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DELAYED GeV–TeV PHOTONS FROM GAMMA-RAY BURSTS PRODUCING HIGH-ENERGY COSMIC RAYS

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ABSTRACT

A scenario in which cosmic rays (CRs) above 10^{20} eV are produced by cosmological gamma-ray bursts (GRBs) is consistent with observations, provided that deflections by the intergalactic magnetic field (IGMF) delay and spread the arrival time of the CRs over ≥ 50 yr. The energy lost by the CRs as they propagate and interact with the microwave background is transformed by cascading into secondary GeV–TeV photons. We show that a significant fraction of these photons can arrive with delays much smaller than the CR delay if much of intergalactic space is occupied by large-scale magnetic "voids," regions of a size $\gtrsim 5$ Mpc and a field weaker than 10^{-15} G. Such voids might be expected, for example, in models where a weak primordial field is amplified in shocked, turbulent regions of the intergalactic medium during the formation of large-scale structure. For a field strength $\sim 4 \times 10^{-11}$ G in the high-field regions, the value required to account for observed galactic fields if the IGMF were frozen in the protogalactic plasma, the delay of CRs produced by a burst at a distance of 100 Mpc is ~ 100 yr, and the fluence of secondary photons above 10 GeV on hour–day timescales is $I(>E) \sim 10^{-6}\, E_{\rm TeV}^{-1}$ cm^{-2}. This fluence is close to the detection threshold of current high-energy gamma-ray experiments. Detection of the delayed flux would support the GRB-CR association and would also provide information on the IGMF structure.

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

1. INTRODUCTION

Recent gamma-ray and cosmic-ray observations show increasing evidence that the sources of gamma-ray bursts (GRBs) and of cosmic rays (CRs) with energy $E > 10^{19}$ eV are cosmological (see Fishman & Meegan 1995 for GRB observations review, and Bird et al. 1994, Yoshida et al. 1995, and Waxman 1995b for CRs). The sources of both phenomena, however, remain unknown. In particular, most of the CR sources discussed so far have difficulties in accelerating CRs up to the highest observed energies (e.g., Cronin 1992). Although the source of GRBs is unknown, their observational characteristics impose strong constraints on the physical conditions in the gamma-ray–emitting region (e.g., Mészáros 1996), which implies that protons may be accelerated in this region to energies 10^{20}–10^{21} eV (Waxman 1995a; Vietri 1995). In addition, the average rate (over volume and time) at which energy is emitted as gamma-rays by GRBs and in CRs above 10^{19} eV in the cosmological scenario is remarkably comparable (Waxman 1995a, 1995b). These two facts suggest that GRBs and high-energy CRs may have a common origin.

An essential ingredient of the GRB model for CRs is the time delay due to intergalactic magnetic fields. The energy of the most energetic CR detected by the Fly's Eye experiment is in excess of 2×10^{20} eV (Bird et al. 1994), and that of the most energetic AGASA event is above 10^{20} eV (Yoshida et al. 1995). On a cosmological scale, the distance traveled by such energetic particles is small: less than 100 Mpc (50 Mpc) for the AGASA (Fly's Eye) event (e.g., Cronin 1992). Thus, the detection of these events over a ~ 5 yr period can be reconciled with the rate of nearby GRBs, ~ 1 per 50 yr in the field of view of the CR experiments out to 100 Mpc in a standard cosmological scenario (e.g., Cohen & Piran 1995), only if there is a large dispersion, ≥ 50 yr, in the arrival time of protons produced in a single burst. (Note that this implies that if a direct correlation between high-energy CR events and GRBs, as recently suggested by Milgrom & Usov 1995, is observed on a ~ 10 yr timescale, it would be strong evidence *against* a cosmological GRB hypothesis.) The required dispersion may result from deflections of CR protons by the intergalactic magnetic field (Waxman 1995a).

