TOPOLOGICAL DEFECT MODELS OF ULTRA-HIGH ENERGY COSMIC RAYS

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Abstract

We give an overview over models in which cosmic rays above $\sim 1\,\mathrm{EeV}$ ($= 10^{18}\,\mathrm{eV}$) are produced by the decay of supermassive "X"particles released from topological defects possibly created in cosmological phase transitions. We note that, for an interesting particle physics parameter range, these models are still consistent with current data, and discuss signatures for the topological defect mechanism which can be tested by the next generation experiments.

1 Introduction

The highest energy cosmic ray (HECR) events observed above $100\,\mathrm{EeV}$ [1,2] are difficult to explain within conventional models involving first order Fermi acceleration of charged particles at astrophysical shocks. On the one hand, even the most powerful astrophysical objects such as radio galaxies and active galactic nuclei (AGN) are barely able to accelerate charged particles to such energies. [3] On the other hand, above $\simeq 70\,\mathrm{EeV}$ the range of nucleons is limited by photopion production on the cosmic microwave background (CMB) to about $30\,\mathrm{Mpc}$ (which is known as the GZK-effect [4]), whereas heavy nuclei are photodisintegrated on an even shorter distance scale. [5] In addition, for commonly assumed values of the parameters characterizing the galactic and extragalactic magnetic fields, protons above $100\,\mathrm{EeV}$ are deflected by only a few degrees over these distances [6] and obvious powerful sources have not been found in the arrival direction of the observed HECR events. [7]

Within "top-down" (TD) scenarios, in contrast, predominantly γ-rays and neutrinos are initially produced at ultra-high energies (UHEs) by quantum mechanical decay of supermassive elementary X particles related to some grand unified theory (GUT). Such X particles could be released from topological defect relics of phase transitions which might have been caused by spontaneous breaking of GUT symmetries in the early universe. [8] Topological defects from phase transitions in the early universe such as cosmic strings, monopoles, and domain walls are topologically stable, but nevertheless can release part of their energy via collapse or annihilation in the form of X particles. The X particles can be gauge bosons, Higgs bosons, superheavy fermions, etc. depending on the specific GUT, their mass m_X being comparable to the symmetry breaking scale. They subsequently typically decay into a lepton and a quark which roughly share the initial energy equally. The quark then hadronizes into nucleons (Ns) and pions, the latter ones in turn decaying into γ-rays, electrons, and neutrinos. Given the X particle injection rate, dn_X/dt, the effective injection spectrum of particle species a ($a = \gamma, N, e^{\pm}, \nu$) can be written as $(dn_X/dt)(2/m_X)(dN_a/dx)$, where $x \equiv 2E/m_X$, and dN_a/dx is the relevant effective fragmentation function. We take the primary lepton to be an electron injected with energy $m_X/2$. The total hadronic fragmentation function dN_h/dx can be taken from solutions of the QCD evolution equations in modified leading logarithmic approximation which provide good fits to accelerator data at LEP energies.[9] Fig. 1 shows this function for $m_X = 2\times10^{16}\,\mathrm{eV}$ in comparison to approximations used in earlier work.[10,8] Motivated by LEP data at lower energies, we assume that about 3% of the total hadronic content consists of nucleons and the rest is produced as pions and distributed equally among the three charge states. The standard pion decay spectra then determine the injection spectra of γ-rays, electrons, and neutrinos. The X particle injection rate is assumed to be spatially uniform and in the matter-dominated era can be parametrized[8] as $dn_X/dt \propto t^{-4+p}$, where p depends on the specific defect scenario. The case $p = 1$ is representative for a network of ordinary cosmic strings[11] and annihilation of monopole-antimonopole pairs.[12]

Since the absolute flux level predicted by TD models is very model dependent,[13] we will allow an arbitrary flux normalization noting that certain TD scenarios such as annihilation of magnetic monopole-antimonopole pairs[12] yield HECR fluxes consistent with observations without violating bounds on monopole abundances. Such models are attractive in explaining HECRs because they predict injection spectra which are considerably harder than shock acceleration spectra and, unlike the GZK effect for nucleons, there is no threshold effect in the attenuation of UHE γ-rays whose mean free path in the cosmic low energy photon background is probably larger than that for nucleons (see, e.g.[14]).

