CORRECTED SIDEREAL ANISOTROPY FOR UNDERGROUND MUONS

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ABSTRACT

Data from underground muon telescopes in New Mexico and Bolivia are analyzed in sidereal time and anti-sidereal time in the rigidity range 20 GV to a few 100's of GV. Using both vertical and north- and south- pointing telescopes in both hemispheres, a latitude range of 70°N to 50°S is covered. It is shown that there is an anti-sidereal variation of the P_1^1 type, having opposite phase in the northern and southern hemispheres, and maximum amplitude at mid latitudes. The anti-sidereal data are used to correct the sidereal data, using the Nagashima method (Nagashima, 1984); the resulting corrected sidereal vectors for northern hemisphere telescopes have their sidereal maxima close to 3h sidereal time, in reasonable agreement with sidereal data at higher energies from small air showers. The Nagashima correction also eliminates effects due to the reversal of the sun's polar magnetic field which show up in the uncorrected sidereal data.

INTRODUCTION: This paper presents data from the vertical and north- and south-pointing telescopes of the underground cosmic ray muon detectors at Embudo Cave (35.2°N, threshold rigidity 19 GV, median rigidity 132 GV), Socorro (34.04°N, threshold rigidity 45 GV, median rigidity 305 GV) and Bolivia (16.31°S, threshold rigidity 16 GV, median rigidity 125 GV). The asymptotic directions of viewing for these nine telescopes are given by Regener and Swinson (1968); they cover a range in latitude from 70°N to 50°S. Data from Embudo for 1965 to 1983, Socorro for 1968 to 1983, and Boliva for 1965 to 1976 are used in this analysis. The data are analyzed both in sidereal time and in anti-sidereal time, and the nature of the anti-sidereal diurnal variation is examined; the anti-sidereal data are then used to apply the Nagashima correction to the observed sidereal data.

Nagashima et al. (1983, 1985) have shown that, owing to the Earth's orbital motion through the interplanetary magnetic field (IMF), the geographical direction of the field at the earth is subject to a systematic arrival variation; as a result, the solar diurnal and semi-diurnal cosmic ray intensity variations produced from this effect show an annual modulation which can be decomposed into sidereal and anti-

sidereal diurnal and semi-diurnal components. The anti-sidereal diurnal variation is expected to vary with latitude according to the relation (Nagashima et al., 1983).

$$P_2^1 (\sin \lambda) = \sqrt{3}.\ Sin\ \lambda.\ Cos\ \lambda \qquad (1)$$

Where λ is the geographic latitude (positive in the northern hemisphere and negative in the southern hemisphere). This function has opposite signs in the two hemispheres, so the expected phases of the anti-sidereal diurnal cosmic ray variation should differ by 180° in the two hemispheres. Note that, in outer space, these phases show eigen values 23.3 h ($\lambda > 0$) and 11.3 h ($\lambda < 0$), respectively (Nagashima, 1984).

ANTI-SIDEREAL DATA: Figure 1 presents data from the nine telescopes listed earlier, displayed as harmonic dials in anti-sidereal time. Each vector represents an average for all available data (19 years for Embudo, 16 years for Socorro, and 12 years for Bolivia). The error circles are determined on the basis of the scatter of the individual daily vectors which are used to arrive at the various resultant vectors. Errors calculated on the basis of counting rate alone are appreciably smaller. The capital letters E, S and B are for Embudo, Socorro and Bolivia, respectively, and the subscripts V, N and S represent vertical, north- and south-pointing telescopes, repectively at each location. With the exception of the Bolivia north-pointing telescope, the northern latitude telescopes are clustered near 21h anti-sidereal time, and the southern latitude telescopes are clustered near 9h anti-sidereal time, thereby showing the ex-
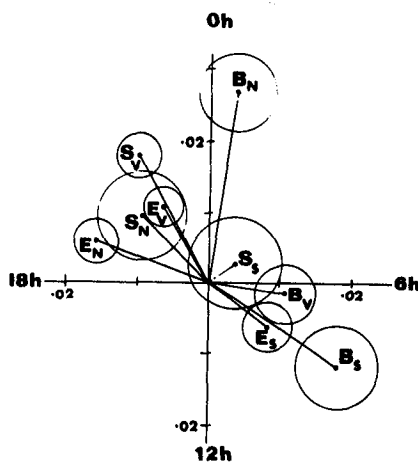

Fig. 1: Harmonic dial in anti-sidereal time for Bolivia, Embudo and Socorro North, South and Vertical Telescopes. Amplitudes are in percent.
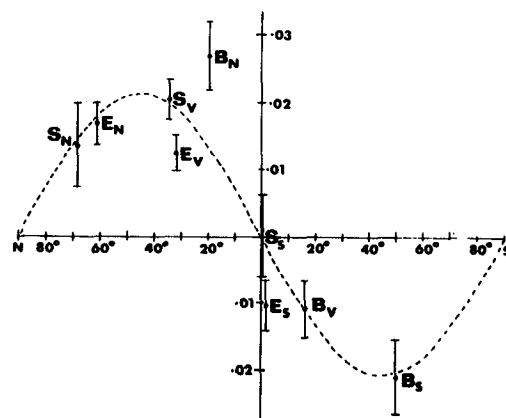
Fig. 2: Amplitude data from Fig. 1 plotted against viewing latitude λ; dashed curve is the function A sinλ Cosλ fitted to the data. Amplitudes are in percent.

pected 180° phase difference between the two hemispheres; the deviations from the corresponding eigen values (23.3 h and 11.3 h) are consistent with the cosmic ray orbital deflection in the geomagnetic field (Fujimoto et al., 1984).

