Hard component of ultra-high energy cosmic rays and vortons

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Abstract

Observed events of ultra-high energy cosmic rays may indicate a hard component for the energy spectrum of their flux, which might have origin in the decay of long-lived vortons presumably condensed in the galactic halo. To be consistent with the needed present density, vortons may have been formed during the breaking of an abelian symmetry contained in a large GUT group like $E_6$ and a part of them could have survived the destabilization caused by the electroweak transition.

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I. Introduction

The events of ultra-high energy cosmic rays (UHECR) corresponding to primary energy above $10^{19}eV$ are difficult to explain with conventional astrophysical objects, both regarding their acceleration mechanism and propagation towards the earth due to the interaction with the cosmic background radiation (CBR) if the source is beyond $\sim 50\text{Mpc}$.

A possible solution of this enigma is given by the so called top-down mechanism where long-lived very massive microscopical objects decay producing the UHECR, which is plausible because so far the events of the latter appear to be roughly isotropic.

In any case the top-down mechanism would imply physics beyond the standard model of particles and their interactions (SM). One alternative corresponds to superheavy relics, quasi-stable because their interactions with the known particles are of gravitational order, which might belong to the hidden sector where supersymmetry is broken. Another possibility is given by cosmic strings formed in the phase transition due to the breaking of a symmetry at the scale of a grand unification theory (GUT). Though the ordinary Kibble strings consisting of Higgs and gauge fields might explain the UHECR using their flux to normalize the model, either the insertion of monopoles forming necklaces or the superconducting Witten strings with the addition of fermionic fields which give quasi-stable closed loops called vortons seem more suitable.

It is the purpose of the present work to analyze the details of vortons as source of UHECR. It had already been seen that they may produce the global flux above $10^{19}eV$ provided their density is dramatically reduced during the electroweak transition in a way that might generate the matter-antimatter asymmetry of the universe.

We now describe the energy spectrum of the flux given by the decay of a superheavy boson emitted by the vorton and conjecture, because of the hadronization of the resulting quark, that it can constitute the hard component that might emerge above the GZK cutoff according to the recent presentation of events. Even though vortons should behave as cold dark matter (CDM) and be concentrated in the galactic halo, we also study the softening caused by redshift if they were distributed uniformly in the space as occurs for necklaces and find that it is not possible to distinguish both cases at present, though in the latter situation a more important effect coming
from the interaction with CBR should produce a depression due to the GZK cutoff followed by a recover of the spectrum caused by its hard nature at emission.

We then face the difficult problem of the dynamics of strings, crucial for determining the vorton density before and after the electroweak transition. We assume that the GUT model allows superconductivity to appear at the same scale of the string formation and evaluate that the delay in the stabilization of vortons is not too relevant to reduce their density. When the universe cools down to the electroweak temperature, we estimate the conditions for the rate of destabilization of vortons due to disappearance of the Dirac zero-modes which originated the superconductivity of exotic quarks and the replacement with those of ordinary fermions. The result is that the collapse of the most abundant short vortons is sufficiently gradual to avoid the reheating that would dilute the baryogenesis, and the surviving long ones succeed in absorbing the ordinary fermions with parameters compatible with the density and lifetime necessary to explain the UHECR.

Finally we discuss which is the possible GUT group consistent with our mechanism. We see that SO(10) is not adequate since at GUT scale only vortons with $\nu_R$ might be formed, which could not give the baryogenesis at the electroweak transition where it is moreover unlikely that long loops might be stabilized by ordinary fermions. On the contrary, $E_6$ is suitable for our purposes because at high temperature vortons with exotic quarks may be formed linked to zero-modes that subsequently disappear at electroweak scale due to mass effects of the light Higgs, whereas new zero-modes for ordinary fermions are allowed by the existence of two additional abelian symmetries of the model apart from the electromagnetic one.

II. Energy spectrum of UHECR flux from vorton decay

Considering sources that emit $\dot{n}(t)$ UHECR per unit space and time the total flux on earth will be

$$F = \frac{1}{4\pi} \int_{t_{in}}^{t_{0}} dt \dot{n}(t) \left( \frac{a(t)}{a(t_0)} \right)^3,$$

(1)
where $a$ is the scale parameter of universe, $t_0$ its present age and $t_{in}$ an initial time which depends on the assumed distribution of sources but in no case is earlier than that which by redshift produces energies at least $\sim 10^{19}$ eV.

If the sources are quasi-stable objects like vortons with density $n(t)$ each one having at time $t$ a probability $\Gamma$ per unit time of emitting UHECR observed on earth,

$$F = \frac{1}{4\pi} \int_{t_{in}}^{t_0} dt \ n(t) \left( \frac{a(t)}{a(t_0)} \right)^3 \Gamma .$$

(2)

We assume that the vorton emits by tunneling a superheavy particle X, Higgs or gauge boson of GUT scale, which very quickly decays in quarks and leptons, the former giving the UHECR by hadronization. We will consider two cases: the more plausible one in which vortons, behaving as nonrelativistic particles, condense in the galactic halo, and the other extreme alternative analogous to ordinary cosmic strings in which they are still uniformly distributed in space.

A. Condensation in halo

In this case redshift may be neglected and $\Gamma = \frac{N_c}{\tau}$, where $\tau$ is the vorton lifetime for emission of X whose decay produces $N_c$ UHECR. Then the total flux will be

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

(3)

where $\Delta t \sim 50kpc$ due to the halo size. As it will be seen in the next section, with $\tau$ larger than $t_0$ and $n_h(t_0)$ a fraction of the dark matter in the galactic halo, a flux of UHECR of the expected order is obtained.

We now turn to the energy spectrum $F(E)$ such that $F = \int dE \ F(E)$, where the limits of integration correspond to the UHECR range. From the probability distribution

$$\frac{d\Gamma}{dE} = \frac{1}{\tau} \sum_{i=1}^{N_c} \delta(E - E_i) ,$$

(4)

the flux spectrum will be

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

(5)
To compare with observations, one must average on the intervals $\Delta E_i$ separating neighbouring particles in energy

$$\overline{F}_h(E_i) = \frac{1}{\Delta E_i} \frac{n_h(t_0)}{4\pi} \frac{\Delta t}{\tau}. \quad (6)$$

If events are equally spaced in $\log E$, which is plausible in hadronization with QCD except for the upper limit $\sim m_X$ as it will be discussed below,

$$\Delta E_i \sim E_i, \quad \overline{F}_h(E_i) \sim \frac{1}{E_i}, \quad (7)$$
corresponding to a hard component compared with the standard behaviour for lower energy which is roughly $F(E) \sim E^{-3}$.

