Search for Ultra-High Energy Photons and Neutrinos using the Telescope Array Scintillator Array Data

G.I. RUBTSOV[1], M. FUKUSHIMA[2], D. IVANOV[3], B. STOKES[3], G. THOMSON[3], S.V. TROITSKY[1] FOR THE TELESCOPE ARRAY COLLABORATION

[1]*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, 117312, Russia*
[2]*ICRR, University of Tokyo, Japan*
[3] *University of Utah, High Energy Astrophysics Institute, Salt Lake City, Utah, USA*

grisha@ms2.inr.ac.ru

Abstract: We search for ultra-high energy photons by analyzing the geometrical properties of shower fronts of events measured by the Telescope Array surface detector over 5 years of observation. We report an upper limit on the absolute flux of primary photons with energies above 10^{19} eV. We also report the results of down-going neutrino search based on the analysis of very inclined events.

Keywords: ultra-high energy photons, high energy neutrino astrophysics, Telescope Array experiment

1 Introduction

Telescope Array (TA) experiment [1, 2] 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 this *Talk* is to present photon and neutrino search capabilities of Telescope Array surface detector and to place the limits on the integral fluxes in the energy region above 10^{19} eV.

Several limits on the UHE photon flux have been set by independent experiments, including Haverah Park [3], AGASA [4], Yakutsk [5, 6] (see also reanalyses of the AGASA [7] and AGASA+Yakutsk [8] data at the highest energies) and the Pierre Auger Observatory [9, 10, 11], but no evidence for primary photons found at present. Photon limits may be used to constrain the parameters of top-down models [12] and in the future photon search may be used to select between different Greisen-Zatsepin-Kuzmin [13, 14] cut-off scenarios which predict photons as everpresent secondaries. Moreover, results of the photon search severely constrain the parameters of Lorentz invariance violation at Planck scale [15, 16, 17, 18, 19]. Finally, photons with energies above $\sim 10^{18}$ eV might be responsible for CR events correlated with BL Lac type objects on the angular scale significantly smaller than the expected deflection of protons in cosmic magnetic fields and thus suggesting neutral primaries [20, 21] (see Ref. [22] for a particular mechanism).

Ultra-high energy *neutrinos* may be generated by the decay of charged pions produced as a secondaries in GZK process [23], by beta-decay of unstable ultra-hugh energy nuclei or by some mechanism related to the new physics. Neutrino flux is constrained in air shower [24, 26, 25], ice shower [27] and radio Cherenkov [28, 29, 30, 31, 32] experiments.

2 Photon search

The Telescope Array surface detector stations contain plastic scintillators of 3 m^2 area which detect both muon and electromagnetic components of the extensive air shower and therefore are sensitive to showers induced by primary photons (see e.g. Ref. [33] for discussion). We use the shower front curvature as a composition-sensitive parameter (C-observable) and we use a modification of event-by-event statistical method [34, 35] to constrain the photon integral flux above the given energy. For the energy-sensitive parameter (E-observable), we use the scintillator signal density at 800 m core distance $\mathscr{S} \equiv S_{800}$. The comparison of event-by-event statistical method with "photon median" method [10] is presented: the results are in the mutual agreement.

2.1 Simulations

Air showers induced by primary photons differ significantly from the hadron-induced events (see e.g. [36] 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 [37] and Migdal [38] (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 simulate 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 showers with fixed zenith and azimuthal angles.

We use CORSIKA [39] with EGS4 [40] model for electromagnetic interactions, PRESHOWER code [41] for geomagnetic interactions, QGSJET II [42] and FLUKA [43] for high and low energy hadronic interactions. There is no significant dependence of the hadronic model because only photon-induced simulated showers are used in calculations.

Telescope Array Search for Ultra-High Energy Photons and Neutrinos
33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013

ICRC
2013

The showers are simulated with thinning and the dethinning procedure is used [44].

Detector response is accounted for by using look-up tables simulated with GEANT4 [45]. Real-time array configuration and detector calibration information are used for each simulated event. Monte-Carlo (MC) events are produced in the same format as real events and analysis procedures are applied in the same way to both [44]. No proton simulations are used in calculating the flux limits.

2.2 Dataset

We use Telescope Array surface detector dataset covering five years of observation from 2008-05-11 to 2013-05-04. Surface detector has been collecting data for more than 95% of time during that period [46].

We reconstruct each event with a joint fit of the geometry and lateral distribution function (LDF) and determine Linsley curvature parameter "a" along with the arrival direction, core location and signal density at 800 meters $\mathscr{S} \equiv S_{800}$. The same reconstruction procedure is applied to both data and Monte-Carlo events.

For each real event "i" we estimate the energy of hypothetical photon primary $E_\gamma^i = E_\gamma(\mathscr{S}^i, \theta^i, \phi^i)$, i.e. the average energy of the primary photon, inducing the shower with the same arrival direction and $\mathscr{S}$. The look-up table for $E_\gamma(\mathscr{S}, \theta, \phi)$ is built using photon MC set; the dependence on azimuthal angle ϕ is relevant for events with $E_\gamma > 10^{19.5}$ eV where geomagnetic preshowering is substantial.

