ISSN 1062-8738, Bulletin of the Russian Academy of Sciences. Physics, 2011, Vol. 75, No. 3, pp. 309–312. © Allerton Press, Inc., 2011.
Original Russian Text © V.I. Galkin, T.A. Gzhatdoev, 2011, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2011, Vol. 75, No. 3, pp. 338–341.

Classifying Groups of PCR Nuclei with Energies of 10^{15}–10^{16} eV According to the Spatial–Angular Distribution of EAS Cherenkov Light

V. I. Galkin[a, b] **and T. A. Gzhatdoev**[a, b]

[a] *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Faculty of Physics, Moscow State University, Moscow, 119991 Russia*
e-mail: v_i_galkin@rambler.ru

Abstract—Multidimensional Bayesian classification criteria are proposed for groups of nuclei of primary cosmic rays based on characteristics of spatial–angular distribution of Cherenkov light of extensive air showers. These criteria allow us in principle to separate no less than 50–60% of the primary protons from heavier nuclei; the classification errors for primary protons and groups of nitrogen and iron nuclei total no more than several per cent. New parameters that substantially improve the separability of classes of showers are also found for angular images of Cherenkov light.

DOI: 10.3103/S1062873811030166

INTRODUCTION

The problem of nuclear composition of primary cosmic rays with superhigh energies (>10^{15} eV) is at present far from finally being solved. In the region of the spectrum knee (10^{15}–10^{16} eV) [1–6], at the higher energies of the second knee (10^{17}–10^{18} eV) [7, 8], and in the region of ultra high energies (10^{19}–10^{20} eV) [9, 10], no reliable data on the shape of the partial spectra of different groups of nuclei of primary cosmic rays (PCRs) have been obtained, and there is no commonly accepted result for the dependence of the PCR mean mass number on energy. Predictions of the nuclear composition of PCRs are often the most pronounced features of different models for the acceleration and propagation of cosmic rays at superhigh energies [7, 8, 11]. The search for what lies behind the discrepancy between the results of different experimental groups is therefore especially topical.

There are substantial differences between the results from measurements performed using similar methods, e.g., the values of the mean mass number $\langle A \rangle$ according to the data on the electronic–muonic component of a shower [1, 2], and the results from several Cherenkov facilities [3–6]. The difference between $\langle A \rangle$ measured by different Cherenkov facilities exceeds considerably the discrepancy between groups working on the charged component of the shower.

This work continues our investigations of the sensitivity of the characteristics of EAS Cherenkov light to mass composition aimed at developing criteria for the individual classification of showers generated by PCR nuclei with different mass numbers. The spatial–angular distribution of EAS Cherenkov light, one of the most informative shower characteristics, is used to construct a method for classifying groups of PCR nuclei. Previous works that studied the spatial–angular distribution of EAS Cherenkov light demonstrated a moderate resolving capability with respect to the mass number [12] comparable to that of criteria based solely on the lateral distribution of Cherenkov light [13, 14]; i.e., they found no specific advantages in using the spatial–angular distribution of EAS Cherenkov light.

CALCULATION AND CLASSIFICATION METHODS

The sample of artificial EAS Cherenkov light used in this study was calculated by full statistical simulation using the CORSIKA 6.500 code [15] and the QGSJET-II [16]/GHEISHA [17] nuclear interaction model. Details of the simulation procedure are given in [18]. The sample volume was 500 events, and the primary energy of all events was 1 PeV. Of these events, 250 corresponded to an observation altitude of 1 km above sea level; the other 250 events, to 4 km a.s.l. Fifty events from primary protons, helium, nitrogen, and iron nuclei were calculated for each of these altitudes. Another 50 showers initiated by sulfur nuclei were considered for an observation level of 1 km, along with 50 events from calcium nuclei for 4 km.

To separate the groups of nuclei, we must determine the so-called feature vector consisting of characteristics of the spatial–angular distribution of EAS Cherenkov light, which is then supplied to the input of the classification procedure. The most traditional approach [12] is that the spot of the angular distribution of EAS Cherenkov light is characterized by [19,

Table 1. Results from the multidimensional classification for primary energy 1 PeV and observation levels (left) 1 km and (right) 4 km

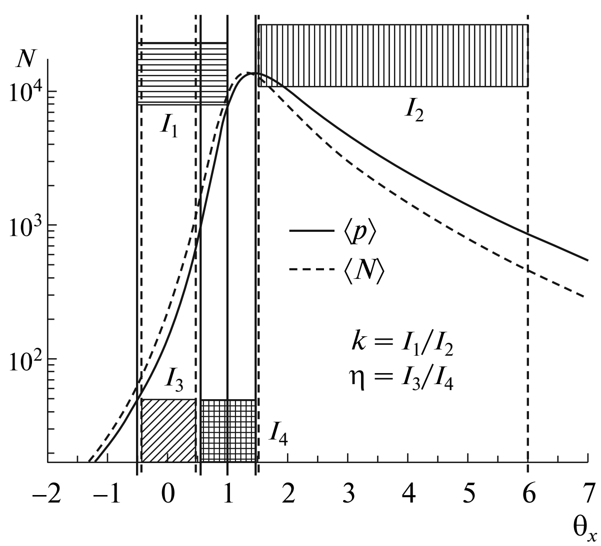
	p	*h*	*n*	*s*	*f*		*p*	*h*	*n*	*c*	*f*
p	0.74	0.26	0.00	0.00	0.00	*p*	0.70	0.28	0.02	0.00	0.00
h	0.02	0.90	0.06	0.02	0.00	*h*	0.00	0.94	0.06	0.00	0.00
n	0.00	0.06	0.92	0.02	0.00	*n*	0.00	0.06	0.92	0.00	0.02
s	0.00	0.00	0.04	0.90	0.06	*c*	0.00	0.00	0.00	0.92	0.08
f	0.00	0.00	0.00	0.00	1.00	*f*	0.00	0.00	0.00	0.14	0.86

