# Large-scale anisotropy of the cosmic-ray muon flux in Kamiokande

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The large-scale anisotropy of cosmic-ray primaries in the celestial coordinate was studied using cosmic-ray muons recorded in a large water Cherenkov detector, Kamiokande. The right-ascension distribution of the muon arrival directions deviated from an isotropic distribution with a 2.8 standard deviation, and agreed well with the first harmonics with an amplitude of $(5.6\pm1.9)\times10^{-4}$ and a phase of $8.0°\pm19.1°$. This is the deepest underground observation of the large-scale anisotropy of cosmic rays, and agrees with observations with other underground experiments and extensive air-shower array experiments. [S0556-2821(97)05013-3]

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The time variations of the cosmic-ray muon flux in deep underground observatories are of interest in both geophysics and astrophysics. In geophysics, the cosmic-ray muon rate reflects a change in the density distribution of the upper atmosphere in the process of the production and decay of parent pions [1]. In a previous paper [2], a significant correlation between the time variation of the cosmic-ray muon rate observed by the Kamiokande-II underground water Cherenkov detector and the time variation in the Matsushiro underground muon observatory was reported. It was also discussed that these time variations agree well with numerical calculations based on the atmospheric temperature data from the Wajima Observatory of the Japan Meteorological Agency.

In astrophysics, the sidereal time variation of the muon flux is interpreted as the right-ascension distribution of the primary cosmic-ray flux in celestial coordinates, which provides information about the large-scale anisotropy of the primary cosmic-ray intensity in and around the solar system. Several shallow underground observatories have reported [3–14] on the anisotropy of cosmic-ray muons with a primary proton energy range of $\sim10^{11}$ eV to $\sim5\times10^{12}$ eV. On the other hand, extensive air-shower-array experiments [15–18] have also observed anisotropies in the primary proton energy range from $\sim10^{13}$ eV to $\sim10^{14}$ eV. Accordingly, no underground observation in the energy range of around $\sim10^{13}$ eV has been reported which would connect the results of two different observation methods in two different primary energy ranges. In this paper, the large-scale anisotropy of the cosmic-ray muon flux in the Kamiokande detector recorded over seven years is presented.

The Kamiokande(-II and -III) detector is located 2700 meters of water equivalent (m.w.e.) underground in the Kamioka mine (36.42°N, 137.31°E), about 250 km west of Tokyo. A cylindrical steel tank contains 2400 tons of water viewed by 948 20-in. photomultiplier tubes (PMT's) covering 20% of the tank inner surface. This inner detector is surrounded by a $4\pi$ steradian water anticounter that is at least 1.2 m thick, viewed by 123 20-in. PMT's. The muon energy threshold at the detector site is $1.2\times10^{12}$ eV [19], which corresponds to a primary cosmic-ray proton energy of $1.2\times10^{13}$ eV [20]. More detailed descriptions of the

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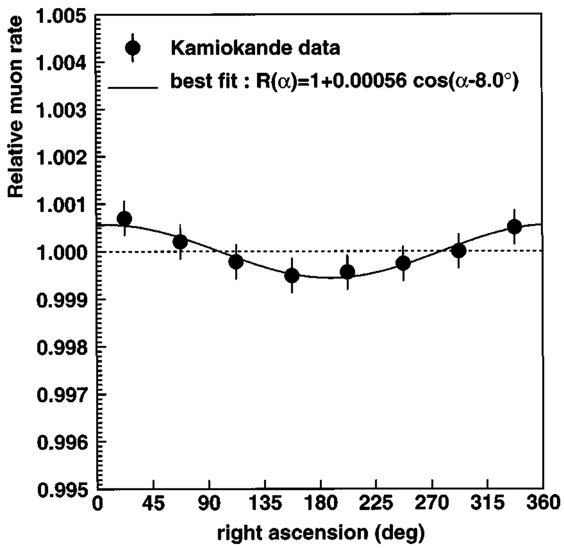


FIG. 1. Cosmic-ray muon rate as a function of the right-ascension of the arrival direction in Kamiokande. The average muon rate was normalized to be 1. The solid line shows the best-fit curve, assuming the first Fourier harmonics: $R(\alpha)=1+r_0\cos(\alpha-\alpha_0)$, where $r_0=5.6\times10^{-4}$ and $\alpha_0=8.0°$.

Kamiokande-II and Kamiokande-III detectors are given in Ref. [21] and Ref. [22], respectively.

