

SOLAR TRI-DIURNAL VARIATION OF COSMIC RAYS  
IN A WIDE RANGE OF RIGIDITY

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ABSTRACT

Solar tri-diurnal variations of cosmic rays have been analyzed in a wide range of rigidity, using data from neutron monitors, and the surface and underground muon telescopes for the period 1978-1983. The rigidity spectrum of the anisotropy in space is assumed to be of power-exponential type as  $(P/\gamma P_0)^{\gamma} \exp(\gamma - P/P_0)$ . By means of the best-fit method between the observed and the expected variations, it is obtained that the spectrum has a peak at  $P (= \gamma P_0) \approx 90$  GV, where  $\gamma \approx 3.0$  and  $P_0 \approx 30$  GV. The phase in space of the tri-diurnal variation is also obtained as 7.0 hr (15 hr and 23 hr LT), which is quite different from that of  $\sim 1$  hr, arising from the axis-symmetric distribution of cosmic rays with respect to the IMF.

### 1. Introduction

Studies of higher harmonics in the daily variation of cosmic rays provide valuable informations as to the nature of the cosmic ray modulation in the heliosphere. So far a great many investigation has been performed of the solar tri-diurnal variation, and some of its characteristic natures have been revealed; its extra-terrestrial origin and also its rising spectrum with rigidity (e.g., Bieber et al., 1983; Mori et al., 1984; hereafter referred to as Paper I).

These results, however, have not yet been firmly founded because of the statistical uncertainty of the data used which is largely due to limited rigidity range. In particular, there is a wide divergence of opinion as to the direction of the anisotropy; some analyses reported  $\sim 1$  hr direction, while some obtained  $\sim 7$  hr direction. This discrepancy is crucial for determining the modulation mechanism; 1 hr direction is in favor of the 'loss-cone' model (Fujii, 1971) or the model of Bieber et al. (1983), whereas 7 hr direction requires other kind of model such as the one presented by Munakata and Nagashima (1985; in this issue).

In the present analysis, we try to obtain a definite form of the anisotropy responsible for the averaged tri-diurnal variations over 6 years (1978-1985), using data in a wide range of rigidity from neutron monitors to underground muon telescopes, which respond to the effective rigidity of 10 to 600 GV.

### 2. Analysis of Data

The present experimental data include 2 to 6-year averages of neutron monitor data in a worldwide network (36 stations from the polar to the equatorial regions) and 6-year averages of the surface (NAGOYA) and underground (MISATO and SAKASHITA) muon telescopes for the period 1978-1983.

Fig. 1 illustrates the summation harmonic dial, showing clearly the persistency of year-to-year changes of the observed tri-diurnal variations of three muon telescopes at NAGOYA (surface) for 1971-1983, at MISATO

(34 m.w.e. in depth underground) for 1974-1983 and at SAKASHITA (80 m.w.e. in depth underground) for 1978-1983. In the present analysis, 6-year averages over 1978-1983 were used; of 13 directional components at NAGOYA, 9 components at MISATO and 10 components at SAKASHITA, and these are listed in Paper I.

SOLAR TRI-DIURNAL VARIATION  
(Vertical component)

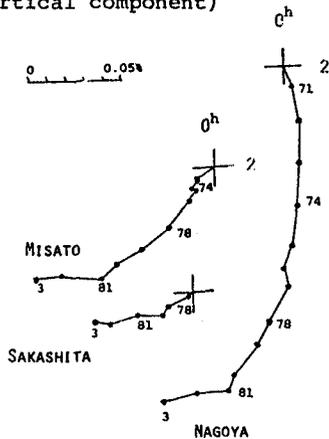


Fig. 1 Observed solar tri-diurnal variations of V-component at NAGOYA, MISATO and SAKASHITA in summation dial.

In order to derive the 3rd order anisotropy, the tri-diurnal variation produced by the anisotropy with a certain form of the rigidity spectrum  $G(P)$ , will be compared with the observed results. In the analysis,  $G(P)$  is assumed to be of power-exponential type as

$$G(P) = (P/\gamma P_0)^\gamma \exp(\gamma - P/P_0) \quad (1)$$

Evidently,  $G(P)$  becomes maximum at  $P = \gamma P_0$  for  $\gamma > 0$ , and is normalized to unity.

