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Estimation of the sidereal time anisotropy of cosmic rays by Yakutsk EAS array data

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Abstract. The harmonic analysis in shower distribution in sidereal time by using all events registered by the Yakutsk array from October 1991 to May 2000 has been carried out. The estimation of an amplitude at $E_0 \approx 10^{17}$ eV for 715216 events selected by the trigger-500 is made, and at $E_0 \approx 10^{18}$ eV the showers selected by the trigger-1000 are used. To determine the amplitude characterizing a degree of anisotropy of primary radiation we have analyzed the contribution due to both the inhomogeneity of the sky survey by the array, and seasonal-diurnal variations in frequency of registered showers.

1 Introduction

In determination of the main sources of cosmic rays the data on the anisotropy of the particle flux for different energies are of major importance. To investigate the cosmic ray anisotropy in the range of $E_0 > 10^{17}$ eV the harmonic analysis of the event distribution in right ascension (RA) is used as one of the methods (Linsley, 1975). The large statistics is required for reliable estimations because the anisotropy degree is small.

At the Yakutsk EAS array more than 10^6 events have been accumulated. Mainly, these are showers with$\sim 10^{17}$ eV near the registration threshold. The determination of individual parameters (the arrival direction of the primary particle and shower core coordinates) were carried out till the middle of 1995 only in showers which satisfied the definite criteria. Since autumn of 1982 the following condition was used as the criteria: it should be registered more than 4 particles at 3 stations. It allowed to select the events in which the individual parameters were determined with the best accuracy, but they accounted for (25-30)% of the total number of showers registered at the array. At the same time to estimate the anisotropy near the EAS array threshold, all events can be used if we investigate their distribution in sidereal time as it is carried out in experiments in which the primary particle direction is not determined.

In the process of the long-term operation of the EAS array, the registration of events is sometimes interrupted by technical and technological reasons. The effective area of event registration can also be changed due to the temporal failure of individual detectors. This can result in the inhomogeneous sky survey at different time instants both of the solar and sidereal days. Besides, near the threshold of array the atmospheric conditions, which have diurnal and seasonal variations, influence the frequency of the shower event registration. Since the direction survey conditions at different right ascensions depend on sidereal time, the inhomogeneity of the sky survey and variation of the atmospheric conditions can make a considerable contribution to measurements, which distorts the true anisotropy of the primary radiation, and at examination of rihgt ascentions . The degree of influence on the results of the analysis can be different in different experiments; it depends on a variety of factors, such as climate conditions, the design of trigger array (its effective area depends on temperature and pressure), criteria of event selection, possible systematic errors in determining the parameters and energy of showers under various atmospheric conditions, and the frequency of short-term switching off of the array at some moments of the day.

In previous works (Pravdin et al., 1999; 2001) we suggested the methods to estimate the contribution the above mentioned factors into the observation data. It was shown that the significant amplitude of the first harmonic at 10^{17} eV found in the earlier work (Mikhailov and Pravdin, 1997) was defined by operations of the Yakutsk EAS array and atmospheric variations of the shower frequency.

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2 Taking account of inhomogeneity of the sky survey and atmospheric variation

Most often, the array is switched off by technical and technological reasons in the daytime; thus, these periods of time are inhomogeneously distributed across the day. The inhomogeneity of sky survey is also affected by variations of the effective area caused by temporary failure of certain observation stations. In the Yakutsk experiment, a list of time moments at which registration was switched off and on is maintained, and information on stations actually operating at every instance of time is registered. Any change in the configuration of the trigger system is fixed as the beginning of a new period even if the array was not switched off.

