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UPPER LIMIT ON GAMMA-RAY FLUX ABOVE 10^{19} eV ESTIMATED BY THE AKENO GIANT AIR SHOWER ARRAY EXPERIMENT

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ABSTRACT

The origin of the highest energy cosmic rays ($\geq 10^{20}$ eV) is not well understood. Interesting models called "top-down" scenarios have been proposed to explain the origin. The γ-ray flux in ultra–high-energy cosmic rays is a key parameter for giving constraints on such models. To study the properties of γ-ray showers, we carry out simulation studies that take into account both the Landau-Pomeranchuk-Migdal effect and electromagnetic interactions in the geomagnetic field. Based on an analysis of muons in air showers observed by the Akeno Giant Air Shower Array, the upper limits on the γ-ray flux are estimated to be 28% above 10^{19} eV and 67% above $10^{19.5}$ eV in the observed air showers at a confidence level of 95%. Above 10^{20} eV, the primary composition is in agreement with an extrapolation from lower energies, and there is no indication that the observed events are mostly γ-ray showers. These results provide observational constraints for origin models up to the highest energies.

Subject headings: cosmic rays — dark matter — gamma rays: observations

1. INTRODUCTION

Cosmic rays have been detected clearly beyond the expected Greisen-Zatsepin-Kuz'min (GZK) cutoff energy (Greisen 1966; Zatsepin & Kuz'min 1966) around 5×10^{19} eV (see Nagano & Watson 2000 for review). So far, 10 cosmic rays have been observed with energies above 10^{20} eV by the Akeno Giant Air Shower Array (AGASA; Takeda et al. 1998; Hayashida et al. 2000). Their origin is not understood with conventional acceleration mechanisms. If we assume that they are protons, their source distances are limited to within several tens of megaparsecs, where no astrophysical objects are known that are capable of accelerating particles to greater than 10^{20} eV energies.

Interesting models of nonacceleration or "top-down" origin have been discussed. In these models, a part or most of the ultra–high-energy cosmic rays (UHECRs; $\geq 10^{19}$ eV) are explained by γ-rays and nucleons that are decay or interaction products of exotic "X"-particles with masses of grand unification theory scale energies. Proposed origin candidates are topological defects (TDs) such as the monopole and cosmic string distributed over the universe (e.g., Sigl et al. 1999), superheavy (SH) relic particles concentrated in the Galactic halo (e.g., Berezinsky, Blasi, & Vilenkin 1998), etc. The cascade process initiated by a super–high-energy neutrino ($\sim 10^{22}$ eV) in the relic neutrino background is another possible scenario that results in a similar prediction for the primary composition (the so-called Z-burst model; Weiler 1982).

These models imply in general that the spectrum of produced particles is harder than that of the observed UHECRs; however, the predicted fluxes depend strongly on the assumed origin. In addition to models of extragalactic origin, the fluxes are uncertain since γ-rays above 10^{20} eV interact mainly with the universal radio background (URB) whose strength is poorly determined (e.g., Sigl et al. 1999; Protheroe & Biermann 1996). Also, extragalactic magnetic fields (EGMFs) affect production of electromagnetic (EM) particles. Although a variety of physical parameters, e.g., the mass of the X-particle (M_X), are loosely subject to observational and theoretical constraints, an experimental measurement of γ-ray fluxes at energies of interest may provide a strong requirement for models.

In the present work, we aim to estimate how many observed air showers could be from γ-ray primaries. To do so, we first need to know the properties of showers from a γ-ray primary. With recent air shower simulations (e.g., Plyasheshnikov & Aharonian 2001; Sciutto 1999), muons produced in γ-ray showers are expected to be much fewer than those in hadronic ones. The Landau-Pomeranchuk-Migdal (LPM) effect (Landau & Pomeranchuk 1953; Migdal 1956) is important in shower development at energies above $\sim 10^{19}$ eV in the atmosphere. For primary γ-rays above $\sim 10^{19.5}$ eV, pair creation may occur in the geomagnetic field (GF) a few thousand kilometers above the ground, and subsequently the energy of the primary γ-ray is shared among a number of photons and a few $e^{\pm}$ pairs

