Ultra-high-energy cosmic rays from relic topological defects

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Abstract. It is difficult for conventional sources to accelerate cosmic ray particles to the highest energies that have been observed. Topological defects such as monopoles and strings overcome this difficulty, because their natural energy scale is at or above the observed energies. Monopoles connected by strings are a particularly attractive source, because they would cluster in the galactic halo and thus explain the absence of the GZK cutoff. Heavy monopoles connected by light strings could last for the age of the universe as required. Further observations might support this model by detection of the anisotropy due to the halo, or might refute such models if strong clustering of arrival directions or correlations with known astrophysical objects are confirmed. All top-down models must contend with recent claims that the percentage of photons among the cosmic rays is smaller than such models predict.

INTRODUCTION

The observation of ultra-high-energy cosmic rays (UHECR) with energies above $10^{20}$ eV [1, 2] is hard to explain. First of all, it is not clear that there is any site that at which particles might be accelerated to such large energies. Even if such sites exist, for example in active galactic nuclei, it is hard to explain the absence of the Greisen-Zatsepin-Kuzmin [3, 4] cutoff. Cosmic rays with energies above about $E_{\text{GZK}} = 4 \times 10^{19}$ eV will interact with cosmic microwave background photons and lose energy until they are below $E_{\text{GZK}}$. If the highest energy cosmic rays are produced by sources which are homogeneous in the universe (even if some of the sources are nearby), then there must be a large deficit in particles with $E > E_{\text{GZK}}$ as compared to those with $E < E_{\text{GZK}}$, because the former are converted into the latter. Such a cutoff is not observed.

In this talk, we will try to construct a relic topological defect model (see [5] for a review of such models and others) which addresses these difficulties. A relic model explains the UHECR as the decay products of some very high energy particle. As long as the progenitor has mass $M_X c^2 \gg 10^{20}$ eV, the high energies observed are trivially explained. However, to explain the UHECR, the relic must also be sufficiently long-lived to still be decaying today. This means that the progenitor lifetime must be extremely large as compared to the naive dimensional analysis value $\tau \sim \hbar / (M_X c^2)$.

To solve the GZK problem, the relics must be strongly clustered near us, and the obvious place for this is in the galactic halo. This is easily arranged, as long as the relic velocities are not too high to prevent them from being captured in the gravitational potential of the galaxy.
TOPOLOGICAL DEFECTS

Topological defects result from misalignment of fields after symmetry breaking transitions in the early universe. (For a review, see [6].) Because they are topologically stabilized, they can persist until the present time. If the scale of symmetry breaking is high, for example the grand unification scale $E \sim 10^{25}$ eV, then there is no difficulty reaching the required energies for the UHECR. However, one does need a mechanism by which the energy can be released from the defect at the necessary rate. One also needs an appropriate amount of total energy stored in defects. It must be large enough to explain the observed UHECR flux, while not being so large as to exceed bounds on the total density of the universe.

The dimensionality of the topological defects depends on the symmetry that was broken to create them. One can have monopoles (0-dimensional defects), strings (1-dimensional defects), or domain walls (2-dimensional defects). If there are multiple symmetry breaking transitions, one can have hybrid defects. For example, a high-energy transition can produce monopoles, and then a subsequent transition at a lower energy can confine the flux from the monopoles into strings. In this case, the monopoles’ flux must not be the regular magnetic field, because that is not confined today.

We can now consider the various defect types as UHECR sources. Domain walls are ruled out because they contribute too much total mass to the universe. Cosmic strings would evolve into a scaling regime, so their total mass contribution is not too large. However, strings move relativistically and would not cluster in the galactic halo. Monopoles produced with a thermal abundance would also overclose the universe, but is possible that they were produced with a smaller abundance during reheating or by gravitational particle creation [7]. In this case, they are not ruled out, and they would cluster in the halo. However, it is hard to see how to get the energy out of the monopoles. The only real possibility is monopole-antimonopole annihilation [8, 9]. Unfortunately [10], monopole-antimonopole pairs would not be formed with sufficient density to explain the observed flux.

However, if after the monopoles have formed, a subsequent symmetry breaking transition connects them by strings, then every monopole will be paired with an antimonopole and there will be no problem having sufficient annihilations [10].

SCENARIO

We imagine a first symmetry breaking transition which gives monopoles of mass $m_M$, and a second symmetry breaking transition which connects them by strings of energy scale $T_s$. A system of monopole and antimonopole attached by a string will oscillate with a timescale given by the acceleration of the monopole, $\mu / m_M$, where $\mu$ is the string tension, $\mu \sim T_s^2$.

We take the monopole not to have any unconfined flux, so the loss of energy of the

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1 We will henceforth work in units where $k_B = \hbar = c = 1$. 
system is purely in gravitational radiation. To produce a long lifetime, we want small acceleration, and thus low string tension and high monopole mass, so we take \( T_s \sim 100 \text{ GeV} \), and \( m_M \sim 10^{14} \text{ GeV} \).

To explain the observed UHECR flux we require a sufficient density of monopoles clustered in the halo. The minimum necessary density is achieved when the decay lifetime is approximately the age of the universe. In this case, for \( m_M = 10^{14} \text{ GeV} \), we found the needed present density in the universe as a whole \([10]\),

\[
N_{\text{MM}} > 10^{-30} \text{ /cm}^3. \tag{1}
\]

At the time of string formation, this was

\[
n_M \sim 10^{-32} T_s^3 \sim 10^{-18} \text{ /cm}^3, \tag{2}
\]

which gives a typical monopole separation

\[
L_i \sim 10^{-6} \text{ cm}. \tag{3}
\]

This is much smaller than the horizon distance, \( d_H \sim 3 \text{ cm} \) at \( T \sim 100 \text{ GeV} \).

