

SEARCH FOR DIFFUSE COSMIC GAMMA RAYS ABOVE 200 TEV WITH THE UTAH-MICHIGAN ARRAY

UTAH-MICHIGAN COLLABORATION

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ABSTRACT

We have searched for γ -rays in the cosmic radiation above 200 TeV using a two-level array of scintillators designed to measure both the electromagnetic and muon content of extensive air showers. We find no evidence for an excess number of muon-poor showers and conclude that γ -rays comprise less than 0.4% of all cosmic rays above 200 TeV, and less than 0.05% above 1000 TeV (90% CL). The muon content of showers from the direction of the Galactic disk is the same as that of showers from other regions of the sky. The ratio of the flux of Galactic γ -rays to that of cosmic rays is $< 8.0 \times 10^{-5}$ (90% CL). This limit, based on muon measurements, represents a significant improvement over previous experiments and approaches predicted levels for diffuse γ -rays from the Galactic plane.

INTRODUCTION

Regardless of whether compact sources of UHE γ -rays exist, the interaction of the highest energy cosmic rays with the cosmic background radiation or with interstellar gas would generate diffuse fluxes of γ -rays. Diffuse γ -ray fluxes can be either isotropic or concentrated along the Galactic disk, depending upon the production mechanism.

If UHE cosmic rays are of extragalactic origin an isotropic flux of γ -rays will result from the interaction of cosmic ray protons above 10^{19} eV with the cosmic background radiation (CBR). Secondary e^+ , e^- , and γ -rays encounter other CBR photons over intergalactic distances and subsequently cascade^{1,2}. An enhanced flux of γ -rays near 10^{14} eV results when the cascades terminate near the e^+e^- production threshold.

A flux of γ -rays from the direction of the Galactic disk should arise from interactions of primary cosmic rays on gas and dust. The intensity of these γ -rays should reflect the distribution of interstellar material¹. In the 30 MeV to 5 GeV regime, photons produced in this manner have been observed by COS-B and SAS-2 satellites and used to map the density of Galactic hydrogen³.

Recent calculations suggest that, above 100 TeV, the flux of Galactic γ -rays should dominate the isotropic diffuse flux. The ratio of the Galactic flux I_γ to that of ordinary hadronic cosmic rays has been predicted to be 7×10^{-5} , from the direction of the Galactic center¹. Previous experiments have not observed this flux, setting limits $I_\gamma/I_{CR} < 1\%$ from the Galactic plane.⁴

We have searched for diffuse γ -ray emission using the muon content of extensive air showers to distinguish γ -ray-induced events. The validity of this approach is based on the assumption that UHE γ -rays have interaction properties which can be extrapolated from lower energies. There have been some hints that muon production in γ -showers is somehow enhanced⁵. This has become one of the outstanding questions of cosmic-ray physics, but the data is inconclusive and no convincing theoretical model exists. Observation of diffuse fluxes of γ -rays by means of muon discrimination would confirm the standard model of muon photoproduction and provide a valuable "test beam" with which to calibrate the muon content of γ -showers.

EVENT SELECTION

The Utah-Michigan array is located at Dugway, Utah, at the site of the Fly's Eye installation (atmospheric depth 870 g/cm²). This experiment was the first stage of the Utah-Michigan-Chicago (UMC) experiment and is more fully described elsewhere^{6,7}. The present data are from 33 surface scintillator stations distributed within a circle of 100 m radius and 512 muon counters (1280 m²) buried 3 m below the ground in eight widely spaced patches. This is the largest muon detector ever employed in an air shower array.

The data here are restricted to showers whose total sizes N lie in the range $3 \times 10^4 < N < 10^6$, cores within 100m of the center of the array, and directions within 40° of the zenith. We estimate⁶, based on detector simulations, that the γ -ray energy threshold E_t is about 200 TeV after these cuts. If the minimum size cut is increased to $N > 3 \times 10^5$, then E_t increases to about 1000 TeV.

We compute N and the muon size N_μ by fitting the lateral distribution of surface and buried counters to standard functions⁷. The muon content of individual showers fluctuates about the mean value for showers of the same size and zenith angle. We define the *relative muon size* R_μ of individual showers as

$$R_\mu \equiv \log_{10} N_\mu - \langle \log_{10} N_\mu \rangle. \quad (1)$$

where $\langle \log_{10} N_\mu \rangle$ is a function of N and θ and is computed separately for each data run of about 24 h duration.

The distribution of R_μ is shown in Figure 1. We select individual air showers as candidates for γ -ray-induced showers when the muon size is less than one-tenth the expected (mean) value. Specifically, we accept showers with $R_\mu < -1.0$ as candidates. We find, by simulating the detector's response, that 80% of γ showers with $N > 3 \times 10^4$ satisfy the above criterion, rising to 90% for $N > 10^5$.

ISOTROPIC DIFFUSE EMISSION

Figure 1 displays the distribution of relative muon sizes R_μ for data from 1988 April 3 until 1990 February 20 (1.9×10^7 events). Events with $R_\mu < -1.0$

are mainly small showers ($N \approx 3 \times 10^4$). The fluctuation of the muon size for small hadronic cosmic-ray showers is substantial and the shape of the curve is in accord with simulations of proton induced cascades and muon counting statistics in the detector. We set the most conservative limits on the isotropic flux of γ -rays by taking *all* showers with $R_\mu < -1$ as candidates. The ratio of γ -rays to the total cosmic ray flux is then $I_\gamma/I_{CR} < 4.3 \times 10^{-3}$ (90% CL) for $E_\gamma > 200$ TeV. If we consider the largest showers ($E_\gamma > 1000$ TeV), the above limit is lowered to $I_\gamma/I_{CR} < 4.8 \times 10^{-4}$ (90% CL).