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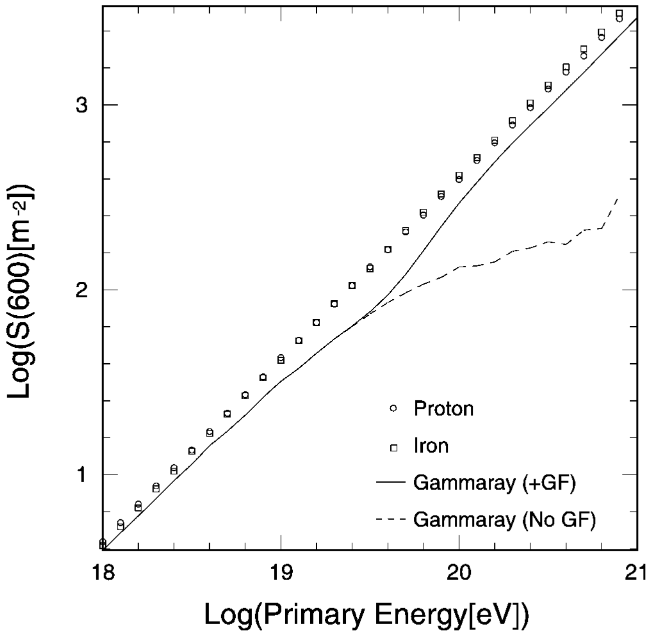

FIG. 1.—Average $S(600)$ for $\theta = 25°$ as function of primary energy for proton (*circles*), iron (*squares*), and γ-ray showers with (*solid curve*) and without (*dashed curve*) a GF.

through the synchrotron process (McBreen & Lambert 1981). As a result, the shower development in the atmosphere is similar to that without the LPM effect resulting from a superposition of lower energy subshowers.

So far, no experimental application has been made that takes into account both the LPM effect and EM interactions in the GF. In the following, we present properties of hadronic and γ-ray showers from simulation studies. We analyze muon data from showers observed by AGASA. The upper limit on the γ-ray flux above 10^{19} eV is estimated and is compared with predictions from origin models. A possible dominance of γ-rays above 10^{20} eV is also tested.

2. EXPERIMENT

AGASA (Ohoka et al. 1997) is located at latitude 35°47′ north, longitude 138°30′ east, and 900 m above sea level (atmospheric depth of 920 g cm^{-2}), which is deployed with 111 surface detectors of 2.2 m^2 area over an ~100 km^2 area. In the southern region of AGASA, 27 muon detectors with 2.8–20 m^2 area are placed near surface detectors. Each muon detector consists of 14–20 proportional counters aligned under a shield of 30 cm of iron or 1 m of concrete. The threshold energy is 0.5 GeV for vertically incident muons.

As a primary energy estimator, we use the local charged particle density (particles per m^2) at 600 m from the shower core [$S(600)$]. The relation between $S(600)$ and primary energy (E_0) was evaluated to be $E_0\,[\mathrm{eV}] = 2.03 \times 10^{17} S(600)$ for vertical showers by Monte Carlo simulations (Dai et al. 1988). It was found to be applicable to hadronic showers of up to 10^{20} eV energies (Sakaki et al. 2001). The $S(600)$ for an inclined shower is converted to that of a vertical one using the attenuation function obtained from the equi-intensity cut method (Yoshida et al. 1994). Hereafter, E_0 refers to an energy estimated by the above method. The accuracies of E_0 are ~30% at 10^{19} eV and ~25% at 10^{20} eV for hadronic showers (Takeda et al. 1998).

In the present work, events recorded between 1995 December and 2000 December are selected by the following criteria (referred to as "cut A"): (1) $E_0 \geq 10^{19}$ eV; (2) a zenith angle $\theta \leq 36°$; (3) six or more hit surface detectors; (4) good fitting on shower geometry; (5) a core location greater than 600 m inside the boundary of the surface detector deployed area; and (6) more than two muon detectors within 800–1600 m of the shower core. The numbers of selected events are 102, 14, and 4 above 10^{19}, $10^{19.5}$, and 10^{20} eV, respectively. For $E_0 \geq 10^{20}$ eV, we pick out six events by requiring more than one muon detector instead of two in criterion 6 from the database since 1993 September (referred to as "cut B").

We employ the muon density at 1000 m from the shower cores [$\rho_\mu(1000)$] as a primary mass estimator; $\rho_\mu(1000)$ is determined for each event by fitting density data between core distances of 800 and 1600 m with the empirical lateral distribution function (Hayashida et al. 1995). This function is found to be in agreement with experimental data up to 10^{20} eV (K. Shinozaki et al. 2002, in preparation). The accuracy of $\rho_\mu(1000)$ is evaluated to be ~40% by analyzing artificial showers that satisfy cut A.

3. SIMULATIONS

To interpret the experimental data, we perform simulation studies for proton, iron, and γ-ray showers using the AIRES code (Sciutto 1999) with the QGSJET hadronic interaction model (Kalmykov & Ostapchenko 1993). In the case of γ-ray showers, EM interactions in the GF are implemented with the Monte Carlo code used in Anguelov & Vankov (1999) that simulates pair creation and synchrotron radiation processes in the GF. In this code, the spatial structure of the GF is that defined by the International Geomagnetic Reference Field (distributed by the National Geophysical Data Center)[19] and its extrapolation. Each particle reaching the top of the atmosphere (50 km above sea level) is followed by a γ-ray shower generated with AIRES.

