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A SEARCH FOR ULTRA–HIGH-ENERGY GAMMA-RAY EMISSION FROM FIVE SUPERNOVA REMNANTS

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ABSTRACT

The majority of the cosmic rays in our Galaxy with energies in the range of $\sim 10^{10}$–10^{14} eV are thought to be accelerated in supernova remnants (SNRs). Measurements of SNR gamma-ray spectra in this energy region could support or contradict this concept. The Energetic Gamma-Ray Experiment Telescope (EGRET) collaboration has reported six sources of gamma rays above 10^8 eV whose coordinates are coincident with SNRs. Five of these sources are within the field of view of the CYGNUS extensive air shower detector. A search of the CYGNUS data set reveals no evidence of gamma-ray emission at energies $\sim 10^{14}$ eV for these five SNRs. The flux upper limits from the CYGNUS data are compared to the lower energy fluxes measured with the EGRET detector using Drury, Aharonian, & Völk's recent model of gamma-ray production in the shocks of SNRs. The results suggest one or more of the following: (1) the gamma-ray spectra for these five SNRs soften by about 10^{14} eV, (2) the integral gamma-ray spectra of the SNRs are steeper than about $E^{-1.3}$, or (3) most of the gamma rays detected with the EGRET instrument for each SNR are not produced in the SNR's shock but are produced at some other site (such as a pulsar).

Subject headings: gamma rays: observations — supernovae: general

1. INTRODUCTION

The observed spectrum of all cosmic-ray nuclei from $\sim 10^{10}$ to 3×10^{18} eV is fairly well described by a broken power law (e.g., Hillas 1984). Below about 5×10^{15} eV, the integral spectrum $\propto E^{-1.7}$. At approximately 5×10^{15} eV (the "knee"), the integral spectral index changes abruptly from 1.7 to 2. Thereafter, the flux continues to about 3×10^{18} eV with the same spectral index.

The spectrum produced at the sites of cosmic-ray acceleration is believed to be somewhat harder than the observed spectrum. Due to an energy-dependent mean escape time from the Galaxy, the observed spectrum is thought to include a contribution $\propto E^{-\alpha}$, where α is estimated to be in the range from ~ 0.3 (e.g., Biermann 1993) to 0.6 (e.g., Swordy et al. 1990). Therefore, cosmic-ray accelerators should produce an integral spectrum below the knee $\propto E^{-\beta}$, where β is in the range from ~ 1.1 to 1.4.

Since the all-particle cosmic-ray flux produced at the sites of cosmic-ray acceleration is thought to have a nearly uniform power-law spectrum below the knee, a single production mechanism for cosmic rays in this energy range is appealing. Furthermore, the range of values for the integral spectral index β is consistent with the predicted indices for cosmic rays accelerated in SNRs by diffusive shock acceleration (e.g., Blandford & Eichler 1987, § 4.4). These two arguments and others lead to the hypothesis that Galactic cosmic rays with energies below the knee are accelerated predominantly in SNRs.

This hypothesis remains the subject of debate, in part because of different estimates of the maximum cosmic-ray energy produced in SNRs. While a typical estimate of the maximum cosmic-ray energy per unit charge is roughly 10^{14} eV (e.g., Lagage & Cesarsky 1983), Völk & Biermann (1988) suggest that expansion of a SNR into a stellar wind cavity could readily produce cosmic rays with energies $\geq 10^{15}$ eV. Furthermore, Jokipii (1987) mentions that the maximum cosmic-ray energy could be substantially increased if a SNR expands into a uniform magnetic field. Because of the large discrepancies in these estimates, experimental clarification is needed.

