient GZK are successfully reproduced.

A check of the calculation is that the normalization for the bin of $10^{19}\text{eV}$ must be

$$\frac{\alpha}{t_0^{2}} \ln \left( \frac{t_0}{t_{\text{in}}} \right) \; N_1 = \frac{1}{km^2 \text{yr}}, \quad (15)$$

which is satisfied for $\alpha = 10^{37} \text{sec}^{-1}$ coming from $m_X = 10^{15}\text{GeV}$.

This is similar to the normalization for ordinary strings\[9\] the difference being that for them $\mu \sim m_X^2$ and the present separation between strings is three orders of magnitude larger than for necklaces. As a consequence our simplified treatment is much more suitable for the latter because protons for sources within a radius $\sim 50\text{Mpc}$ would be detected whereas photons would be mostly absorbed.

It is clear that the feature of fig.2 is consequence of the hard component corresponding to quark hadronization reflected in the last term of eq.(14). If one should have considered an ordinary law $1/E^3$ at emission, the corresponding flux due to uniformly distributed extragalactic sources would be
given by eq.(14) without the last term and as shown in fig.3 would reasonably reproduce the observed events below the GZK cutoff but without recovery above it.

We must note comparing figs. 1 and 2 that \( J \) is one order of magnitude larger for necklaces than for vortons which is consequence of the fact that the latter fit the flux at \( \sim 10^{20} eV \) and the former that at \( \sim 10^{19} eV \) with a partial compensation due to degrading of energy. It is important to note that with the above values of \( r, \mu \) and a monopole mass \( m \sim 10^{16} GeV \) the energy per unit length due to monopoles turns out to be \( \sim 10^{22} GeV^2 \) and the fraction of critical density \( \sim 10^{-9} \), slightly smaller than that of ordinary strings.

4 Conclusions

We have seen that both vortons in halo and necklaces in universe may be a solution for the problem of UHECR above \( 10^{20} eV \). From the observational point of view the difference will be the expected anisotropy in the former case because of the asymmetric position of the sun in the galaxy compared to the isotropy of the latter characteristic of a cosmological origin. Regarding this, it must be noted that the anisotropy detected below the ankle is not observed above it\(^{10} \), which would be consistent with the appearance of an extragalactic component, a larger statistics being needed at the highest energy to see if new galactic sources contribute.

Referring to elementary particle theory it is interesting that the most appropriate GUT models are different. For necklaces, since it is necessary that the breaking of the abelian symmetry leaves a discrete \( Z_2 \) unbroken, a GUT model based on \( SO(10) \) is suitable. For vortons on the other hand the \( E_6 \) GUT model is better because the breaking of the contained additional abelian symmetry produces the necessary superconducting current with exotic fermions, whereas necklaces would not be formed due to the fact that its Higgs content does not allow an unbroken \( Z_2 \).

Acknowledgement

We are grateful to Pedro Miranda and the organizing committee of the Chacaltaya Meeting on Cosmic Rays Physics for the warm hospitality at La Paz. MO thanks Fundación Antorchas for partial financial support.
References

[1] K. Greisen, *Phys. Rev. Lett.* **16** (1966) 798; G. Zatsepin and V. Kuzmin, *JETP Lett.* **4** (1966) 78; F. Aharonian and J. Cronin, *Phys. Rev.* **D 50** (1994) 1892.

[2] M. Takeda *et al.*, *Phys. Rev. Lett.* **81** (1998) 1163; D. J. Bird *et al.*, *Astropart. Phys.* **441** (1995) 144.

[3] A. V. Olinto, astro-ph/0002006; V. Berezinski, astro-ph/0001163.

[4] R. L. Davis and E. P. S. Shellard, *Nucl. Phys.* **B 323** (1989) 209; R. Brandenberger, B. Carter, A. C. Davis and M. Trodden, *Phys. Rev.* **D 54** (1996) 6059.

[5] V. A. Kuzmin and V. A. Rubakov, *Yadern. Fiz.* **61** (1998) 1122; V. Berezinsky, M. Kachelriess and A. Vilenkin, *Phys. Rev. Lett.* **79** (1997) 4302; K. Hamaguchi, Y. Nomura and T. Yanagida, *Phys. Rev.* **D 59** (1999) 063503; R. Benakli, J. Ellis and D. V. Nanopoulos, *Phys. Rev.* **D 59** (1999) 047301.

[6] V. Berezinski and A. Vilenkin, *Phys. Rev. Lett.* **79** (1997) 5202; V. Berezinski, P. Blasi and A. Vilenkin, *Phys. Rev.* **D 58** (1998) 103515.

[7] M. Birkel and S. Sarkar, *Astropart. Phys.* **9** (1998) 297.

[8] L. Masperi and M. Orsaria, *Int. J. Mod. Phys.* **A 14** (1999) 3581.

[9] P. Bhattacharjee, *Phys. Rev. Lett.* **81** (1998) 260.

[10] M. Takeda *et al.*, astro-ph/9902239.