To estimate the fluctuations in $\rho_\mu(1000)$, we analyze a large number of artificial showers generated by the above simulation. An input spectrum of each primary is sampled to reproduce the UHECR spectrum observed by AGASA. The expected $\rho_\mu(1000)$ distributions are obtained for different primaries in E_0 bins with a width of $\Delta \log E_0 = 0.25$ above 10^{19} eV.

4. RESULTS AND DISCUSSION

Figure 1 shows the average $S(600)$ for $\theta = 25°$ as a function of primary energy (Shinozaki et al. 2001). The circles and squares indicate the behavior for proton and iron showers. For γ-ray showers, the solid and dashed curves represent the cases with and without the GF, respectively.

$S(600)$ for γ-ray showers nearly equals that for hadronic showers at energies around 10^{18} eV. Around 10^{19} eV, it becomes smaller by ~30% compared with hadronic showers, and hence E_0 underestimates the real primary energy. As shown by the solid curve in the figure, this difference is most significant around $10^{19.5}$ eV in the realistic GF and is ~50%, and it shrinks to be ~20% above 10^{20} eV. However, if the GF is not taken into account, the difference increases with energy because of the LPM effect, as shown by the dashed curve in the same figure. These results are consistent with those from Plyasheshnikov & Aharonian (2001).

In Figure 2, $\rho_\mu(1000)$ versus E_0 is shown for the events that pass cut A (*circles*) and cut B (*squares*). The solid line represents the average relation, derived by fitting data between 10^{19} and 10^{20} eV. The expected 1 σ bound for simulated γ-ray showers

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[19] See http://www.ngdc.noaa.gov.

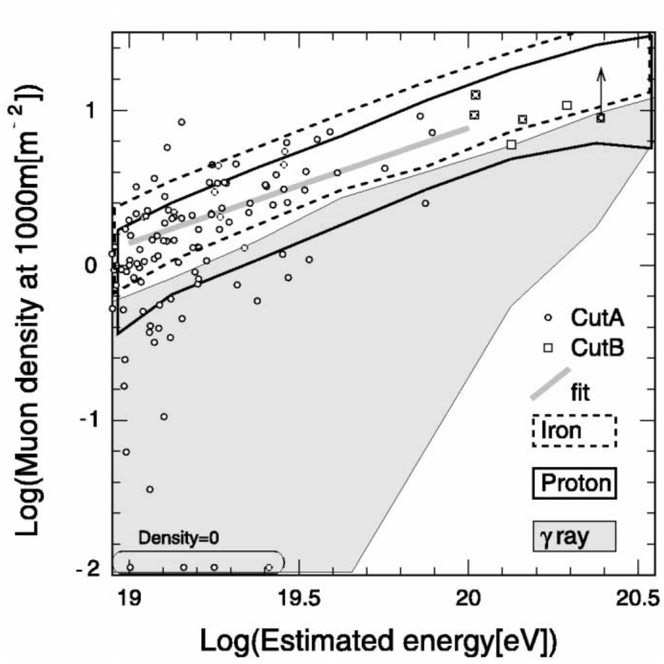

FIG. 2.—The $\rho_\mu(1000)$ vs. E_0 relation for observed events (*circles and squares*). The solid line is a fit to data between 10^{19} and 10^{20} eV. The expected 1 σ bound for simulated γ-ray showers is indicated by the shaded region, and those for proton and iron showers are enclosed by solid and dashed curves, respectively. See text for description of cuts A and B.

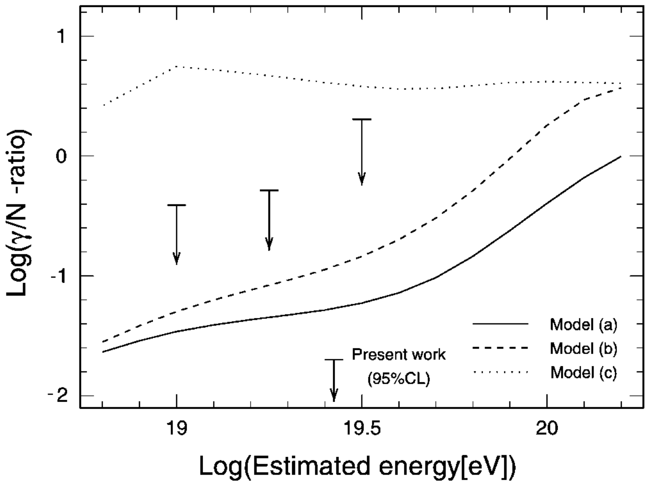

FIG. 3.—The γ/N ratio as function of E_0. The present upper limits are shown at a 95% CL by arrows. The different curves correspond to the predictions from the following origin models: (*a*) a decay from TDs (*solid curve*); (*b*) the Z-burst model (*dashed curve*; Sigl 2001); and (*c*) a decay from SH particles (*dotted curve*; Berezinsky et al. 1998). See text for details.

is indicated by the shaded region, and those for proton and iron showers are enclosed by solid and dashed curves, respectively. The average relation from the experiment fits the proton expectation best among the simulated primaries (K. Shinozaki et al. 2002, in preparation) and is consistent with an extrapolation from lower energies (discussed in Nagano et al. 2000).

