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CUTOFF IN THE TeV ENERGY SPECTRUM OF MARKARIAN 421 DURING STRONG FLARES IN 2001

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ABSTRACT

Exceptionally strong and long-lasting flaring activity of the blazar Mrk 421 occurred between 2001 January and March. Based on the excellent signal-to-noise ratio of the data, we derive the energy spectrum between 260 GeV and 17 TeV with unprecedented statistical precision. The spectrum is not well described by a simple power law even with a curvature term. Instead, the data can be described by a power law with exponential cutoff: $dN/dE \propto E^{-2.14\pm0.03_{\rm stat}}e^{-E/E_0}$ m^{-2} s^{-1} TeV^{-1} with $E_0 = 4.3 \pm 0.3_{\rm stat}$ TeV. Mrk 421 is the second γ-ray blazar that unambiguously exhibits an absorption-like feature in its spectral energy distribution at 3–6 TeV.
Subject headings: BL Lacertae objects: individual (Markarian 421) — gamma rays: observations

1. INTRODUCTION

Since the discovery of TeV γ-rays from BL Lac objects Mrk 421 (Punch et al. 1992) and Mrk 501 (Quinn et al. 1996), detailed very high energy observations of these nearby blazars ($z = 0.031$, $z = 0.034$) have been made. Measurements of flux variation with time, particularly simultaneous measurements at several wavelengths, constrain models of particle acceleration and γ-ray production in the jets. Spectral energy density measurements constrain both the models of the jets and of the infrared photon density in the intervening intergalactic medium. The possibility of absorption of γ-rays by IR radiation has been predicted for some time (Nikishov 1962; Gould & Schrèder 1967; Stecker, De Jager, & Salamon 1992), and implications of recent observations have been discussed (see, e.g., Biller et al. 1998; Stanev & Franceschini 1998; Vassiliev 1999).

The general picture that has emerged for the spectral energy density of emitted radiation from BL Lac objects has two components: a lower one with energies extended up to about 100 keV attributed to synchrotron radiation from electrons and a higher one with energies sometimes extending to the TeV range, usually attributed to inverse Compton (IC) scattering (see, e.g., Maraschi, Ghisellini, & Celotti 1992; Marscher & Travis 1996). There are also competing models (Mannheim & Biermann 1992; Mannheim 1993, 1998) that assume that the higher energy component arises from protons, either by proton-induced synchrotron cascades or by decays and/or interactions of secondary particles such as neutral pions and neutrons, or synchrotron radiation from proton beams (Mücke & Protheroe 2001; Aharonian 2000). See Catanese & Weekes (1999) and Mukherjee et al. (2001) for reviews of TeV observations and relevant models.

Mrk 421 and Mrk 501 are particularly useful in separating the spectral characteristics intrinsic to the object from absorption effects in the intervening medium because they have almost the same redshift. They also exhibit strong flares in the TeV energy regime, well above typical quiescent levels, making detailed spectral measurements possible for both (Gaidos et al. 1996; Catanese et al. 1997; Protheroe et al. 1997; Aharonian et al. 1997).

Measurements by various TeV astronomy groups have shown that the energy spectrum of Mrk 501 has significant curvature (Samuelson et al. 1998; Aharonian et al. 1999a, 2001; Djannati-Ataï et al. 1999). The two-component nature of the multiwavelength picture of blazars implies that, over a sufficiently wide energy range, TeV spectra must be intrinsically curved. The measured curvature, however, depends on the distance of the energy range of the data from the IC peak. During the strong flaring activity, the synchrotron peak of Mrk 501 appears to shift to above 100 keV (Catanese et al. 1997; Pian et al. 1998), with the IC peak shifting to several hundred GeV (Samuelson et al. 1998). Measurements of the High-Energy Gamma-Ray Astronomy (HEGRA) collaboration have the highest energies extending to ≈20 TeV; their spectrum is fitted with an exponential cutoff at ≈6–8 TeV (Aharonian et al. 1999a, 2001).