When the strings are formed they may have excitations on scales smaller than the distance between monopoles, but these will propagate relativistically and thus be quickly smoothed out by gravitational radiation, leaving a straight string. The energy stored in the string is then \( \mu L_i \). This is smaller than the monopole mass by the ratio

\[
\frac{\mu L_i}{m_M} \sim 10^{-2}, \tag{4}
\]

so the monopoles will move non-relativistically.

We thus have a system of monopole and antimonopole connected by a straight string, which produces a constant force of acceleration \( a = \mu/m_M \). The monopoles will move in elliptical orbits, but since their thermal velocities at the time of string formation will be small compared to the velocities they acquire during acceleration, the motion will be nearly linear, although with enough angular momentum to prevent the monopoles from colliding as they pass by.

To estimate the gravitational radiation rate, we will take the linear motion, in which a half oscillation of one monopole is parameterized by

\[
x(t) = (2aL)^{1/2}t - \frac{1}{2}at^2 \tag{5}
\]

for \( 0 < t < (8L/a)^{1/2} \). Using the quadrupole approximation,\(^2\) the rate of energy loss of the system is

\[
\frac{dE}{dt} = 288 \frac{G^2}{45} \mu^2 \left( \frac{\mu L}{m_M} \right). \tag{6}
\]

\(^2\) The fully relativistic situation was considered in [11].
Now $\mu L$ is just the energy in the string, so we can write $dE/dt = \mu dL/dt$, and integrate to get

$$L = L_i e^{-t/\tau_g} \quad (7)$$

with

$$\tau_g = \frac{45}{288} \frac{m_M}{G \mu^2} = \frac{45}{288} \frac{m_{pl}^2 m_M}{T_s^4}. \quad (8)$$

The monopoles thus move on smaller and smaller orbits, until they annihilate, approximately when $L$ reaches the monopole core radius, $r_M \sim m^{-1}$. The system thus lives for a time about $\tau_g \ln(L_i/r_M)$. With $T_s \sim 100$ GeV and $m_M \sim 10^{14}$ GeV, Eq. (8) gives $\tau_g \sim 10^{17}$ sec, comparable with the age of the universe.

**OBSERVATIONAL CONSEQUENCES**

How can a model such as that presented here be verified or disproved? Unfortunately, all models which involve topological relics or relic particles decaying in the halo gave rise to the same observations, dependent essentially on one unknown parameter, the mass of the decaying primary. Thus, the specific model of monopoles bound by strings cannot be verified by cosmic ray observations. However, the low string energy scale which is necessary for long lifetimes means that the string fields might be detected in future accelerators.

Halo relic models as a class, however, do have observable consequences.

**Spectrum.** All relic models produce the observed cosmic ray primaries by the decay and fragmentation of super-heavy particles (produced, in this case, by monopole-antimonopole annihilation). The spectrum, thus, has little dependence on the type of defect that is decaying, but rather results primarily from the fragmentation process. Fragmentation of such high-energy particles is not completely understood, but we know that the spectrum we observe depends on the mass of the decaying particle, and in all cases it is much harder than the steeply falling spectrum of cosmic rays at lower energies. Current data does not constrain the ultra-high-energy spectrum tightly, but future experiments [12, 13] should be able to validate decaying particle models and determine the particle mass.

**Particle type.** Fragmentation also produces a large fraction of photons, and thus a generic prediction of relic models is that most of the observed cosmic rays will be photons. Identifying individual particles is difficult, but recent studies [14] of large zenith angle showers have found that no more than about 40% of the particles can be photons at the highest energies. If the studies are correct, then all relic models appear to be ruled out.

**Anisotropy.** Because the earth is not at the center of the galactic halo, cosmic rays coming from halo sources would be seen to somewhat higher degree from the direction of the galactic center. (See [15] and references therein.) The low number of observed
events, combined with the lack of an observatory in the Southern Hemisphere where
the galactic center is located, prevents a clear confirmation or disconfirmation of this
effect. However, a statistically insignificant anisotropy is observed of generally the right
form. The strongest confirmation of a halo model would be to see enhancements of the
cosmic ray flux coming from the halo of M31. Unfortunately, this also must wait for
future experiments.

No clustering. Any model of relic particles or monopoles will have all observed
cosmic rays coming from different sources. Thus we would not expect arrival directions
to be clustered into multiplets, except for an effect due to inhomogeneities in the dark
matter distribution [16]. Current claims of doublets and triplets are consistent with dark
matter inhomogeneity, but if further data yields greater multiplets, model such as this
will be ruled out.

No correlations with known astrophysical sources. If the UHECR come from
otherwise-invisible particles in the halo, there should be no correlation in arrival direc-
tion with any known object. Such correlations have been claimed [17, 18], but there is
some question [19] about the correctness of these claims.

DISCUSSION

We have argued that relic topological defects have several advantages as sources of the
observed ultra-high-energy cosmic rays. They naturally explain very high energies and
can cluster in galactic halos and thus explain the absence of the GZK cutoff. However,
most topological defect models do not have the required properties. Monopoles bound
by strings seem to be a good candidate. With heavy monopoles and light strings, the
required lifetime can be achieved, and because there is perfect efficiency in monopole-
antimonopole binding, the required monopole density is quite small. (Necklaces —
monopoles connected to two strings each [20] — also seem like a good candidate.)

Of course, hybrid topological defects are “exotic”, in the sense that they involve two
extra fields introduced just for this purpose. However, since conventional mechanisms do
not solve the puzzle of UHECR origin, it seems reasonable to consider exotic models.
Unfortunately, it appears that even exotic models don’t seem to be in agreement with
observation, especially the low bound on the photon fraction from recent studies [14].

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