Direct measurements of the cosmic-ray spectrum from a SNR are not possible because interstellar magnetic fields deflect charged particles over distances that are typically much shorter than the distances to SNRs. For instance, a cosmic-ray nucleus of charge Z spirals with a gyroradius $r = 1.08 E_{15}/ZB_{-6}$ pc, where E_{15} is the cosmic-ray's energy in units of 10^{15} eV and B_{-6} is the magnetic field component normal to the cosmic-ray's direction of motion in units of 10^{-6} G. Therefore, cosmic rays with energies below the knee have gyroradii $\lesssim 10$ pc. Since most SNRs are more than 1 kpc from Earth, the incident directions of the cosmic rays accelerated in SNRs will not point to the sites of the SNRs.

On the other hand, stable neutral particles, such as gamma rays, do point to their production sites. If interactions of cosmic rays accelerated in a SNR with other nuclei in the SNR produce a sufficiently large flux of high-energy gamma rays, gamma-ray observations could reveal the nature of cosmic-ray acceleration in SNRs.

The gamma-ray flux from SNRs may be detectable with present gamma-ray experiments. The EGRET collaboration recently reported (Dingus 1994) six sources of gamma rays

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TABLE 1

CYGNUS RESULTS[a]

Supernova Remnant	$\Delta\alpha \times \Delta\delta$[b]	N_s[c]	N_b[d]	σ[e]	f_{90}[f]	E_m[g] (TeV)	$\phi_\gamma(\geq E_m)$[h] (10^{-14} cm^{-2} s^{-1})	$\phi_E(\geq 10^8$ eV)[i] (10^{-7} cm^{-2} s^{-1})
1. G34.7−0.4 (W44)	1°.9 × 1°.9	10,259	10,279	−0.2	0.0070	365	0.66 (0.69)	7.4
2. G78.2+2.1 (γ Cygni)	2°.9 × 2°.2	101,622	102,200	−1.7	0.0018	175	0.69 (0.67)	13.4
3. G89.0+4.7 (HB 21)	4°.6 × 2°.9	142,410	143,366	−2.4	0.0012	210	0.53 (1.1)	1.9
4. G189.1+3.0 (IC 443)	2°.2 × 2°.0	59,557	59,516	+0.2	0.0042	200	1.1 (1.4)	4.3
5. G205.5+0.5 (Monoceros)	4°.4 × 4°.4	95,152	95,331	−0.6	0.0021	325	1.1 (1.5)	2.2

[a] Results from the muon-poor subset of the 8.4 yr data set, unless stated otherwise. The values of E_m and ϕ_γ are computed using an ultra–high-energy gamma-ray spectrum with an integral spectral index of 1.1 and no cutoff.

[b] The size of the CYGNUS source bin (see text) in right ascension ($\Delta\alpha$) and declination ($\Delta\delta$).

[c] The total number of events in the source bin.

[d] The expected number of background events in the source bin.

[e] The significance of the excess or deficit of N_s with respect to N_b in standard deviations.

[f] The 90% confidence level upper limit on the number of source events in the source bin as a fraction of N_b.

[g] The expected median energy of detected gamma rays.

[h] The 90% confidence level upper limit on the gamma-ray flux above E_m for the muon-poor data. The value in parentheses is the flux limit for the entire data set (no muon-poor cut).

[i] The gamma-ray flux above 10^8 eV reported by the EGRET collaboration (Dingus 1994).

above 10^8 eV whose coordinates are coincident with SNRs. Predictions of the gamma-ray flux from SNRs (Drury, Aharonian, & Völk 1994, hereafter DAV) suggest that SNRs may produce detectable fluxes of ultra–high-energy gamma rays. We have searched the CYGNUS data set for evidence of ultra–high-energy gamma-ray emission from five of the SNRs reported by the EGRET group. The sixth source is outside the field of view of the detector.