Several groups have determined energy spectra for Mrk 421, both at low average flux levels (<1 crab; flux levels are given in units of the Crab Nebula flux; Aharonian et al. 1999b; Kraw-

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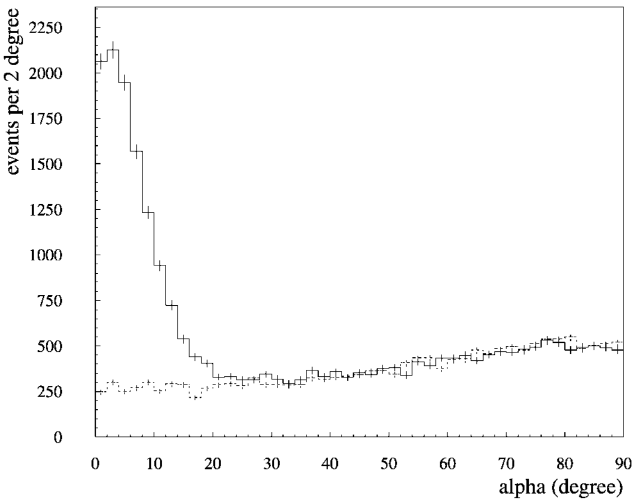

FIG. 1.—Alpha distribution for on-source events (above ≈1 TeV) shown by the solid line and background events (off-source, *dashed line*) for the 30.8 hr of observations of flaring states of Mrk 421. The orientation angle alpha is defined as the angle between the major axis of an elliptical γ-ray image and the source position.

czynski et al. 2001; Bazer-Bachi et al. 2001) and from intense flares (2.8–7.4 crab at 350 GeV; Zweerink et al. 1997; Krennrich et al. 1999a). Analysis of the intense flare data showed that Mrk 421 had a spectral index different (softer) from Mrk 501. The data could be acceptably fitted with a simple power law, although there was weak evidence for curvature (Krennrich et al. 1999a). The fact that the energy spectra of Mrk 421 and Mrk 501 were found to be different was attributed to different intrinsic source spectra, and an interpretation in the framework of a multiwavelength picture was given. The shape of the spectral energy distribution for Mrk 421 (Aharonian et al. 1999b; Krennrich et al. 1999b) and Mrk 501 generally appears independent of the flux level (Aharonian et al. 1999a), although some evidence for spectral variability has been reported by Djannati-Ataï et al. (1999) and Krawczynski et al. (2001) for Mrk 501.

In this Letter, we present results from γ-ray observations of Mrk 421 taken during intense flares in 2001 January–March with the Whipple Observatory 10 m telescope, yielding an energy spectrum between 260 GeV and 17 TeV. The spectrum has high statistical precision and shows a cutoff with a characteristic energy of about 3–6 TeV.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were made with the Whipple Observatory 10 m γ-ray telescope equipped with the GRANITE-III high-resolution camera (J. Finley et al. 2001, in preparation). The fine granularity (0°.12) of the 379 photomultiplier tube (PMT) camera provides good sensitivity for point sources. The sensitive energy range of the instrument is ≈200 GeV to greater than 20 TeV. Based on finer sampling of γ-ray images, the linear response of the telescope at the highest energies is improved in comparison with previous camera configurations.

The use of a different type of PMT, a complete recoating of the mirrors, and the installation of new light concentrators (J. Finley et al. 2001, in preparation) necessitated a comprehensive new calibration of the telescope. Three methods were used: the first was based on laboratory measurements of the individual instrument components, the second utilized the calibrated Cerenkov light signal from single secondary cosmic-ray muons, and the third used simulated cosmic-ray showers to match observed distributions of the parameters of the background images. The first method provides a direct calibration for which uncertainties (≈10%) arise from the limitations of reflectivity, quantum efficiency, and gain measurements and associated variations in a large quantity of pixels. The linearity of the system has been verified over the full range of the analog-to-digital converters.

Method 3 is also sensitive to the atmospheric transmission of light and, therefore, is complementary to method 1. Method 3 relies on modeling of hadronic cosmic-ray interactions of protons and heavier elements. By deriving a cosmic-ray spectrum on a nightly basis (at zenith), we also measure the relative atmospheric transparency changes convoluted with instrumental drifts (throughput factor). The data selected in this analysis show variations in the throughput factor of less than 10%. All three methods provide an energy calibration consistent within 20% for the absolute energy of primary γ-rays. The effect of a 20% shift in the throughput factor translates into a 20% shift in the reconstructed γ-ray energy over the range of 200 GeV to 20 TeV. The effect of a 20% throughput variation is included in the estimate of systematic uncertainty of the flux constant and the cutoff energy of the spectra presented.