Events with a total photoelectrons (p.e.) larger than 1000 p.e. were selected as cosmic-ray muons. In fact, all of the events which satisfied this condition were cosmic-ray muons, except for small contamination of events from atmospheric neutrinos, whose rate was less than 1 event per day, about $3\times10^{-5}$ of the muon flux. Systematic errors due to the change of the PMT gain, the attenuation length of the water, and history of dead PMT's, were corrected to be less than 0.1%.

Data from January 1987 to December 1989 (Kamiokande-II) and from January 1991 to December 1994 (Kamiokande-III) were used in the analysis. The total observation time was $1.790\times10^8$ s, which corresponded to 81% of the elapsed time. The number of muon events in this period was 58 840 472, and the averaged muon rate was 0.33 Hz. The nonuniformity of the observation period in the sidereal time was less than 3%.

Most of the muons in Kamiokande travel almost downward, because of a large rock overburden in the horizontal direction. The average of the angular difference between the right ascension of the muon arrival direction ($\alpha_\mu$) and the right ascension of the zenith ($\alpha_z$) was found to be $\overline{|\alpha_\mu-\alpha_z|}=28°$. To calculate the right ascension, we fixed the muon arrival direction to be zenith, since this does not cause a large error in the right-ascension distribution, for which we divide the data into eight bins only. The anisotropy of the muon flux is obtained in the following way. The observation period ($T_i$) and the number of muon events ($N_i$) from the $i$th right-ascension bin are counted on a second-by-second basis. The relative error of $T_i$ is less than $10^{-6}$. The relative muon rate from the $i$th celestial bin $[R_{\rm data}(\alpha_i)]$ and its statistical error $[\Delta R_{\rm data}(\alpha_i)]$ are calculated using

$$R_{\rm data}(\alpha_i)=N_i/T_i/\overline{(N_i/T_i)} \qquad (1)$$

and

$$\Delta R_{\rm data}(\alpha_i)=\sqrt{N_i}/T_i/\overline{(N_i/T_i)}. \qquad (2)$$

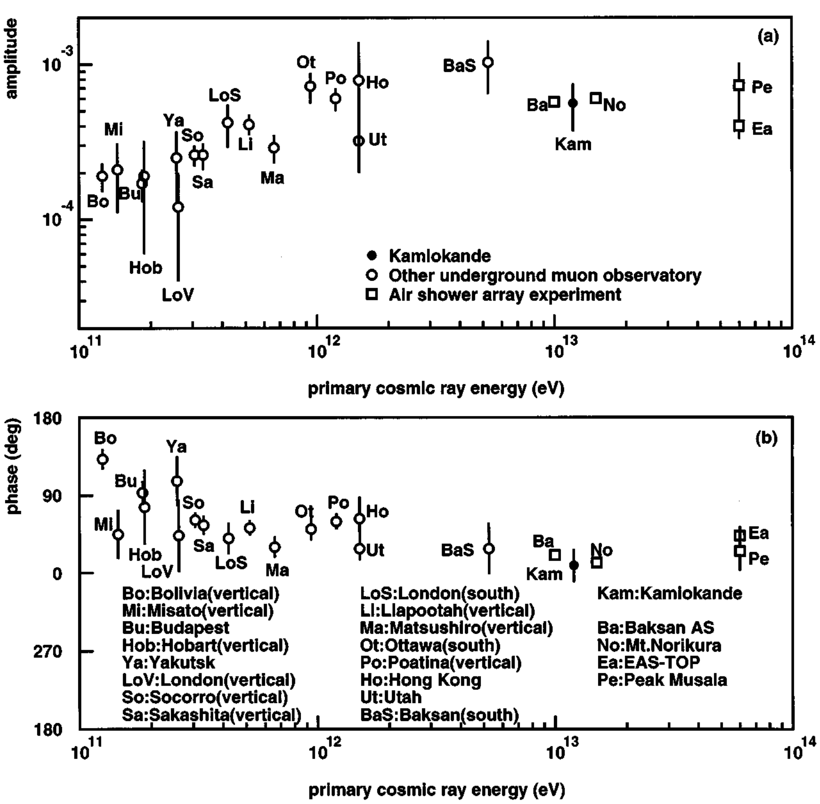


FIG. 2. Anisotropy of the cosmic-ray primaries obtained by underground muon observations and extensive air-shower-array experiments. The amplitude (a) and phase (b) of the first Fourier harmonics in the sidereal-time variation are plotted as a function of the primary cosmic-ray energies. They are Kamiokande (●), other underground muon observatories (○), and extensive air-shower-array experiments (□). The experimental groups in the figure are Bo (Bolivia vertical [6]), So (Socorro vertical [6]), Mi (Misato vertical [5]), Bu (Budapest [5]), Hob (Hobart vertical [5]), Ya (Yakutsk [5]), LoV (London vertical [5]), Sa (Sakashita vertical [9]), LoS (London south [4]), Li (Liapootah vertical [12]), Ma (Matsushiro vertical [13]), Ot (Ottawa south [3]), Po (Poatina vertical [11]), Ut (Utah [10]), Ho (Hong Kong [7]), BaS (Baksan south [8]), Ba (Baksan air shower [17]), No (Mt. Norikura [15]), Pe (Peak Musala [16]), and Ea (EAS-TOP [18]).

