Regions of an excessive flux of cosmic rays according to data of the FIAN and MSU arrays

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Abstract

Results of a blind search for localised regions of an excessive flux of cosmic rays in the energy range from 50 TeV to 20 PeV with the data of the FIAN KLARA-Chronotron experiment, the EAS MSU array and the Prototype of the EAS-1000 array are presented. A number of regions with a significant excess of the registered flux over an expected isotropic background are found. Some of the regions are present in at least two of the data sets considered.

1 Introduction

Results of the Super-Kamiokande, Tibet-ASγ, Milagro, IceCube and some other experiments revealed localised regions of excess of primary cosmic rays (PCRs) in the TeV-PeV energy range and thus attracted considerable attention because the large-scale distribution of arrival directions of such PCRs is almost isotropic, see the recent review [1]. In the present work, we continue the series of anisotropy studies of PCRs at medium angular scales basing on the data of the KLARA-Chronotron experiment carried out at the Tian Shan station of the Lebedev Physical Institute of the Russian Academy of Sciences (FIAN) (43.04°N, 76.97°E, $P = 690$ g cm$^2$) and two experiments carried out at Lomonosov Moscow State University (MSU), one with the EAS MSU array, another one with the prototype of the EAS-1000 array (PRO-1000 in what follows) (55.70°N, 37.54°E) [2–9]. To the contrary to the previous works, the data of all three experiments are analysed with a unified method, namely the shuffling technique, which has demonstrated its effectiveness in similar anisotropy studies. This allows us to compare the results basing on the common ground.

2 Main Results

The KLARA-Chronotron experiment was carried out by FIAN together with the Central Institute for Physics Research (KFKI) of the Hungarian Academy of Sciences at a separate installation located at the Tian Shan scientific station [3]. The experiment was specifically designed for continuous studies of anisotropy of PCRs and worked simultaneously but independently of the main FIAN EAS array. Twenty three million events with energies from 50 TeV to 0.5 PeV with zenith angles in the 20°–60° range registered in 1978–1982 were selected for the present analysis. Half a million events registered with the EAS MSU array in 1984–1990 [10] and 1.3 million events of PRO-1000 (1997–1999) [11] were selected of the MSU data sets. 95% of these events correspond to PCRs in the energy range approximately 0.2–20 PeV in the first case, and from 50 TeV to 5 PeV in the latter one. Thus, the energy range of events registered with the FIAN array is fully covered
by the PRO-1000 data. The MSU events selected for the analysis have zenith angles $< 45^\circ$. The accuracy of arrival directions in all three experiments is estimated to be of the order of $3^\circ$.

The analysis of the data was performed over the whole fields of view of the experiments, namely for declination $\delta > -20^\circ$ for the FIAN experiment and $\delta > 10^\circ$ for those of MSU. The fields of view were covered with a grid with $0.2^\circ \times 0.2^\circ$ cells and scanned with circular regions of different radii from $2^\circ$ to $8^\circ$. For the further analysis, we selected regions in which the expected number of events exceeded 10000, 400 and 200 for the FIAN, PRO-1000 and EAS MSU data sets respectively. The (pre-trial) statistical significance $S$ of deviation of the real number of events registered in a particular region from the expected background was calculated with the formula by Li and Ma, traditionally used in anisotropy studies [12].

Regions found in the FIAN and MSU data sets such that the registered number of events inside them exceeds the expected background by $S > 3$ (regions with an excessive flux, REFs in what follows) are shown in Fig. 1. For convenience, the same regions of the celestial sphere are shown in all three cases. Numbers in the upper panel (the FIAN data) mark nine regions that have a close counterpart in at least one of the MSU data sets. Let us briefly discuss coincidences that are the most interesting from our point of view.

Region 2 is located in the Galactic plane at $\delta \approx 14^\circ - 28^\circ$. The maximum deviation from the expected background flux is observed in a circle of radius $4.4^\circ$ centred at $(87.2^\circ, 18.6^\circ)$. 78061 events are registered inside the circle with the expected 77061.2 events, which gives the pre-trial significance $S = 3.6$. REF 2 intersects with an extended region in the PRO-1000 data set ($\delta \approx 18^\circ - 38^\circ$) and a small region in the EAS MSU data. This part of the celestial sphere is interesting due to numerous potential sources of PCRs of TeV–PeV energies, among them the Crab Nebula (SN1054), the supernova remnants IC443, PKS 0607+17, S147 and a number of energetic pulsars including Geminga [13,14], see Fig. 2.

Region 4 is located near the Supergalactic plane. In this case, the maximum deviation from the isotropic flux almost reaches $S = 4$. The EAS MSU and PRO-1000 data sets also demonstrate similar extended REFs, for which the excess of the registered flux over the expected background exceeds 3.8 standard deviations. Possible sources of PCRs with TeV–PeV energies are not known in this part of the celestial sphere except for the close pulsar B0809+74 (0.43 kpc from the Solar system), which is capable to accelerate protons up to $\sim 4$ TeV, and pulsar B0904+77, for which these values are not known at the moment [14].

REF 8, which has the maximum deviation from the background flux in a circle of radius $2.8^\circ$ centred at $(301.6^\circ, 45.4^\circ)$, also draws certain interest. 26970 events are registered within this circle with the expected number equal to 26327.2, which gives $S = 3.9$. The region adjoins a REF in the EAS MSU data set, which has a similar size. Both regions are located in the direction to the Cygnum superbubble, which contains multiple supernova remnants, energetic pulsars and OB-associations, see Fig. 2. Some of these objects are located at distances $< 1$ kpc from the Solar system. A cocoon filled with PCRs accelerated up to energies $\sim 0.3$ PeV was discovered by the Fermi-LAT experiment approximately in this part of the sky [15].