B. Uniform distribution in universe

Since we consider vortons as quasi-stable particles, if we assume a hypothetical uniform density $n_u(t_0)$ at present, from Eq.(2) the spectrum at earth would be

$$F_u(E) = \frac{1}{4\pi} n_u(t_0) \int_{t_{eq}}^{t_0} dt \frac{d\Gamma}{dE_{em}} \frac{dE_{em}}{dE}, \quad (8)$$

where the lower limit is approximatively the matter-radiation equivalence time $t_{eq}$ in order to include into UHECR particles redshifted from $\sim 10^{24} eV$ which we take as the maximum energy. If we disregard for the moment the attenuation due to interaction with CBR, the probability distribution is the same as Eq.(4) but referred to emission energy $E_{em}$

$$\frac{d\Gamma}{dE_{em}} = \frac{1}{\tau} \sum_{i=1}^{N_c} \delta(E_{em} - E_i), \quad (9)$$

where the relation with observed energy is given by redshift $z$

$$E_{em} = (1 + z)E, \quad 1 + z = \left(\frac{t_0}{t}\right)^{\frac{2}{3}}. \quad (10)$$

Therefore the spectrum Eq.(8) becomes, being $t_0 >> t_{eq}$,

$$F_u(E) = \frac{3}{8\pi} n_u(t_0) \frac{t_0}{\tau} E_{em}^{\frac{2}{3}} \sum_{i=1}^{N_c} 1 \frac{1}{E_i^2} \theta(E_i - E). \quad (11)$$
The total flux for UHECR defined for \( E > E_0 \) is, with \( E_0 < E_i \),

\[
F_u = \int_{E_0}^{\infty} dE \ F_u(E) = \frac{1}{4\pi} n_u(t_0) \frac{t_0}{\tau} \left[ N_c - \sum_{i=1}^{N_c} \left( \frac{E_0}{E_i} \right)^{3/2} \right].
\]  

(12)

Averaging the spectrum in intervals defined for convenience as

\[
\overline{F}_u(E_j) = \frac{1}{\Delta E_j} \int_{E_{j-1}}^{E_j} dE \ F_u(E)
\]

and with the above hypothesis of \( \Delta E_j \sim E_j \)

\[
\overline{F}_u(E_j) = \frac{1}{4\pi} n_u(t_0) \frac{t_0}{\tau} \frac{1}{\Delta E_j} \left[ 1 - \left( \frac{E_{j-1}}{E_{N_c}} \right)^{3/2} \right],
\]  

(14)

it is clear that redshift will produce a softening of the law \( E_j \) through the bracket factor, which will be slight except for the highest \( j \).

C. Comparison with observations

Considering that the probability per unit time for a vorton to emit particles with energy between \( E_L \simeq 10^{19} eV \) and \( E_H \simeq 10^{24} eV \) from the decay of X is

\[
\int_{E_L}^{E_H} \frac{d\Gamma}{dE_{em}} \ dE_{em} = \frac{N_c}{\tau},
\]  

(15)

the definition of the average on intervals according to Eqs. (9) and (7)

\[
\frac{d\Gamma}{dE_{em}} \simeq \frac{1}{\tau} \frac{1}{E_{em}},
\]  

(16)

gives, from Eq.(15), \( N_c \sim 10 \) which is a reasonable value compared with the extrapolation of fragmentation functions. This is consistent with the total energy emitted by a vorton per unit time, being \( m_X \sim E_H \),

\[
\int_0^{E_H} dE_{em} \frac{d\Gamma}{dE_{em}} E_{em} = \frac{1}{\tau} E_H.
\]  

(17)

Therefore we may take the equally spaced particles in log \( E \) according to \( E_1 \simeq 10^{19} eV, E_2 \simeq 10^{19.5} eV \ldots E_9 = 10^{23} eV, E_{10} \simeq 10^{23.5} eV \), and
\[ E_0 \simeq 10^{18.5}\text{eV}, \] so that with the previous definition \( \Delta E_j = \left(1 - \frac{1}{10^{18.5}}\right) E_j \) quite compatible with Eq.(16).

For the vortons condensed in the halo, since from Eq.(6) the flux in each bin is the same, one might roughly normalize it at the observed value for \(10^{19}\text{eV}\) i.e.

\[
\frac{n_h(t_0) \Delta t}{4\pi \tau} = \frac{1}{km^2 \text{yr}} .
\] (18)

Being the mass of a vorton \( \sim N_L m_X \) and representing a fraction \( f \) of the halo average energy density \( \sim 0.3 \frac{GeV}{cm^3} \) it turns out

\[
\frac{n_h(t_0) \Delta t}{4\pi \tau} \simeq \frac{f t_0}{N_L \tau km^2 \text{yr}} 10^7 ,
\] (19)

so that for \( \tau \sim t_0 \) and \( N_L \sim 10^3 \) which is a sensible number as will be discussed in Sec.III, a fraction \( f \sim 10^{-4} \) of dark matter would be enough. More precisely, from the recent presentation of data shown in Fig.1, there seems to be an extragalactic component above the “ankle” and then the hard component dominating beyond the GZK cutoff. With this interpretation the contribution of vortons is a small part of flux at \(10^{19}\text{eV}\) and \( f \) may be even two orders of magnitude smaller. The fact that our fit normalizes the hard component at \( \sim 10^{20}\text{eV}\) allows to reproduce data with \( m_X \sim 10^{15}\text{GeV} \) at variance with a similar discussion for superheavy relics\(^{16}\).