2. THE CYGNUS EXPERIMENT

The CYGNUS array of extensive air shower detectors is located around the Los Alamos Meson Physics Facility beam stop in Los Alamos, NM (106°15′W, 35°52′N, 2120 m above sea level). It has been in continuous operation since 1986 April. This Letter describes the analysis of data taken with the CYGNUS-I array, which currently has 108 scintillation detectors, each 1 m^2 in area, deployed over an area of 2.2×10^4 m^2. CYGNUS-I also contains about 44 m^2 of shielded multiwire proportional counters used to measure the muon content of each extensive air shower event (Allen et al. 1992). The CYGNUS-I array has an angular resolution of 0°.66 (Alexandreas et al. 1993a; 1991) and an event rate of 3.5 s^{-1}. A detailed description of the CYGNUS experiment can be found elsewhere (Alexandreas et al. 1992).

Simulations are used to estimate the median energy, E_m, of the gamma rays initiating the air shower events detected by the CYGNUS-I array. The expected median energy for a gamma-ray source that passes directly overhead (declination = 35°.9) is 175 TeV (65 TeV) if the source's gamma-ray flux has an unbroken power-law spectrum with an integral spectral index of 1.1 (1.7).

3. DATA ANALYSIS

This Letter describes the analysis of the entire set, and a muon-poor subset, of the 4.74×10^6 CYGNUS-I events detected from 1986 April 2 to 1994 August 21. The muon-poor subset excludes events with one or more particle tracks in the multiwire proportional counters used to detect muons. Since extensive air shower events initiated by gamma rays are expected to have significantly fewer muons than events initiated by cosmic rays (e.g., Stanev, Gaisser, & Halzen 1985), the fraction of gamma-ray events excluded (<10%; Alexandreas et al. 1993b) is estimated to be much smaller than the fraction of cosmic-ray events excluded (~50%). For this analysis, the muon-poor cut improves the gamma-ray flux sensitivity by a factor of 1.3 on average.

The technique employed to search for ultra–high-energy gamma-ray emission is identical to our standard binned point-source search method (Alexandreas et al. 1993a) except for the sizes of the source bins. Because the SNRs are extended objects whose sizes (0°.5–3°.2 in diameter; e.g. Green 1988) are comparable to or larger than the angular resolution of the CYGNUS detector, the optimum sizes of the source bins are larger than the optimum size of a point-source bin for all but the smallest SNR, G34.7−0.4.

The bin sizes used in this analysis are computed as follows. Since each of the five SNRs is a shell-type SNR, most of the gamma-ray flux is believed to originate near the SNR's perimeter. Therefore, the gamma-ray flux is taken to be uniformly distributed around an elliptical ring whose right ascension and declination axes have the widths given by Jones, Smith, & Angellini (1993, Fig. 3), Higgs, Landecker, & Roger (1977, Fig. 3), Haslam et al. (1975, Fig. 2), Green (1988), and Davies et al. (1978, Fig. 8) for SNRs 1–5 of Table 1, respectively. These rings are convoluted with a two-dimensional Gaussian to incorporate the effects of the detector's angular resolution. The resulting flux distributions are used to find the sizes of the "optimum" source bins. Here, the optimum source bin is defined to be the square bin that maximizes the ratio $\epsilon/\sqrt{N_b}$, where ϵ is the fraction of the source events expected to fall in the bin and N_b is the expected number of background events in the bin. Table 1 lists the sizes of the source bins used.

Each search is performed by comparing the total number of events, N_s, whose celestial coordinates are within the predetermined source bin boundaries to the expected number of cosmic-ray background events, N_b, in the same bin. A detailed description of the technique used to estimate the number of background events can be found elsewhere (Alexandreas et al. 1993a). The statistical significance, σ, of the excess or deficit of N_s with respect to N_b, in standard deviations, is calculated using the prescription of Li & Ma (1983). These results are listed in Table 1 for the muon-poor subset of the data. None of the searches reveals evidence of ultra–high-energy gamma-ray emission. Also listed for each SNR are (1) f_{90}, the 90%