The intergalactic magnetic field (IGMF) has not been detected so far. Faraday-rotation measures set an upper limit of $\sim 10^{-9}$ G for a field with 1 Mpc correlation length (see Kronberg 1994 for review). Other methods have recently been proposed to probe fields in the range 10^{-10} to 10^{-20} G (e.g., Plaga 1995; Lee, Olinto, & Sigl 1995). Theoretical considerations regarding the existence and strength of the IGMF are related to the formation of the observed microgauss fields in galaxies. Recent studies suggest that a galactic dynamo cannot produce the observed large-scale fields in galactic disks (Kulsrud & Anderson 1992) and that one must turn to alternative mechanisms, which typically rely on a preexisting field. Galactic fields might be created, for example, by compression of much weaker fields in collapsing protogalactic regions. This mechanism requires a protogalactic field of strength 10^{-11} to 10^{-10} G and correlation length of order 1 Mpc. Such fields could be primordial, in which case they would likely permeate all intergalactic space. However, this need not be the case. For example, such fields could be generated from a much weaker primordial field, $\sim 10^{-20}$ G, due to the turbulence induced in the formation of large-scale structure in the universe (Kulsrud et al. 1996). In this picture, the IGMF would "trace the mass," with high 10^{-11} to 10^{-10} G fields in the high-density (protogalactic) regions of the large-scale structure and very low fields in the intervening voids.

Most of the energy lost by the CRs as they propagate and interact with the microwave background is transformed by cascading into secondary GeV–TeV photons (e.g., Aharonian, Coppi, & Völk 1994; Protheroe & Johnson 1996). In this Letter we show that, even though the CR time delay must be $\gtrsim 50$ yr, a significant fraction of the GeV–TeV cascade radiation can arrive with much shorter delays, on the order of hours to days, provided that a large fraction of the intergalactic space is occupied by magnetic "voids," regions of very low magnetic field ($<10^{-15}$ G). In § 2 we present a qualitative discussion of the development of electromagnetic cascades in the presence of an IGMF. In § 3 the expected high-energy photon flux is calculated using detailed Monte Carlo simulations. Implications for current and future high-energy gamma-ray experiments are discussed in § 4.

2. ELECTROMAGNETIC CASCADES AND THE INTERGALACTIC MAGNETIC FIELD

As they propagate, nucleons with energy in excess of 10^{20} eV lose energy due to the photoproduction of pions in interactions with microwave background photons. Pion decay converts $\sim 40\%$ of the energy lost by nucleons to neutrinos, and the rest to photons, electrons, and positrons. The energetic, $\sim 10^{19}$ eV, secondary photons, electrons, and positrons further interact with the microwave background to form electromagnetic cascades: high-energy photons interact with background photons and produce electron-positron pairs, which, in turn, lose their energy by inverse Compton scattering of background photons. The mean energy of the secondary photons is degraded until it drops below the threshold for pair production, $\sim 10^{14}$ eV for interaction with microwave photons. The development of an electromagnetic cascade, typically over a ~ 10 Mpc distance, converts most of the secondary particles energy to $\sim$TeV photons. The distance out to which greater than TeV cascade photons may be observed is limited since they may further interact with infrared background photons. Current limits on the infrared background radiation energy density constrain the mean free path for pair production on infrared photons to lie in the range ~ 0.6–2 Gpc for 1 TeV photons and ~ 20–200 Mpc for 10–100 TeV photons (Stecker, DeJager, & Salamon 1992).

We now estimate the arrival-time delays of cascade photons resulting from deflections by the IGMF, of the protons initiating the cascades, and of the pairs produced during the cascades. We consider the propagation of protons and secondary particles through an IGMF, where a fraction η of intergalactic space is occupied by structures of typical size λ and coherent magnetic field B, and where the rest of space is filled with a much weaker field.

First, consider the deflection of a proton with energy E_p. After traveling a distance d through the IGMF, the proton accumulates a typical deflection angle $\theta_p \sim (\eta d/\lambda)^{1/2}\lambda/R_{\rm L}$, where $R_{\rm L} = E_p/eB$ is the Larmor radius. This deflection results in a time delay

$$\tau \sim \frac{\theta_p^2 d}{2c} \approx \frac{2}{3}\left(\frac{eB}{E_p}d\right)^2 \frac{\lambda\eta}{2c} \simeq 60\left(\frac{B_{-11}}{E_{p,20}}d_{100}\right)^2 \eta_{0.2}\lambda_3 \text{ yr}, \tag{1}$$