If we instead imagine vortons uniformly distributed, they should constitute a fraction of the critical density of universe \( \rho_c(t_0) \simeq 10^{-29} \frac{\text{GeV}}{cm^3} \). Disregarding the redshift depression and GZK cutoff \( J = \frac{1}{4\pi} n_u(t_0) \frac{t_0}{\tau} \) gives a flux 3 times larger than that of Eq.(19) because the smaller \( n_u \) is compensated by the larger \( t_0 \) compared to \( \Delta t \). The decrease due to redshift corresponds to the bracket in Eq.(12) which is just 0.98. Similarly the bracket in the energy spectrum of Eq.(14) gives \( F_u(E) \propto \frac{1}{E^{1+K}} \) where \( K \simeq 0.011 \) as is seen by the fit of Fig.2. Therefore it would not be possible to distinguish the two cases with the present statistics by the redshift effect. But certainly more important is the effect of the GZK cutoff which is not so drastic for the hard vorton component\(^{43}\) giving an effective spectrum \( F_u(E) \propto \frac{1}{E^2} \) between \(10^{19}\) and \(10^{20}\text{eV}\) and a recovering behaviour \( \propto \frac{1}{E^{1+\alpha}} \) in the range from \(10^{20}\) to \(10^{21}\text{eV}\). Therefore the fraction \( f \) of dark matter should be one order of magnitude larger than in the case of condensation in halo. Similarly, it has been evaluated\(^{43}\) that the hard component of UHECR emitted from observed galaxies avoids the GZK cutoff.
Regarding the absolute contribution of other galaxies apart from ours, since luminous matter is $\Omega_L \simeq 5 \times 10^{-3}$ and halos are 10 times larger $\Omega_h \simeq 5 \times 10^{-2}$, a fraction of vortons $\sim 10^{-6}$ would give $5 \times 10^{-8}$ of critical density. This would be 200 times smaller than the required extragalactic vortons as said above. This estimation of the negligible contribution of halos of other galaxies is consistent with detailed computations.

More statistics is needed to test the anisotropy in favour of larger mass concentration in the halo case. It is interesting that UHECR above $5 \times 10^{19}$ eV seems to show a small anisotropy not related to the structure of the local universe. One must remark that the uniform distribution of superheavy relics is critically constrained by the diffuse gamma flux at GeV scale from EGRET requiring a low extragalactic magnetic field $\sim 10^{-12}$ Gauss.

A hard component similar to Eq. (7) appears from accurate calculation with QCD but it is also suggested by semiquantitative arguments. On one side the quark which comes from decay of X may be considered as a ultra-relativistic particle suffering a constant force due to friction. Therefore the decrease of its momentum is proportional to time and since this corresponds to hadronization, to produce a more energetic particle it takes more time, i.e. the law of Eq. (16) follows. In another way, the hadronization results from the emission of a gluon with energy similar to that of the quark and close to its direction. Thus the transition amplitude is $\sim \frac{1}{E}$ and the number of final states $EdE$ to keep a fixed angle around the quark, i.e. the probability of hadronization from vorton

$$d\Gamma \simeq \frac{1}{\tau E^2} EdE,$$

is Eq. (16).

All what said in this Section is valid both for vortons and superheavy relics. The next one will be devoted to dynamics of vortons to discuss in which way they may have the required density for UHECR.

### III. String dynamics and vorton densities

The dynamics which may lead to the vorton density necessary for UHECR consists of several stages. First of all we will discuss the possible vorton density above the electroweak (EW) transition temperature. For the formation of vortons there are four temperatures: production of ordinary strings...
$T_X$, appearance of superconductivity $T_\sigma$, incorporation of fermionic carriers by loops giving the protovortons $T_f$, elimination of excess energy relaxing to classically stable configuration $T_r$. We will take the alternative that superconductivity, i.e. zero-modes of $x$-$y$ Dirac equation in presence of bosonic string fields, appears in the same phase transition where strings are generated by Kibble mechanism i.e. $T_\sigma = T_X$. This allows the possibility of producing the matter-antimatter asymmetry through the subsequent elimination of most of vortons. The number density of protovortons formed at the temperature $T_f$ is

$$ n(T_f) \simeq \frac{1}{[\xi(T_f)]^3} \quad (21) $$

where $\xi$ is the length below which smaller scale structure will have been smoothed by friction damping. Once vortons are formed, their density evolution corresponds to quasi-stable particles in an expanding universe and is related to that of protovortons which originate them by

$$ n_v(T) = n(T_f) \left( \frac{T}{T_f} \right)^3 \quad (22) $$

If vortons could be formed in the friction stage of Kibble strings produced in a phase transition of GUT scale $T_X$, $\xi$ is a sort of average between the string damping time \( \tau_d \simeq \frac{T_X^2}{T_f^2} \) and the Hubble time \( H^{-1} \simeq \frac{m_{pl}}{T_f^2} \) i.e.

$$ \xi \simeq \sqrt{\tau_d H^{-1}} = (m_{pl})^{\frac{1}{2}} \frac{T_X}{T_f^{\frac{3}{2}}} \quad (23) $$

Since we take $T_\sigma = T_X$, this will be true if the time necessary for fermions to be absorbed by the string forming protovortons is short. Moreover the subsequent interval for getting rid of excess of energy to reach the optimum radius of stabilized vortons must preserve the friction regime $T > \frac{r^2}{m_{pl}}$ to avoid radiation from the not yet static protovortons. If this occurs, from Eqs.\(21-23\)

$$ n_v(T) \simeq \left( \frac{T_f}{m_{pl}} \right)^{\frac{3}{2}} \left( \frac{T_f T}{T_X} \right)^3 \quad (24) $$

and since as we will show $T_f$ is close to $T_X$ the large density

$$ n_v(T) \simeq \left( \frac{T_X}{m_{pl}} \right)^{\frac{3}{2}} T^3 \quad (25) $$

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is enough to produce the expected matter-antimatter asymmetry if most of
vortons collapse at the EW transition\textsuperscript{11}. In the chiral case which corresponds
to our fermionic carriers, their number in the loop is\textsuperscript{22}

\[ N \approx \xi T_X \]  

and from $\xi(T_f)$ of Eq.(23) $N \approx \left(\frac{m_o}{T_X}\right)^\frac{1}{2}$ which for the GUT scale $T_X \sim 10^{16}GeV$ will give the most abundant vortons with $N \sim 10$ carriers.