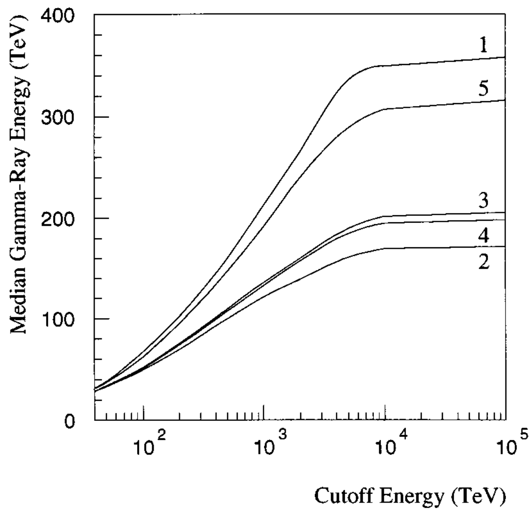

FIG. 1.—The five curves, bearing the numerical labels of Table 1, show the dependence of the expected median energy of detected gamma rays on the cutoff energy in the gamma-ray spectrum for the five SNRs.

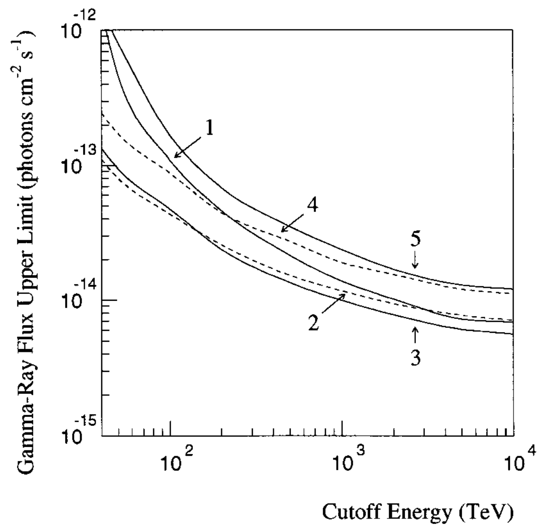

FIG. 2.—The solid (1, 3, and 5) and dashed (2 and 4) curves, bearing the numerical labels of Table 1, show the dependence of the muon-poor gamma-ray flux limits on the cutoff energy in the gamma-ray spectrum for the five SNRs.

confidence level upper limit on the number of source events in the source bin as a fraction of the corresponding value of N_b; (2) E_m, the expected median energy of detected gamma rays; and (3) ϕ_γ, the 90% confidence level upper limit on the gamma-ray flux above E_m.

The flux limits are estimated to be

$$\phi_\gamma(\geq E_m) = \frac{f_{90}\ \phi_{\rm cr}(\geq E_m)\Omega}{\mu\epsilon R_\gamma} \qquad (1)$$

(Alexandreas et al. 1993a), where $\phi_{\rm cr}$ [$=1.8 \times 10^{-5}(E/{\rm TeV})^{-1.76}$ cm^{-2} s^{-1} sr^{-1}] is the integral all-particle cosmic-ray flux above an energy E (Burnett et al. 1990; Alexandreas et al. 1993a), Ω is the solid angle of the source bin, μ is the fraction of gamma-ray events expected to satisfy the muon-poor criterion (if it is used), ϵ is the fraction of the gamma-ray source events expected to fall in the source bin, and R_γ is the ratio of the detection efficiency for gamma rays to the detection efficiency for cosmic rays. The value of μ is conservatively estimated to be 0.9 for the muon-poor analysis (Alexandreas et al. 1993b) and is 1 for the analysis of the entire data set. For these five SNRs, ϵ ranges from 0.70 (for G34.7−0.4) to 0.83 (for G205.5+0.5).

The values of E_m, R_γ, and, consequently, ϕ_γ are sensitive to the declination of the SNR and the shape of the gamma-ray spectrum. Here, SNRs are assumed to have integral gamma-ray spectra $\propto E^{-\gamma}$ for energies below some cutoff energy and to have no flux above the cutoff energy. The integral spectral index, γ, is taken to be 1.1 throughout this analysis because the gamma-ray flux limits are fairly insensitive to the value of the index for indices from 1.0 to 1.7.

