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EXTRAGALACTIC MAGNETIC FIELD AND THE HIGHEST ENERGY COSMIC RAYS

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ABSTRACT

The strength and spectrum of the extragalactic magnetic field (EGMF) are still unknown. Its measurement would help answer the question of whether galactic fields are purely a primordial relic or whether they were dynamically enhanced from a much smaller cosmological seed field. In this Letter, we show that the composition, spectrum, and directional distribution of extragalactic ultra–high-energy cosmic rays, with energies above $\simeq 10^{18}$ eV, can probe the large-scale component of the EGMF below the present observational upper limit of 10^{-9} G. Cosmic-ray detectors under construction or currently in the proposal stage should be able to test the existence of the EGMFs on scales of a few to tens of megaparsecs and strengths in the range $\simeq 10^{-10}$ to 10^{-9} G.

Subject headings: cosmic rays — gamma rays: theory — magnetic fields

1. INTRODUCTION

Magnetic fields are universally present in astronomical bodies ranging from the Earth to distant quasars, but it is still unknown whether magnetic fields permeate the universe as a whole. Astrophysical magnetic fields may arise due to the existence of a primordial magnetic field that grows as galaxies form. The discovery of an extragalactic magnetic field (EGMF) on scales larger than virialized systems (i.e., larger than clusters of galaxies) would reveal the presence of a primordial field. The existence of such a primordial field would help us understand the origin of astrophysical magnetic fields and may open a new window into processes ocurring in the early universe.

In this Letter, we show that the study of ultra–high-energy cosmic rays (UHE CRs) with energies above $\simeq 10^{18}$ eV can probe primordial fields below the current upper bound. Our proposed method is complementary to traditional ones (e.g., Kronberg 1994) and to more recent suggestions (e.g., Plaga 1995). At present, the most stringent constraint on large-scale extragalactic fields comes from limits on the Faraday rotation of light coming to us from distant quasars. The upper bound on a widespread, all-pervading field is $\sim 10^{-9}$ G (e.g., Kronberg 1994). There are weaker constraints derived from the synchrotron emission from nearby galaxy clusters (Kim et al. 1989) and the cosmic microwave background isotropy.

UHE CR nucleons from extragalactic sources are attenuated in energy while propagating through the cosmic microwave background (CMB). Above a few times 10^{19} eV, nucleons produce pions on the CMB photons, and the energy of the cosmic-ray nucleons is degraded rapidly, which is known as the Greisen-Zatsepin-Kuzmin (GZK) effect (Greisen 1966; Zatsepin & Kuzmin 1966). Produced pions, on the other hand, decay into secondary leptons such as electrons, muons, and neutrinos, and photons. Since muons decay into electrons and neutrinos, the final secondary particles are photons, electrons, and neutrinos, among which photons are more readily detectable.

Very energetic secondary photons and electrons couple to form an electromagnetic (EM) cascade. The γ-rays produce electron pairs on the CMB and the universal radio background photons (see Lee & Sigl 1995; Lee et al. 1995 and references therein for more detailed discussions). The resulting electrons (or positrons), in turn, upscatter background photons via inverse Compton scattering (ICS), thus completing a cycle. It is through these two processes that an EM cascade develops in the intergalactic medium. As a result, if one propagates a purely protonic spectrum, one gets a processed nucleon spectrum with the GZK cutoff and a secondary EM (photons and electrons) spectrum. Since the center-of-mass energy for these interactions on the infrared (IR) background photons lies well off peak in the energy range we consider, and the IR flux is much weaker than the CMB, the role of the IR background in this energy range is negligible.

The EGMF influences the UHE CR flux mainly through its charged components, namely, the primary hadrons and the secondary electrons. In the energy range under consideration, the hadrons are deflected with negligible energy loss due to synchrotron radiation, whereas the electrons are negligibly deflected before they lose most of their energy. In § 2 we explore the effect of the electron energy loss due to the EGMF on the secondary EM cascade spectrum. We then discuss, in § 3, the deflection of the hadronic component in the EGMF. Finally, in § 4 we summarize our findings.