The calibration can be evaluated by checking the energy spectrum of the Crab Nebula, which is a standard candle for TeV γ-ray astronomy. The measurements of the spectrum of the Crab Nebula with the Whipple telescope over several years of data using different camera configurations are all statistically consistent, showing the same flux constant and energy spectral index. Therefore, we also show the Crab spectrum in this Letter for comparison with the Mrk 421 spectrum. The Crab data consist of 15.4 hr of on-source observations (zenith angle $<35°$) with the same amount of data for the background estimate.

Mrk 421 was more active in 2000 and 2001 than in previous years of observations, with the most intense flaring episodes in 2001. The unusually high flaring states in 2001 provide remarkable statistics, and we have chosen the strongest flares for the analysis of the spectral energy distribution. Observations of flaring states on 2001 January 21 and 31, February 1, 2, 3, and 27, and March 19, 21, 26, and 27 provide together ≈23,000 photons above 260 GeV. To test the validity of combining various flares, we have also divided the data into two subsets and found no statistical inconsistency in the derived energy spectral indices.

The selected 2001 flaring data consist of 30.8 hr of on-source observations at zenith angles less than 35°. For background comparison, off-source data are used from observations made at similar zenith angles. The data exhibit an average rate of 12.5γ minute^{-1}, corresponding to 3.7 crab (at ≈500 GeV, using extended supercuts). The excellent signal-to-background ratio can be seen from Figure 1. This plot shows the alpha distribution (alpha is the orientation angle between the major axis of an elliptical γ-ray image and the source position; also see Reynolds et al. 1993) of events with energies greater than ≈1 TeV from the source (*solid line*) after applying γ-ray selection criteria. The dotted line shows the corresponding distribution for the background measurements.

The data analysis, γ-ray selection and energy estimate use the methods developed by Mohanty et al. (1998). These γ-ray selection criteria are derived from parameter distributions of simulated γ-ray showers as a function of their total light intensity (size) in the camera. The criteria (extended supercuts) vary with size and are set so that they keep 90% of the γ-ray images whose centroids lie within 0°.4–1°.0 of the center of the camera. The distributions of simulated γ-ray events are compared with data to verify the selection efficiencies of cuts. To avoid the difficulties of modeling the trigger electronics, we apply an additional cut, requiring that a signal of at least 15.1, 13.6, and 12.1 photoelectrons be present in the three highest image pixels, respectively.

3. RESULTS

The differential energy flux values derived from the intense flaring states of Mrk 421 in 2001, and for comparison the Crab Nebula, are shown in Figure 2. The spectrum of the Crab Nebula can be well fitted by a power law of the form

$$\frac{dN}{dE} = (3.11 \pm 0.30_{\rm stat} \pm 0.62_{\rm syst}) \times 10^{-7} E^{-2.74 \pm 0.08_{\rm stat} \pm 0.05_{\rm syst}}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}},$$

giving a χ^2 of 6.9 for 10 degrees of freedom ($P = 73\%$). This result is consistent, within its limited statistics, with previous measurements made by the Whipple collaboration (Hillas et al. 1998; Mohanty et al. 1998; Krennrich et al. 1999a), showing that the analysis methods, the calibration of the detector, and the reconstruction of energy spectra are all consistent at the 2 σ level, including systematic uncertainties. The first set of errors on the measured spectral index are statistical and the second are systematic. The systematic errors on flux constant and spectral index are determined by varying the assumed gain of the system by 20% and varying the γ-ray selection efficiency for extended supercuts.

