Upper Limit on the Diffuse Gamma Ray Flux using GRAPES-3 Experiment

M. Minamino*, S.R. Dugad†, T. Fujii*, U.D. Goswami†, S.K. Gupta†, Y. Hayashi*, N. Ito*, S. Kawakami*, H. Kojima‡, T. Matsuyama*, H. Miyauchi*, P.K. Mohanty†, S.D. Morris†, P.K. Nayak†, T. Nonaka*, S. Ogio*, T. Okuda*, A. Oshima†, M. Sasano*, K. Sivaprasad†, H. Tanaka*, S.C. Tonwar†, E. Usui* and Y. Yamashita*

**Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*
†*Tata Institute of Fundamental Research, Mumbai 400005, India*
‡*Aichi Institute of Technology, Aichi 470-0392, Japan*

***Abstract*. Isotropic gamma ray flux is expected as a result of interactions of ultra high energy cosmic rays ($E > 10^{19}$ eV) with the cosmic microwave background radiation and/or the annihilation/decay of topological defects. On the other hand, diffuse gamma ray flux from the galactic plane is expected as a result of interactions of cosmic rays with the interstellar matter. Thus these gamma rays are one of the possible probes to study cosmic rays and their source distribution. We search for diffuse gamma rays with the GRAPES-3 air shower array. It is a high-density array of 1 m^2 area plastic scintillation detectors and the large area (560 m^2) shielded muon detectors, and it is located at Ooty in the southern India. High statistics with such large area muon detectors help us to distinguish gamma ray showers with hadron showers. Based on the observations from March 2000 to July 2004 we obtained a new upper limit of the ratio of isotropic gamma rays to cosmic rays in the energy range of 20 – 400 TeV, and also we obtained an upper limit of galactic gamma ray flux ($|b| < 2°$).**

***Keywords*: diffuse radiation, gamma rays, air shower observation**

I. INTRODUCTION

There are a variety of possible sources of the diffuse radiation in very high energies. We make a list of possible astrophysical scenarios below;

1) unresolved point sources in extra galactic astronomical objects [1] [2]
2) electromagnetic cascades induced by the interaction of ultra high energy cosmic rays (UHECRs) with the cosmic microwave background radiation [3]
3) radiation induced by the annihilation/decay of topological defects [4]
4) the inverse Compton scattering of cosmic ray electrons with interstellar photons [5] [6]
5) cascading products by the collision of cosmic rays with interstellar medium [7]

In scenarios 1) to 3), an isotropic diffuse gamma ray flux is expected. On the other hand, in scenarios 4) and 5), the diffuse gamma ray flux is expected to have a excess on the galactic plane.

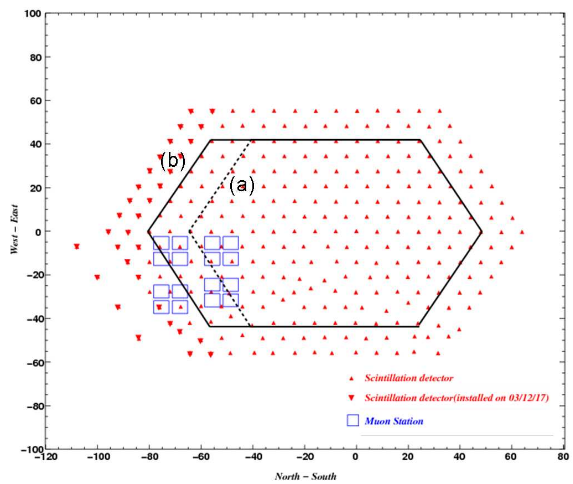

Fig. 1. The GRAPES-3 air shower array; The detectors in the regions bounded by the solid line and dotted line are the trigger detectors.

Based on the observations with the GRAPES-3 air shower array, we searched for diffuse gamma rays and hear we report upper limits of the isotropic flux and of the galactic component.

II. GRAPES-3 EXPERIMENT

The GRAPES-3 experiment is located at Ooty (N 11.4, E 76.7 and 2200 m a.s.l.) in the southern India. It consists of the two types of detectors, namely the surface scintillation detectors and the shielded muon tracking detectors under thick absorber material. It can detect air showers induced by cosmic rays and gamma rays in the energy range from 10 TeV to several tens of PeV with an adequate triggering condition. The 257 surface detectors of 1 m^2 area consisting of 5 cm thick plastic scintillator are located on the hexagonal grid of 8 m span. In 17 Dec. 2003, more 32 detectors were deployed near the muon detectors, then the total number of the surface detectors is 289 (see Fig. 1).