where $E_p = 10^{20}\,E_{p,20}$ eV, $d = 100 d_{100}$ Mpc, $\eta = 0.2\eta_{0.2}$, $B = 10^{-11}B_{-11}$ G, and $\lambda = 3\lambda_3$ Mpc (the 2/3 factor is due to random field orientations). For IGMF parameters that might be expected in models where galactic fields result from the compression of an IGMF produced by turbulence induced in the formation of large-scale structure, $\eta \sim 0.2$, $\lambda \sim 1$ Mpc and $B \sim 4 \times 10^{-11}$ G, the time delay accumulated by CR protons propagating ~ 100 Mpc distance is large enough to reconcile the observed CR event rate with the rate of nearby GRBs (τ depends sensitively on E_p, so that the stochastic proton energy loss via pion production results in a broadening of the CR pulse over a time comparable to τ). The time delay for cascade photons may be much shorter than the CR delay, since the protons lose a significant fraction of their energy over a distance much shorter than the ~ 100 Mpc distance over which they accumulate their total time delay. Protons of initial energy greater than 2×10^{20} eV lose 10% of their energy and therefore initiate electromagnetic cascades carrying $\sim 10\%$ of the total cascade radiation energy, over a distance $d_{\rm init} \sim 1$ Mpc. If the secondary photons and subsequent cascade particles produced in these cascades were to propagate rectilinearly to the observer, the time delay of the resulting cascade photons would be $\leq d_{\rm init}^3/6R_{\rm L}^2 c \sim 0.2B_{-11}^2$ days if the burst went off in a high-field region, or much shorter if the burst happened to go off in a region of low field. If bursts occur inside galaxies, regions of potentially much higher field (microgauss on a kiloparsec scale), the initial time delay accumulated by 3×10^{20} eV protons as they traverse and leave the host galaxy is only ~ 1 day.

The pairs produced in a cascade are also subject to deflection by the IGMF, and this can lead to much larger photon arrival-time delays. The Compton energy-loss distance for pairs of energy $E_e = 10^{18}$ and 10^{15} eV (corresponding to the high- and low-energy ends of the cascade) is $\Lambda_{\rm IC} \simeq 1$, 0.01 Mpc. If these pairs were created in a high-field region, their deflection by the magnetic field, $\theta_e \sim eB\Lambda_{\rm IC}/E_e$, would delay subsequent cascade photons by $\sim 10^3$ and $10^5 B_{-11}^2$ yr, respectively. Thus, the only photons arriving with reasonably short time delays are those produced by branches of the cascades where pairs were produced in IGMF voids. (A minimum delay shorter than a day requires a "void" field less than 10^{-15} G.) The following characteristics of an electromagnetic cascade's development ensure that a significant fraction of the cascade photons are produced by such branches, provided that a large fraction of the intergalactic space is occupied by large-scale, ~ 5 Mpc, voids. The distance over which CR protons decelerate, ~ 10 Mpc, and the mean free paths of photons at the high-energy (10^{18}–10^{19} eV) part of the cascade, ~ 1 Mpc, are comparable to, or larger than, the typical size of the high-field regions. This ensures that a significant fraction of the cascades are initiated inside voids, and also implies that, at the high-energy end of a cascade, a particular cascade branch can "skip" over high-field regions without accumulating time delay. The short mean free paths of particles at the low-energy part of the cascade, $\Lambda_{\rm IC} < 0.1$ Mpc for $E_e < 10^{17}$ eV, then imply that the development of a branch, whose $\sim 10^{17}$ eV particles are created in a void region, is likely to be completed in this region.

3. NUMERICAL RESULTS

We now present numerical results for the flux of delayed cascade photons expected in an IGMF where a large fraction

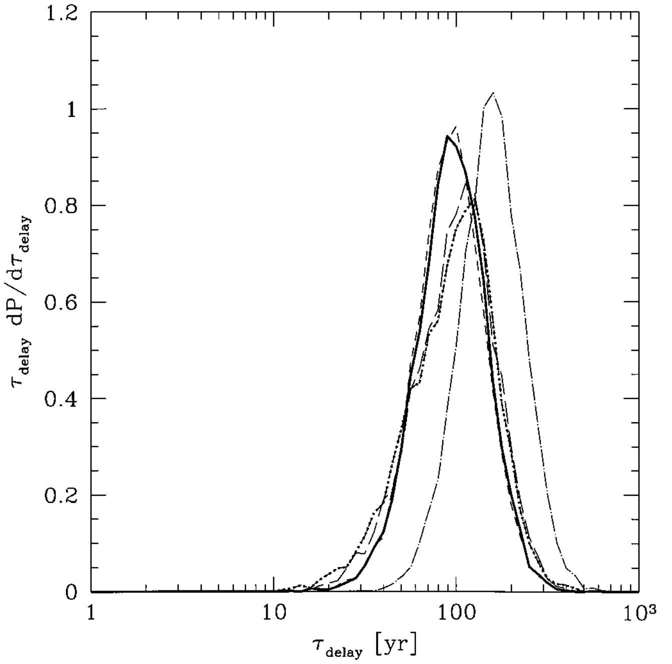

FIG. 1.—The distribution of arrival-time delays of greater than 10^{20} eV protons produced by a burst at a distance of 100 Mpc, for various IGMF structures where a fraction ~0.2 of the intergalactic space is occupied by ~1 Mpc regions of a coherent 4×10^{-11} G field.

