Search for ultra-high energy photons in the Telescope Array surface detector first-year data

G.I. Rubtsov*, D. Ivanov†, B.T. Stokes†, G.B. Thomson†, S.V. Troitsky*
for the Telescope Array Collaboration

**Institute for Nuclear Research of the Russian Academy of Sciences,*
60th October Anniversary Prospect 7a, Moscow 117312 Russia
†*Department of Physics and Astronomy, Rutgers — The State University of New Jersey*
Piscataway, New Jersey, 08854, USA

***Abstract*. We search for ultra-high energy photons by analyzing geometrical properties of shower fronts of events registered by the Telescope Array surface detector in its first year of operation. By making use of an event-by-event statistical method, we derive upper limit on the absolute flux of primary photons with energies above 10^{19} eV. The limit is not sensitive to the choice of the hadronic interaction model.**

***Keywords*: photon flux limit, Telescope Array experiment, surface detector**

I. Introduction

Telescope Array (TA) experiment [1] is a hybrid detector operating in Utah, USA. TA consists of a surface detector array of 507 plastic scintillators with 1.2 km spacing covering 700 km^2 area and three fluorescence detectors. The purpose of the Talk is to discuss photon search capabilities of Telescope Array surface detector and to present the first year limits on the photon integral flux above 10^{19} eV.

Several limits on the UHE photon flux have been set by independent experiments, including Haverah Park [2], AGASA [3], Yakutsk [4] (see also reanalyses of the AGASA [5] and AGASA+Yakutsk [6] data at the highest energies) and the Pierre Auger Observatory [7], [8], [9], but no evidence for primary photons found at present. Photon limits may be used to constrain the parameters of top-down models and in the future photon search may be used to select between different Greisen-Zatsepin-Kuzmin [10], [11] cut-off scenarios which predict photons as everpresent secondaries.

The Telescope Array surface detector stations contain plastic scintillators of 3 m^2 area which are sensitive to both muon and electromagnetic component of the extensive air shower and therefore are sensitive to showers induced by primary photons (see e.g. Ref. [12] for discussion). We use the shower front curvature as a composition-sensitive parameter (C-parameter) and we use a modification of event-by-event statistical method [13] to constrain the photon intergral flux above the given energy. For the energy-sensitive parameter (E-parameter), we use the scintillator signal density at 800 m core distance $S(800)$.

II. Simulations

Air showers induced by primary photons differ significantly from the hadron-induced events (see e.g. [14] for a review). At the highest energies there are two competitive effects responsible for the diversity of showers induced by primary photons. First, due to the Landau, Pomeranchuk [15] and Migdal [16] (LPM) effect the electromagnetic cross-section is suppressed at energies $E > 10^{19}$ eV. The LPM effect leads to the delay of the first interaction and the shower arrives to the ground level underdeveloped. Another effect is the $e^{\pm}$ pair production due to photon interaction with the geomagnetic field above the atmosphere. Secondary electrons produce gamma rays by synchrotron radiation generating a cascade in the geomagnetic field. The probability of this effect is proportional to the square of the product of photon energy and perpendicular component of geomagnetic field. The shower development therefore depends on both zenith and azimuthal angles of photon arrival direction.

Event-by-event method requires us to have a set of simulated photon-induced showers for the analysis of each real shower. We simulated the library of these showers with different primary energies and arrival directions. For the highest energy candidates (events which may be induced by photon with primary energy above $10^{19.5}$ eV) we simulate individual sets of simulated showers with fixed zenith and azimutal angles.

We use CORSIKA [17] with EGS4 [18] model for electromagnetic interactions and the PRESHOWER code [19] for geomagnetic interactions. There is no significant dependence of the hadronic model because only photon-induced simulated showers are used in present work. Detector response is accounted for by using look-up tables simulated with GEANT4 [20]. The showers are simulated with thinning and the dethinning procedure is used. The details of simulations and dethinning procedure are presented at this conference [21].

III. Dataset

We use first year Telescope Array surface detector dataset with zenith angle below 45° with the following cuts:

1) The number of detectors triggered is 7 or more.

2) Shower core is within the array boundary.
3) Fit quality cut on χ^2/d.o.f.

Under the cuts above the array exposure is close to geometrical for showers induced by primary photons with energy above 10^{19} eV (an exception is a small fraction of underdeveloped showers which are accounted for separately as "lost" photons). For the purpose of the present analysis we reestimated the energy of each event under the assumption of a photon primary.

IV. Method

To estimate the flux limit we use event-by-event method. Linsley curvature parameter "a" is used as a C-observable and $\mathcal{S} \equiv S(800)$ is used as E-observable. For each real event "i" we estimate the pair of parameters ($\mathcal{S}^i_{obs}$, a^i_{obs}) and the arrival direction (θ^i, ϕ^i) from the fit of shower front geometry and LDF. We select a simulated gamma-induced showers compatible with the observed θ^i, ϕ^i and $\mathcal{S}^i_{obs}$ and calculate the distribution of the simulated showers in curvature $f^i_\gamma(a)$ as discussed in Ref. [13]. For each event, we determine the quantity

$$\mathcal{C}^i = \int_{-\infty}^{a^i_{obs}} f^i_\gamma(a) da$$

which is the value of the integral probability distribution function for the observed curvature. Though the distributions $f^i_\gamma(a)$ vary with energy and arrival directions, $\mathcal{C}^i$ for gamma-ray primaries would be distributed between 0 and 1 uniformly by definition. However, the front curvature is smaller for hadron-induced showers which develop higher in the atmosphere and therefore the actual distribution of $\mathcal{C}^i$ in the data is strongly non-uniform (most of the events have $\mathcal{C}^i$ close to 0).