2 Signatures for and Constraints on TD Models

Based on the general features of the type of TD scenarios discussed in the previous section, there are two distinctive signatures for them at energies above 100 EeV: First, the observed primaries should be predominantly γ-rays.[15] Second, there could be a spectral feature in the form of a "gap".[16] Increase of the

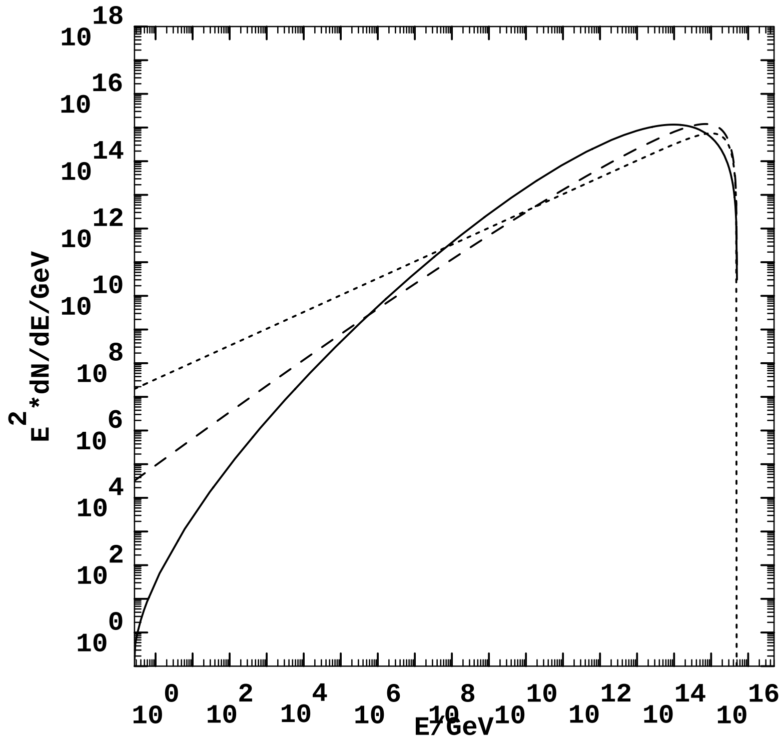

Figure 1: Approximations to the hadronic fragmentation function dN_h/dE for $m_X = 2 \times 10^{16}$ GeV. The solid line indicates the solution to the QCD evolution equations in modified leading logarithmic approximation,[9] the dashed line is the one used in,[8] and the dotted line represents the approximation $dN_h/dx = (15/16)x^{-1.5}(1-x)^2$ used in [10,12,21] and in Fig. 2.

current total exposure at these energies by factors of a few could distinguish between acceleration type sources and TD mechanisms at the 99% confidence level.[16] This should easily be possible with next generation experiments under construction such as the High Resolution Fly's Eye[17] or in the proposal stage[18] such as the Pierre Auger project.

Recently, there has been considerable discussion in the literature whether the γ-ray, nucleon, and neutrino fluxes predicted by TD scenarios are consistent with observational data and constraints at any energy.[19,20,21] To thoroughly investigate this, we have performed extensive numerical simulations for the propagation of extragalactic nucleons, γ-rays, and electrons with energies between 10^8 eV and 10^{25} eV through the universal low energy photon background,[14,22] which includes the radio background, the CMB, and the infrared/optical (IR/O) background. All relevant interactions have been taken into account, including synchrotron loss in the EGMF of the electronic component of the electromagnetic cascades which result from UHE γ-ray injection into the universal radiation background.

