33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Method for the primary mass composition study of ultra-high-energy cosmic rays with the Telescope Array surface detector

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

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

grisha@ms2.inr.ac.ru

Abstract: The Telescope Array (TA) surface detector (SD) stations record the temporal development of the signal from the extensive air shower front which carries information about the type of the primary particle. We develop methods for studies of the primary mass composition of ultra-high-energy cosmic rays with the TA SD data and report preliminary results of these studies.

Keywords: ultra-high energy cosmic ray composition, Telescope Array surface detector

1 Introduction

The Telescope Array (TA) experiment [1, 2] is a hybrid detector operating in Utah, USA. The 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. This *Poster* presents a new technique for the primary mass composition study of ultra-high-energy cosmic rays (UHECR) based on the time-resolved data from surface detector. The sensitivity of the method for energies higher than 10^{19} eV is confirmed with Monte-Carlo modeling.

Primary mass composition is one of the main research targets for large scale extensive air shower detectors. The highest accuracy is achieved in X_{max} measurements with air fluorescence detectors such as HiRes, Pierre Auger and TA [3, 4, 5]. The results of different experiments lead to different interpretations - Hires and TA data are compatible with pure proton composition, while Pierre Auger Observatory suggests a transition to heavier elements at high energies. The primary mass composition play a primary role in the identification of cosmic ray sources [6, 7] and interpretation of the observed cut-off of the spectrum [8, 9, 10, 11, 12].

The surface detector is capable of measuring chemical composition independently of the fluorescence telescopes. Moreover, the SD provides more statictics at the puzzling highest energy range due to it's 95% duty cycle. One of the SD techniques is based on independent measurement of muon component. The Yakutsk array has shown that the muon density for $E > 10^{19}$ eV showers is a factor 1.5 higher than the SIBYLL 2.1 [13] model prediction for iron primaries and may be interpreted using EPOS model [14] as mixed proton and iron composition [15]. Yakutsk muon data suggest that the composition become heavier at energies $E \gtrsim 10^{19}$ eV [16]. Pierre Auger uses two observables for composition study with SD: asymmetry of signal risetime and muon production depth profile [17]. Both agree with the composition becoming heavier at the highest energies. Note, that the mass sensitivity of all of the listed SD observables is determined by their sensitivity to the muon component of the shower. One may not neglect the muon component for SD composition study as the electon-photon shower component is much less sensitive to primary particle type and shower depth due to the universality of electromagnetic shower [18, 19].

2 Method

Each of 507 TA surface detectors records time-resolved signals with a time step of 20 ns. For each detector we define Area-over-Peak (*AoP*) as the ratio of the integral of the FADC trace to it's peak value. The *AoP* therefore is measured in time units (ns). The muons arrive close in time to the shower front making *AoP* smaller, while electron-photon cascade shift *AoP* towards larger values. The *AoP* observable was previously introduced by Pierre Auger collaboration for neutrino identification [20]. We fit *AoP* as a linear function of the core distance:

$$AoP(r) = \alpha - \beta(r - 1200\,\mathrm{m}),$$

where α has a meaning of *AoP* value at 1200 meters and β is the *AoP* slope.

Following [21, 22] we define percentile ranks of α and β parameters for proton primaries $\mathscr{C}_\alpha$,$\mathscr{C}_\beta$:

$$\mathscr{C}^i_\alpha = \int_{-\infty}^{\alpha^i} f^i_{MC,p}(\alpha)d\alpha,$$

$$\mathscr{C}^i_\beta = \int_{-\infty}^{\beta^i} f^i_{MC,p}(\beta)d\beta,$$

where $f^i_{MC,p}(\alpha)$ is an α distribution function for proton QGSJETII-03 Monte-Carlo events compatible by zenith angle with the real event "i".

3 Data and Monte-Carlo sets

We use Telescope Array surface detector data set 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 [10]. The following cuts are applied to both data and MC events:

1. Quality cuts used for spectral analysis [10];
2. Zenith angle cut: $0^\circ < \theta < 45^\circ$;
3. The number of detectors triggered is 7 or more.

For $AoP(r)$ fit we require that the detector is not saturated and has a core distance larger than 600 m.

We use CORSIKA [23] with both QGSJET II-03 [24] and SIBYLL [13] models to generate hadronic showers induced by primary protons and iron. The showers are simulated with thinning and the dethinning procedure is adopted [25] to simulate realistic shower fluctuations. The detector response is accounted for by using look-up tables generated by GEANT4 [26] simulations. Real-time array status and detector calibration information are used for each Monte Carlo (MC) simulated event. The Monte-Carlo events are produced in the same format as real events and the analysis procedures are applied in the same way to both [27].