The expected 3rd harmonic components ( $A_{ij}$ ,  $B_{ij}$ ) for  $j$ -th components telescopes of  $i$ -th station including neutron monitor station, are related to the space harmonic components ( $X$ ,  $Y$ ) by the following equations with coupling coefficients  $c_{ij}$  and  $s_{ij}$  as

$$A_{ij} = (c_{ij}X + s_{ij}Y), \quad B_{ij} = (-s_{ij}X + c_{ij}Y) \quad (2)$$

The coefficients  $c_{ij}$  and  $s_{ij}$  were derived from the differential coupling coefficients  $dc_{ij}$  and  $ds_{ij}$  given by Fujimoto et al. (1984). The best-fit parameters satisfying the following equation are determined.

$$\sum_{ij} w_{ij} \{ (A_{ij} - a_{ij})^2 + (B_{ij} - b_{ij})^2 \} = \text{minimum} = \delta^2 \quad (3)$$

In Eq. (3), the weight  $w_{ij}$  is given for the observed  $a_{ij}$  and  $b_{ij}$  so as to balance the difference in the number of the data used in the rigidity interval; 6 divisions in all the ranges of 10 to 600 GV to have equal weight. Also each vector in all the muon components was subtracted from the reference component to eliminate the atmospheric temperature effect; in this analysis, V-component for NAGOYA and MISATO and SE-component for SAKASHITA were taken as the reference.

### 3. Results and Discussions

The contour map of equal  $\delta^2$ 's obtained from the residual sum of the

observed vectors and the expected vectors computed by Eq. (2), is shown against  $\gamma$  and  $P_0$  in Fig. 2. As is seen in the figure, minimal  $\delta^2$  region

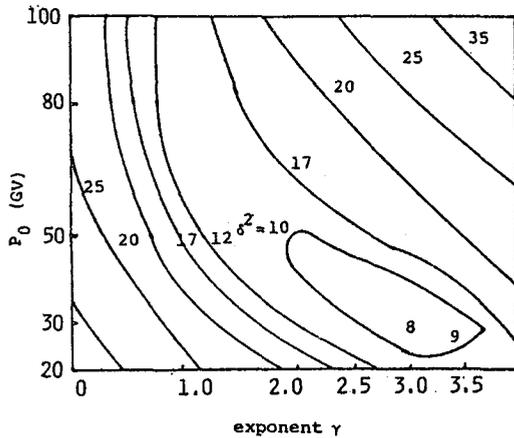


Fig. 2 Contour map of equal  $\delta^2$  plotted against  $\gamma$  and  $P_0$ , showing minimal  $\delta^2$  ( $\approx 8$ ) for  $\gamma \approx 3.0$  and  $P_0 \approx 30$  GV.

locates in relatively narrow regions of  $\gamma$  and  $P_0$ -value. It is noted that in these regions the product of  $\gamma$  and  $P_0$  keeps almost invariant as  $\gamma P_0 \approx 90$  GV. The best-fit parameters were obtained as that  $\gamma \approx 3.0$  and  $P_0 \approx 30$  GV.

The direction (phase) of the anisotropy was obtained as 7.0 hr. It is also noted that this direction shows almost constant value for the above minimal region.

The fitness of the reproduced variations computed by Eq. (2) in the best-fit case to the observed ones is shown in Fig. 3; (a) for NAGOYA, (b) for MISATO and (c) for SAKASHITA, respectively. The observed vectors are shown with the solid circles (●) and the

reproduced ones with the open circles (○). Also the reference component mentioned above is shown by the symbol (⊙) and the origin of the diagram in the best-fit case is given by the cross (X). A fairly good agreement can be seen between two patterns drawn by connecting each observed point (solid line) and each reproduced point (dotted line) for each station.

The present analysis can obtain a definite parameter set as;  $\gamma \approx 3.0$  and  $P_0 \approx 30$  GV. As shown in Paper I, where only muon data at the above three stations (NAGOYA, MISATO and SAKASHITA) were used, parameter set ( $\gamma, P_0$ ) rather spreads as;  $\gamma = 2 \sim 12$  and  $P_0 = 50 \sim 8$  GV. The present form can be derived by adding neutron monitor data to Paper I. Note that the observed vectors of neutron monitors from 36 stations are so divergent even if in the best-fit case, which may be largely due to inaccurate barometric correction in the data.