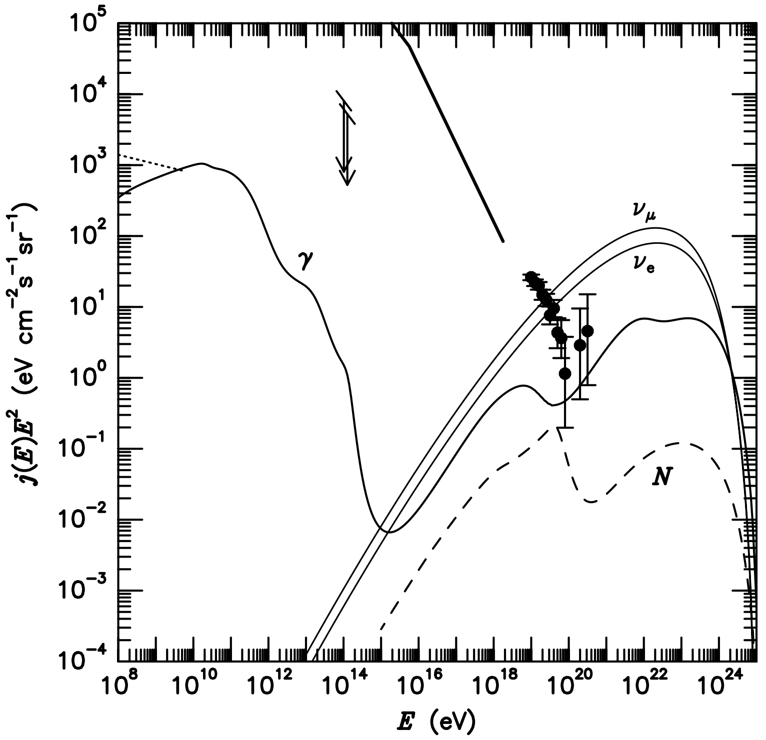

Figure 2: Predictions for the average differential fluxes of γ-rays, nucleons and muon and electron neutrinos by a typical TD scenario as described in the text. We used the hadronic fragmentation function in modified leading logarithmic approximation[9] for $m_X = 2 \times 10^{25}$ eV. The average EGMF strength was assumed to be 10^{-12} G. Also shown are the combined data from the Fly's Eye[1] and the AGASA[2] experiments above 10 EeV (dots with error bars), piecewise power law fits to the observed charged CR flux (thick solid line) and experimental upper limits on the γ-ray flux below 10 GeV from[24] (dotted line on left margin). The arrows indicate limits on the γ-ray flux from.[33]

Fig. 2 shows the results for the γ-ray and nucleon fluxes from a typical TD scenario, assuming an EGMF of average strength 10^{-12} G, along with current observational constraints on the γ-ray flux. The spectrum was normalized in the best possible way to allow for an explanation of the observed HECR events, assuming their consistency with a nucleon or γ-ray primary (although a γ-ray primary is somewhat disfavored [23]). The flux below a few tens of EeV is presumably caused by conventional acceleration. The likelihood significance of the fit (see [16] for details) in Fig. 2 is $\simeq 50\%$ for the energy range above 100 EeV. While the shapes of our spectra are similar to the ones obtained in, [21] this is in contrast to their procedure of normalizing to the observed differential flux at 300 EeV which overproduces the integral flux at higher energies.

Since the comparatively large amount of energy injected at high redshifts is recycled to lower energy γ-rays, TD models are significantly constrained [19,20] by current limits on the diffuse γ-ray background in the 100 MeV − 10 GeV region. [24] Note that the IR/O background strongly depletes the γ-ray flux in the range $10^{11} - 10^{14}$ eV, recycling it to energies below 10 GeV (see Fig. 2). Constraints from limits on CMB distortions and light element abundances from ^{4}He-photodisintegration are comparable to the bound from the directly observed γ-rays. [20] The scenario in Fig. 2 obeys all current constraints within the normalization ambiguities and is therefore quite viable.

Whereas the UHE nucleon and γ-ray fluxes are independent of cosmological evolution, the γ-ray flux below $\simeq 10^{11}$ eV and the neutrino flux are proportional to the total energy injection which, for all other parameters held fixed, increases with decreasing p. [20] For $m_X = 2 \times 10^{25}$ eV, scenarios with $p \lesssim 1$ are therefore ruled out (see Fig. 2), whereas constant comoving injection rates ($p = 2$) are well within the limits. Since the EM flux above $\simeq 10^{22}$ eV is efficiently recycled to lower energies, this constraint turns out to be basically independent of m_X in case of a low EGMF, [22] in contrast to earlier analytical estimates based on the continuous energy loss approximation which underestimates the flux around 100 EeV. [19,20] The constraints from the flux limits below 10 GeV become somewhat tighter for an EGMF of strength $\gtrsim 10^{-11}$ G.