$R_{\rm data}(\alpha_i)$ is plotted in Fig. 1. The distribution shows a clear first Fourier harmonics with the phase in the direction of $\alpha=0°–45°$ bin.

This sidereal-time distribution $[R(\alpha)]$ is compared with the isotropic distribution plus the first Fourier harmonic:

$$R_{\rm fit}(\alpha)=1+r_0\cos(\alpha-\alpha_0), \tag{3}$$

where $r_0$ is amplitude of the first Fourier harmonic, and $\alpha_0$ is the phase in the right ascension. The agreement between $R_{\rm data}(\alpha)$ and $R_{\rm fit}(\alpha)$ is examined using $\chi^2$, defined by

$$\chi^2\equiv\sum_{i=1}^{8}\left(\frac{R_{\rm data}(\alpha_i)-R_{\rm fit}(\alpha_i)}{\Delta R_{\rm data}(\alpha_i)}\right)^2. \tag{4}$$

The amplitude and the phase, which minimize $\chi^2$, were calculated to be $r_0=5.6\times10^{-4}$ and $\alpha_0=8.0°$. The minimum $\chi^2$ ($\chi^2_{\rm min}$) was obtained to be 0.269. On the other hand, $\chi^2$ for the isotropic distribution ($r_0=0$) was calculated to be $\chi^2_0=9.554$. Since $\chi^2_{\rm min}$ is smaller than $\chi^2_0$ by 9.285, the anisotropy of the right-ascension distribution is statistically significant. The standard errors of the amplitude and phase were obtained from $\chi^2=\chi^2_{\rm min}+2.3$. Finally, $r_0$ and $\alpha_0$ were found to be

$$r_0=(5.6\pm1.9)\times10^{-4} \tag{5}$$

and

$$\alpha_0=(8.0°\pm19.1°), \tag{6}$$

respectively.

The following analysis was performed in order to check for any possible systematic errors related to the stability of the observation. The period of ''sidereal one day'' was changed from 23 h 55 min 05.11 s to 23 h 57 min 03.07 s in every 0.92 s. The corresponding fake right-ascension distributions were calculated in the same way as in the method for the real one sidereal day. Among 130 amplitudes of the first Fourier harmonics of the right-ascension distributions, the amplitude for the real one sidereal day (23 h 56 min 04.09 s) is the largest. This supports the idea that the sidereal anisotropy observed in Kamiokande is not due to systematic errors related to the instability of the observation.

Figure 2 shows the amplitude [Fig. 2(a)] and phase [Fig. 2(b)] of the first Fourier harmonics obtained by the Kamiokande experiment together with observations by other deep underground muon experiments [3–14] and extensive air-shower-array experiments [15–18]. The Kamiokande result is the deepest underground observation, and agrees with other experiments in both amplitude and phase.

The following interpretation for the amplitude and phase shown in Fig. 2 is widely accepted [23,24]. The anisotropies from shallow underground muon observatories show an amplitude of $\sim2\times10^{-4}$ and a phase of $\sim100°$. These are thought to be modulated by the solar magnetic fields because cosmic-ray primaries with an energy of $\sim10^{11}$ eV are completely diffused in the solar system, and lose their original direction from outside of the solar system. On the other hand, the anisotropies in the energy range $\sim10^{14}$ eV, obtained from extensive air-shower-array experiments, show an amplitude of $\sim10^{-3}$ and a phase of $\sim30°$. Since primaries with an energy larger than $10^{13}$ eV maintain their original direction in the solar magnetic field, they are thought to be as reflecting local structure of the galactic magnetic field around the solar system. Underground muon anisotropies between $\sim10^{11}$ eV and $\sim5\times10^{12}$ eV are just in between, and reflect the effect of the solar magnetic field as well as that of the galactic magnetic field.

The Kamiokande results agree well with the air-shower experiments of a similar energy range, and smoothly connect from an energy range of $\sim10^{12}$ eV to that of $\sim10^{14}$ eV. This result may provide some knowledge about theoretical models [15,24], which explain the structure of the galactic magnetic field and its interference with the solar magnetic field.

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