Figure 1 shows the dependence of E_m on the cutoff energy for the five SNRs. The relative differences between the five curves in this figure, at a common cutoff energy, are due to the dependence of the detector's sensitivity on the declination of the source. If the gamma-ray spectra of the SNRs are not cut off, the values for R_γ range from about 1.0 to 1.2. If the gamma-ray spectra are cut off below 10^{14} eV, the values for R_γ will be smaller. Figure 2 shows the dependence of ϕ_γ on the cutoff energy for the five SNRs. Table 1 lists the values of E_m and ϕ_γ for each SNR with no cutoff in the gamma-ray spectrum.

4. DISCUSSION

None of the searches reveals evidence of ultra–high-energy gamma-ray emission from the five SNRs. A comparison of the muon-poor flux limits of Table 1 with EGRET's gamma-ray fluxes using the shape of the predicted gamma-ray spectrum (DAV) may constrain the shapes of the cosmic-ray spectra of the SNRs. The shape of DAV's gamma-ray spectrum is determined by the energy dependence of the inelastic proton-proton cross section and by the shape of the accelerated proton spectrum. DAV use a constant cross section above a center-of-momentum energy of a few GeV and consider integral proton spectra $\propto E^{-1.1}$, $E^{-1.2}$, and $E^{-1.3}$. Because the inelastic cross section increases with increasing energy, the gamma-ray spectra of the SNRs may be slightly harder than DAV's gamma-ray spectra. The spectral indices of the three proton spectra are used to label the corresponding predictions for the integral gamma-ray spectra reproduced in Figure 3. These spectra are plotted as a fraction of the predicted gamma-ray fluxes above 10^8 eV because the absolute normalizations are highly uncertain. Similarly, the CYGNUS flux limits in Figure 3 are plotted as a fraction of the corresponding EGRET gamma-ray fluxes above 10^8 eV.

Provided the shapes of DAV's gamma-ray spectra are correct, the normalized flux limits of Figure 3 exclude the three gamma-ray spectra. This result suggests one or more of the following: (1) the gamma-ray spectra for the five SNRs soften by about 10^{14} eV, (2) the integral gamma-ray spectra of the SNRs are steeper than about $E^{-1.3}$, or (3) most of the gamma rays detected with the EGRET instrument for each SNR are not produced in the SNR's shock but are produced at some other site (such as a pulsar).

Although we extrapolated the spectra in Figure 3 to 10^{16} eV with no spectral change, the gamma-ray spectra are expected to steepen because the maximum energy of the cosmic rays accelerated in a SNR is limited by the cosmic-ray diffusion length in the SNR and the lifetime of the SNR. If the

