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Comparison of UHECR spectra from necklaces and vortons(*)

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Summary. — Cosmic rays of energy higher than 10^{19} eV may be explained by topological defects produced in the early universe. Two alternatives are necklaces and vortons. The former are uniformly distributed in the universe, may account for cosmic rays above the ankle and suffer a transient GZK cutoff with a subsequent recovery. 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.

PACS 98.70 – Unidentified sources of radiation outside the Solar System.
PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).
PACS 98.80.Cq – Particle-theory and field-theory models of the early Universe (including cosmic pancakes, cosmic strings, chaotic phenomena, inflationary universe, etc.).
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1. – Introduction

The ultra-high energy cosmic rays (UHECR) have an energy spectrum of their flux $F(E)$ that shows for $E^3F(E)$ a minimum around 5×10^{18} eV, the ankle, then a maximum before the GZK cutoff [1] at 5×10^{19} eV and a recovery after it. Whereas the cosmic rays below the ankle are most probably of galactic origin, the following rise might be due to an extragalactic source if a partial GZK cutoff is confirmed. The subsequent observed spectrum up to the highest energy event of 3×10^{20} eV indicates a hard component which may be or not related to that above the ankle. It is difficult to explain the observed events [2] beyond the GZK cutoff with ordinary astrophysical objects which are

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not identified if they are close to us, and that would require messengers not interacting with CBR if they are very far away [3].

A solution may be the top-down mechanism where superheavy microscopical objects decay very slowly producing the observed UHECR, being either condensed in the galactic halo or uniformly distributed in the universe. The former case may correspond to vortons [4] or to superheavy particles with an extremely weak interaction with the ordinary ones [5] , which should be produced at the Grand Unification Theory (GUT) scale, behave afterwards as cold dark matter (CDM) and concentrate 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 uniform distribution in space, incorporate monopoles and antimonopoles that annihilate very slowly.

We will show that if vortons are a small fraction of the halo CDM, they may account for the apparent hard component of the UHECR spectrum above 10^{20} eV. Compared to this, an also small fraction of the critical density of the universe given by necklaces may produce, with a reasonable law for the degrading due to interaction with CBR, the maximum of $E^3F(E)$ immediately below the GZK cutoff and a recovery above it which would be impossible for extragalactic sources with the ordinary energy spectrum.

2. – Vortons in halo

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

$$F=\frac{1}{4\pi}\int_{t_{\rm in}}^{t_0}{\rm d}tN_c\dot{n}_X(t)\left(\frac{a(t)}{a(t_0)}\right)^3, \tag{1}$$

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

For quasistable objects like vortons concentrated in halo of size $\Delta t\sim 50$ kpc with density $n(t)$ which emit by tunneling an X with a lifetime τ, $\dot{n}_X=n/\tau$ and

$$F_h=\frac{N_c}{4\pi}n_h(t_0)\frac{\Delta t}{\tau}. \tag{2}$$

The energy spectrum averaged on the intervals ΔE_i between produced particles will be

$$\overline{F}_h(E_i)=\frac{1}{\Delta E_i}\frac{n_h(t_0)}{4\pi}\frac{\Delta t}{\tau}. \tag{3}$$

Since the production of UHECR comes from the hadronization of the very energetic quark into which X decays, by dimensional arguments we may expect

$$\Delta E_i\sim E_i,\ \overline{F}_h(E_i)\propto\frac{1}{E_i}, \tag{4}$$

i.e. a hard spectrum consistent with accurate QCD calculations [7]. According to eq. (4) a reasonable accepted value [8] is $N_c\sim 10$ particles which we take equally spaced in $\log E$ from $E_1\simeq 10^{19}$ eV to $E_{10}\simeq 10^{23.5}$ eV.