Photon-induced showers are naturally highly fluctuating and consequently the accuracy of determination of E_γ is 50% at one sigma level. In the present analysis E_γ is used for event selection only and therefore it's fluctuations are well accounted in exposure calculation: the result of these fluctuation is a fraction of lost photons [34] which will be estimated in Section 2.4.

The following cuts are applied to both data and MC events:

1. Zenith angle cut: $45° < \theta < 60°$;

2. The number of detectors triggered is 7 or more;

3. Shower core is inside the array boundary with the distance to the boundary larger than 1200 meters;

4. Joint fit quality cut, $\chi^2/\text{d.o.f.} < 5$;

5. $E_\gamma(S_{800}^i, \theta^i, \phi^i) > 10^{19}$ eV.

The cuts determine photon registration efficiency which is higher that 50% for showers induced by primary photons with energy above 10^{19} eV.

2.3 Method

To estimate the flux limit we use event-by-event method. Linsley curvature parameter "a" is used as a C-observable and $\mathscr{S} \equiv S_{800}$ is used as E-observable. For each real event "i" we estimate the pair of parameters ($\mathscr{S}_{obs}^i$, a_{obs}^i) 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 $\mathscr{S}_{obs}^i$ and calculate the curvature distribution of the simulated showers $f_\gamma^i(a)$ as discussed in Ref. [34]. For each event, we determine the quantity

$$\mathscr{C}^i = \int_{-\infty}^{a_{obs}^i} f_\gamma^i(a)\,da$$

which is the value of the integral probability distribution function for the observed curvature.

Though the distributions $f_\gamma^i(a)$ vary with energy and arrival direction, $\mathscr{C}^i$ for gamma-ray primaries would be distributed between 0 and 1 uniformly by definition.

Since the simulations of hadron-induced showers depend strongly on the hadronic interaction model, we do not use the hadronic showers simulations in calculation of the limit.

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

$$\bar{n}(F_\gamma) = F_\gamma A_{geom}(1 - \lambda) \tag{1}$$

photon events in average, where A_{geom} is the geometrical 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 due to cuts).

Let $\mathscr{P}(n)$ be a conservative probability to have n photons in a dataset which is defined as a maximum over all subsets of n real events:

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

where $\mathscr{P}(\{i_1, \ldots, i_n\})$ 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). At this point any non-parametric statistical test may be used to compare the distribution. We use Smirnov-Cramer-von Mises "omega-square" test because it allows simple and quick numerical procedure to maximize the probability over all subsets of eventset. To constrain the flux F_γ at the confidence level of ξ one requires

$$\sum_n \mathscr{P}(n)W(n, \bar{n}(F_\gamma)) < 1 - \xi, \tag{2}$$

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 [5, 6, 8]).

2.4 Exposure

Geometrical exposure for considered SD observation period with $45° < \theta < 60°$ and boundary cut is given by

$$A_{geom} = 1225 \text{ km}^2 \text{ sr yr}. \tag{3}$$

The fraction of the lost photons is calculated using photon MC set conservatively assuming E^{-3} photon spectrum.

The statistical method (Eq. 2) gives the constraint on the expected number of photons in the dataset $\bar{n}$ thus leading to the following result

$$F_\gamma < \frac{\bar{n}}{A_{geom}(1 - \lambda)}, \tag{4}$$

The result does not depend on the choice of hadronic interaction model, nor on possible systematics in the energy determination of hadronic primaries.

3 Neutrino search

As opposed to hadron and photon-induced showers, neutrino-induced shower may be originated in any part of the atmosphere. Therefore very inclined young showers may be considered as a neutrino candidates. To separate young showers we count the number of peaks in the waveforms. To suppress accidental peaks as a result of FADC noise we define a peak as a time bin with signal above 0.2 VEM and higher than a signal of 3 preceeding and 3 consequent time bins. For each event we count the total number of peaks over upper and lower layers of all detectors hit. Very inclined hadronic showers are old and contain mostly muons, which propagate rectilinearly producing mostly single-peaked waveforms. On the contrary, young showers produce long, indented waveforms. Neutrino is expected to produce young showers for all zenith angles.

For neutrino search we use Telescope Array surface detector data from 2008-05-11 to 2013-05-04 with cuts 2, 3 and 4 from Section 2.2. We calculate the exposure using CORSIKA [39] neutrino-induced Monte-Carlo events.

4 Results

Limits on the photon and neutrino fluxes above 10^{19} eV will be presented at the conference.

References

[1] T. Abu-Zayyad et al. [Telescope Array Collaboration], Nucl. Instrum. Meth. A **689**, 87 (2012).

[2] H. Tokuno et al. [Telescope Array Collaboration] Nucl. Instrum. Meth. A **676**, 54 (2012).

[3] M. Ave, J. A. Hinton, R. A. Vazquez, A. A. Watson and E. Zas, Phys. Rev. Lett. **85**, 2244 (2000).