Moreover, there are 16 muon detector modules. One module is a stack of four layers of the propotional counter tubes (the cross-sectional area of 10 $\times$ 10 cm^2 and the length of 6 m), and the layers are separated by the 15 cm thick concrete plate each other. The number of the propotional counters per layer is 58, thus the detection area is 35 m^2 per module. Each module is covered with 2 m thick concrete absorber, and it is equivarent to the detection threshold energy for muons of 1 GeV.

The triggering condition is any ten or more surface detector hits out of 120 detectors in the central area of the array. The triggering rate was about 13 Hz, and after the additional deployments it became about 24 Hz.

III. Analysis

We analyzed data from March 2000 to July 2004 when the total live time is 1389 days. The data recorded by the surface array are used for the estimation of the primary energy and the core location of air showers. The data obtained by the shielded muon detector are used for the selection of primary gamma ray candidates.

A. The Surface Array

In the analysis for the surface array data we used the following event selection criteria:

1) Air shower core should be inside a hexagonal bounded by the line (a) or (b) which are shown in Fig. 1.
2) Ratio of the detected particles by outermost two rings to the total detected particles $< 35\%$.
3) Age parameter, $s < 1.8$
4) Number of hit ADC $(N_{\rm ADC}) \geq 7$
5) Number of hit TDC $(N_{\rm TDC}) \geq 15$
6) $0.5 < N_{\rm ADC}/N_{\rm TDC} < 2.0$

The core location, arrival direction, and total number of detected particles of the electromagnetic component were determined for each shower. The core location is estimated to be the centroid of the seven largest hit detectors. The arrival direction is determined from fitting the hit timings to a conical air shower front structure. In order to avoid misidentifying a large air shower falling out of the array as a small shower we used the criterion 2). The selection efficiency for the criterion was calculated with semi-Monte Carlo simulation based on GENAS ver 2.2. As a result the contamination of showers out of the array is estimated to be $<$ 1% in the energy range $>$ 30 TeV.

B. Shielded Muon Detectors

In the muon component analysis we calculate the number of muons from the observed tracks in the detector modules which have the same direction of air showers. We identify a track with any three hit-layer coincidence out of four layers. The number of detected muons depends on the primary energy, core distance from the muon detectors. Typically in our experiment several muons are detected for a shower with the total hits of 100 particles and with the distance from the muon detectors of 40 m.

While the gate width is 10 μs, in order to reduce chance muons we normally apply the narrower software gate of 3.5 μs. The counting rate of muon tracks, unrelated to air shower triggers, is about 3900 Hz per module. Therefore, the average number of muons due to the chance coincidence is very small, estimated to be about 0.07 per event.

IV. Simulation and Calculation

Many theoretical and numerical researches predict that the number of muons in gamma ray showers are much less than that in hadron showers at the same primary energy. For example, a detailed Monte Carlo simulation for our experiment with CORSIKA ver 5.62 shows that the detected number of muons is expected to be reduced to 2 – 3% of the number of muons by proton showers. Since the typical events observed in the GRAPES-3 air shower array have 0 to several tens of muons, we classified the obtained data into two groups: one is muon-poor, that is, the group of air showers with no associated muon, and the other is remainder, and then we assumed muon-poor events are gamma ray candidates.

We calculated the upper limit of the ratio of gamma rays to cosmic rays. For this analysis, we calculated the gamma ray selection efficiency, ϵ_γ, that is the ratio of the number of remaining gamma ray candidates after the muon-poor selection to the incident primary gamma rays with the Monte Carlo simulations. The efficiencies are obtained for the different air shower sizes and core locations.

V. Results and Discussion

A. Isotropic Gamma Rays

We select the events with the zenith angle less than 25°, and we calculate the upper limit of the ratio of gamma rays to cosmic rays by:

$$\frac{I_\gamma}{I_{\rm CR}} \leq \frac{N^{\mu=0}_{90\%{\rm C.L.}}}{N_{\rm all}} \frac{1}{\epsilon_\gamma} \frac{1}{1 - n_{\rm chance}}$$

where $N^{\mu=0}_{90\%{\rm C.L.}}$ is a 90% confidence level upper limit on the number of muon-poor air showers assuming Poisson distribution, $N_{\rm all}$ is the total number of air showers. $n_{\rm chance}$ is the average number of muons due to a chance coincidence [8] [9] [10]. The result is shown in Fig. 2 and compared with the upper limits given by other groups [11] [12] [13] [14].