of intergalactic space is occupied by large-scale voids, and the field strength in the high-field regions is high enough to produce a ~100 yr delay in the CR arrival time. We constructed a Monte Carlo code that propagates high-energy nucleons through the microwave background and calculates the evolution of the cascades they initiate. All the relevant particle interaction processes are included, and the gyration of charged particles about the IGMF is explicitly calculated. Since we are only interested in source distances of order 200 Mpc, cosmological evolution effects were not included. The cosmic background radiation field was chosen to be a superposition of (1) a blackbody of temperature 2.7 K; (2) an infrared/optical power-law distribution at energies $\epsilon > 0.02$ eV with density $n(\epsilon) = 8 \times 10^{-4}$ $(\epsilon/\mathrm{eV})^{-2}$ cm^{-3} eV^{-1}, corresponding to the lower bound of current estimates of the intensity; and (3) a truncated power-law distribution at radio energies with density $n(\epsilon) = 3.5 \times 10^{-7}$ $(\epsilon/\mathrm{eV})^{-1.75}$ $\exp(-\epsilon/10^{-5}\ \mathrm{eV})$ cm^{-3} eV^{-1} (e.g., Sironi et al. 1990). Our results depend only weakly on the radio background intensity, since the cascades are initiated by particles with energies $\lesssim 10^{19}$ eV, for which interaction with the radio background is only marginally important. The infrared/optical radiation does not influence significantly the less than 10 TeV flux but may strongly affect the flux at higher energies. This is further addressed below.

We generated several IGMF structures by sampling the sizes of high-field (low-field) regions along the line of sight from exponential size distribution with mean 2 Mpc (10 Mpc). The field in each region was randomly oriented with magnitude $B = 4 \times 10^{-11}$ G in the high-field regions and 10^{-20} G in the "void" regions (the "void" field can be as high as $\sim 10^{-16}$ G without significantly affecting the results shown). The resulting distributions for $\geq 10^{20}$ eV CR arrival-time delays are shown in Figure 1 for five different realizations of the IGMF.

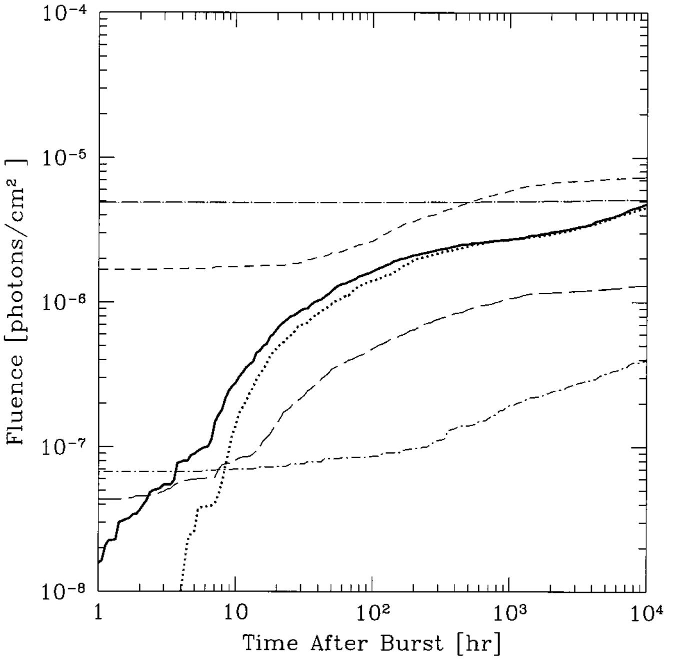

FIG. 2.—The fluence of greater than 1 TeV secondary photons, following a GRB producing 10^{51} ergs as greater than 10^{20} eV protons at a distance of 100 Mpc. The IGMF structures are the same as those used in Fig. 1, and similar line styles correspond to the same field structure in both figures. The heavy dotted line gives the fluence obtained when a 1 μG host galaxy magnetic field is added to the field structure corresponding to the heavy solid line.