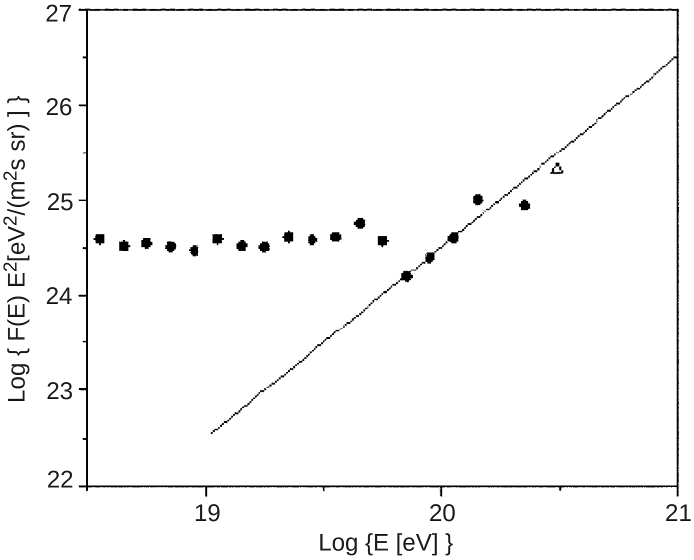

Fig. 1. – Vortons in halo. Hard component from eq. (10) with $N_i = 1$ and $\log(J) = 22.5$. Observed data ● from AGASA and △ from Fly's Eye.

Since from eq. (3) the flux in each energy bin is the same, we normalize it at 10^{20} eV

$$\frac{n_h(t_0)}{4\pi}\frac{\Delta t}{\tau} = \frac{1}{\text{km}^2\text{century}}. \tag{5}$$

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 whose decay with emission of X by tunneling gives a lifetime $\tau \sim t_0$ for $N \sim 1000$. Therefore to satisfy eq. (5) one needs a fraction $\sim 10^{-6}$ of the energy density of the halo 0.3 GeV/cm^3 represented by vortons if $m_X \sim 10^{15}$ GeV. This contribution will be a hard component which reproduces the observed flux above the GZK cutoff as is seen in fig. 1. One must complement it with another extragalactic component to explain the spectrum between the ankle and GZK energy.

3. – Necklaces in the universe

These defects may be formed by a sequence of symmetry breakings

$$G \to H \times U(1) \to H \times Z_2, \tag{6}$$

where in the first monopoles they would be produced and then attached to the ordinary strings which appear in the second one. The parameter for the dynamics is $r = m/(\mu d)$, where m is the monopole mass, d its separation from the antimonopole in the string and μ the tension of the latter. For $r \sim 10^6$ the distance between strings at present is ~ 3 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 at the end would annihilate producing X particles with a rate

$$\dot{n}_X(t) \sim \frac{r^2\mu}{t^3 m_X} = \frac{\alpha}{t^3}. \tag{7}$$

The expression for the UHECR flux eq. (1) applies with a t_{in} which avoids redshift below 10^{19} eV. $r^2\mu$ cannot be larger than 10^{28} GeV^2 to prevent excessive diffuse gamma radiation. Then

$$F_u = N_c \frac{\alpha}{t_0^2} \ln\left(\frac{t_0}{t_{\text{in}}}\right). \tag{8}$$

Even though at emission the UHECR produced by an X are equally spaced in $\log E_{\text{em}}$, their redshift would cause a softening of the spectrum on Earth. More important is the interaction of cosmic rays with CBR with a $p\gamma$ total cross-section ~ 0.2 mb at the highest energy, and up to ~ 0.6 mb for the Δ resonance mass. To evaluate the flux spectrum, we take N_i cosmic rays in each bin to account for the degrading of energy so that

$$\overline{F}_u(E_i) = \frac{\alpha}{t_0^2} \ln\left(\frac{t_0}{t_{\text{in}}}\right) \frac{N_i}{\Delta E_i}. \tag{9}$$

Therefore, we may parameterize for all cases

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

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

To determine the effective N_i for necklaces, considering the mean free path associated to the quoted $\sigma_{p\gamma}$ photons, we take 1% of probability that the cosmic ray for Δ production keeps its energy and up to 3% for higher E_i being the missing events transferred to the lower bins. In this way one obtains the flux of fig. 2 where the existence of an ankle and the recovery after a transient GZK are reproduced.

The normalization at $\sim 10^{19}$ eV is similar to that 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.