The Yakutsk EAS array selects a shower when an event is registered simultaneously by three neighboring stations forming a triangle. The selection scheme is based on two types of station configurations. The first one consists of stations located at the nodes of a triangular grid with a side of 500 m (Trigger-500); the other one is similar, but the side is 1000 m (Trigger-1000). In the first case, the registration threshold corresponds to showers with the energy of $(3-5)\cdot 10^{16}$ eV; in the second case, the energy is about 10^{18} eV. For showers registered in the vicinity of the threshold, the effective area is proportional to the number of triangles in the trigger-500 or trigger-100 that actually register the events. In order to determine the degree of relative inhomogeneity of the sky survey over the whole period of observation, the total number of operating trigger triangles was counted for every minute of each day. The values obtained were normalized by the average value over all minutes. For the same periods in solar time, similar distributions over minutes in sidereal and antisidereal time can be easily obtained. Such a method takes into account both the switching off the array on the whole and the change of area due to temporal failure of the individual station.

The proportionality of the collection area of the events to number of operating triangles is violated as the energy increases. But at sufficiently high energies this area is constant and doesn't change practically during the short-time switching off of one station if we restrict it within the trigger location. For such energies the irregularity of the sky survey can be estimated by the list of periods considering the effective area as a constant for every minute.

The inhomogeneity of the sky survey results in different observation conditions for different magnitudes of the right ascension, which depend on the distribution of the events over the zenith angle and the latitude of the array. In order to determine the sky observation conditions in the RA, it is necessary to determine the zenith-angular distribution of the showers. The calculation of the inhomogeneity of the sky survey in the RA will be carried out with use of distribution in sidereal time. The contribution to the narrow interval of the RA from the part of the sky that is visible by the array at the fixed zenith angle θ and at the fixed value of the sidereal time t_S is proportional to the number of events in the zenith-angular distribution of the showers multiplied by the value corresponding to t_S in the relative distribution of the sky survey in sidereal time. In order to find the total distribution, these contributions were summed over all azimuth angles from 0 to 2π (assuming that they are distributed uniformly), as well as over all θ and t_S.

To take into account the inhomogeneity of the sky survey when determining the anisotropy vector parameters, the number of events in a certain minute-long interval of time or RA was normalized by the corresponding value in the relative distribution of the observation conditions.

To take into account the influence of the variations caused by diurnal and seasonal cycles on the frequency of the events, the distribution of the same events in "antisidereal" time is analyzed using the method suggested in (Farley and Storey, 1954). The vector that appears due to seasonal variations and contributes to the result observed in the sidereal time equals to the antisidereal vector in absolute value and has the phase mirror symmetric with respect to the solar one.

The contribution of seasonal variations into summary vector in right ascension can be estimated as in the case of the calculation of the relative distribution of the sky survey in RA. In this calculation the experimental shower distribution by a zenith angle is also used and instead of the installation survey distribution in sidereal time the analytical dependence corresponding to the atmospheric contribution to the sidereal vector is used.

3 Data analysis

To estimate the degree of anisotropy of cosmic rays at $E_0 \approx 10^{17}$ eV we have analyzed the distribution of all trigger-500 events in sidereal time from October 1991 to May 2000 (sampling-I). All showers with $E_0 \approx 10^{18}$ eV selected by the trigger-1000 for the same time period have been analyzed analogously (sampling-II). Besides, we present here the analysis result of the distribution of $3\cdot 10^{16} - 3\cdot 10^{17}$ eV events both in sidereal time and in right ascension for the period of September 1982 to May 2000 (sampling-III). In the sampling-III we have selected events in which at 3 stations forming a cell of trigger-500 the particle density is more than $1\ m^{-2}$ (4 particles at total area of the detectors) and a zenith angle $< 60°$.

Table 1 lists the amplitudes $r(\%)$ and phase φ (hours) for vectors of the first and second harmonics in solar, sidereal and antisidereal time for the sampling-I and with and without consideration for the influence of inhomogeneity of the sky survey by the EAS array. The harmonic parameters obtained for the distribution itself of the sky survey are also presented. The analogous results for the sampling-II are listed in Table 2.