The source was chosen to be at a distance of 100 Mpc and assumed to produce a power-law proton spectrum $dN/dE \propto E^{-2}$ in the range 10^{20}–10^{21} eV. The corresponding photon fluences above 1 TeV are shown in Figure 2. The fluence is normalized for a burst producing 10^{51} ergs in greater than 10^{20} eV protons, as would be required to account for the observed CR flux. The cascade radiation spectrum is determined by the development of the low-energy end of the cascade and is therefore independent of the proton production spectrum. For the short time delays of interest here, the low-energy development of the relevant cascade branches always occurs in void regions. Thus, the spectrum is similar to that obtained in the absence of an IGMF and is time independent. The integral photon number flux (above energy E) is approximately given by $I(>E) \propto E^{-0.8}$ for 3 GeV $< E <$ 200 GeV, $I(>E) \propto E^{-1.0}$ for 200 GeV $< E <$ 10 TeV, and $I(>E) \propto E^{-1.4}$ for 10 TeV $< E <$ 70 TeV.

The spread in the typical CR time delay obtained for different field structure realizations is small, since this delay is accumulated over a 100 Mpc propagation. The spread in the photon fluence obtained on a timescale of days is larger, since it is determined by the IGMF structure near the source, at distances ≤ 20 Mpc, where the development of most of the relevant electromagnetic cascades take place: the highest fluence was obtained for a case where the first 20 Mpc were free of high-field regions, and the lowest for a case where 50% of the first 20 Mpc were occupied by two ~5 Mpc high-field regions. This reflects the results of a large set of Monte Carlo calculations, which show that, for $B \sim 4 \times 10^{-11}$ G and void region sizes in the range 5–10 Mpc, the fluence increases from $\sim 10^{-7}$ cm^{-2} to $\sim 10^{-6}$ cm^{-2} as the fraction of the volume occupied by high-field regions within 20 Mpc from the source decreases from 0.4 to 0.2. The presence of a host galaxy near the burst is expected to introduce a minimum delay of order 1 day in the cascade photon arrival times and is not expected to significantly affect the fluence on longer timescales. This is demonstrated in Figure 2 by the two Monte Carlo calculations, shown with the heavy lines, one of which includes a 1 μG magnetic field over the first 1 kpc propagation distance to simulate the effect of a host galaxy magnetic field. It should be noted that the host galaxy delay can be considerably shorter if the burst produces a significant amount of energy in protons with energies $\gtrsim 10^{21}$ eV, for which a host galaxy would introduce only a $\sim$1 hr delay.

Photons arriving with $\lesssim$1 day delay are produced by cascades initiated by pions created over the first 10 Mpc propagation distance of the protons. Most of these pions are produced by protons with energy $\geq 2 \times 10^{20}$ eV, which lose $\sim$1/2 their energy over this distance. The typical greater than 1 TeV fluence obtained on a day timescale, $\sim 10^{-6}$ cm^{-2} ($\sim 10^{-5}$ ergs cm^{-2}), corresponds to $\sim$2% of the energy produced by the burst as $\geq 2 \times 10^{20}$ eV protons.

4. CONCLUSIONS

Although a scenario in which CRs above 10^{20} eV are produced by cosmological GRBs requires the arrival time of CRs to be delayed with respect to the gamma-rays by more than $\sim$50 yr, we have shown that the delay of secondary, 0.01–100 TeV cascade photons may be much smaller. A short delay is possible, provided that a large fraction of the intergalactic medium is occupied by large-scale magnetic "voids," regions of a size $\gtrsim$5 Mpc and a field weaker than 10^{-15} G. For a field strength of $\sim 4 \times 10^{-11}$ G in the high-field intergalactic regions, which would account for the observed galactic fields if it were frozen in the protogalactic plasma, the delay of CRs produced by a burst at a distance of 100 Mpc is $\sim$100 yr. At the same time, the fluence of secondary, greater than 1 TeV photons on a 1 day timescale would be $\sim 10^{-6}$ cm^{-2}, provided that $\sim$80% of the 20 Mpc region around the source is occupied by magnetic "voids." (The fluence is inversely proportional to the burst distance squared, since the photon time delay is independent of the burst distance.) The integral photon number flux in the energy range 10 GeV $< E <$ 10 TeV is approximately $I(>E) \propto E^{-1.0}$. The flux at higher energies is very sensitive to the infrared background intensity. If the intensity is near the lower bound of current estimates, the flux extends beyond 10 TeV, approximately as $I(>E) \propto E^{-1.4}$. If the intensity is close to its current upper bound, it would completely suppress the greater than 10 TeV flux from distances $\geq$100 Mpc.

