Limits on Models of the Ultrahigh Energy Cosmic Rays Based on Topological Defects

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Using the propagation of ultrahigh energy nucleons, photons, and electrons in the universal radiation backgrounds, we obtain limits on the luminosity of topological defect scenarios for the origin of the highest energy cosmic rays. The limits are set as a function of the mass of the X particles emitted by the cosmic strings or other defects, the cosmological evolution of the topological defects, and the strength of the extragalactic magnetic fields. The existing data on the cosmic ray spectrum and on the isotropic 100 MeV gamma-ray background limit significantly the parameter space in which topological defects can generate the flux of the highest energy cosmic rays, and rule out models with the standard X-particle mass of 10^{16} GeV and higher. [S0031-9007(96)01553-0]

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The cosmic-ray events with the highest energies so far detected have energies of 2×10^{11} GeV [1] and 3×10^{11} GeV [2]. The question of the origin of these cosmic rays having energy significantly above 10^{11} GeV is complicated by propagation of such energetic particles through the Universe. The threshold for pion photoproduction on the microwave background is $\sim 2 \times 10^{10}$ GeV, and at 3×10^{11} GeV the energy-loss distance is about 20 Mpc. Propagation of cosmic rays over substantially larger distances gives rise to a cutoff in the spectrum at $\sim 10^{11}$ GeV as was first shown by Greisen [3], and Zatsepin and Kuz'min [4], the "GZK cutoff."

The standard cosmic-ray acceleration mechanism, shock acceleration, leads to a power-law energy spectrum, $dn/dE \propto E^{-\alpha}$, with differential index $\alpha > 2$. To reach energies of $\sim 10^{11}$ GeV one requires the conditions present in powerful radio galaxies [5].

An alternative explanation of the highest energy cosmic rays is the topological defect (TD) scenario [6–9], where the observed cosmic rays are a result of top-down cascading, from the grand unified theory (GUT) scale energy of $\sim 10^{16}$ GeV or higher [10], down to 10^{11} GeV and lower energies. Generally, these models put out much of the energy in a very flat spectrum of photons and electrons extending up to the mass of the "X particles" emitted. Approximating this spectrum by monoenergetic injection of photons of energy 10^{15} GeV, Protheroe and Johnson [11] showed that spectra from single TD sources cannot explain the $(2-3) \times 10^{11}$ GeV events.

The main problem with topological defect models is the wide range of model parameters in which this scenario could, in principle, be applied. Parameters of TD scenarios include mass of the X particle, energy spectra and final state composition of the decay products, and cosmological evolution of the topological defect injection rate [12,13]. The problem of propagation is more severe than for the case of acceleration scenarios because most of the energy from X-particle decay emerges in electrons, photons, and neutrinos, with only about 3% in nucleons. The electrons and photons initiate electromagnetic cascades in the extragalactic radiation fields and magnetic field, resulting in a complicated spectrum of electrons and photons which is very sensitive to the radiation and magnetic environment. For example, recently the HEGRA group [14] have placed an upper limit on the ratio of γ rays to cosmic rays of $\sim 10^{-2}$ at 10^5 GeV and, using a TD model calculation [7] which neglected the IR background and gave a higher ratio, argued that TD models were ruled out. However, inclusion of the IR would reduce the 10^5 GeV γ-ray intensity to well below the HEGRA limit.

Protheroe and Johnson [15] considered one set of parameters ($M_X c^2 = 10^{15}$ GeV, constant injection per comoving volume, $B = 10^{-9}$ G) and ruled out TD as the origin of the $(2-3) \times 10^{11}$ GeV events. This was mainly due to the high gamma-ray intensities at observable energies in the electromagnetic cascade initiated by electrons and photons in the TD spectrum above 10^{11} GeV. The unification mass obtained from an analysis of LEP data [10] is $10^{16.0 \pm 0.3}$ GeV, and the X-particle mass cannot be far from this. For an X-particle mass close to the unification mass, i.e., higher than the 10^{15} GeV used in Ref. [15], even more energy would be injected into this cascade, and the gamma-ray intensities would violate the observational contraints even more. Reference [15] has therefore already ruled out TD as the origin of the $(2-3) \times 10^{11}$ GeV events. Recently, however, Lee [13] and Sigl, Lee, and Coppi [16] have claimed that lower X-particle masses are possible, and adopting $M_X c^2 = 10^{14}$ GeV, and a lower magnetic field, suggested the TD scenario is not ruled out. In this Letter we consider several TD scenarios to put limits on the luminosity of the particle fluxes injected by topological defects as a function of the X-particle mass, the cosmological evolution of the topological defects, and the strength of the extragalactic magnetic field, and consider for what range of parameters TD could explain the $(2-3) \times 10^{11}$ GeV events. We confirm the conclusion of Protheroe and Johnson [15] that for X-particle masses of 10^{15} GeV or higher TD cannot

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explain the (2–3) $\times$ 10^{11} GeV events and severely limit models with lower M_X.