From the above results it is seen that the inhomogeneity of observation conditions for the different time of day for the considered operation period of the Yakutsk array for the first harmonic is comparable with the analysis result in shower distribution, and its accounting decreases essentially the amplitude and changes the phase of all variables. With consid-

Table 1. Parameters of anisotropy vectors for the sampling-I at $E_0 \approx 10^{17}$ eV. The number of events is 715216.

Vector	H	Sky survey	
		$r,\%$	φ,h
Solar	1	2.60	23.3
	2	0.64	7.5
Sidereal	1	1.27	7.9
	2	0.09	19.6
Antisidereal	1	1.01	14.0
	2	0.30	15.1
		Distribution of events Without regard to survey	
		$r,\%$	φ,h
Solar	1	3.11 ± 0.17	22.3 ± 0.21
	2	0.89 ± 0.17	7.9 ± 0.73
Sidereal	1	1.57 ± 0.17	8.3 ± 0.41
	2	0.37 ± 0.17	8.9 ± 1.8
Antisidereal	1	0.96 ± 0.17	12.1 ± 0.68
	2	0.91 ± 0.17	15.2 ± 0.71
Sidereal$-\boldsymbol{VAR}$	1	0.61 ± 0.24	8.1 ± 1.5
	2	1.16 ± 0.24	11.6 ± 0.79
		Distribution of events With regard to survey	
		$r,\%$	φ,h
Solar	1	0.86 ± 0.17	18.9 ± 0.76
	2	0.25 ± 0.17	9.3 ± 2.6
Sidereal	1	0.28 ± 0.17	10.1 ± 2.3
	2	0.46 ± 0.17	8.6 ± 1.4
Antisidereal	1	0.44 ± 0.17	6.2 ± 1.5
	2	0.61 ± 0.17	15.1 ± 1.1
Sidereal$-\boldsymbol{VAR}$	1	0.27 ± 0.24	17.1 ± 3.4
	2	$0.67\pm$	$12.7\pm$

Table 2. Parameters of anisotropy vectors for the sampling-II at $E_0 \approx 10^{18}$ eV. The number of events is 20490.

Vector	H	Sky survey	
		$r,\%$	φ,h
Solar	1	2.81	23.0
	2	0.86	7.4
Sidereal	1	1.59	7.3
	2	0.17	19.2
Antisidereal	1	1.09	14.1
	2	0.23	16.1
		Distribution of events Without regard to survey	
		$r,\%$	φ,h
Solar	1	5.1 ± 1.0	20.5 ± 0.75
	2	0.14 ± 1.0	6.5 ± 24
Sidereal	1	3.4 ± 1.0	6.8 ± 1.1
	2	2.0 ± 1.0	4.4 ± 1.9
Antisidereal	1	1.6 ± 1.0	7.7 ± 2.4
	2	2.1 ± 1.0	13.5 ± 1.8
Sidereal$-\boldsymbol{VAR}$	1	2.4 ± 1.4	5.1 ± 2.2
	2	$2.5\pm$	$8.0\pm$
		Distribution of events With regard to survey	
		$r,\%$	φ,h
Solar	1	3.3 ± 1.0	18.5 ± 1.2
	2	0.7 ± 1.0	19.7 ± 5.8
Sidereal	1	1.8 ± 1.0	6.3 ± 2.1
	2	2.1 ± 1.0	4.7 ± 1.8
Antisidereal	1	2.0 ± 1.0	5.3 ± 1.9
	2	1.9 ± 1.0	13.3 ± 1.9
Sidereal$-\boldsymbol{VAR}$	1	0.7 ± 1.4	0.2 ± 7.6
	2	$1.3\pm$	$9.0\pm$

eration for the sky survey, the anisotropy of $> 3 \cdot \sigma$ amplitude in solar time and some influence of seasonal variations remain. Denote the vector, occurring because of seasonal variations and contributing to the result observed in sidereal time, as $\boldsymbol{VAR}$. In next to the last rows of Tables 1 and 2 an estimation of the anisotropy of primary radiation in sidereal time after the subtraction of the vector $\boldsymbol{VAR}$ is given. For the first harmonic at $E_0 \approx 10^{17}$ eV for the sampling-I the amplitude and phase are $r_1(I) = (0.27 \pm 0.24)\%$, $\varphi_1(I) = (17.1 \pm 3.4)$ h; at $E_0 \approx 10^{18}$ eV for the sampling-II $r_1(II) = (0.7 \pm 1.4)\%$, $\varphi_1(II) = (0.2 \pm 7.6)$ h.