On the other hand, the direction (phase) of the anisotropy in space was obtained as  $\sim 7$  hr ( $\sim 15$  hr and  $\sim 23$  hr LT). So far there has been a wide divergence of opinion as to the direction;  $\sim 1$  hr direction was reported by the analyses of neutron monitor data alone, while  $\sim 7$  hr direction was reported by using muon data. The former is in favor of the 'loss-cone' model (Fujii, 1971) or the model of Bieber et al. (1983), arising from the axis-symmetric distribution of cosmic rays with respect to the IMF. On the other hand, the latter requires other kind of model such as the one presented by Munakata and Nagashima (1985, in this issue). The present result provides a firm basis for the latter model.

A further analysis would be necessary to derive the detailed form and its year-to-year variation.

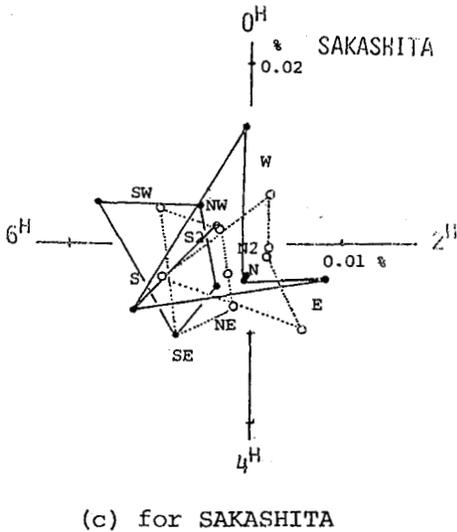
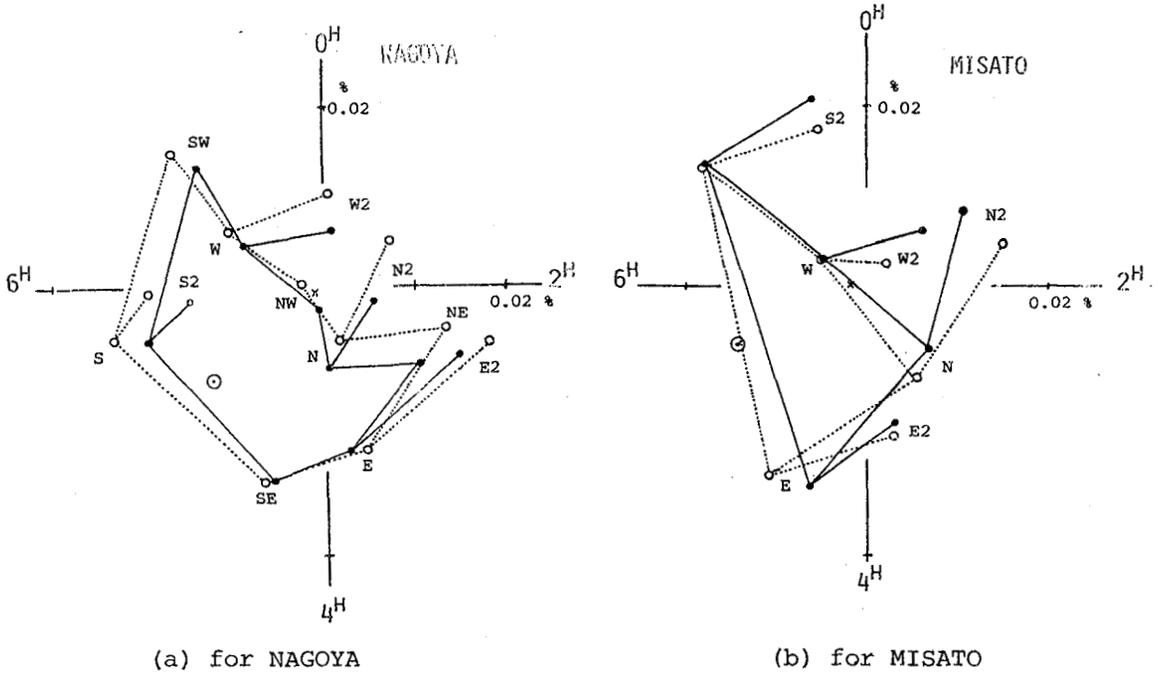


Fig. 3 Fitness between the observed (●) and the reproduced (○) variations; (a) for NAGOYA, (b) for MISATO and (c) for SAKASHITA for the period 1978-1983.

#### 4. Acknowledgements

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