2. EXTRAGALACTIC MAGNETIC FIELD AND ULTRA–HIGH-ENERGY γ-RAY FLUX

The EGMF plays a crucial role in the development of the EM cascade. In the presence of the magnetic field, electrons lose energy via synchrotron radiation loss, which is given by

$$\frac{dE}{dt} = -\frac{2c}{3} r_0^2 B^2 \left(\frac{E}{m_e c^2}\right)^2 \simeq -3.8 \times 10^7 \left(\frac{B}{10^{-9}\ \mathrm{G}}\right)^2 \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^2 \mathrm{eV\ s^{-1}}, \quad (1)$$

where B is the strength of the large-scale EGMF, r_0 is the classical electron radius, and m_e is the electron mass (Protheroe & Johnson 1995).

In Figure 1 we show the rates of ICS and synchrotron loss for electrons. Whereas the rate of ICS responsible for EM cascade development decreases with energy, the synchrotron-loss rate increases with energy. Therefore, in a narrow energy

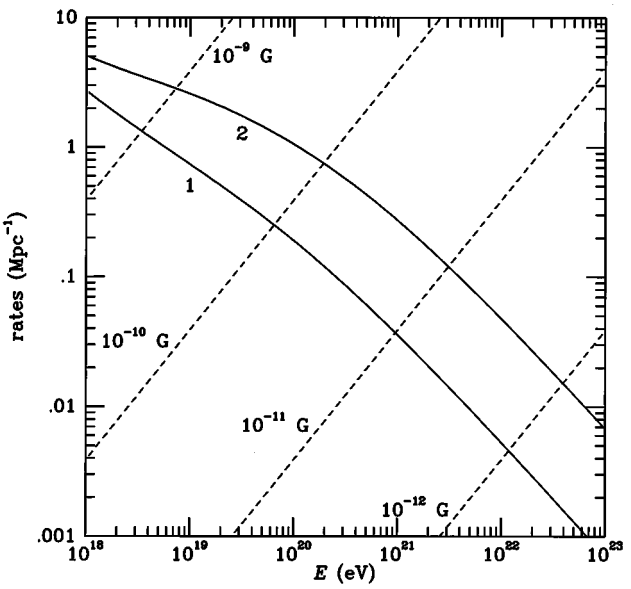

FIG. 1.—Rate of ICS (*solid lines*) and the fractional synchrotron-loss rate (*dashed lines*) for different magnetic fields as functions of energy. Curve 1 is for a frequency cutoff at 2 MHz in the diffuse radio background, and curve 2 is for 0.5 MHz.

range a transition occurs between a regime where ICS is dominant and electrons couple to photons efficiently, and another where electrons are rapidly lost due to synchrotron loss and the cascade is suppressed. Below $\simeq 10^{20}$ eV (the threshold for pair production on the radio background), cascade development in the absence of an EGMF would give rise to a generic power-law photon spectrum with index $\simeq -1.5$. The above-mentioned transition in the secondary γ-ray spectrum will therefore occur between this generic cascade shape and a synchrotron-loss–dominated spectrum. As long as synchrotron quanta can be neglected, the latter is given by the photons produced "directly" by source injection or from pion production by nucleons, before undergoing pair production in the low-energy photon background.

In a magnetic field of strength B measured in gauss, the synchrotron spectrum produced by an electron of energy E_e peaks at

$$E_{\rm syn} \simeq 6.8 \times 10^{13} \left(\frac{E_e}{10^{21}\ {\rm eV}}\right)^2 \left(\frac{B}{10^{-9}\ {\rm G}}\right) {\rm eV}, \qquad (2)$$

and falls off exponentially at higher energies. In the following, we assume that most of the EM energy is in γ-rays and electrons with energy $E \lesssim 10^{21}$ eV. Then, according to equation (2), the contribution of synchrotron radiation to the γ-ray flux above 10^{18} eV can be safely neglected as long as $B \lesssim 10^{-6}$ G everywhere.

The energy where the transition in the γ-ray spectrum occurs is, in general, a function of the magnetic field strength and the background photon spectrum, but is *not* a function of the source distance or the injection spectrum. If we consider only the CMB, the relation between the transition energy $E_{\rm tr}$ and the magnetic field strength is $E_{\rm tr} \propto B^{-1}$. In order to take the less well known diffuse extragalactic radio background into consideration, we adopt its usual description by a power law, with an overall amplitude and a lower frequency cutoff as parameters (Clark, Brown, & Alexander 1970). The lower frequency cutoff is the main source of uncertainty. Using a cutoff at 2 MHz, as suggested by Clark et al. (1970), the above relation is modified to

$$E_{\rm tr} \simeq 10^{19} \left(\frac{B}{10^{-9}\ {\rm G}}\right)^{-1.3} {\rm eV} \quad (B \gtrsim 10^{-10}\ {\rm G}). \qquad (3)$$

For the same magnetic field, a cutoff at lower frequencies would increase the rate of ICS of the then more abundant low-frequency radio photons and thus the value for $E_{\rm tr}$ (see Fig. 1). Assuming that the radio cutoff frequency lies somewhere in the range between 0.5 and 3 MHz for a given $E_{\rm tr}$, the EGMF strength B is uncertain within about a factor of 5.