Fitting a power law to the energy distribution of Mrk 421 yields the following result:

$$\frac{dN}{dE} \propto E^{-2.64 \pm 0.01_{\rm stat} \pm 0.05_{\rm syst}}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}},$$

giving a χ^2 of 410.7 for 10 degrees of freedom. The spectrum is clearly not compatible with a simple power-law form. The systematic uncertainties (Fig. 2, *shaded area*) have been derived from varying the selection efficiency of extended supercuts, raising the software trigger cut, using various methods for off-source background matching, and accounting for the pointing accuracy of the telescope. A curvature fit for the Mrk 421 spectrum yields

$$\frac{dN}{dE} \propto E^{-2.47 \pm 0.02_{\rm stat} \pm 0.05_{\rm syst} - (0.51 \pm 0.03_{\rm stat} \pm 0.05_{\rm syst}) \log E}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}},$$

giving a $\chi^2 = 56.5$ for 9 degrees of freedom with a chance probability of 6×10^{-9}. As shown in Figure 2, the Mrk 421 spectrum exhibits clear curvature, but a parabola is not a suitable shape. Assuming that the curvature in the spectrum is due to a cutoff, the data are fitted by

$$\frac{dN}{dE} \propto E^{-2.14 \pm 0.03_{\rm stat} \pm 0.10_{\rm syst}} e^{-E/E_0}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}},$$

with $E_0 = 4.3 \pm 0.3_{\rm stat}(-1.4 + 1.7)_{\rm syst}$ TeV.

While the χ^2 (25.2 for 9 degrees of freedom, $P = 0.3\%$) is not good, the fit using an exponential cutoff is much better than the fits using the two simple forms considered above. It should be noted that a parametrization by a power law times an exponential is a simplification of the convolution of an intrinsic source spectrum with γ-ray absorption models, and more realistic parameterizations will be presented elsewhere (V. V. Vassiliev et al. 2001, in preparation).

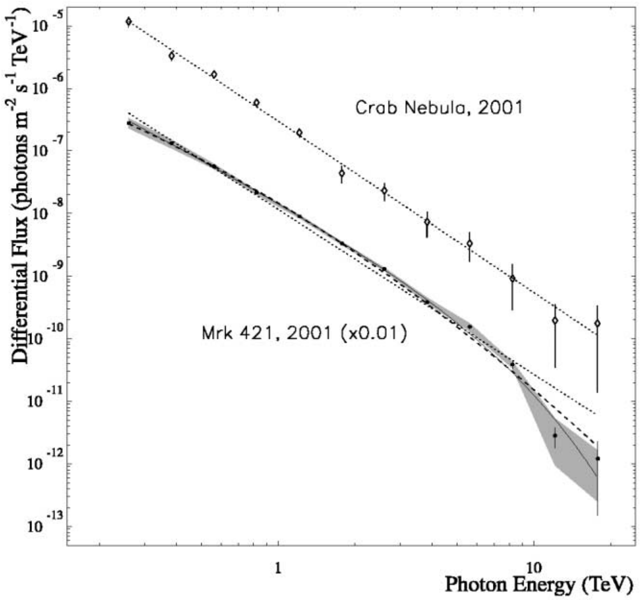

FIG. 2.—Energy spectra of Mrk 421 (*filled circles*) and the Crab Nebula (*diamonds*) for the 2001 data set. The dotted lines correspond to power-law fits, the dashed line (Mrk 421) corresponds to a parabolic fit, and the solid line is the result from a fit with an exponential cutoff. Note that the Mrk 421 spectrum has been offset by a factor of 0.01 in flux for clearer presentation, and errors shown include only statistical uncertainty. The shaded area shows the systematic uncertainties except for the 20% uncertainty in absolute energy.

We should point out here that statistical errors of the flux measurements in TeV astronomy reached the level of 2%, likely making systematic uncertainties dominant. We have also examined the flux values at 5.6 and 8.2 TeV, which appear high to the eye, 2.6 $\sigma_{\rm stat}$ and 1.8 $\sigma_{\rm stat}$, respectively, above the exponential cutoff fit. Considering the statistical uncertainties, we do not regard this as a significant feature in the data. In derivation of the cutoff energy, we have included in addition to the above mentioned systematics the uncertainties in the reconstruction of the spectrum with a cutoff derived from simulation tests (test spectra) and uncertainty in absolute energy calibration of the instrument (20%).