To estimate the fraction of γ-ray showers in the observed events (hereafter denoted by F_γ), χ^2-values for different F_γ are evaluated in each E_0 bin defined previously by fitting the experimental $\rho_\mu(1000)$ distribution with simulated distributions. Assuming that hadronic primaries are only protons, we determine an allowed interval of F_γ. From this analysis, the upper limits on F_γ at a confidence level (CL) of 95% are obtained to be 28%, 34%, and 67% above 10^{19}, $10^{19.25}$, and $10^{19.5}$ eV, respectively. To give constraints on origin models, F_γ-values are converted to integral fluxes from the UHECR spectrum observed by AGASA. The upper limits on fluxes of γ-ray showers at a 95% CL are 4.5×10^{-15} m^{-2} s^{-1} sr^{-1} above 10^{19} eV and 1.4×10^{-15} m^{-2} s^{-1} sr^{-1} above $10^{19.5}$ eV.

In Figure 3, we test three different origin models by comparing predicted ratios in integral fluxes of γ-ray showers to nucleonic ones (γ/N ratios) with those derived from the present analysis. Arrows indicate the present upper limits at a 95% CL. The different curves correspond to the predictions from the following models: (*a*) a decay from TDs for $M_X = 10^{16}$ GeV (*solid curve*); (*b*) a Z-burst model (*dashed curve*); and (*c*) a decay from SH particles for $M_X = 10^{14}$ GeV (*dotted curve*; Berezinsky et al. 1998). Models *a* and *b* are referred to by Sigl (2001) and are revised from Sigl et al. (1999) and Yoshida, Sigl, & Lee (1998), respectively. We show the case of an intermediate URB proposed in Protheroe & Biermann (1996) and an EGMF of $\ll 10^{-11}$ G for model *a*. The effect of underestimating energy for γ-ray primaries, as seen in Figure 1, is taken into account in the predictions from models.

Following the referred literature, the predicted particle fluxes in models *a* and *b* are normalized to explain the observed UHECR spectrum above 10^{20} eV. The component of UHECRs accelerated from lower energies is included by assuming an expected spectrum consistent with the GZK prediction for the uniform source assumption (Yoshida & Teshima 1993). From both models, the predicted γ/N ratios are several times lower than the present upper limits.

In model *c*, extragalactic components of UHECRs are suppressed by the small density of SH particles outside the Galaxy, and hence decayed particles from the halo are dominant in UHECRs above ~10^{19} eV. In the figure, we show the case of all UHECRs above 10^{19} eV being decay products of SH particles. The predicted γ/N ratio is about 5, which is much higher than the present upper limits. This was also claimed by Ave et al. (2002) in an analysis of Haverah Park data.

In some models, such as models *b* and *c*, γ-rays are expected to be dominant above 10^{20} eV. As seen in Figure 2, $\rho_\mu(1000)$ values for the events passing cut B are close to an extrapolation from 10^{19} eV energies and seem to be explained by simulated hadronic showers. Using the expected $\rho_\mu(1000)$ distribution for simulated γ-ray showers above 10^{20} eV, we evaluate the chance probability of selecting six simulated γ-ray showers whose average $\rho_\mu(1000)$ is larger than that of the experimental data. The result is less than 0.4% from 10^5 samples.

If all events above 10^{20} eV are γ-ray showers, an anisotropy in the arrival direction distribution may be expected with respect to the GF direction since the magnitude of EM interactions depends on both the γ-ray energy and the strength of the GF component perpendicular to the trajectory. In this case, an excess of showers from the northern sky region is expected at Akeno. The distribution of the observed 10 events with $\theta \leq 45°$ does not show any anisotropy expected for the γ-ray–dominant hypothesis.

5. CONCLUSION

The experimental $\rho_\mu(1000)$ versus E_0 relation above 10^{19} eV is consistent with an extrapolation from lower energies and is explained by simulated hadronic showers of up to 10^{20} eV. Comparing with simulation results, the upper limits on F_γ at a 95% CL are 28% above 10^{19} eV and 67% above $10^{19.5}$ eV. Corresponding fluxes of γ-ray showers at the same CL are less than

4.5×10^{-15} and 1.4×10^{-15} $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}}$ for E_0 above 10^{19} and $10^{19.5}$ eV, respectively. Above 10^{20} eV, no indication of γ-ray dominance is found in both $\rho_\mu(1000)$ and arrival direction distributions. These results provide observational constraints on origin models up to the highest energies.

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