4 Results

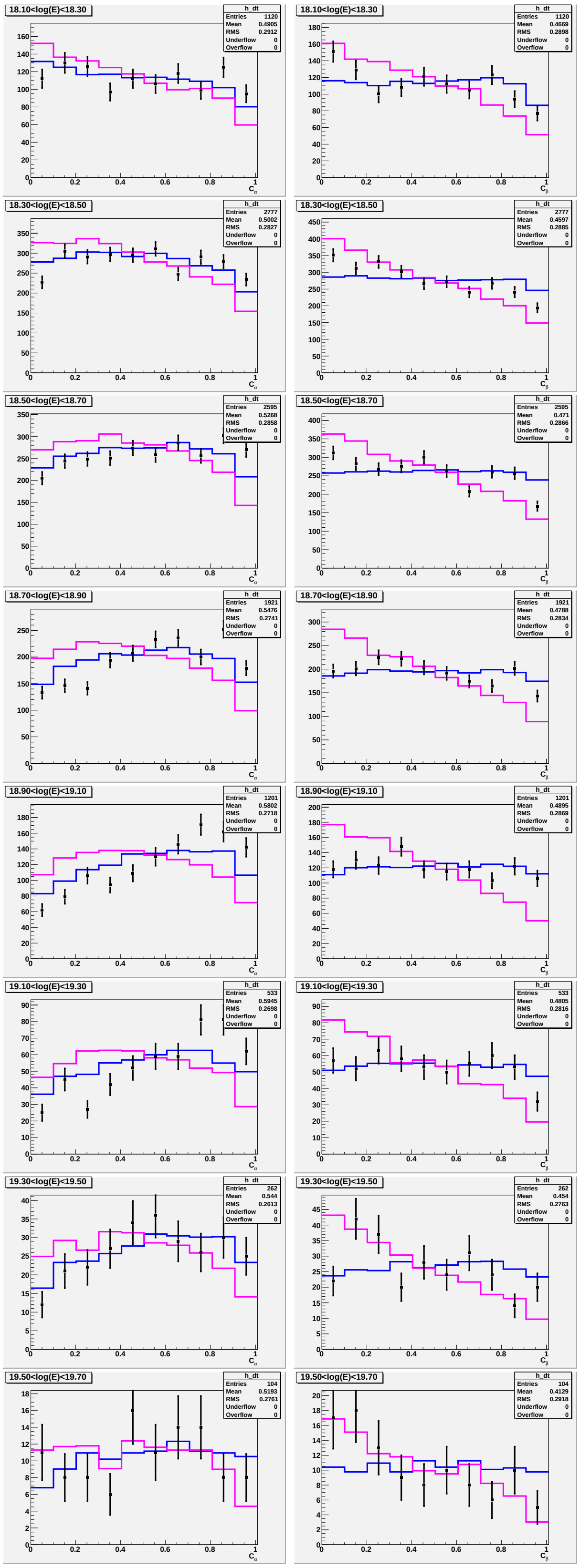
The histograms of $\mathscr{C}_\alpha$ and $\mathscr{C}_\beta$ for data and QGSJET-II-03 and SIBYLL Monte-Carlo are shown in Figures 1,2. One may see that the parameter $\mathscr{C}_\beta$ corresponding to AoP slope points to systematically heavier composition than $\mathscr{C}_\alpha$ corresponding to AoP at 1200 meters. The difference between $\mathscr{C}_\alpha$ and $\mathscr{C}_\beta$ results shows up in both QGSJET-II and SIBYLL Monte-Carlo sets. Up to statistical uncertanties the results are compatible with mostly proton composition for energies higher than 10^{19} eV.

Acknowledgment: The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) "Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays", and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, by grants of the President of the Russian Federation NS-5590.2012.2, MK-1170.2013.2, Dynasty Foundation, RFBR grants 11-02-01528, 13-02-01311 and 13-02-01293 (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). 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 and the University of Utah Center for High Performance Computing (CHPC). The cluster of the Theoretical Division of INR RAS was used for the numerical part of the work.