The influence of the inhomogeneity of the sky survey for the second harmonic is significant smaller. Variations in solar time are insignificant. Therefore to estimate the anisotropy of primary particles we can use the parameters of sidereal vector without considering the contribution of the vector $\boldsymbol{VAR}$. For the sampling-I at $E_0 \approx 10^{17}$ eV we obtain $r_2(I) = (0.46 \pm 0.17)\%$, $\varphi_2 = (8.6 \pm 1.4)$ h.

Parameters of the anisotropy vectors with consideration for the sky survey for the sampling-III are given in Table 3. In this case we have also analyzed the distribution of showers in right ascension. The average energy of showers in this sampling is $1.7 \cdot 10^{17}$ eV, the characteristic obtained both in sidereal time and in RA are in agreement with the results for the sampling-I. The contribution of atmospheric variations of $\boldsymbol{VAR(RA)}$ is determined starting from the parameters of the $\boldsymbol{VAR}$ for the given sampling and with consideration for the zenith-angular distribution of the events.

Table 3. Parameters of anisotropy vectors for the sampling-III at $E_0 = 1.7 \cdot 10^{17}$ eV. The number of events is 172756.

Vector	H	$r,\%$	φ,h
Solar	1	1.08 ± 0.34	1.6 ± 1.2
	2	1.06 ± 0.34	6.2 ± 1.2
Sidereal	1	0.94 ± 0.34	18.7 ± 1.4
	2	0.42 ± 0.34	12.2 ± 3.1
Antisidereal	1	0.83 ± 0.34	12.4 ± 1.6
	2	0.96 ± 0.34	20.9 ± 1.4
Sidereal$-\boldsymbol{VAR}$	1	0.88 ± 0.5	22.3 ± 2.2
	2	0.76 ± 0.5	5.2 ± 2.5
RA	1	0.55 ± 0.34	18.1 ± 2.4
	2	0.98 ± 0.34	9.9 ± 1.3
RA$-\boldsymbol{VAR(RA)}$	1	0.49 ± 0.5	22.7 ± 3.9
	2	1.00 ± 0.5	8.6 ± 1.9

4 Conclusions

The results obtained in this study show that the inhomogeneity of the sky survey must be taken into account when analyzing data with the purpose of estimating the anisotropy of the primary radiation. The inhomogeneity arises due to short-term switching off of the array and variations of its effective area. In addition, seasonal variations of the frequency of events of atmospheric origin make a contribution to the vector observed both in sidereal time and in right ascension. This contribution can be estimated by the vector in antisidereal time and the zenith-angular distribution of the showers.

Taking account of the distorting factor, at $E_0 \approx 10^{17}$ eV the statistical significant amplitude of the first harmonic is not observed, it is smaller than 0.8% at the probability 0.95. The amplitude of the second harmonic in sidereal time for the sampling-I is $r_2(I) = (0.46 \pm 0.17)\%$, the probability of chance in the isotropic distribution is equal to 0.025.

By data of the sampling II at $E_0 \approx 10^{18}$ eV the statistical significant anisotropy of the first and second harmonics is not observed: the amplitude of the first harmonic is smaller than 3.0% with the probability 0.95 and for the second harmonic it is 3.3%. In the present work we have analyzed only the part of showers registered with the trigger-1000. The analysis of all showers will allow to increase statistics in this energy region in 3-4 times.

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