The predicted neutrino fluxes [25] are also consistent with bounds from the Fréjus experiment. [26] At these flux levels, neutrinos are unlikely candidates for the observed HECR events due to their small interaction probability in the atmosphere. [27] A future detection of an appreciable neutrino flux above ~ 1 EeV, for example, by a km^3 scale neutrino observatory [28] could establish an experimental lower limit on the ratio of energy injected as neutrinos versus electromagnetically interacting particles and thus probe GUT scale physics. [25] In the scenario shown in Figs. 1 and 2, this ratio is about 0.3.

Our simulations show that an isotropic γ-ray to total CR (γ/CR) flux ratio at $\simeq 10$ EeV as high as 10% can be attained. However, this is only possible if a TD mechanism of the type discussed above is responsible for most of the

HECR above $\simeq 100\,\mathrm{EeV}$, and if the EGMF is weaker than $\simeq 10^{-11}\,\mathrm{G}$ on scales of a few to tens of Mpc. In case of acceleration sources of the HECRs, such high γ/CR flux ratios at $\simeq 10\,\mathrm{EeV}$ can only be attained in the direction of powerful nearby acceleration sources. In contrast to the TD models, in this case the γ-rays would be produced as secondaries of nucleons interacting with the CMB. The spectral shape of the γ-ray flux also depends on the EGMF which determines where the energy loss of γ-rays is dominated by synchrotron loss rather than inverse Compton scattering on the CMB and thus could be used to "measure" the EGMF in the range $\simeq 10^{-10} - 10^{-9}\,\mathrm{G}$. [29]

Information on the EGMF structure could also be obtained by observing the energy and and arrival time distribution of nucleons from sources which release UHE cosmic rays on a time scale short compared to $\simeq 1\,\mathrm{yr}$, i.e. in a burst. [30,31,32]. This is because the average time delay caused by deflection in the EGMF is $\simeq 0.9(E/100\,\mathrm{EeV})^{-2}(r/10\,\mathrm{Mpc})^2(B/10^{-11}\,\mathrm{G})^2(l_c/1\,\mathrm{Mpc})\,\mathrm{yr}$, where E is the observed nucleon energy, r is the source distance, and B and l_c is the typical strength and the coherence length of the EGMF, respectively. Some TD scenarios such as the ones involving collapsing cosmic string loops [11] would imply the existence of such bursting sources.

3 Conclusions

Some TD type scenarios of HECR origin are still unconstrained by current data and bounds on γ-ray and UHE CR fluxes. For example, in case of an EGMF $\lesssim 10^{-9}\,\mathrm{G}$, spatially uniform annihilation of magnetic monopoles and antimonopoles is still a viable model for GUT scales up to $10^{16}\,\mathrm{GeV}$. In such scenarios, the flux would be dominated by γ-rays above $\simeq 100\,\mathrm{EeV}$ and the possibility of a gap in the spectrum arises. A solid angle averaged γ/CR flux ratio at the 10% level at $\simeq 10\,\mathrm{EeV}$ is a signature of a non-acceleration origin of HECRs hinting to the presence of a TD mechanism. At the same time it would put an independent new upper limit of $\simeq 10^{-11}\,\mathrm{G}$ on the poorly known EGMF on scales of a few to tens of Mpc.

The fact that some TD mechanisms would imply bursting sources could provide another "probe" of the EGMF.

Acknowledgments

I acknowledge my collaborators in the work on which this article is based, namely, Venya Berezinsky, Pijush Bhattacharjee, Paolo Coppi, Christopher Hill, Karsten Jedamzik, Sangjin Lee, Martin Lemoine, Angela Olinto, and David Schramm. This work was supported by the DoE, NSF and NASA at the University of Chicago, by the DoE and by NASA through grant NAG 5-2788 at Fermilab, and by the Alexander-von-Humboldt Foundation.

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