We use the same injection spectra and TD evolution as in Ref. [16]. This is approximately an $E^{-1.5}$ spectrum extending up to $\sim M_X c^2/2$ containing $\sim 3\%$ nucleons and 97% pions. In the matter dominated era of the Universe, and assuming $q_0 = 0.5$, the injection rate per comoving volume is $Q(t) = Q_0(t/t_0)^{-2+p}$ where $p = 1$ for ordinary cosmic strings and monopole-antimonopole annihilation, $p = 0$ for superconducting cosmic strings, and $p = 2$ for models with constant injection.

We inject this spectrum at various distances and carry out a Monte Carlo matrix propagation calculation as described in Ref. [11]. The following processes are included: $\gamma\gamma \rightarrow e^+e^-$ on the microwave, radio, and IR-optical background, IC scattering on the same backgrounds, triplet pair production and double pair production on the microwave background, synchrotron radiation in the extragalactic magnetic field, and redshifting due to expansion of the Universe. Nucleons undergo pion photoproduction interactions and protons undergo Bethe-Heitler pair production in the same environment, and neutron production and decay are taken into account.

For the radio background we use the spectrum of Clark *et al.* [17]. Other estimates of the radio background based on data on radio galaxies and ordinary galaxies give a radio background extending to significantly lower frequencies [18,19], and we shall discuss the effect of using different radio spectra elsewhere [20]. Magnetic field values we use are $10^{-15}, 10^{-12}, 10^{-11}, \ldots, 10^{-8}$ G. The values at the high end of this range may be appropriate if topological defects are seeds for the formation of galaxies and larger structures in the Universe [21] where fields are generally higher than average. For the infrared background we adopt a spectrum [22] which is based on the model of Stecker *et al.* [23] but constrained at low frequencies by upper limits derived by us from the error bars on the microwave background measured by the FIRAS experiment on COBE [24]. At 3×10^{-3} eV, where the microwave background is decreasing rapidly with energy, our IR spectrum is a factor of 5 lower than that used by Lee [13].

For a uniform distribution of topological defects we obtain the total intensity by integrating over the redshift results obtained for propagation over fixed distances, taking account of topological defect evolution and cosmological expansion assuming $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. The result for $M_X c^2 = 10^{14.1}$ GeV, a magnetic field of 10^{-9} G, and $p = 2$, is shown in Fig. 1 where we have normalized the spectrum of "observable particles" (nucleons, photons, electrons) to the 3×10^{11} GeV point (cosmic-ray data are taken from [25], and the highest point is from [2]). Lee [13] has published a spectrum for similar input parameters, and it is in acceptable agreement with the present work except for MeV–PeV γ rays where our result is about a factor of 10 lower. We suspect this is because of our lower IR field, and this appears to be confirmed by results presented by Lee which show the γ-ray intensity to be significantly lower if the IR field is neglected. With our lower IR field, and consequent lower γ-ray intensity, we are less likely to rule out topological defect models due to excess γ-ray production. For normalization to the 3×10^{11} GeV data, the injection rate of energy in X particles would be $\sim 6 \times 10^{-44}$ erg cm^{-1} s^{-1}. Notice that above 10^{11} GeV photons dominate the spectra of observable particles, and that over some ranges of energy electrons dominate the electromagnetic component. Also note that the predicted γ-ray flux at GeV energies is comparable to the observed background, and as pointed out by Lee [13], the extragalactic γ-ray background at these energies will place a strong constraint on the topological defect models. Figure 2 shows the energy injection rate at the present epoch, such that the intensity of observable particles is normalized to the 3×10^{11} GeV point, as a function of M_X for various extragalactic magnetic fields and evolution models.