A 3 σ detection of $\geq$1 TeV photons by current high-energy gamma-ray experiments requires a fluence $\sim 10^{-6}$ cm^{-2} $(t_{\rm day})^{1/2}$ $E^{-1}_{\rm min,\,TeV}$, where $t_{\rm day}$ is the observation time measured in days and $E_{\rm min,\,TeV}$ is the detector threshold energy in TeV (see Alexandreas et al. 1991 for CYGNUS, Funk et al. 1996 for HEGRA, McKay et al. 1993 for CASA-MIA, and Cawley & Weeks 1996 for Whipple). This fluence is close to that expected from a burst at a distance of $\sim$100 Mpc. However, in a cosmological model, the rate at which GRBs occur in a 100 Mpc sphere around us is low, $\sim$0.1 yr^{-1}. A factor of 10 increase in the sensitivity of TeV detectors, as expected, for example, in the near future in the Whipple and HEGRA observatories, would allow the detection of the delayed flux from bursts occurring at distances up to $\sim$300 Mpc. The rate of such bursts is $\sim$2 yr^{-1}.

Lower threshold energy, space-based detectors such as EGRET may also detect the delayed flux. At 10 GeV, EGRET has an effective area of $\sim 10^3$ cm^2. Thus, for the greater than 10 GeV fluence expected from a burst at a 100 Mpc distance, $\sim 10^{-4}$ cm^{-2} in one day, the probability that EGRET detects a greater than 10 GeV photon is $\sim$0.1. This probability, although not negligible, is small. Therefore, detection of the delayed flux would probably require next-generation GeV instruments, such as GLAST (Bloom 1996), that are expected to have order-of-magnitude better sensitivity. (It should be noted, however, that EGRET has detected an 18 GeV photon from the direction of one of the strongest BATSE bursts [second in fluence], with $\sim$1.5 hr delay [Hurley et al. 1994]).

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REFERENCES

Aharonian, F. A., Coppi, P. S., & Völk, H. J. 1994, ApJ, 423, L5
Alexandreas, D. E., et al. 1991, ApJ, 383, L53
Bird, D. J., et al. 1994, ApJ, 424, 491
Bloom, E. D. 1996, Space Sci. Rev., submitted
Cawley, M. F., & Weeks, T. C. 1996, Exp. Astron., in press
Cohen, E., & Piran, T. 1995, ApJ, 444, L25
Cronin, J. W. 1992, Nucl. Phys. B, 28B, 213
Fishman, G. J., & Meegan, C. A. 1995, ARA&A, 33, 415
Funk, B., et al. 1996, in Proc. Third Huntsville Symposium on Gamma-Ray Bursts, ed. C. Kouveliotou et al. (New York: AIP), in press
Hurley, K., et al. 1994, Nature, 372, 652
Kronberg, P. P. 1994, Rep. Prog. Phys., 57, 325
Kulsrud, R., Cowley, S., Gruzinov, A., & Sudan, R., 1996, Phys. Rep., in press
Kulsrud, R. M., & Anderson, S. W. 1992, ApJ, 396, 606
Lee, S., Olinto, A. V., & Sigl, G. 1995, ApJ, 455, L21
McKay, T. A., et al. 1993, ApJ, 417, 742
Mészáros, P. 1996, in Ann. NY Acad. Sci., Proc. 17th Texas Conf. Relativistic Astrophysics, in press
Milgrom, M., & Usov, V. 1995, ApJ, 449, L37
Plaga, R. 1995, Nature, 374, 430
Protheroe, R. J., & Johnson, P. A. 1996, Astropart. Phys., in press
Sironi, G., et al. 1990, ApJ, 357, 301
Stecker, F. W., DeJager, O. C., & Salamon, M. H. 1992, ApJ, 390, 49
Vietri, M. 1995, ApJ, 453, 883
Waxman, E. 1995a, Phys. Rev. Lett., 75, 386
———. 1995b, ApJ, 452, L1
Yoshida, S., et al. 1995, Astropart. Phys., 3, 151