B. Galactic Diffuse Gamma Rays

We select the events with the zenith angle less than 30°, and we define the region of the galactic latitude $|b| < 2°$ as the galactic plane region and $4° \leq |b| < 20°$ as the background region. Then we compare the number of events on two regions for different shower size as shown in Fig. 3.

As a result we cannot find any significant excess on the galactic plane. The significance and the involved

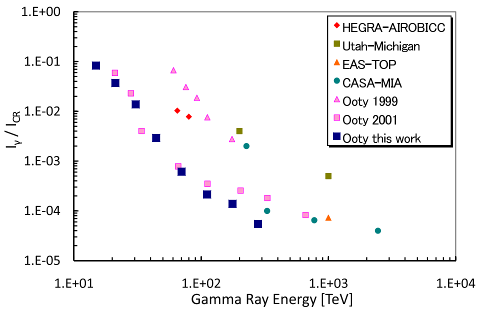

Fig. 2. Upper limit of the ratio of isotropic gamma rays to cosmic rays. The results of the HEGRA-AIROBICC [11], Utah-Michigan [12], EAS-TOP [13] and CASA-MIA [14] experiments and previous (1999 [8], 2001 [9]) and this work with the GRAPES-3 experiment are shown by the points, as indicated in the legend.

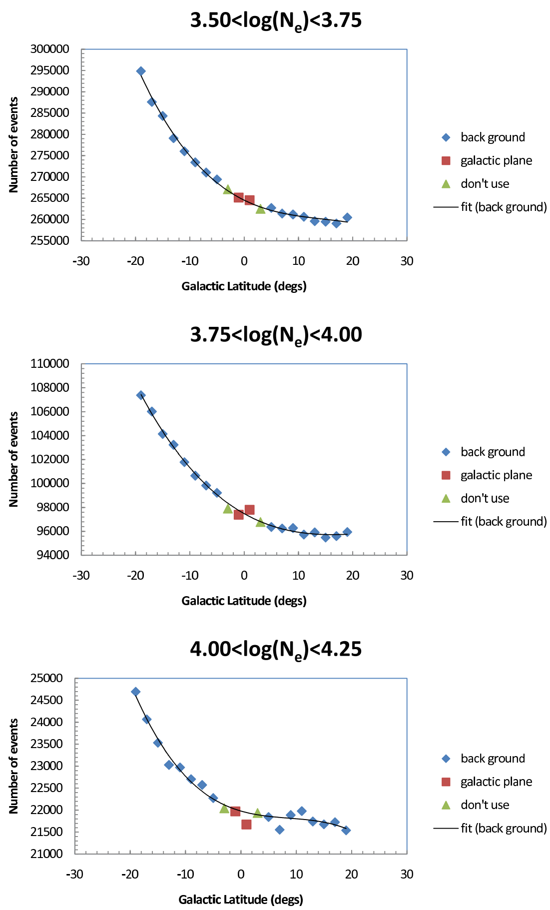

Fig. 3. Distribution of the number of events in the galactic latitude range of $-20°$ to $20°$. The background level at the galactic plane region is determined from fitting the number of events at the background region ignoring the region of the galactic latitude $2° < |b| < 4°$.

90% confidence level upper limit at different energies are listed in Table I and II.

Fig. 4 and 5 show the flux upper limits for the inner galactic plane and for the outer galactic plane.

VI. CONCLUSIONS

We obtained the upper limits of diffuse gamma rays based on the observations from March 2000 to July 2004 with the GRAPES-3 air shower array. A search for isotropic diffuse gamma rays resulted in a 90% C.L. upper limit of 5.5×10^{-5} at 280 TeV. And we also obtained the upper limits of gamma ray flux from the inner and outer galactic planes.