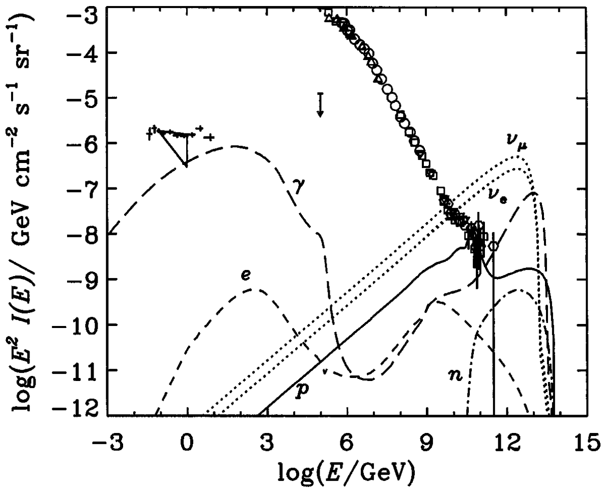

FIG. 1. Spectra at Earth for the topological defect model discussed in the text. SAS-2 and EGRET γ-ray data are shown at GeV energies, and HEGRA data at 100 TeV.

Synchrotron radiation is very important in determining the γ-ray spectrum at MeV–PeV energies which can vary by orders of magnitude depending on the magnetic field. Limits on the injection rate obtained from comparing the predicted 0.1–10 GeV intensities with SAS-II [26] and preliminary EGRET [27] data are only lower than the injection rate obtained from normalization at 3×10^{11} GeV [and thus rule out a TD origin for the (2–3) $\times$ 10^{11} GeV events] for the highest magnetic fields. Where this limit is lower than the injection rate obtained from normalizing the intensity of observable particles to the 3×10^{11} GeV point, these limits have been added to Fig. 2 for the three evolution models. We see that the γ-ray data provide the strongest constraint for models with high M_X, high B, and weak evolution. No models with $M_X c^2 < 10^{14.4}$ GeV are excluded by the constraints imposed so far, so if we used only these two constraints we would agree with Sigl *et al.* [16] that TD scenarios are not ruled out.

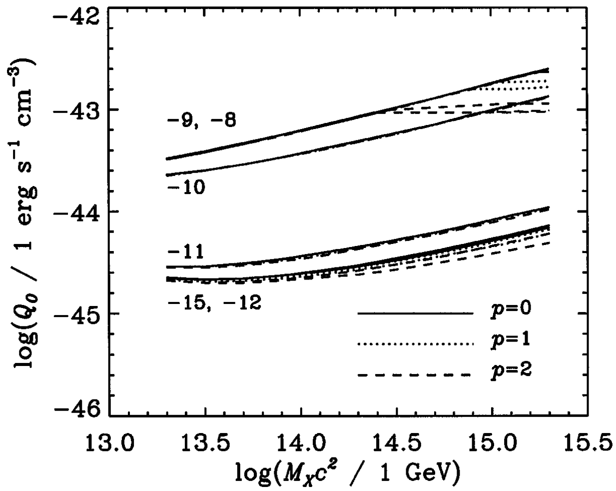

FIG. 2. Maximum rate of injection of energy in X particles as a function of M_X for various magnetic fields and evolution models based on normalization of predicted intensity of "observable particles" to the 3×10^{11} GeV point, or using the γ-ray data as upper limits (the lower of the two is plotted). Numbers attached to curves give $\log[B/(1\text{ G})]$.

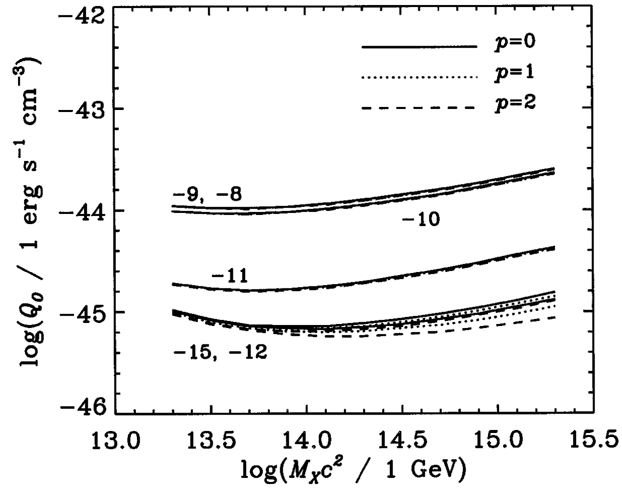

FIG. 3. Maximum rate of injection of energy in X particles as a function of M_X for various magnetic fields and evolution models based on the nonobservation of cosmic rays above 3×10^{11} GeV.