We also tried a "superexponential" form (e.g., see Stecker, De Jager & Salamon 1992; Aharonian et al. 2001) but with no improvement in quality of fit. The result is

$$\frac{dN}{dE} \propto E^{-2.24 \pm 0.09_{\rm stat}} e^{-(E/E_0)^{1.3 \pm 0.4}}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}},$$

with $E_0 = 5.8 \pm 1.5_{\rm stat}$ TeV. The χ^2 of the fit is 24.0 for 8 degrees of freedom ($P = 0.2\%$).

4. DISCUSSION

For the first time, the Mrk 421 energy spectrum at very high energy has been determined over a sufficiently wide energy range, and with sufficient statistical precision, that an important feature (a cutoff) could be discerned. The spectrum is best

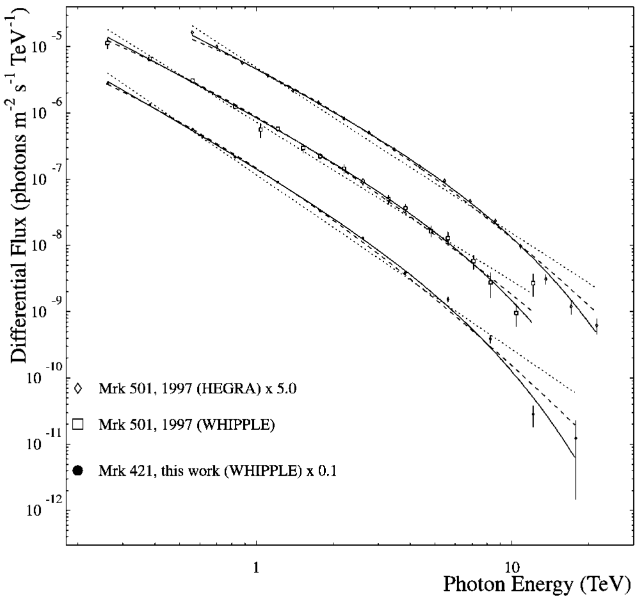

FIG. 3.—Comparison of the Mrk 501 spectra published by the Whipple (Samuelson et al. 1998) and the HEGRA collaborations (Aharonian et al. 1999a) and the Mrk 421 spectrum (this work). The dotted lines indicate power-law fits, the dashed lines are parabolic fits, and the solid lines show the power-law plus exponential cutoff fits. A common feature to all three spectra is a cutoff at 4–6 TeV. Also note that both the Mrk 501 spectrum (Aharonian et al. 1999a) and the Mrk 421 spectrum reported in this Letter are not well described by a parabolic spectrum. Also note that spectra have been offset for clearer presentation.

described by a power law attenuated by an exponential cutoff at an energy of $E_0 = 4.3 \pm 0.3_{\rm stat}(-1.4 + 1.7)_{\rm syst}$ TeV.

The cutoff could have several origins, e.g., the termination of the particle energy distribution in the primary beam, the sharp fall in the Klein-Nishina scattering cross section (Hillas 1999), absorption near the γ-ray source (Dermer & Schlickeiser 1994), or absorption by the IR background. If the cutoff energy varied in time, or differed for Mrk 421 and 501, it would be due to the source and not due to extragalactic absorption. We examined our previous published flare spectrum of Mrk 421 (Krennrich et al. 1999a) and found it consistent with the new spectrum. Fitting the previous Mrk 421 spectrum with the parametrization of $dN/dE \propto E^{-2.14\pm0.03_{\rm stat}} e^{-E/4.3\ {\rm TeV}}$ m^{-2} s^{-1} TeV^{-1} results in an acceptable χ^2 of 19.4 for 13 degrees of freedom ($P = 11\%$).

We also examined our previously published spectrum for Mrk 501 (Samuelson et al. 1998) and find that its spectrum can be fitted by $dN/dE \propto E^{-1.95\pm0.07_{\rm stat}} e^{-E/E_0}$ m^{-2} s^{-1} TeV^{-1}, with $E_0 = 4.6 \pm 0.8_{\rm stat}$ TeV. However, fitting the Mrk 501 spectrum with $dN/dE \propto E^{-2.14\pm0.03_{\rm stat}} e^{-E/4.3\ {\rm TeV}}$ m^{-2} s^{-1} TeV^{-1} results in a poor fit (note that error bars in spectral index and cutoff energy are correlated) with a χ^2 of 37.6 for 13 degrees of freedom ($P = 3 \times 10^{-4}$). The cutoff for Mrk 501 is consistent with the cutoff energy for Mrk 421, but a different spectral index is required for an acceptable fit. More detailed studies of spectral variability of Mrk 421 will be presented elsewhere.