According to some approaches\textsuperscript{23}, it is hard that vortons can be formed
in the friction stage of string dynamics. We will use a simplified model to
estimate $T_f$ and $T_r$ to verify that they are in the friction regime. Adopting the
phenomenological criterium of seeing whether the fermions can be absorbed
by the Kibble string to give way to a protovorton before the loop collapses,
the rate of their incorporation may be given by

\[ \frac{dn_i(t)}{dt} = \alpha n_o , \]  

where $n_o$ is the outer fermionic density. We assume, subject to consistency,
that the process is fast enough to disregard the universe expansion and con-
sider the above fixed number of fermions to be incorporated to the string. $n_o$
will roughly correspond to a radiation mode at GUT scale $n_o \sim T_X^3$. We re-
quire that the density inside the string passes from zero at the time of Kibble
string formation $t = 0$, to a final value $n_i$ in one direction due to field fluctu-
ation such that $n_iL_p \frac{1}{T_X} \approx N$, where $L_p$ is the protovorton length and $\frac{1}{T_X}$ its
width. The probability per unit time of fermion absorption $\alpha = \alpha_0 \sqrt{1 - v^2}$
will include the Lorentz factor for time dilatation due to the loop velocity
of contraction $v$ which is qualitatively consistent with the statement that
vorton formation is more difficult for large velocity\textsuperscript{23}. The probability in
the rest frame must be $\alpha_0 = h m_X$ because it increases with the difference
between the mass of the fermion outside due to symmetry breaking at GUT
scale and its zero value inside the string which favours its flow there. $h$ is a
free parameter presumably smaller than 1 if the mass of the exotic fermion
is smaller than that of the GUT gauge boson as occurs for most of ordinary
fermions compared to EW bosons. Therefore we require from Eq.(27)

\[ \frac{N}{L_p} = h m_X \int_0^{\Delta t} dt \sqrt{1 - v^2} , \]  

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for $\Delta t$ smaller than the collapse time of string. Since the protovorton must subsequently lose the excess of energy to reach stabilization as a vorton of length $L_v = \frac{N}{m_X}$, the original length of the string will be $L_0 > L_p > L_v$.

For the step between the formation of the Kibble string of length $L_0$ up to the absorption of $N$ carriers to have a protovorton of length $L_p$ we consider that the loop contracts due to the tension $\mu = m_X^2$, which is also the energy per unit length, according to

$$-m_X^2 = \frac{d}{dt} (E \cdot v) ,$$

with $E = L \cdot m_X^2$, $v = \frac{dL}{dt}$. The result is

$$\frac{L}{L_0} = \frac{1}{(1 + v^2)^{\frac{1}{2}}} ,$$

which, inserted into Eq.(28), gives

$$\frac{2}{N} = h \cdot \lambda_0^2 \frac{L_p}{L_0} I ,$$

where $\lambda_0 = \frac{L_0}{L_v}$, $I = \int_0^\pi \frac{\pi}{2 \sin \left( \frac{L_p}{L_0} \right)} \left( \cos z \right)^{\frac{1}{2}} dz$.

The procedure is to choose a value of $h$ and $N = 10$ as said above if Eq.(25) holds. Assuming an initial length $\lambda_0$, one obtains $\frac{L_p}{L_0}$ from Eq.(31) and then the protovorton velocity $v_p$ from Eq.(30) which must be consistent with the subsequent step to determine $\lambda_0$.

This corresponds to the delay between protovorton and vorton. When the former is planar it has an energy

$$E = \mu L + \frac{N^2}{L} ,$$

where, to the Kibble contribution of the first term, the kinetic one for massless fermionic carriers is added. Vortons are the classically stable loops corresponding to the minimum of $E$.

But on top of the energy $E$ of the ground state of the string Eq.(32), for the protovorton one may add the energies corresponding to the possibility of twisting its $N$ pieces. The energy of each twist may be taken as

$$E_t = c \frac{N}{L - L_v} ,$$

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because for $L \gg L_v$ it is reasonable that it corresponds to the current, $e$ being the charge. When $L \to L_v$, $E_t \to \infty$, indicating that only the plane state of the vorton is possible. As a consequence, the thermodynamical calculation of minimization of total free energy $F_{tot} = E + F$ must be done with $F = -T \ln Z$ in terms of the partition function

$$Z = \sum_{m=0}^{N} \left( \frac{N}{m} \right) e^{-\left( \frac{mE_t}{T} \right)} , \quad (34)$$

where $m$ is the number of twists. $F_{tot}(L)$ is a function flatter than $E(L)$ but with the same minimum. Its variation is given by

$$-dF_{tot}(L) = d(Ev) v + SdT - \hat{\mu}dL , \quad (35)$$

where $\hat{\mu}$ is the chemical potential for the protovorton but, being the last term equivalent to $-dE$, the equation to be solved involves in the left hand side only the variation of the partition function of twists. Since moreover the second term on the right hand side is small because it corresponds to the reheating produced by the disappearance of a piece of protovorton transformed into radiation, being at this stage the density of protovortons much smaller than that of the radiation, Eq.(35) reduces essentially to

$$T \frac{d}{dt} \ln Z(L) \simeq d[E(L)v] v . \quad (36)$$

Eq.(36) is solved numerically with the condition that at the end, when the stabilized vorton is reached, $v = 0$. Taking $e \simeq 0.3$ the partition function is evaluated for the two contributions $N \ E_t < T$ and $(\tilde{N} + 1) \ E_t > T$ as $Z = Z_1 + Z_2$ with

$$Z_1 = \sum_{m=0}^{N} \left( \frac{N}{m} \right) e^{-\left( \frac{mE_t}{T} \right)} \simeq \sum_{m=0}^{N} \left( \frac{N}{m} \right) \left( 1 - m \frac{E_t}{T} + ... \right) , \quad (a)$$

$$Z_2 = \sum_{m=\tilde{N}+1}^{N} \left( \frac{N}{m} \right) e^{-\left( \frac{mE_t}{T} \right)} \simeq \left( \frac{N}{\tilde{N}+1} \right) e^{-\left( \frac{N+1}{\tilde{N}+1} \right) \frac{E_t}{T}} + ... . \quad (b) \quad (37)$$

Thus Eq.(36) allows to go back step by step obtaining the velocity for each possible initial protovorton length.