A further constraint, not considered by Sigl *et al.* [16], comes from the intensity of potentially observable particles above 3×10^{11} GeV. This constraint has already been used by Protheroe and Johnson [15] to rule out the model with $M_X = 10^{15}$ GeV, $p = 2$, and $B = 10^{-9}$ G. Here we use the fact that 1 event was observed by the Fly's Eye between $10^{11.45}$ and $10^{11.55}$ GeV, together with the published intensity at $10^{11.5}$ GeV, to obtain the exposure factor of the Fly's Eye experiment at this energy. Assuming the exposure factor has the same value also at higher energies (a reasonable assumption as at these energies optical transmission will limit the distance to observable air showers rather than the inverse-square law), we can estimate the number of events which should have been observed above 3×10^{11} GeV. Given that no events have been seen above this energy, we set a 90% upper limit of 2.3 events which, when compared with the expected number of events, sets a new upper limit to the rate of injection of energy in X particles. This limit is approximately independent of topological defect evolution and is plotted in Fig. 3 against M_X for various magnetic fields. In *all cases* this limit is lower than the injection rate required to explain the $(2-3) \times 10^{11}$ GeV events, and so it would appear that, subject to γ rays and electrons above this energy being detectable by the Fly's Eye as discussed below, topological defect models are ruled out as the explanation of the $(2-3) \times 10^{11}$ GeV events. Comparing Figs. 2 and 3, and extrapolating to 10^{16} GeV, it is obvious that TD models with standard M_X are also ruled out.

The limits on the injection rate of energy in X particles from the number of "observable particles" above 3×10^{11} GeV may actually be weaker than given in Fig. 3 because these particles are dominated by photons and electrons which might be undetectable. Energetic γ rays entering the atmosphere will be subject to the LPM effect [28] (the suppression of electromagnetic cross sections at high energy) which becomes very important. The radiation length changes as $(E/E_{\text{LPM}})^{1/2}$, where $E_{\text{LPM}} = 6.15 \times 10^4 \ell_{\text{rad}}$ GeV, and ℓ_{rad} is the standard Bethe-Heitler radiation length in cm [29]. We find that the average shower maximum will be reached below sea level for energies 5×10^{11}, 8×10^{11}, and 1.3×10^{12} GeV for gamma rays entering the atmosphere at $\cos\theta = 1$, 0.75, and 0.5, respectively. Such showers would be very difficult to reconstruct by experiments such as Fly's Eye and at best would be assigned a lower energy. In this case, we should treat electrons and γ rays as unobservable, and normalize the *nucleon intensity* to the 3×10^{11} GeV data. This has the effect of increasing the predicted γ-ray intensities, and the new upper limits to the rate of injection of energy in X particles would be as given in Fig. 4. We now see that normalizing to the 3×10^{11} GeV data violates the γ-ray data for all models with $p = 2$, models with $p = 1$ and $M_X > 10^{13.1}-10^{13.7}$ GeV depending on B, and models with $p = 0$ and $M_X > 10^{13.9}-10^{14.9}$ GeV depending on B. Thus, models with standard M_X would also be ruled out as the explanation of the $(2-3) \times 10^{11}$ GeV events.

Before entering the Earth's atmosphere γ rays and electrons are likely to interact on the geomagnetic field (see Erber [30] for a review of the theoretical and experimental understanding of the interactions). In such a case the γ rays propagating perpendicular to the geomagnetic field lines would cascade in the geomagnetic field, i.e., pair production followed by synchrotron radiation. The cascade process would degrade the γ-ray energies to some extent (depending on pitch angle), and the atmospheric cascade would then be generated by a bunch of γ rays of lower energy. Aharonian *et al.* [31] have considered this possibility and conclude that this bunch would appear as

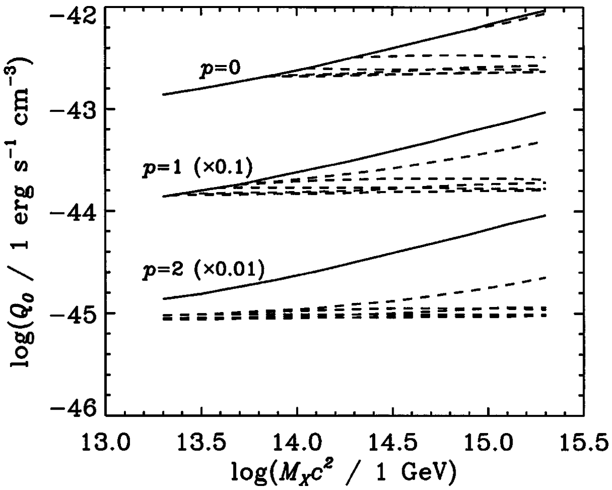

FIG. 4. Maximum rate of injection of energy in X particles as a function of M_X for various magnetic fields and evolution models based on normalization of predicted intensity of nucleons (solid curves), and using the γ-ray data as upper limits (dashed curves) for $B = 10^{-15}$ G (highest curves) to $B = 10^{-8}$ G (lowest curves).