Energy spectra for Mrk 421 reported by the HEGRA collaboration (Aharonian et al. 1999b) are based on data taken in 1997/1998 with the source at a lower average flux level ($\approx$0.5 crab). The primary sensitivity of HEGRA is at energies above 1 TeV requiring a comparison above that energy. Those results indicate a power-law spectrum of $dN/dE \propto E^{-3.09\pm0.07\pm0.1}$. When the Mrk 421 spectral data presented here are fitted with a power law using data points between 1 and 5.6 TeV (the primary range of the HEGRA spectrum), a spectral index of $-2.74 \pm 0.08_{\rm stat} \pm 0.05_{\rm syst}$ with a χ^2 of 2.06 for 3 degrees of freedom ($P = 56\%$) is measured. The difference in spectral index is at the 2.3 σ level (considering statistical and systematic errors), which we do not consider significant. Further studies are necessary to establish spectral variability.

In summary, we have presented a Mrk 421 spectrum over the energy range from 260 GeV to 17 TeV that shows an exponential-like cutoff in the range 3–6 TeV, similar to the cutoff found earlier for Mrk 501 (see Fig. 3).

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REFERENCES

Aharonian, F. A. 2000, NewA, 5, 377
Aharonian, F. A., et al. 1997, A&A, 327, L5
———. 1999a, A&A, 349, 11
———. 1999b, A&A, 350, 757
———. 2001, A&A, in press
Bazer-Bachi, R., et al. 2001, in AIP Conf. Proc. 558, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian & H. J. Völk (New York: AIP), 643
Biller, S. D., et al. 1998, Phys. Rev. Lett., 80, 2992
Catanese, M., & Weekes, T. C. 1999, PASP, 111, 1193
Catanese, M., et al. 1997, ApJ, 487, L143
Dermer, C. D., & Schlickeiser, R. 1994, ApJS, 90, 945
Djannati-Ataï, A., et al. 1999, A&A, 350, 17
Gaidos, J. A., et al. 1996, Nature, 383, 319
Gould, R. J., & Schrèder, G. 1967, Phys. Rev., 155, 1408
Hillas, A. M. 1999, Astropart. Phys., 11, 27
Hillas, A. M., et al. 1998, ApJ, 503, 744
Krawczynski, H., et al. 2001, in AIP Conf. Proc. 558, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian & H. J. Völk (New York: AIP), 639
Krennrich, F., et al. 1999a, ApJ, 511, 149
———. 1999b, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 3, 301
Mannheim, K. 1993, A&A, 269, 67
Mannheim, K. 1998, Science, 279, 684
Mannheim, K., & Biermann, P. L. 1992, A&A, 253, L21
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
Marscher, A. P., & Travis, J. P. 1996, A&AS, 120, 537
Mohanty, G., et al. 1998, Astropart. Phys., 9, 15
Mücke, A., & Protheroe, R. J. 2001, Astropart. Phys., 15, 121
Mukherjee, R., et al. 2001, in AIP Conf. Proc. 558, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian & H. J. Völk (New York: AIP), 324
Nikishov, A. I. 1962, Soviet Phys.—JETP Lett., 14, 393
Pian, E., et al. 1998, ApJ, 492, L17
Protheroe, R. J., Bhat, C. L., Fleury, P., Lorenz, E., Teshima, M., & Weekes, T. C. 1998, Proc. 25th Int. Cosmic-Ray Conf. (Durban), 8, 317
Punch, M., et al. 1992, Nature, 358, 477
Quinn, J., et al. 1996, ApJ, 456, L83
Reynolds, P. T., et al. 1993, ApJ, 404, 206
Samuelson, F. W., et al. 1998, ApJ, 501, L17
Stanev, T., & Franceschini, A. 1998, ApJ, 494, L159
Stecker, F. W., De Jager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49
Vassiliev, V. V. 1999, Astropart. Phys., 12, 217
Zweerink, J., et al. 1997, ApJ, 490, L141