As said before, the end of the absorption of fermions must be joined to the beginning of the process of stabilization of protovortons. In Fig.3 the two
cases of \( h = \frac{1}{15} \) and \( h = \frac{1}{13} \) are shown. From these curves the total interval of time from the formation of the Kibble string to the birth of the stabilized vorton may be obtained according to

\[
\Delta t_{\text{tot}} = L v \int_{1}^{\lambda_0} \frac{1}{|v|} d\left(\frac{L}{L_v}\right).
\] (38)

The results are respectively \( \Delta t_{\text{tot}} = 3.2 \times 10^{-38} \text{ sec} \) and \( 4.5 \times 10^{-38} \text{ sec} \) for the two cases of \( h \).

Therefore, since the time after big bang of the GUT transition is at least \( 10^{-36} \text{ sec} \), the delay for the formation of vortons appears to be small so that \( T_r \approx T_f \approx T_X \) and their density Eq.(25) should hold.

The next step is to analyze what happens to vortons, whose density evolves according to Eq.(25), when the universe cools down to the temperature \( T_{EW} \) for the electroweak transition. If the GUT model is such that the zero-modes for heavy quarks disappear, most of vortons collapse and the non-equilibrium process may allow to produce the needed matter-antimatter asymmetry. But if all vortons lose these zero-modes instantaneously the reheating would be so large that the baryogenesis would result very much diluted.

The rate of destabilization of vortons depends on the model, and presumably it is due to the mixture of Higgs mechanisms at GUT and EW scales where the latter is responsible for the loss of zero-modes which allowed the exotic fermion to be stable inside the string. Therefore it is likely that, being the rate of decay of the fermion outside the string \( \sim \alpha_{\text{GUT}} m_X \), the rate of destabilization of vorton is

\[
\gamma \sim \alpha_{\text{GUT}} m_X \left(\frac{T_{EW}}{T_X}\right)^2 \sim 10^{11} \text{ sec}^{-1},
\] (39)

which is smaller than the Hubble parameter at the beginning of the EW transition thus smoothing considerably the reheating effect.

Also depending on the model new zero-modes, this time corresponding to ordinary fermions, may appear at the EW temperature. Then vortons stabilized by them may be formed. But since the loops are collapsing due to the loss of the original zero-modes, one has to see whether the ordinary fermions succeed in being absorbed to reach the required density before the strings disappear. It is understandable that the surviving vortons will be the long ones.
The string is composed now by superheavy bosons X in its inner core and by the EW bosons in the outer part. The length of the inner core is still \( \frac{N}{m_X} \) and its width \( \frac{1}{m_X} \) so that the energy per unit length both of the Higgs potential and magnetic GUT contributions is \( \sim m_X^2 \). The outer ring will have a width \( \sim \frac{1}{m_W} \) and consequently a length \( \frac{N}{m_W} \) so that the Higgs potential and magnetic weak contributions will be \( \sim m_W^2 \ll m_X^2 \). Regarding the density of ordinary fermions to have a new vorton, it must be \( n_i \sim m_W^3 \).

An argument similar to the one following Eq.(27), and since outside the string now \( n_o \sim T_{EW}^3 \), indicates that

\[
n_i \simeq h \ T_{EW}^4 \Delta t,
\]

which requires that \( \Delta t \) is smaller than the collapse time \( \tau_c \). Since for masses of ordinary fermions \( h \sim 10^{-3} \) and \( \tau_c \geq \frac{N}{m_{EW}} \) because all the string configuration including its electroweak part must collapse together to avoid energy divergences, Eq.(40) will be satisfied by long strings with \( N \sim 10^3 \) and not for the most abundant vortons with \( N \sim 10 \).

According to the discussion of Sec.2, the ratio of the density of long vortons \( N_L \sim 1000 \) which allow to produce UHECR and that of short ones \( N \sim 10 \) Eq.(25) which would give the expected baryogenesis should be

\[
\frac{n_L(T)}{n_v(T)} \sim 10^{-27} - 10^{-28}.
\]

It is a very delicate matter to explain this ratio which cannot be related to that of the corresponding Boltzmann factors for vortons but more reasonably to the Kibble loops at the beginning of the acquisition of fermions which means that their energy is one half of that of vortons of the same length L according to Eq.(32), giving a ratio which is still too small.

But one must remember that, at variance from vortons which are plane, the protovortons which originated them may be rough and therefore have entropy. Thinking that a protovorton is a chain of \( N \) objects that can be horizontal or vertical, the degeneracy without considering the energy of twists is \( d \sim 2^N \), which can enlarge the density of long vortons in such a way that Eq.(41) may be satisfied.

The last important point is to assure that the vorton lifetime for emission of an X is at least of the order of the universe age to allow the production of UHECR in recent times. The estimation may be done through the bounce
instanton where, to simplify things, we consider the vorton as an object in the x-y plane so that the Euclidean action $S_E$ may be taken as the difference of the three-dimensional energy of a tube which contracts emitting an X and that of the non-contracted one. The most important contribution to this difference will be given by the gradient of the GUT Higgs field $\phi$ so that

$$S_E \sim \int \left( \frac{\partial \phi}{\partial z} \right)^2 \delta\, dx dy dz \sim \frac{(\Delta \phi)^2}{\Delta z} \delta^2 L . \quad (42)$$

$\Delta \phi \sim m_X$ because it is the change from broken to unbroken vacuum. $\delta^2 \sim \frac{1}{m_X^2}$ is the section of the inner core of the string where GUT fields are concentrated. Finally $\Delta z \geq m_X^{-1}$, because the length for the variation of the tube size must be at least of the order of the Compton length of the emitted X particle. Since $L \simeq N_L/m_X$, Eq.(42) with all the above estimations gives $S_E \leq N_L$ and the lifetime for the emission of one X is, being the vorton mass $m_v \sim N_L m_X$,

$$\tau \sim \frac{1}{m_v} e^{S_E} \leq \frac{1}{N_L m_X} e^{N_L} , \quad (43)$$

which, as an order of magnitude, ensures $\tau$ larger than $t_0$ for $N_L \sim 10^3$.