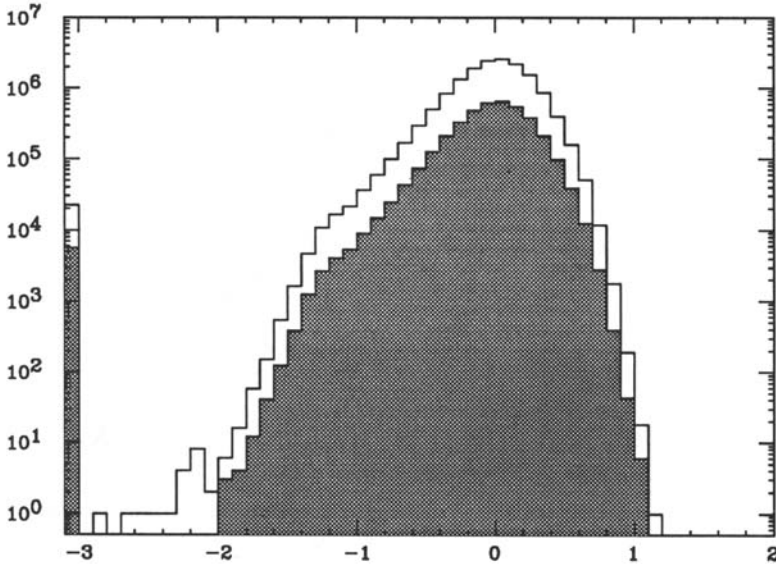


Figure 1. Distribution of relative muon size R_μ (Eq. 1). Data is divided into two groups: Galactic (shaded, $|b| < 10^\circ$) and Non-Galactic ($|b| > 10^\circ$). Showers with no recorded muons are plotted as underflows in the leftmost bin.

Our sensitivity to γ -rays can be further improved by estimating the expected number of showers with $R_\mu < -1$ due to downward fluctuations of muon size in ordinary cosmic ray showers. We merely note here that our simulations of the detector's response to proton showers shows qualitative agreement with the shape of the R_μ distribution for $R_\mu < 0$. It is not necessary to include *any* γ -rays in the cosmic radiation to explain the data.

GALACTIC DIFFUSE EMISSION

We search for enhanced Galactic γ -ray emission by comparing the muon content of showers from the direction of the Galactic plane with all other events

("non-Galactic" events). We define the Galactic disk here by Galactic latitudes $|b^{II}| < 10^\circ$. Because of our northern latitude, this sample of events is mainly from the region $30^\circ < \ell^{II} < 220^\circ$ in Galactic longitude.

Figure 1 shows the R_μ distributions separately for Galactic and non-Galactic showers. Galactic data are shaded. The non-Galactic sample has about four times as many events as the Galactic data. There is no evidence for excess muon-poor showers either from the Galactic disk or non-Galactic directions. Since the majority of showers in each set are hadron induced, we predict the expected background of muon-poor showers in the Galactic data by scaling the non-Galactic distribution so that the number of showers with $R_\mu > 0$ is the same in both samples.

We observe 19537 muon-poor showers from the Galactic disk and expect 19503 ± 71 . With 90% confidence, there are less than 249 excess muon-poor showers from the total Galactic sample of 3.9×10^6 events. An upper limit on the ratio of γ -ray showers to cosmic rays is then

$$I_\gamma/I_{CR} < \frac{249}{0.8 \times (3.9 \times 10^6)} = 8.0 \times 10^{-5}$$

for $E_\gamma > 200\text{TeV}$ and in the Galactic region defined above. Similar limits are obtained when the data set is restricted to higher energies. This limit is very close to some predicted values¹.

MOLECULAR CLOUD EMISSION

Satellite observations reveal that the intensity of low energy (> 30 MeV) γ -rays varies along the Galactic plane³. To the extent that these γ -rays are products of interactions of cosmic rays with gas and dust, the variation is due to nonuniformities of the interstellar medium. We find no significant excess emission of muon-poor showers (> 200 TeV) from any part of the Galactic plane visible to the detector.

Table 1 lists four northern hemisphere molecular clouds which are sources of 100 MeV γ -rays⁸. We also list regions near the Galactic center (note: the array acceptance drops off rapidly below $\ell^{II} = 30^\circ$) and the center of the Virgo cluster, where an enhanced diffuse γ flux has been predicted⁹. The listed areas of the objects are the sizes of the acceptance windows used in the analysis. The energy thresholds E_t vary with the declination of the object.

No significant excess signals are seen from any of the objects listed. We compute limits on the ratio I_γ/I_{CR} as described in the previous section and obtain the corresponding flux using the all-particle cosmic ray intensity I_{CR} given by Protheroe⁵. We have included a factor which estimates the loss of signal due to reconstruction errors. The flux upper limits are generally at least ten times larger than values obtained by extrapolating satellite results to our energy thresholds¹⁰.

Object	Coordinates		Area (deg ²)	E _t (TeV)	L _γ /ICR (90% CL upper limit) (10 ⁻⁴)	L _γ > E _t (90% CL upper limit) (10 ¹⁴ cm ⁻² s ⁻¹)
	ℓ ^{II} (deg)	b ^{II} (deg)				
Cas OB6	135	2	28	300	3.8	0.87
Per OB2	157	-21	28	200	9.6	4.1
Cygnus	80	3	28	200	6.2	2.7
Taurus	172	-15	100	250	4.0	3.8
"Central" Gal.	30-40	±10	200	1100	9.6	1.5
Virgo (M87)	-74	74	78	500	4.7	.95

Table 1. Observations of selected molecular clouds, the central Galaxy, and Virgo.

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