With an ordinary law $1/E^3$ at emission, the flux due to uniformly distributed extragalactic sources would be given by eq. (10) without the last term and as shown in fig. 3 would reproduce the events below the GZK cutoff but without recovery above it.

Comparing figs. 1 and 2, J is one order of magnitude larger for necklaces than for vortons because 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. With a monopole mass $m \sim 10^{16}$ GeV the energy per unit length of necklaces gives a fraction $\sim 10^{-9}$ of critical density.

Regarding observations, the difference between vortons and necklaces will be the anisotropy in the former due to our asymmetric position in the galaxy compared to the isotropy of the latter characteristic of a cosmological origin. The anisotropy detected below the ankle is not observed above it [10] , consistent with the appearance of an extragalactic component, a larger statistics being needed at the highest energy to see if new galactic sources contribute.

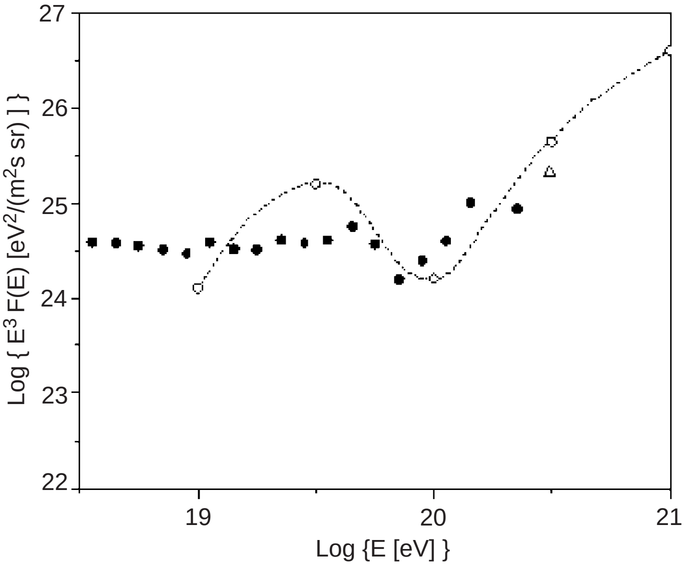

Fig. 2. – Necklaces in the universe. Broken line drawn to help the eye with points ○ calculated with N_i from degrading energy and $\log(J) = 23.5$.

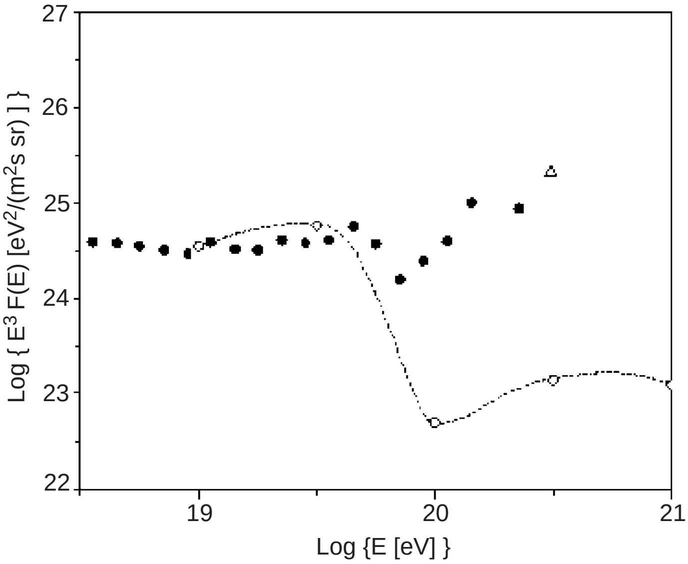

Fig. 3. – Ordinary extragalactic component. Broken line drawn to help the eye with points ○ calculated with $F(E) \propto E^{-3}$ and $\log(J) = 24$.

Referring to the elementary particle theory, a GUT model based on the $SO(10)$ group is suitable for necklaces. For vortons E_6 is better because the breaking of the additional Abelian symmetry produces the superconducting current with exotic fermions, whereas necklaces would not be formed since its Higgs content does not allow an unbroken Z_2.

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