In this way we have shown the feasibility of the mechanism for UHECR according to Eq.(19).

**IV. GUT models and possible vortons**

To build a Kibble string it is necessary to break an abelian $\tilde{U}(1)$ symmetry different from the electromagnetic $U(1)$. If the model is simply

$$U(1) \times \tilde{U}(1) \rightarrow U(1) , \quad (44)$$

one such infinite string is stable. But if $\tilde{U}(1)$ is contained in a larger group G, a discrete symmetry $Z_N$ of the continuous $\tilde{U}(1)$ must remain unbroken to avoid that the corresponding monopoles make the string unstable by cutting it. This depends on the Higgs mechanism and in general the discrete symmetry does not survive if the Higgs field corresponds to the fundamental representation of G.

On the other hand the string will become superconducting if a fermion acquires mass through a Higgs that winds it. Subsequent phase transitions caused by different Higgs fields may produce the disappearance of a previous zero-mode.
A. SO(10)

It has 45 generators and one of its maximum subgroups is $SU(5) \times \tilde{U}(1)$, suitable for string formation.

There should be four subsequent breakings with the indicated relevant Higgs multiplets

$$SO(10) \rightarrow SU(5) \times U(1)$$

The decomposition in $SU(5) \times \tilde{U}(1)$ of the involved Higgs and fermion multiplets is

$$45 = 1^0 + 10^2 + \overline{10}^{-2} + 24^0$$
$$126 = 1^5 + 5^1 + 10^3 + \overline{15}^{-3} + 45^{-1} + 50^1$$
$$10 = \overline{5}^1 + 5^{-1}$$
$$16 = \overline{5}^{\frac{3}{2}} + 10^{-\frac{1}{2}} + 1^{-\frac{5}{2}}.$$

The first breaking must be done by a $\phi_{45}$ non vanishing in the $1^0$ component to keep the $SU(5) \times \tilde{U}(1)$ invariance. The second by $\phi_{126} = \phi_{15}$ to preserve $SU(5)$ symmetry. Regarding fermions, since $16 \times 16 = 126 + 120 + 10$, only the second breaking produces mass for one of them, the $\nu_R$, through a Majorana term which is invariant under $\tilde{U}(1)$ as is seen from Eq. (46). There also stable infinite strings are produced with winding number $n = 1$

$$\phi_{15} \rightarrow \eta_{\tilde{U}} \ e^{i\theta}, \quad \tilde{A}_\theta \rightarrow \frac{1}{r} \frac{1}{\overline{5}e} \ r,$$

and loops will be classically stabilized as vortons by the superconducting current of $\nu_R$. Since $SU(5)$ is still valid, which will presumably require SUSY, $\eta_{\tilde{U}} \sim 10^{16}GeV$.

The third phase transition does not affect the string because it is done by a $\phi_{45}$ in $24^0$, with components which break $SU(5)$ but keep the invariance under $SU(3)_c \times SU(2)_L \times U(1)_Y$, that does not feel the $\tilde{U}(1)$ charge $\tilde{e}$.

On the contrary the last breaking, the EW one, has several consequences. Since ordinary fermions get Dirac mass from the $SU(5)$ products

$$5 \times 10 = 5 + 45 \quad , \quad 10 \times 10 = \overline{5} + 45 + 50,$$
the $5^1$ part of $\phi_{10}$ will give mass to the quark $u$ and $\bar{5}^{-1}$ to quark $d$. Due to the fact that in $SO(10)$ these masses come from a single mass term $16 \times 16$, to avoid the degeneracy of $u$ and $d$ either one takes different expectation values in the neutral components of $5^1$ and $\bar{5}^{-1}$, or we repeat this term twice with ad-hoc coefficients, one multiplied by $\phi_{10}$ nontrivial in $5^1$ and the other with $\phi_{10}$ nontrivial in $\bar{5}^{-1}$ with the same expectation value.

Regarding the string, $\phi_{10}$ cannot be constant everywhere because the $\tilde{U}(1)$ charge would give a contribution to the covariant derivative $D_\theta$ producing a divergent energy. Therefore we must accept the possibility of winding $\phi_{5^1}$ and $\phi_{\bar{5}^{-1}}$, and also the inclusion of a neutral $Z$ contribution

$$D_\theta \phi_{5^1} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} - i e \tilde{A}_\theta - i g_\varphi Z_\theta \right) \phi_{5^1},$$

$$D_\theta \phi_{\bar{5}^{-1}} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} + i e \tilde{A}_\theta + i g_\varphi Z_\theta \right) \phi_{\bar{5}^{-1}}.$$  

If we assume that the winding number of $\phi_{5^1}$ is $m$, the condition to cancel its covariant derivative is

$$m - \frac{1}{5} - \chi = 0,$$

where $\chi$ is the contribution of $Z$. Obviously, to cancel also the covariant derivative of $\phi_{\bar{5}^{-1}}$, which behaves as $\phi_{5^1}^*$, the same condition Eq.(50) holds meaning that it would wind with $-m$.

But the minimization of the magnetic energy of $Z$ requires $m = 0$ so that $\phi_{5^1}$ and $\phi_{\bar{5}^{-1}}$ do not wind and no zero-modes appear for ordinary fermions.

Moreover $\phi_{10}$ gives rise to a coupling $\nu_R \nu_L$ and, since $\phi_{10}$ does not wind, this small massive contribution to the state of $\nu_R$ makes the corresponding zero-mode disappear so that all the vortons would collapse at the EW phase transition.