[4] K. Shinozaki et al., Astrophys. J. **571**, L117 (2002).

[5] A. V. Glushkov et al., JETP Lett. **85**, 131 (2007).

[6] A. V. Glushkov et al., Phys. Rev. **D82**, 041101 (2010).

[7] M. Risse et al., Phys. Rev. Lett. **95**, 171102 (2005).

[8] G. I. Rubtsov et al., Phys. Rev. D **73**, 063009 (2006).

[9] J. Abraham et al. [Pierre Auger Collaboration], Astropart. Phys. **27**, 155 (2007).

[10] J. Abraham et al. [Pierre Auger Collaboration], Astropart. Phys. **29**, 243 (2008).

[11] J. Abraham et al. [The Pierre Auger Collaboration], Astropart. Phys. **31**, 399-406 (2009).

[12] V. Berezinsky, P. Blasi and A. Vilenkin, Phys. Rev. D **58**, 103515 (1998).

[13] K. Griesen, Phys. Rev. Lett. **16**, 748 (1966)

[14] Z. T. Zatsepin and V. A. Kuz'min, Zh. Eksp. Teor. Fiz. Pis'ma Red. **4**, 144 (1966)

[15] S. R. Coleman and S. L. Glashow, Phys. Rev. D **59**, 116008 (1999).

[16] M. Galaverni and G. Sigl, Phys. Rev. Lett. **100**, 021102 (2008).

[17] L. Maccione, S. Liberati and G. Sigl, Phys. Rev. Lett. **105**, 021101 (2010).

[18] G. Rubtsov, P. Satunin and S. Sibiryakov, Phys. Rev. D **86**, 085012 (2012).

[19] P. Satunin, arXiv:1301.5707 [hep-th].

[20] D. S. Gorbunov et al., JETP Lett. **80**, 145 (2004).

[21] R. U. Abbasi et al. [HiRes Collaboration], Astrophys. J. **636**, 680 (2006).

[22] M. Fairbairn, T. Rashba and S. Troitsky, arXiv:0901.4085 [astro-ph.HE].

[23] O. E. Kalashev, V. A. Kuzmin, D. V. Semikoz et al., *Ultrahigh-energy neutrino fluxes and their constraints*, *Phys. Rev.* **D66** (2002) 063004

[24] R. Abbasi et al. [HiRes Collaboration], Astrophys. J. **684**, (2008) 790.

[25] P. Abreu et al. [Pierre Auger Collaboration], Phys. Rev. D **84**, (2011) 122005.

[26] P. Abreu et al. [Pierre Auger Collaboration], Astrophys. J. **755** (2012) L4.

[27] R. Abbasi et al. [IceCube Collaboration], Phys. Rev. D **83**, (2011) 092003.

[28] P.W. Gorham et al. [ANITA Collaboration], Phys. Rev. D **85**, (2012) 049901(E).

[29] I. Kravchenko et al. [RICE Collaboration], Phys. Rev. D **85**, (2012) 062004.

[30] T.R. Jaeger, R.L. Mutel, K.G. Gayley [RESUN Collab.], Astropart. Phys. **34**, (2010) 293.

[31] O. Scholten et al., Phys. Rev. Lett. **103**, (2009) 191301.

[32] C.W. James et al. [LUNASKA Collaboration], Phys. Rev. D **81**, (2010) 042003.

[33] O. E. Kalashev, G. I. Rubtsov, S. V. Troitsky, Phys. Rev. **D80**, 103006 (2009).

[34] D. S. Gorbunov, G. I. Rubtsov and S. V. Troitsky, Astropart. Phys. **28**, 28 (2007).

[35] T. Abu-Zayyad et al. [Telescope Array Collaboration], arXiv:1304.5614 [astro-ph.HE].

[36] M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749 (2007).

[37] L. D. Landau and I. Ya. Pomeranchuk, Dokl. Acad. Nauk SSSR, **92**, 535, 735 (1953)

[38] A. B. Migdal, Phys. Rev. **103**, 1811 (1956)

[39] D. Heck et al., Report FZKA-6019 (1998), Forschungszentrum Karlsruhe.

[40] W. R. Nelson, H. Hirayama, D.W.O. Rogers, SLAC-0265.

[41] P. Homola et al., Comp. Phys. Comm. **173** (2005) 71.

[42] S. Ostapchenko, Nucl. Phys. Proc. Suppl. **151**, 143 (2006).

[43] A. Ferrari et al., CERN-2005-010; A. Fasso, A. Ferrari, J. Ranft et al., eConf **C0303241**, MOMT005 (2003).

[44] B. Stokes et al., *Proc. of the International Symposium on UHECR, Nagoya, December 10-12*, (2010).

[45] S. Agostinelli et al. [GEANT4 Collaboration], Nucl. Instrum. Meth. A **506**, 250 (2003).

[46] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma, E. Barcikowski, J. W. Belz and D. R. Bergman et al., Astrophys. J. **768**, L1 (2013).