Since both the hadronic composition of the primary particles is unknown and the simulations of hadron-induced showers depend strongly on the hadronic interaction model, we do not use the hadronic showers simulations in the analysis.

Suppose that the integral flux of primary photons over a given energy range is F_γ. Then we expect to detect

$$\bar{n}(F_\gamma) = F_\gamma A(1-\lambda)$$

photon events in average, where A is the exposure of the experiment for a given dataset and λ is fraction of "lost" photon (i.e. photons with primary energies within the interesting region which failed to enter the dataset because of errors in the energy reconstruction). Let $\mathcal{P}(n)$ be a conservative probability to have n photons in a dataset which is defined as a maximum over all subsets of n real events:

$$\mathcal{P}(n) = \max_{i_1<i_2<\ldots<i_n} \mathcal{P}(\{i_1, \ldots, i_n\}) ,$$

where $\mathcal{P}(\{i_1, \ldots, i_n\})$ is a statistical probability of the subset $\{i_1, \ldots, i_n\}$ to be compatible with uniform distribution (i.e. may include 100% photon events). We use a non-parametric statistical test to compare the distributions. To constrain the flux F_γ at the confidence level of ξ one requires

$$\sum_n \mathcal{P}(n) W(n, \bar{n}(F_\gamma)) < 1 - \xi ,$$

where $W(n, \bar{n})$ is the Poisson distribution with average $\bar{n}$.

The method is conservative by construction and doesn't require any assumptions about hadron-induced showers. This modification of the original method does not require the C-observable to be strongly discriminating (like the muon density used in previous applications [4], [6]). The shower front curvature is in fact a moderately descriminating parameter because distributions of curvature for photon and hadron-induced showers intersect significantly.

V. Results

Both the use of plastic scintillators sensitive to photon-induced showers and the application of a powerful event-by-event statistical method allowed us to put stringent limits on the flux of primary photons with energies in excess of 10^{19} eV already with the data obtained during the first 7 months of the TA operation. The result does not depend on the choice of hadronic interaction model, nor on possible systematics in the energy determination of hadronic primaries. The limit will be presented at the conference.

Acknowledgments

The Telescope Array experiment is supported by the Ministry of Education, Culture, Sports, Science and Technology-Japan through Kakenhi grants on priority area (431) "Highest Energy Cosmic Rays", basic research awards 18204020(A), 18403004(B) and 20340057(B); by the U.S. National Science Foundation awards PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the Korean Science and Engineering Foundation (KOSEF, Grant No. R01-2007-000-21088-0); by the Russian Academy of Sciences, RFBR grants 07-02-00820a and 09-07-00388a (INR), the FNRS contract 1.5.335.08, IISN and Belgian Science Policy under IUAP VI/11 (ULB). The work is supperted in part by the grants of the President of the Russian Federation NS-1616.2008.2, MK-61.2008.2 (GR). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions.

REFERENCES

[1] H. Kawai *et al.*, Nucl. Phys. Proc. Suppl. **175-176**, 221 (2008).
[2] M. Ave, J. A. Hinton, R. A. Vazquez, A. A. Watson and E. Zas, Phys. Rev. Lett. **85**, 2244 (2000).
[3] K. Shinozaki *et al.*, Astrophys. J. **571**, L117 (2002).
[4] A. V. Glushkov *et al.*, JETP Lett. **85**, 131 (2007).
[5] M. Risse *et al.*, Phys. Rev. Lett. **95**, 171102 (2005).
[6] G. I. Rubtsov *et al.*, Phys. Rev. D **73**, 063009 (2006).
[7] J. Abraham *et al.* [Pierre Auger Collaboration], Astropart. Phys. **27**, 155 (2007).
[8] J. Abraham *et al.* [Pierre Auger Collaboration], Astropart. Phys. **29**, 243 (2008).
[9] J. Abraham *et al.* [Pierre Auger Collaboration], arXiv:0903.1127 [astro-ph.HE].
[10] K. Griesen, Phys. Rev. Lett. **16**, 748 (1966)
[11] Z. T. Zatsepin and V. A. Kuz'min, Zh. Eksp. Teor. Fiz. Pis'ma Red. **4**, 144 (1966)
[12] O. E. Kalashev, G. I. Rubtsov and S. V. Troitsky, arXiv:0812.1020 [astro-ph].
[13] D. S. Gorbunov, G. I. Rubtsov and S. V. Troitsky, Astropart. Phys. **28**, 28 (2007).
[14] M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749 (2007).
[15] L. D. Landau and I. Ya. Pomeranchuk, Dokl. Acad. Nauk SSSR, **92**, 535, 735 (1953)
[16] A. B. Migdal, Phys. Rev. **103**, 1811 (1956)
[17] D. Heck *et al.*, Report FZKA-6019 (1998), Forschungszentrum Karlsruhe.
[18] W. R. Nelson, H. Hirayama, D.W.O. Rogers, SLAC-0265 (permanently updated since 1985).
[19] P. Homola *et al.*, Comp. Phys. Comm. **173** (2005) 71.
[20] S. Agostinelli *et al.* [GEANT4 Collaboration], Nucl. Instrum. Meth. A **506**, 250 (2003).
[21] B. Stokes *et al Proceedings of the 31th ICRC in Lodz*