In Figure 2, the data from Figure 1 are displayed in terms of the anti-sidereal amplitude for each of the nine telescopes, plotted as a function of its asymptotic latitude. Superimposed upon the diagram is a graph of the function $A \sin\lambda.\cos\lambda$ (dashed line), with the amplitude A adjusted to provide the best fit to the experimental points. The data conform very well the theoretical expectation (equation 1).

CORRECTED SIDEREAL DATA   Nagashima et al [1985] have demonstrated that the anti-sidereal data can be used to remove the related spurious sidereal diurnal variation from the observed diurnal variation in sidereal time. The correction is achieved by rotating the observed anti-sidereal vector by 4.53 hours counter-clockwise, reducing its amplitude by a factor of 0.947, and then subtracting it from the observed sidereal vector. This method has been applied to the data from the nine telescopes used here, and the resulting corrected sidereal diurnal variation vectors for each telescope, for all available data, are presented in Figure 3 as harmonic dials in sidereal time. The vectors for the northern hemisphere telescopes (Embudo and Socorro) all lie in the first quadrant, in the vicinity of 3h sidereal time. The amplitude for the Socorro telescope (median regidity 305 GV) is significantly greater than that of the Embudo telescope (median rigidity 132 GV). These results are consistent with the observations by Bercovitch [1984], using surface telescopes detecting muons arriving at large zenith angles, in which, as the median rigidity increased beyond about 100GV, the sidereal amplitude increased with rigidity, with the phase remaining consistently near 3h sidereal time. The northern hemisphere data in Figure 3 are also consistent with the corrected sidereal data presented by Nagashima et al. [1985], in which the London telescope had a maximum at about 3h sidereal time, with the Hobart telescope observing a somewhat later maximum near 6h sidereal time. The Bolivia (southern hemisphere) data in Figure 3 show a maximum close to 9h sidereal time, which is even later than what is seen at Hobart; at the moment there is no clear explanation for the later phase in the southern hemisphere.

When the Nagashima correction is applied to the observed sidereal data, the correction is relatively effective in reducing or removing phase changes which occur in uncorrected data upon the reversal of the sun's polar magnetic field in 1969-71 and 1980-81 [Swinson, 1976, 1984]. Data from the Socorro vertical telescope (where the sidereal anisotropy is greatest) are shown in Figure 4. In the uncorrected data, a clear phase change can be seen in 1971 and 1981, after the

Fig. 4. Yearly harmonic dials in sidereal time for the Socorro vertical telescope, uncorrected and with the Nagashima correction.
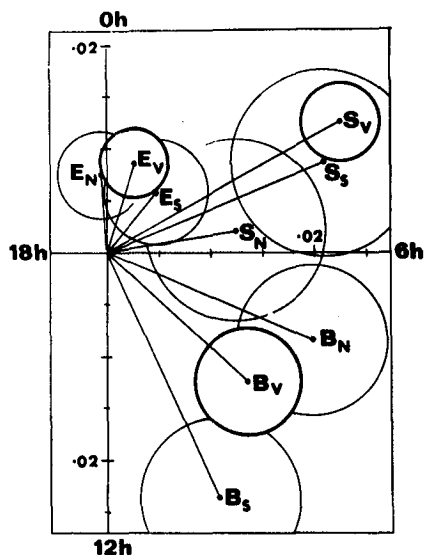
Fig. 3. Harmonic dial in sidereal time for Bolivia, Embudo & Socorro North, South and Vertical telescopes with the Nagashima correction. Amplitude scale is in percent.
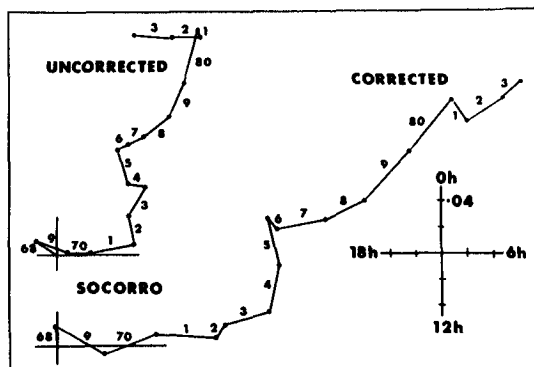

two most recent solar field reversals. The data corrected by the Nagashima method, however, show very little change, with the yearly vectors remaining relatively consistent, regardless of the magnetic configuration of the heliosphere. This gives one more confidence that the data, corrected in this fashion, are representative of a truly galactic anisotropy.

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