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] R. U. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **104** 161101 (2010).
[4] J. Abraham *et al.* [Pierre Auger Observatory Collaboration], Phys. Rev. Lett. **104** 091101 (2010).
[5] Y. Tsunesada *et al.* [Telescope Array Collaboration], Proceeding of 33rd ICRC, Talk 132 (2013).
[6] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma, E. Barcikowski, J. W. Belz and D. R. Bergman *et al.*, Astrophys. J. **757**, 26 (2012).
[7] P. Abreu *et al.* [Pierre Auger Collaboration], [arXiv:1305.1576 [astro-ph.HE]].
[8] R. U. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **100** 101101 (2008).
[9] J. Abraham *et al.* [The Pierre Auger Collaboration], Phys. Lett. B **685** 239 (2010).
[10] 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).
[11] R. Aloisio, V. Berezinsky, P. Blasi, *et al.* Astropart. Phys. **27** 76 (2007).
[12] R. Aloisio, V. Berezinsky and A. Gazizov, Astropart. Phys. **34**, 620 (2011)
[13] R. S. Fletcher, T. K. Gaisser, P. Lipari and T. Stanev, Phys. Rev. D **50** 5710 (1994).
[14] K. Werner, F. M. Liu and T. Pierog, Phys. Rev. C **74** 044902 (2006).
[15] A. V. Glushkov, *et al.*, JETP Lett. **87** 190 (2008).
[16] L. G. Dedenko, , *et al.*, J. Phys. G **39**, 095202 (2012).
[17] P. Abreu *et al.* [Pierre Auger Collaboration], Proceedings of 32nd ICRC, Beijing, 2011, arXiv:1107.4804.
[18] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).
[19] P. Lipari, Phys. Rev. D **79**, 063001 (2009).
[20] P. Abreu *et al.* [Pierre Auger Collaboration], Phys. Rev. D **84** 122005 (2011).
[21] D. S. Gorbunov, G. I. Rubtsov and S. V. Troitsky, Astropart. Phys. **28**, 28 (2007).
[22] T. Abu-Zayyad *et al.* [Telescope Array Collaboration], arXiv:1304.5614 [astro-ph.HE].
[23] D. Heck *et al.*, Report FZKA-6019 (1998), Forschungszentrum Karlsruhe.
[24] S. Ostapchenko, Nucl. Phys. Proc. Suppl. **151** 143 (2006).
[25] B. T. Stokes *et al.*, Astropart. Phys. **35**, 759 (2012).
[26] S. Agostinelli *et al.* [GEANT4 Collaboration], Nucl. Instrum. Meth. A **506**, 250 (2003).
[27] B. Stokes *et al.* "Using CORSIKA to quantify Telescope Array surface detector response" *Proceedings of the 31th ICRC in Lodz* (2009).

QGSJET-II-03



SIBYLL

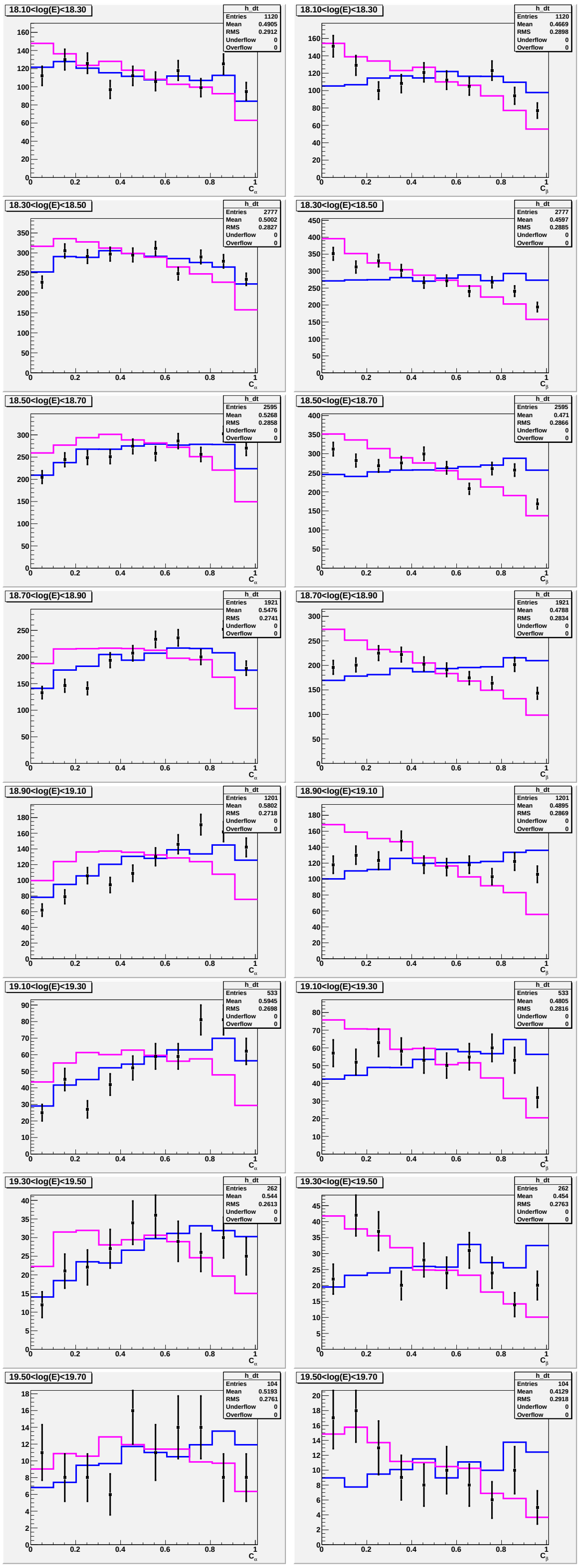


Fig. 1: $\mathscr{C}_\alpha$ (left) and $\mathscr{C}_\beta$ (right) distributions for data and QGSJET-II Monte-Carlo (blue - protons, magenta - iron). /PRELIMINARY/

Fig. 2: $\mathscr{C}_\alpha$ (left) and $\mathscr{C}_\beta$ (right) distributions for data and SIBYLL Monte-Carlo (blue - protons, magenta - iron). /PRELIMINARY/