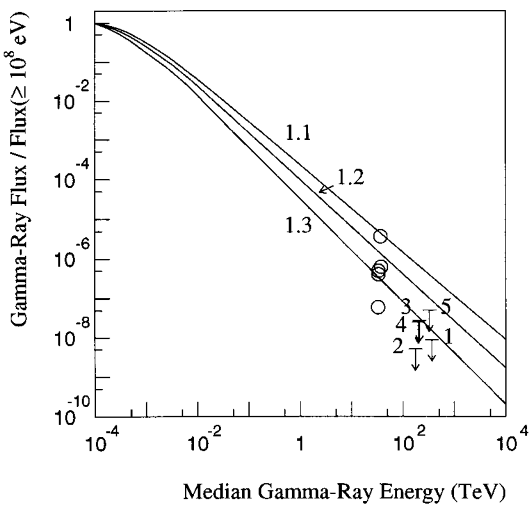

FIG. 3.—The three gamma-ray spectra are DAV's predictions of the gamma-ray flux produced in the shocks of SNRs for SNRs with integral cosmic-ray spectra $\propto E^{-1.1}$, $E^{-1.2}$, and $E^{-1.3}$. These spectra are plotted as a fraction of the predicted integral gamma-ray flux above 10^8 eV and are extrapolated to 10^{16} eV with no cutoff. The five flux limits, bearing the numerical labels of Table 1, are the 90% confidence level upper limits on the gamma-ray flux (the muon-poor ϕ_γ of Table 1) above the corresponding expected median energy (E_m of Table 1) of detected gamma rays. These limits are plotted as a fraction of the gamma-ray flux above 10^8 eV (ϕ_E of Table 1) reported by the EGRET collaboration (Dingus 1994). The five open circles, source numbers 5, 1, 3, 4, and 2 (*top to bottom*), show what the flux limits are if the gamma-ray spectra of the SNRs are cut off at 50 TeV.

gamma-ray spectra from the five SNRs soften below 10^{16} eV, the gamma-ray flux limits are understated (Fig. 2), and the expected median energies are overstated (Fig. 1). For example, the open circles of Figure 3 are the normalized flux limits above the corresponding expected median energies for gamma-ray spectra that $\propto E^{-1.1}$ below 50 TeV and are truncated at 50 TeV. The circles show that the $E^{-1.1}$ spectrum is excluded for cutoff energies as low as 50 TeV. A similar comparison to the $E^{-1.3}$ spectrum of Figure 3 shows that four of the five normalized flux limits are below this spectrum for cutoff energies as low as 200 TeV. Therefore, if the integral gamma-ray spectral indices for the five SNRs are in the range from 1.1 to 1.3, the normalized flux limits of Figure 3 imply that the gamma-ray spectra of the SNRs are cut off below about 10^{14} eV. In this case, the cosmic-ray spectra of the SNRs would soften below about 10^{15} eV (Naito & Takahara 1994, Fig. 5). Since this energy is too low to be consistent with the break in the observed all-particle cosmic-ray spectrum at 5×10^{15} eV (the knee), the results could contradict the hypothesis that Galactic cosmic rays below the knee are accelerated predominantly in the shocks of SNRs.

If the gamma-ray spectra of the five SNRs do not cut off, the normalized flux limits of Figure 3 imply that these integral spectra are steeper than $E^{-1.3}$. In this case, the cosmic-ray spectra of the SNRs would also be steeper than $E^{-1.3}$ because the shape of a SNR's gamma-ray spectrum closely follows the shape of the spectrum of accelerated cosmic rays (DAV). A cosmic-ray spectrum steeper than $E^{-1.3}$ may be too steep to be consistent with the spectral index (1.7) of the observed all-particle cosmic-ray spectrum, if the spectral contribution of the mean escape time from the Galaxy is steeper than about $E^{-0.4}$.

However, the implication that the gamma-ray spectrum is steeper than about $E^{-1.3}$ or is cut off below about 10^{14} eV requires the EGRET indentifications to be correct. Because the angular resolution of the EGRET detector is $\sim 1°$ (Thompson et al. 1993), this instrument cannot resolve features in the SNRs. The gamma-ray flux attributed to each SNR may not originate in the shock of the SNR. For example, if 90% of EGRET's gamma-ray flux from each SNR is produced at a pulsar associated with the SNR and 10% is produced in the SNR's shock, the normalized flux limits in Figure 3 should be increased by a factor of 10. The values of the absolute flux limits in Table 1 and Figure 2, which apply to all sources of gamma rays in the corresponding source bins, would not be affected.

In summary, the CYGNUS data set shows no evidence of ultra–high-energy gamma-ray emission from five SNRs reported by the EGRET collaboration. If the gamma-ray flux detected with the EGRET instrument is produced in the shocks of the SNRs and if DAV's prediction for the shapes of the gamma-ray spectra is correct, our gamma-ray flux limits impose significant constraints on the nature of cosmic-ray acceleration in the five SNRs.

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