Therefore, for $B \gtrsim 10^{-10}$ G it is possible to determine approximately the EGMF strength by searching for a dip in the γ-ray flux below 10^{20} eV, which would mark a transition between an ICS and a synchrotron-loss–dominated regime. For $B \lesssim 10^{-10}$ G, this transition occurs above the pair production threshold on the radio background, where the γ-ray flux increasingly depends on several unknown factors, such as the charged cosmic-ray flux above the GZK cutoff. Thus, even though the γ-ray flux can be comparable to the nucleon flux above 10^{20} eV, a discussion of possible magnetic field signatures in its spectrum would be presently too speculative.

We developed a numerical code for the propagation of nucleons, photons, and electrons through the intergalactic medium which employs a transport equation formalism, the details of which can be found in Lee (1995). In this numerical code, all the important processes, such as pair production by photons, double pair production, ICS, triplet pair production, photopion production by protons, are fully implemented, and both the CMB and the radio background are included as the background radiation field. The observed UHE CR flux below 10^{20} eV (see, e.g., Bird et al. 1994; Yoshida et al. 1995) is reproduced quite well by a diffuse distribution of sources, injecting protons with a spectrum proportional to $E^{-2.3}$ up to some maximal energy considerably beyond the GZK cutoff (Yoshida & Teshima 1993; Sigl et al. 1995). For the calculations presented here, we therefore adopted this proton injection spectrum with a maximal energy of 10^{22} eV. The EGMF enters the calculation via the synchrotron loss of electrons.

The transition between ICS and synchrotron-loss domination can be easily seen in Figure 2, which shows the processed nucleon and photon spectra for a single source at a distance of 30 Mpc for a range of EGMF strengths. In general, one expects a distribution of cosmic-ray sources rather than a single source at a fixed distance. In Figure 3 we show the diffuse spectrum from a continuous source distribution extending up to 1 Gpc. We assume a flat universe with a zero cosmological constant and a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1}, and a comoving source density scaling as $(1 + z)^2$ in redshift z, as in some "bright phase" models of cosmic-ray sources (e.g., Yoshida & Teshima 1993; Hill & Schramm 1985 and references therein). The results are not very sensitive to these choices. In the diffuse case, the γ-ray–to–nucleon flux ratio tends to be smaller than for a single source, and the spectral features are not as pronounced but still detectable for $B \gtrsim 10^{-10}$ G.

The "EGMF" in this analysis refers to the average component of the EGMF normal to the line of propagation. Primordial magnetic fields are expected to have very little structure on scales below about a few megaparsecs (Jedamzik, Katalinic, & Olinto 1995), but condensed structures such as galaxies and

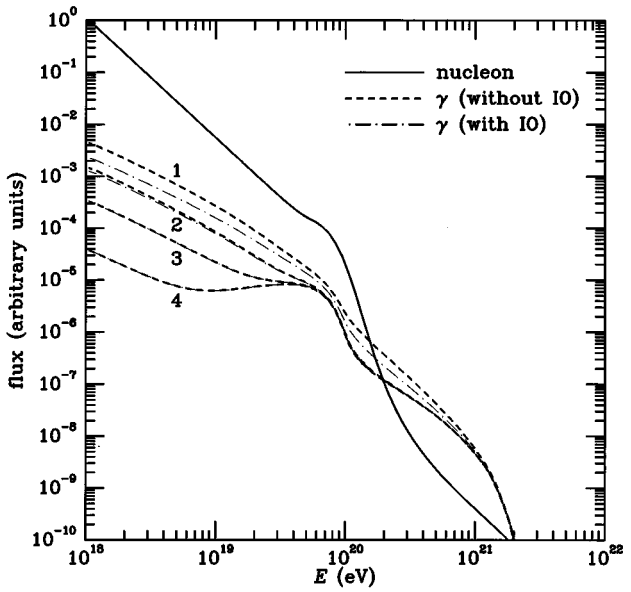

FIG. 2.—Cosmic-ray nucleon spectrum (*solid line*) from a single source at a distance of 30 Mpc and secondary γ-ray spectra for different magnetic fields. The short-dashed lines are for no intervening objects, and the long-dashed lines with dots are for a 5 Mpc–sized object located at 12.5 Mpc from the observer. The magnetic field values are $B = 0$, 10^{-10}, 3×10^{-10}, and 10^{-9} G, for curves 1–4, respectively, from the top.