one air shower made up of the superposition of many subshowers of lower energy where the LPM effect is negligible, the air shower having the energy of the initial γ ray outside the geomagnetic field. If this is the case, then γ rays above 3×10^{11} GeV would be observable by Fly's Eye, etc., and the upper limits presented in Fig. 3 would stand, ruling out a TD origin for the $(2-3) \times 10^{11}$ GeV events. There is, however, some uncertainty as to whether pair production will take place in the geomagnetic field. This depends on whether the geomagnetic field spatial dimension is larger than the formation length of the electron pair, i.e., the length required to achieve a separation between the two electrons which is greater than the classical radius of the electron. This question of whether or not pair production in the geomagnetic field takes place needs further investigation. In any case, we find TD models for the $(2-3) \times 10^{11}$ GeV events are ruled out for standard X-particle masses of 10^{16} GeV or higher, and our results severely constrain models with lower M_X.

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[1] N. Hayashida *et al.*, Phys. Rev. Lett. **73**, 3491 (1994).
[2] D. J. Bird *et al.*, Astrophys. J. **441**, 144 (1995).
[3] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966).
[4] G. T. Zatsepin and V. A. Kuz'min, JETP Lett. **4**, 78 (1966).
[5] J. P. Rachen and P. L. Biermann, Astron. Astrophys. **272**, 161 (1993).
[6] C. T. Hill, Nucl. Phys. **B224**, 469 (1983).
[7] F. A. Aharonian, P. Bhattacharjee, and D. Schramm, Phys. Rev. D **46**, 4188 (1992).
[8] P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. **69**, 567 (1992).
[9] A. J. Gill and T. W. B. Kibble, Phys. Rev. D **50**, 3660 (1994).
[10] U. Amaldi, W. de Boer, and H. Fürstenau, Phys. Lett. B **260**, 447 (1991).
[11] R. J. Protheroe and P. A. Johnson, Astropart. Phys. **4**, 253 (1996); erratum (to be published).
[12] G. Sigl, Space Sci. Rev. (to be published).
[13] S. Lee (to be published).
[14] A. Karle, Phys. Lett. B **347**, 161 (1995).
[15] R. J. Protheroe and P. A. Johnson, "Phenomenological Aspects of Underground Physics (TAUP95)," edited by M. Fratas, Nucl. Phys. B. Proc. Suppl. **48**, 485 (1996).
[16] G. Sigl, S. Lee, and P. Coppi (to be published).
[17] T. A. Clark, L. W. Brown, and J. K. Alexander, Nature (London) **228**, 847 (1970).
[18] V. S. Berezinsky, Yad. Fiz. **11**, 339 (1970).
[19] R. J. Protheroe and P. L. Biermann (to be published).
[20] R. J. Protheroe and T. Stanev (to be published).
[21] R. Brandenburger, in Proceedings of the Pacific Conference on Gravity and Cosmology (World Scientific, Singapore, to be published).
[22] R. J. Protheroe and T. S. Stanev Mon. Not. R. Astron. Soc. **264**, 191 (1993).
[23] F. W. Stecker, O. C. De Jager, and M. H. Salamon, Astrophys. J. **390**, L49 (1992).
[24] J. C. Mather *et al.*, Astrophys. J. **420**, 439 (1994).
[25] T. Stanev, in *Particle Acceleration in Cosmic Plasmas*, edited by G. P. Zank and T. K. Gaisser (AIP, New York, 1992), p. 379.
[26] D. J. Thompson and C. E. Fichtel, Astron. Astrophys. **109**, 352 (1982).
[27] C. E. Fichtel, in Proceedings of the 3rd Compton Observatory Symposium [Astron. Astrophys. Suppl. (to be published)].
[28] L. D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk. SSSR **92**, 535 (1953); A. B. Migdal, Phys. Rev. **103**, 1811 (1956).
[29] T. Stanev *et al.*, Phys. Rev. D **25**, 1291 (1982).
[30] T. Erber, Phys. Rev. **38**, 626 (1968).
[31] F. A. Aharonian, B. L. Kanevsky, and J. Sahakian, J. Phys. G **17**, 1909 (1991).