20] *D* (the angular distance from the direction of the primary particle to the center of gravity of the image), *L* (the mean square half-length of the image), *W* (the mean square half-width of the image), and *Conc* (an image concentration equal to the ratio of the sum of the signal at two maximal cells and the integral image intensity).

The Bayesian approach was used to separate groups of PCR nuclei under the assumption that there was a multidimensional normal distribution of features [21]. The classes of objects correspond to the types of primary nuclei (in this work, the number of classes $M = 5$), and the teaching sample represents the set of shower feature vectors from the set of model events. The classification procedure is described in detail in [18].

CRITERIA BASED ON HILLAS PARAMETERS

We analyzed the criteria for separating nuclei of five types, based on combinations of the parameters (*D*, *L*, *W*, *Conc*) measured simultaneously at several fixed distances from the shower axis: 50, 100, 150, and 200 m. (The dimension of the feature vector is 16.) As in [12], the values of (*D*, *L*, *W*, *Conc*) were calculated using those angular cells of the spatial–angular distribution of Cherenkov light whose signal exceeded 100 photoelectrons, in order to reduce the influence of signal fluctuations in peripheral regions of the spatial–angular distribution of Cherenkov light.



Schematic diagram for selecting integration boundaries. The integral over the horizontal band of the angular distribution of EAS Cherenkov light is displaced along the ordinate axis (θ_x is measured in deg). The width of the integration band is 1.5°.

The results from separating groups of nuclei with a feature vector consisting of 16 parameters (*D*, *L*, *W*, *Conc*) taken at 4 distances from the shower axis (50, 100, 150, 200 m) is given in Table 1 (left). The altitude of the observation level was 1 km. Each row gives the results from recognizing (in fractions of unity) showers of the type symbolically indicated at the beginning of the row. The fraction of correctly classified events of a particular type is given in the main diagonal of the obtained matrix. In this case, *p* denotes protons; *h*, helium; *n*, nitrogen; *s*, sulfur; and *f*, iron nuclei. The numbers in the first row therefore mean that 74% of the showers from primary protons were classified correctly, while the remaining 26% were classified as primary helium nuclei. Those cells of the table that contain zero values correspond to an estimated classification error of <2%.

Similar results for an observation level of 4 km are given in Table 1 (right). We recall that in this case, EASs initiated by primary calcium nuclei (denoted by *c*) were calculated instead of showers from sulfur nuclei. Errors in classifying primary protons and helium and nitrogen nuclei for an observation level of 4 km are comparable to the similar values for 1 km.

CRITERIA BASED ON NEW PARAMETERS

New parameters of the spatial–angular distribution of EAS Cherenkov light equal to the ratio of integrals for two bands of Cherenkov light angular distributions were proposed in [18] (the scheme for selecting the two variables *k* and η is shown in the figure). In that work, showers were classified using the two new parameters at a certain distance from the axis. The band parameters (there are eight such parameters for two variables and fixed band width) were chosen based on phenomenological considerations.

Table 2. Results from multidimensional classification with 8 parameters (D, L) for five primary nuclei at primary energy 1 PeV and observation level 1 km (left). On the right are the results from multidimensional classification with 8 new parameters for the same conditions as in the left part of the table

	p	*h*	*n*	*s*	*f*		*p*	*h*	*n*	*s*	*f*
p	0.48	0.40	0.12	0.00	0.00	*p*	0.68	0.24	0.08	0.00	0.00
h	0.06	0.74	0.20	0.00	0.00	*h*	0.08	0.68	0.24	0.00	0.00
n	0.02	0.12	0.68	0.12	0.06	*n*	0.02	0.16	0.52	0.22	0.08
s	0.00	0.04	0.18	0.38	0.40	*s*	0.00	0.00	0.12	0.62	0.26
f	0.00	0.00	0.08	0.06	0.86	*f*	0.00	0.00	0.02	0.20	0.78

It was immediately obvious that the two new variables used in [18] for classifying showers from primary protons and nitrogen nuclei provide relatively good (with a classification error of about 10–15%) separation of showers initiated by primary protons and nitrogen and iron nuclei. The same parameters allow us to separate ≈38% of all primary protons with complete suppression of showers from helium (and heavier) nuclei, with an accuracy of up to the available figures.