It must be noticed that the situation would change if an additional Higgs, which does not generate mass, $210 = 5^{-4} + \bar{5}^4 + \ldots$ with expectation value in $5^{-4}$ is present. To compensate the covariant derivative of such a nonwinding field

$$D_\theta \phi_{5^{-4}} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} + i 4e \tilde{A}_\theta - i g_\varphi Z_\theta \right) \phi_{5^{-4}},$$

$Z_\theta$ needs to behave $Z_\theta \rightarrow \frac{4}{5} \frac{1}{g_\varphi} \frac{1}{r}$ which introduced into Eq.(49) requires $m = 1$. In this rather artificial way, ordinary fermions would have zero-modes and GUT vortons should not collapse.
B. $E_6$

It has 78 generators and one maximum subgroup is $SO(10) \times U(1)$ with the relevant chain of breakings

$$E_6 \xrightarrow{78} SO(10) \times U(1) \xrightarrow{27} SO(10) \ldots$$

$$\ldots SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{27} SU(3)_c \times U(1) \ldots$$

The decompositions in $SO(10) \times U(1)$ of the fundamental and adjoint representations are respectively

$$27 = 1^1 + 10^-^\frac{1}{2} + 16^+^\frac{1}{2} \quad (53)$$

$$78 = 1^0 + 16^-^\frac{3}{4} + 45^0 \quad (54)$$

The first breaking must be done by $\phi_{78} \equiv \phi_{10}$ to keep the invariance of $SO(10) \times U(1)$ and since $27 \times 27 = 27_S + 351_S + 351_A$, no fermion gets mass in it. Fermion masses come from Higgs in 27 or 351 (which explains the decomposition of 126 in Eq.(46)). Thus the second breaking done by $\phi_{27} \equiv \phi_{11}$ to preserve the invariance of $SO(10)$, gives mass to the exotic fermions contained in $10^-^\frac{1}{2} \times 27$ through a term $\phi_{11} \psi_{10^-^\frac{1}{2}} \psi_{10^-^\frac{1}{2}}$. These exotic fermions, one quark $D$ of charge $-\frac{1}{3}$ with 3 colours and an electron $E$ with its neutrino $N$ may be the carriers of a vorton based on the string

$$\phi_{11} \rightarrow \eta U e^{i\theta}, \quad \overline{\varphi}_\theta \rightarrow \frac{1}{e} \frac{1}{r} \quad (54)$$

Due to the fact that 27 is the fundamental (spinorial) representation, a $Z_2$ symmetry is not preserved and the infinite string is not absolutely stable. However it is stable enough if the scale $\eta U \sim 10^{16} GeV$ for the breaking of $U(1)$ is at least one order of magnitude lower than that of breaking of $E_6$.

In the last breaking, an expectation value of Higgs in $10^-^\frac{1}{2}$ gives mass to ordinary fermions through a term $\phi_{10^-^\frac{1}{2}} \psi_{16^+^\frac{1}{2}} \psi_{16^+^\frac{1}{2}}$. Regarding the influence of $\phi_{10^-^\frac{1}{2}}$ on the string, the difference with the case of $SO(10)$ is that now the $U(1)$ charge $-\frac{1}{2}$ is common to both $5^1$ and $\overline{5}^{-1}$ of $SU(5) \times U(1)$, i.e.

$$D_\theta \phi_{5^1} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} + i \frac{\varphi}{2} \overline{\varphi}_\theta - i \bar{e} \bar{A}_\theta - ig_\varphi Z_\theta \right) \phi_{5^1} \quad (a)$$

$$D_\theta \phi_{\overline{5}^{-1}} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} + i \frac{\varphi}{2} \overline{\varphi}_\theta + i e \bar{A}_\theta + ig_\varphi Z_\theta \right) \phi_{\overline{5}^{-1}} \quad (b)$$
If $\phi_5^1$ winds at the EW scale as $\phi_5^1 \rightarrow \eta_{EW} e^{im\theta}$, to avoid energy divergence coming from Eq.(55a) it must be
\[ m + \frac{1}{2} - \chi = 0, \] (56)
where now $\chi$ is the contribution from $\tilde{A}_\theta$ and $Z_\theta$.

If the minimization of energy favours $\chi = -\frac{1}{2}$, from Eq.(56) $m = -1$ and since $\varphi_{5^1}$ gives mass to $u$ and $\nu$ they will have zero-modes and the corresponding carriers will run in the direction $-z$ of the string axis. Now from Eq.(55b) with $\chi = -\frac{1}{2}$ the energy divergence is avoided if $\phi_{5^{-1}}$ does not wind and, since it gives mass to $d$ and electron, they will have no zero-modes. Conversely if energy minimization favours $\chi = \frac{1}{2}$, $\phi_{5^{-1}}$ will wind as $\phi_{5^{-1}} \rightarrow \eta_{EW} e^{im\theta}$ with $m = -1$, $d$ and $e$ will have zero-modes and they will be the vorton carriers running along $-z$ of string axis.

Therefore, with a scheme based on $E_6$, vortons formed at scale $\eta_{\text{IR}}$ with exotic fermions E and D would remain essentially stable down to scale $\eta_{EW}$ where would incorporate new carriers either $u$ and $\nu$ or $d$ and $e$.

But if the EW breaking is done with a Higgs in 27 of $E_6$ which has not only expectation value in its component $10^{-\frac{1}{2}}$ but also in $16^{\frac{1}{2}}$, there may be an ordinary-exotic mass term $\phi_{16^{\frac{1}{2}}} \tilde{\psi}_{10^{-\frac{1}{2}}} \psi_{16^{\frac{1}{2}}}$, which will mix E and D with $e$ and $d$. Being $10 = 5^1 + 5^{-1}$, $5^1$ contains $D$, $\overline{E}$ and $\overline{N}$ and $5^{-1}$ $\overline{D}$, $E$ and $N$.

Therefore if the situation that minimizes energy is the first described above, i.e. $\chi = -\frac{1}{2}$, $d$ and $e$ will have no zero-modes and their mixing with D and E will destroy the zero-modes of the latter producing our baryogenesis mechanism. On the other hand, the new zero-modes of $u$ and $\nu$ would be responsible for the quasi-stability of the long vortons from the EW age to our days giving rise, through quantum decay, to a possible source of UHECR.