clusters of galaxies can "pollute" the intergalactic medium with stronger magnetic fields on smaller scales. Fortunately, the effect of the EGMF on the γ-ray spectral shape discussed here is most sensitive to the average field on large scales. When the EM cascade goes through a strong field region, the electrons in the cascade lose energy rapidly and drop out of the UHE range. In contrast, the UHE nucleon and γ-ray fluxes are usually hardly affected directly by the radiation field of the intervening object (Stecker et al. 1991; Szabo & Protheroe 1994; Norman, Melrose, & Achterberg 1995). After escaping the object, the cascade redevelops, and the cascade spectrum recovers quickly at only a slightly smaller amplitude. The influence of intervening objects decreases with the increasing strength of the large-scale field and becomes important only when the objects are very close to the observer (e.g., less than ~5 Mpc away) or when their linear size is significant compared to the total propagation distance. We can derive conditions for the filling factors for such objects by requiring that they be much more sparsely populated along the line of sight to the source than the typical cascade regeneration length s_c (e.g., ~5 Mpc). For an average linear size $\bar{l}_{\rm iv}$ of the intervening objects, their filling factor $f_{\rm iv}$ must satisfy

$$f_{\rm iv} \ll \frac{\bar{l}_{\rm iv}}{s_c} . \tag{4}$$

For field galaxies, the above relation is $f_g \ll 10^{-3}$, and for clusters of galaxies, $f_c \ll 0.1$. The actual filling factors for galaxies, $f_g \lesssim 10^{-7}$, and galaxy clusters, $f_c \lesssim 10^{-4}$ (Kolb & Turner 1990; Nichol, Briel, & Henry 1994), satisfy these constraints. Therefore, intervening objects do not modify the above discussion substantially. One interesting exception may be the effect of nearby large structures, such as the Virgo Cluster. If Virgo has strong magnetic fields, e.g., $\sim 10^{-7}$ G on megaparsec scales, the UHE γ-ray flux from background sources might be modified across Virgo's angular extension (see Fig. 2).

The ability of future detectors to study EGMF features depends crucially on the γ-ray–to–nucleon flux ratio. For nearby strong sources, the secondary γ-ray flux could be measurable with instruments which are sensitive to ratios down to ≃1%. This could be achieved by the proposed Pierre Auger project (see, e.g., Boratav et al. 1992), which would also allow an angular resolution of ≃1°. The case of a diffuse source distribution is more challenging; the γ-ray flux is typically smaller, and the EGMF feature is less pronounced than for a single source at moderate distances (see Figs. 2 and 3), but the dip in the γ-ray spectrum may still be detectable. Thus, measuring the γ-ray flux between ≃10^{18} and ≃10^{20} eV has the potential to either detect or find strong evidence against an EGMF $\gtrsim 10^{-10}$ G.