Application of feature vectors with dimensions higher than 2 enables us to reduce classification errors further. The question of which method for searching the set of new variables in order to achieve good separation of groups of PCR nuclei then arises. In this work, we consider the question for the case of separating protons and helium nuclei; it is shown below that the separation of other nuclei is not seriously exacerbated. An algorithm based on successive optimization of the fraction of correctly identified proton events at four distances from the shower axis was used to search for new variables. Although this method does not lead to finding the global optimum in multidimensional parameter space, it does allow the classification error to be reduced substantially as compared to using longitudinal Hillas parameters D and L.

The results from classifying with eight D and L parameters are given in Table 2 (left). The error in classifying primary protons is 52%. Similar results for the case of new parameters optimized for the separation of primary protons are given in Table 2 (right). The error in classifying primary protons is 32%, i.e., considerably lower than when D and L are used.

CONCLUSIONS

Multidimensional Bayesian criteria for separating groups of nuclei of primary cosmic rays of superhigh energies were constructed on the basis of a full statistical simulation of the spatial–angular distribution of the Cherenkov light of extensive air showers.

Our method of classification allows us to identify a considerable (tens of per cent) part of the showers belonging to each of these groups of nuclei. Along with the application of parameters (D, L, W, $Conc$) typical of gamma astronomy, new quantities characterizing the angular image of the spatial–angular distribution of EAS Cherenkov light were found; these quantities enable us to increase the sensitivity of the method to the mass of a primary nucleus.

ACKNOWLEDGMENTS

This work was supported in part by the Federal Agency for Science and Innovation, State Contract no. 02.740.11.5092 and NSh grant no. 3517.2010.2.

REFERENCES

1. Antoni, T., Apel, W.D., Badea, A.F., et al. (The KASCADE Collab.), *Astropart. Phys.*, 2005, vol. 24, pp. 1–25.
2. Aglietta, M., Alessandro, B., Antonioli, P., et al. (The EAS–TOP Collab.), *Astropart. Phys.*, 2004, vol. 21, pp. 583–596.
3. Fowler, J.W., Fortson, L.F., Jui, C.C.H., et al., *Astropart. Phys.*, 2001, vol. 15, pp. 49–64.
4. Arqueros, F., Barrio, J.A., Bernlohr, K., et al. (The HEGRA Collab.), *Astron. Astrophys.,* 2000, vol. 359, pp. 682–694.
5. Tsunesada, Y., Kakimoto, F., Furuhata, F., et al. (The BASJE Collab.), *Proc. 30th ICRC,* Merkla, 2008, vol. 4, pp. 127–130.
6. Chernov, D.V., Korosteleva, E.E., Kuzmichev, L.A., et al. (The Tunka Collab.), *Int. J. Mod. Phys. A*, 2005, vol. 20, pp. 6799–6801.
7. Aloisio, R., Berezinsky, V.S., Blasi, P., and Ostapchenko, S., *Phys. Rev. D: Part. Fields*, 2008, vol. 77, p. 025007.
8. Wibig, T. and Wolfendale, A., *Open Astron. J.*, 2009, vol. 2, p. 95.
9. Abbasi, R.U., Abu-Zayyad, T., Al-Seady, M., et al. (The HiRes Collab.), *Phys. Rev. Lett.*, 2010, vol. 104, p. 161101.
10. Abraham, J., Abreu, P., Aglietta, M., et al. (The Pierre Auger Collab.), *Phys. Rev. Lett.,* 2010, vol. 104, p. 091101.
11. Berezinsky, V.S., Gazizov, A., Grigorieva, S., et al., *Phys. Rev. D: Part. Fields*, 2006, vol. 74, p. 043005.
12. Aharonian, F.A., Bugayov, V.V., Kettler, J., et al., *Nucl. Instrum. Methods Phys. Res. B*, 2003, vol. 201, pp. 217–229.
13. Anokhina, A.M., Antonov, R.A., Bonvech, E.A., et al., *Bull. Lebedev Phys. Instit.*, 2009, vol. 36, pp. 146–149.

14. Antonov, R.A., Anokhina, A.M., Bonvech, E.A., et al., *Proc. 31st ICRC*, Lodz, 2009, p. 0434.
15. Heck, D., Knapp, J., Capdevielle, J.N., et al., Report FZKA no. 6019, Karlsruhe: Forschungszentrum, 1998.
16. Ostapchenko, S., *Nucl. Phys. B, Proc. Suppl.,* 2006, vol. 151, pp. 143–146.
17. Fesefeldt, H.C., Technical Report no. PITHA 85-02 RWTH, 1985.
18. Galkin, V.I and Dzhatdoev, T.A., *Vestn. Mosk. Univ.*, 2010, no. 3, pp. 37–43.
19. Hillas, A.M., *Proc 19th ICRC*, La Jolla, 1985, vol. 3, p. 445.
20. Weekes, T.C., Cawley, M.F., Fegan, D.J., et al., *Astrophys. J.*, 1989, vol. 342, pp. 379–395.
21. Theodoridis, S. and Koutroumbas, K., *Pattern Recognition*, San Diego: Elsevier, 2003.