This is in fact what happens. To cancel the large distance covariant derivative of $\phi_{10^{-\frac{1}{2}}}$ Eq.(55) avoiding the divergence of energy, one needs, together with the already existing $\tilde{A}_\theta$ of Eq.(54),
\[ \tilde{A}_\theta \rightarrow c_1 \frac{1}{e} \frac{1}{r}, \quad Z_\theta \rightarrow c_2 \frac{1}{g_\varphi} \frac{1}{r}, \] (57)
with $c_1 + c_2 = \mp \frac{1}{2}$ which would allow to choose $|c_1| = |c_2| = \frac{1}{4}$ in both cases to minimize the magnetic energy $\frac{1}{2} \left( \tilde{B}^2 + B_2^2 \right)$. 19
But we now have the additional condition of cancelling the covariant derivative of $\phi_{16}$. Because of the decomposition of 16 Eq.(46) in representations of $SU(5) \times \tilde{U}(1)$, the mixing term $\mathcal{D} d$ may come from $\tilde{5}^{-1} \times 10^{-\frac{1}{2}}$ and, due to the fact that $\tilde{5} \times 10 = 5 + 45$, invariance is obtained multiplying by a $\phi_{16}$ with expectation value in $\tilde{5}^\frac{3}{2}$, i.e., $\phi_{\tilde{5}^\frac{3}{2}} \psi_{\tilde{5}} \psi_{10}^{-\frac{1}{2}}$. To respect the symmetry $SU(3)_c \times U(1)$ the nonvanishing component of $\phi_{\tilde{5}^\frac{3}{2}}$ must be the neutral one so that its covariant derivative is

$$D_\theta \phi_{\tilde{5}^\frac{3}{2}} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} - i \frac{e}{4} A_\theta - i \frac{3}{2} e \tilde{A}_\theta - i g'_\varphi Z_\theta \right) \phi_{\tilde{5}^\frac{3}{2}}. \quad (58)$$

Assuming a behaviour $\phi_{\tilde{5}^\frac{3}{2}} \rightarrow \eta_{EW} e^{im\theta}$, the cancellation of energy divergence requires

$$m - \frac{1}{4} - \frac{3}{2} c_1 + c_2 = 0, \quad (59)$$

because $g'_\varphi = -g_\varphi$ as $g_\varphi$ corresponds to 5 and $g'_\varphi$ to $\tilde{5}$.

With the condition appropriate for our model $c_1 + c_2 = -\frac{1}{2}$, Eq.(59) is satisfied with $c_1 = -0.3$, $c_2 = -0.2$ and $m = 0$ producing less magnetic energy than that of the alternative case $c_1 + c_2 = \frac{1}{2}$ which would require much more difference between $|c_1|$ and $|c_2|$.

The other mixing term $\mathcal{D} D$ comes from $\tilde{5}^\frac{3}{2} \times 5^1$ times a nonvanishing $1^{-\frac{5}{2}}$ of $\phi_{16}$ with a covariant derivative

$$D_\theta \phi_{\frac{5}{2}} = \left( \frac{1}{r} \frac{\partial}{\partial \theta} - i \frac{e}{4} A_\theta + i \frac{5}{2} e \tilde{A}_\theta \right) \phi_{\frac{5}{2}}, \quad (60)$$

where $Z$ does not appear because $\phi_{\frac{5}{2}}$ has no interactions of $SU(5)$ and therefore of the SM. If $\phi_{\frac{5}{2}}$ winds with $m$, to cancel Eq.(60)

$$m - \frac{1}{4} + \frac{5}{2} c_1 = 0. \quad (61)$$

and it is easy to see that the case $\chi = -\frac{1}{2}$ gives again more balanced values of $c_1$ and $c_2$ than for $\chi = +\frac{1}{2}$, but less than those emerging from Eq.(59). Then, since it is not possible to cancel simultaneously Eqs.(58) and (60) energy saving suggests that only $\phi_{\tilde{5}^\frac{3}{2}}$ will be nonvanishing.

For the model of vortons based on $E_6$ it is better if the breaking of $SO(10)$ in the missing part of the chain of Eq.(52) does not follow Eq.(45) but the
alternative maximum subgroup $SU(4) \times SU(2)_L \times SU(2)_R$ to avoid the formation of strings $\tilde{U}(1)$ which would complicate things and also to make the GUT unification avoiding $SU(5)$.

V. Conclusions

If the explanation of UHECR requires the top-down mechanism, this will imply new physics beyond the SM. In the case of the superheavy quasi-stable particles, possibly indications on the hidden sector of supersymmetry breaking will be given. As for the explanation through cosmic strings GUT will be explored and, particularly with vortons, details of the groups and Higgs breakings may be revealed.

We have shown the feasibility of this last mechanism. Obviously, due to the semiquantitative evaluation of several effects, only orders of magnitude could be given. More accurate analysis must be performed particularly regarding the quantum decay of vortons and precise details of the replacement of exotic fermions by ordinary ones at the EW transition as carriers of superconducting current inside the string, as it has been proved to be favourable in the case of the $E_6$ symmetry.

Since the features of the UHECR coming from the two quoted alternatives of top-down mechanism are similar due to the fact that they are based on quark hadronization, a deep theoretical study of the models will be useful to falsify some of them.

As for the evidence of sources based on superheavy microscopical objects, particles or vortons, there are analysis to see if there is a possible anisotropy of observed events towards the massive concentration in the galaxy. To determine this, as well as the suggested hard component of the spectrum beyond the GZK cutoff and the required abundance of primary gammas and neutrinos, a much larger statistics is needed as will be supplied by the Auger project.

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Fig. 1. Experimental UHECR including AGASA and Fly’s Eye data together with a fit corresponding to a galactic flux $\sim E^{-3.2}$ followed after the ankle by a possible extragalactic flux $\sim E^{-2.8}$ which exhausts beyond the GZK cutoff giving way to the hard component of vortons in halo $\sim E^{-1}$. 
Fig. 2. Fit of calculated energy spectrum of UHECR from vortons uniformly distributed in universe $\sim E^{-(1+K)}$ without considering interaction with CBR resulting in a redshift correction $K = 0.011$. 
Fig. 3. Velocity of loop contraction $v$ before reaching vorton size $L_v$. Continuous line represents protovorton stabilization. Dashed and dash-dotted lines give protovorton formation with carrier absorption coefficient $h = 1/5$ and $1/13$ respectively.