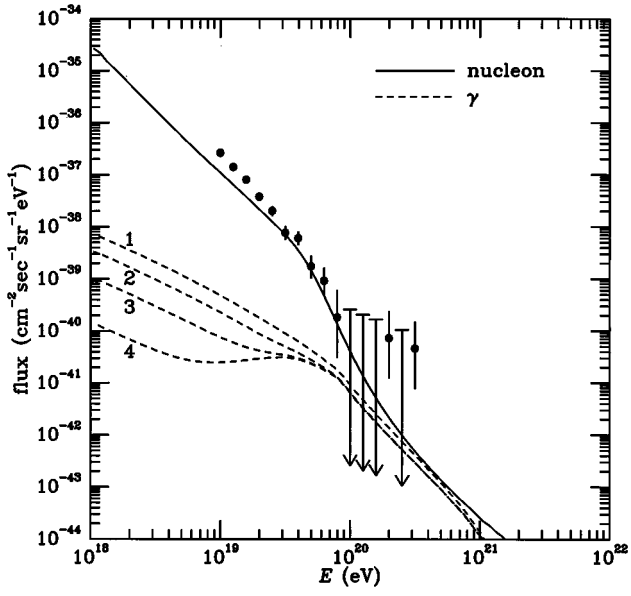

FIG. 3.—Cosmic-ray nucleon spectrum (*solid line*) and secondary γ-ray spectra (*dashed lines*) for a continuous source distribution up to 1 Gpc distance whose comoving density scales as $(1 + z)^2$. The sum of the nucleon and γ-ray flux is fitted to the combined data from the monocular Fly's Eye detector (Bird et al. 1994) and the AGASA experiment (Yoshida et al. 1995). Shown are 1 σ error bars and 84% confidence level upper limits. The magnetic field values are the same as in Fig. 2.

3. CHARGED COSMIC-RAY DEFLECTION BY THE EXTRAGALACTIC MAGNETIC FIELDS

Here we discuss the influence of the EGMF on the charged UHE CR flux from discrete sources. We restrict ourselves to the case of small deflection angles (for the opposite limit see, e.g., Wdowczyk & Wolfendale 1979; Berezinskii, Grigor'eva, & Dogel' 1989). In this case, the energy spectrum of charged UHE CRs from a given source is not significantly altered as compared to a straight-line propagation. However, if the sources are strong enough to cause an anisotropy in the UHE CR flux, the directional correlation of "hot spots" with possible sources will depend on the EGMF. The following discussion relates to this anisotropic component of the charged UHE CR flux.

As in § 2, let us assume that the large-scale EGMF can be characterized by a typical field strength B and a coherence length l_c. Furthermore, let us assume for the moment that the

source distance r is smaller than the energy attenuation length $\lambda = E(dE/dr)^{-1}$ for a charged cosmic ray of energy E, which can then be treated as approximately constant throughout propagation. For nucleons, $\lambda \simeq 10$ Mpc above the GZK cutoff (at $E \simeq 6 \times 10^{19}$ eV), and $\lambda \simeq 1$ Gpc much below the GZK cutoff. A more sophisticated analysis would require a Monte Carlo simulation of both UHE CR propagation and deflection. However, since data on both UHE CR and the EGMF are so sparse at present, we feel that a qualitative discussion of the principal effects is more appropriate at the moment. We now consider two cases.

1. The source distance is smaller than the coherence length, $r \lesssim l_c$. Then, in vectorial notation, the deflection angle α is given by

$$\alpha = -\frac{Ze}{E}\boldsymbol{r} \times \boldsymbol{B}$$

$$= 5.3Z\left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}\left(\frac{r}{10\ \mathrm{Mpc}}\right)\left(\frac{B}{10^{-9}\ \mathrm{G}}\right)(\hat{\boldsymbol{r}} \times \hat{\boldsymbol{B}}), \quad (5)$$

where $\boldsymbol{r}$ is the radius vector pointing to the source, Z is the charge of the UHE CR component, $\hat{\boldsymbol{r}} = \boldsymbol{r}/|\boldsymbol{r}|$, and $\hat{\boldsymbol{B}} = \boldsymbol{B}/|\boldsymbol{B}|$. Thus, a correlation between the UHE CR flux of charge Z and energy E and the source counterparts, systematically shifted by an angle α, would indicate that $l_c \gtrsim r$ and, for a known source distance r, would allow us to measure the combination $B(\hat{\boldsymbol{r}} \times \hat{\boldsymbol{B}})$. The characteristic E and Z dependence of α would provide an additional test for the hypothesis that the deflection is caused by an EGMF.

2. The source distance is considerably larger than the coherence length, $r \gg l_c$. In this case the deflection angle undergoes a diffusion process during propagation, and the source shape in the UHECR flux will be smeared out over a typical angle

$$\alpha_{\mathrm{rms}} \simeq \frac{2}{\pi}\frac{ZeB}{E}(rl_c)^{1/2}$$

$$= 1.1Z\left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}\left(\frac{r}{10\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{10^{-9}\ \mathrm{G}}\right). \quad (6)$$

Therefore, if sources appear spread out in the UHE CR flux of charge Z and energy E by a typical angle α, this would indicate that $l_c \lesssim r$ and, for a known source distance r, would allow us to measure the combination $Bl_c^{1/2}$.