Region 7 is of particular interest since it has close REFs in both MSU data sets, and an excess of the PCR flux over the expected background reaches almost 4 standard deviations in the EAS MSU data [7]. These regions are remarkable in that they are located in the direction to the energetic gamma-ray pulsar J1836+5925, which is similar to the Geminga pulsar and was identified as such by the orbital Fermi-LAT experiment [16,17].

The FIAN data have also been studied by a method that takes into account a dependence of absorption of extensive air showers in the atmosphere on the zenith angle [18].
3 Conclusions

There are a considerable number of localised regions with angular sizes up to several dozen degrees with an excessive flux of PCRs in the energy range from 50 TeV to 20 PeV in the data sets obtained by the KLARA-Chronotron experiment (FIAN) and with the EAS MSU and PRO-1000 arrays, and some of the regions found in different data sets overlap or intersect\footnote{The probability of overlapping regions to appear by chance equals a product of the respective probabilities for the data sets since all three sets were obtained independently.}. As a whole, anisotropy of PCRs found with the FIAN data is closer to that for PRO-1000, which is possibly due to the fact that both experiments covered close energy intervals.

A direct comparison of the presented results with the results on anisotropy of PCRs at similar angular scales obtained by other experiments is not straightforward since the most pronounced
Figure 2: Regions of an excessive flux of PCRs according to the FIAN data, Galactic supernova remnants (circles) according to [13] and gamma-ray pulsars (diamonds) according to [17].

REFs have been observed in the 1–10 TeV energy range but the picture considerably changes becoming more mosaic-like as energy grows. One can notice an intersection of one of the REFs in the FIAN data with an extended RegionB found by the Milagro experiment [19]. All in all, the obtained picture of anisotropy is closer to the results of Tibet-ASγ for energies 50 TeV and 300 TeV [20].

It is difficult to give an unambiguous answer to the question about the origin of the REFs but the regions that have close counterparts in two or all three data sets are undoubtedly interesting, especially in case they are located in parts of the celestial sphere with possible sources of PCRs of the considered energies. Still, an existence of close supernova remnants or pulsars in this case does not mean they are the reason of the REFs. In a $\sim 1 \mu G$ magnetic field, a 1 PeV proton has a gyroradius of just 1 pc, which is much less than the distance to any of the possible sources. Neutrons of these energies must also be excluded from consideration because of the too short lifetime in free state. The fraction of air showers initiated by gamma-quanta in this energy range is likely to be negligibly small [21, 22] and cannot lead to the appearance of the discovered REFs. All this makes explaining the existence of local inhomogeneities of the flux of TeV–PeV PCRs a rather complicated task. At the moment, the most popular models are those based on the influence of various configurations of Galactic magnetic fields, see [1] for a review. There is no doubt that further studies of anisotropy of PCRs in the TeV–PeV energy range are of considerable interest both for the cosmic ray physics and for understanding the structure of the Galactic magnetic field.

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References

1. Di Sciascio G., Iuppa R.//Homage to the Discovery of Cosmic Rays, the Meson-Muon & Solar Cosmic Rays, Ed. by Jorge A. Perez-Peraza, Nova Sci. Publ., N.Y. 2013.

2. Benkó G. et al.//Izv. RAN, Ser. Fiz. 2004. V. 68. P. 1599.
3. Benkó G. et al.//Nucl. Phys. B (Proc. Suppl.). 2008. V. 175. P. 541.
4. Zotov M.Yu., Kulikov G.V.//Bull. Russ. Acad. Sci. Physics. 2004. V. 68. P.1791.
5. Zotov M.Yu., Kulikov G.V.//Bull. Russ. Acad. Sci. Physics. 2007. V. 71. P. 483.
6. Zotov M.Yu., Kulikov G.V.//Bull. Russ. Acad. Sci. Physics. 2009. V. 73. P. 574.
7. Zotov M.Yu., Kulikov G.V.//Astronomy Letters. 2010. V.36. P.645.
8. Zotov M.Yu., Kulikov G.V.//Bull. Russ. Acad. Sci. Physics. 2011. V. 75. P. 342.
9. Zotov M.Yu., Kulikov G.V.//Astron. Lett. 2012. V.38. P.731.
10. Vernov S.N. et al.//Proc. 16th ICRC. Kyoto. 1979. V. 8. P. 129.
11. Fomin Yu.A. et al.//Proc. 26th ICRC. Salt Lake City. 1999. V. 1. P. 286.
12. Li. T.-P., Ma Y.-Q.//Astrophys. J. 1983. V. 272. P. 317.
13. Green D.A.//Bull. Astron. Soc. India. 2009. V. 37. P. 45.
14. Manchester R.N. et al.//Astron. J. 2005. V. 129. P. 1993.
15. Ackermann, M. et al.//Science. 2011. V. 334. P. 1103.
16. Abdo A.A. et al.//Astrophys. J. Suppl. Ser. 2009. V. 183. P. 46.
17. Abdo A.A. et al.//Astrophys. J. Suppl. Ser. 2013. V. 208. P. 17.
18. Gudkova E.N. et al.//Theses 33rd Russ. Cosmic Ray Conf. 2014. Dubna. P. 44.
19. Abdo A. et al.//Phys. Rev. Lett. 2008. V. 101. P. 221101.
20. Amenomori M. et al.//Science. 2006. V. 314. P. 439.
21. Aglietta M. et al.//Astropart. Phys. 1996. V. 6. P. 71.
22. Chantell M.C. et al.//Phys. Rev. Lett. 1997. V. 79. P. 1805.