TABLE I
INNER GALACTIC PLANE

$> E$ (TeV)	Significance (σ)	90%C.L. upper limit ($\mathrm{cm^{-2}s^{-1}sr^{-1}}$)
17.6	0.72	4.72×10^{-12}
27.9	0.15	2.58×10^{-12}
44.3	-0.57	1.19×10^{-12}
70.2	2.23	6.81×10^{-13}
111	-0.48	9.20×10^{-14}
176	-1.51	2.32×10^{-14}

TABLE II
OUTER GALACTIC PLANE

$> E$ (TeV)	Significance (σ)	90%C.L. upper limit ($\mathrm{cm^{-2}s^{-1}sr^{-1}}$)
17.6	-2.34	4.73×10^{-12}
27.9	0.56	3.41×10^{-12}
44.3	-2.63	8.42×10^{-13}
70.2	0.20	3.37×10^{-13}
111	0.58	1.42×10^{-13}
176	-1.22	2.25×10^{-14}

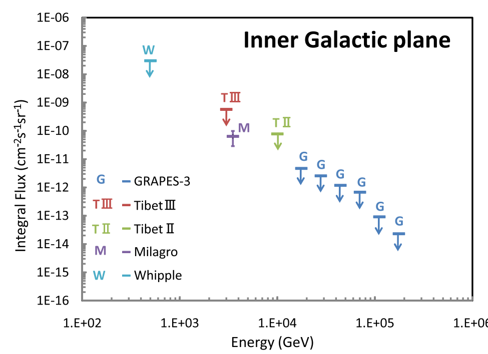

Fig. 4. The experimental results for diffuse gamma rays from the inner galactic plane. The upper limits from the Tibet AS-γ [15] and Whipple [16] experiments are shown by the bars with arrows. The definite flux from Milagro experiments [17] is shown by the bar with error.

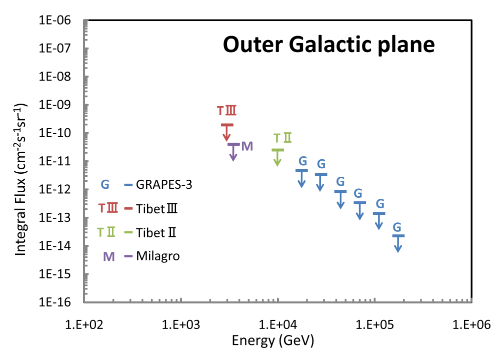

Fig. 5. The experimental results for diffuse gamma rays from the outer galactic plane. The upper limits from the Tibet AS-γ [15] and Milagro [17] experiments are shown by the bars with arrows.

ACKNOWLEDGEMENTS

The GRAPES-3 experiment is supported by the Ministry of Education, Culture, Sports, Science and Technology-Japan through Kakenhi grants on basic research 15403005(B). We also wish to thank the valuable contributions of G. Paul Francis, V. Jeyakumar, K. Manjunath, K. Ramadas, B.S. Rao, C. Ravindran and V. Viswanathan during the installation, operation and maintenance of the instrumentation. We gratefully acknowledge the help and cooperation of the Radio Astronomy Centre for providing facilities for the GRAPES-3 air shower array.

REFERENCES

[1] Rachen J.P., Stanev T., and Biermann P.L., A&A **273** (1993) 377
[2] Sigl G., Schramm D.N., and Bhattacharjee P., Astropart. Phys. **2** (1994) 401
[3] Halzen A.F. et al., Phys. ReV. D **41** (1990) 342
[4] Aharonian F.A. et al., Phys. Rev. D **46** (1992) 4188
[5] Porter T.A. and Protheroe R.J., J. Phys. G **23** (1997) 1765
[6] Tateyama N. and Nishimura J., 28th ICRC(Tsukuba) **4** (2003) 2285
[7] Berezinsky V.S. et al., Astropart. Phys. **1** (1993) 281
[8] Sasano M. et al., 26th ICRC(Salt Lake City) **4** (1999) 85
[9] Hayashi Y. et al., 27th ICRC(Hamburg) **6** (2001) 2385
[10] Hayashi Y. et al., 28th ICRC(Tsukuba) **4** (2003) 2273
[11] Karle A. et al., Phys. Lett. B **347** (1995) 161
[12] Matthews J. et al., ApJ **375** (1991) 202
[13] Aglietta M. et al., Astropart. Phys. **6** (1996) 71
[14] Chantell M.C. et al., Phys. Rev. Lett. **79** (1997) 1805
[15] Amenomori M. et al., ApJ **580** (2002) 887
[16] LeBohec S. et al., ApJ **539** (2000) 209
[17] Atkins R. et al., Phys. Rev. Let. **95** (2005) 251103