If the source distance is larger than the energy attenuation length, $r \gtrsim \lambda$, equations (5) and (6) tend to overestimate α. In fact, in the limit $r \gg \lambda$ the deflection angle α "saturates" as a function of r, and for approximately energy-independent λ, r has to be replaced by λ and $\lambda/2$ in equations (5) and (6), respectively.

Using these properties, we could further probe the EGMF with some of the nearby galaxy clusters and powerful field radio galaxies, since they are expected to contribute significantly to the UHE CR flux (Rachen, Stanev, & Biermann 1993). The accuracy to which the EGMF bending can be determined is limited by the (to date) unknown additional bending by the galactic magnetic field of strength B_g and scale height l_g. Thus, according to equation (5), the sensitivity of deflection measurements of the EGMF is restricted to field parameters satisfying $Br \gtrsim 10^{-9}$ G Mpc $(B_g/\mu\mathrm{G})$ $(l_g/300$ pc), where the fudge factors are the parameter values usually assumed for the galactic magnetic field.

4. CONCLUSIONS

We discussed how composition, spectrum, and directional distribution of UHE CR above $\simeq 10^{18}$ eV can be used to gain information about the large-scale (a few to tens of megaparsecs) EGMF. Spectral features in the γ-ray flux are sensitive to field strengths in the range $\simeq 10^{-10}$ to 10^{-9} G. In a similar range, correlations between an anisotropic charged UHE CR flux component and possible sources could provide independent information on the EGMF, including its polarization. Both effects should yield consistent estimates for the EGMF strength. Strong discrete sources detected in UHE CRs by future instruments with an angular resolution of 1° or better, and a sensitivity to γ-ray–to–nucleon flux ratios of 1% or smaller, would provide the best conditions for detecting an EGMF in the range $\simeq 10^{-10}$ to 10^{-9} G. Since these conditions are not unreasonable, UHE CRs have the potential to provide important information on the properties and the origin of the EGMF.

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REFERENCES

Berezinskii, V. S., Grigor'eva, S. I., & Dogel', V. A. 1989, JETP, 69, 453
Bird, D. J., et al. 1994, ApJ, 424, 491
Boratav, M., et al. 1992, Nucl. Phys. B, 28
Clark, T. A., Brown, L. W., & Alexander, J. K. 1970, Nature, 228, 847
Greisen, K. 1966, Phys. Rev. Lett., 16, 748
Hill, C. T., & Schramm, D. N. 1985, Phys. Rev. D, 31, 564
Jedamzik, K., Katalinic, V., & Olinto, A. V. 1995, in preparation
Kim, K-T., Kronberg, P. P., Giovannini, G., & Venturi, T. 1989, Nature, 341, 720
Kolb, E. W., & Turner, M. S. 1990, The Early Universe (Redwood City: Addison-Wesley)
Kronberg, P. P. 1994, Rep. Prog. Phys., 57, 325
Lee, S., et al. 1995, in preparation
Lee, S., & Sigl, G. 1995, in Proc. 24th Int. Cosmic-Ray Conf. (Rome), 2, 536
Nichol, R. C., Briel, U. G., & Henry, J. P. 1994, MNRAS, 267, 771
Norman, C. A., Melrose, D. B., & Achterberg, A. 1995, ApJ, 454, 60
Plaga, R. 1995, Nature, 374, 430
Protheroe, R. J., Johnson, P. A. 1995, Astropart. Phys., in press
Rachen, J. P., Stanev, T., & Biermann, P. L. 1993, A&A, 273, 377
Sigl, G., Lee, S., Schramm, D. N., & Bhattacharjee, P. 1995, Science, in press
Stecker, F. W., Done, C., Salamon, M. H., & Sommers, P. 1991, Phys. Rev. Lett., 66, 2697
Szabo, A. P., & Protheroe, R. J. 1994, Astropart. Phys., 2, 375
Wdowczyk, J., & Wolfendale, A. W. 1979, Nature, 281, 356
Yoshida, S., & Teshima, M. 1993, Prog. Theor. Phys., 89, 833
Yoshida, S., et al. 1995, Astropart. Phys., 3, 105
Zatsepin, G. T., & Kuzmin, V. A. 1966, Pis'ma Zh. Eksp. Teor. Fiz., 4, 114 (JETP. Lett., 4, 78)