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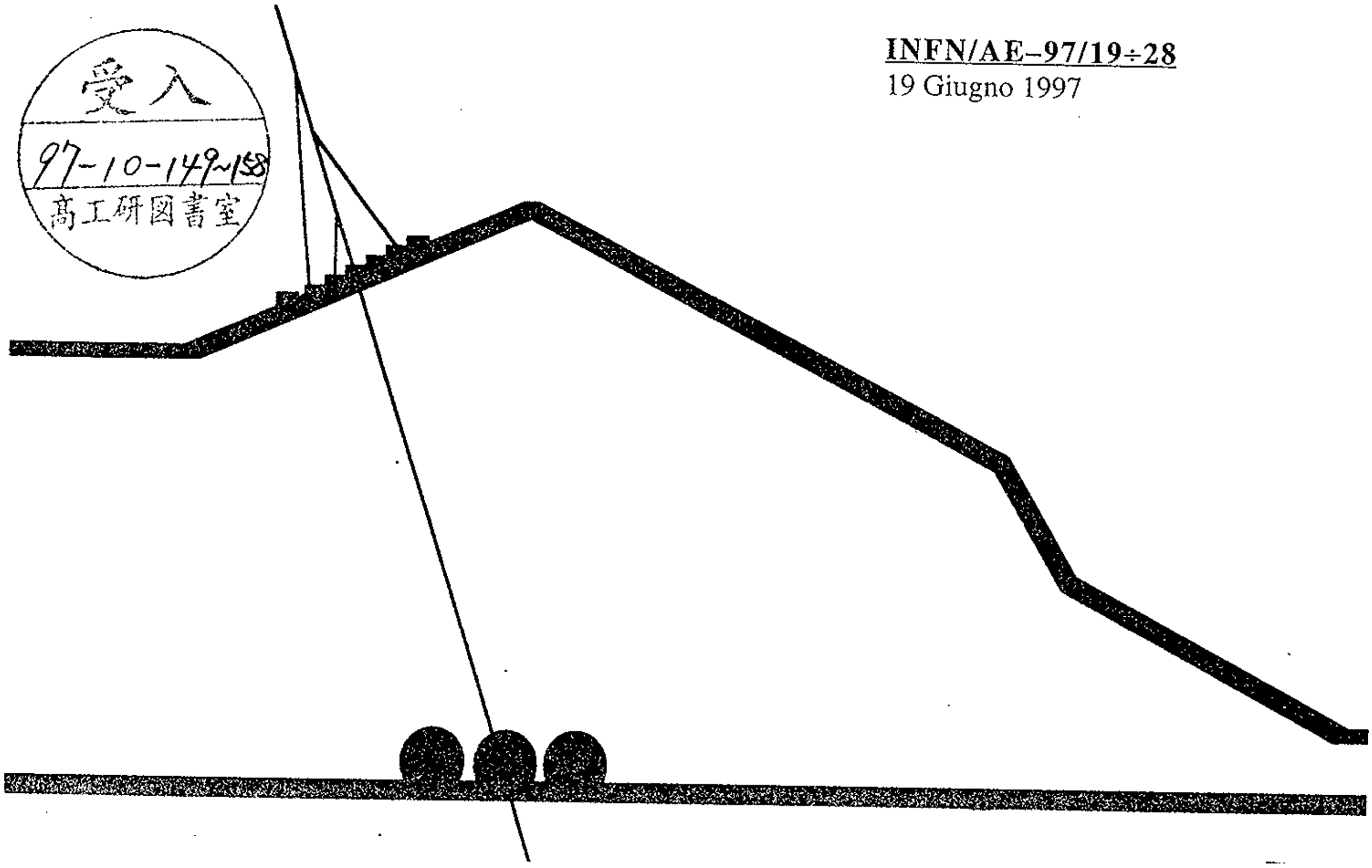

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

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The MACRO Collaboration

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THE SEARCH FOR A SIDERAL ANISOTROPY IN THE UNDERGROUND MUON INTENSITY AS SEEN BY MACRO

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ABSTRACT

We have analyzed 39.2×10^6 muons collected in 5.2×10^4 hours of live time by the MACRO detector during the period from 1989 to 1996. Using a high quality subsample of these data, comprising 4.4×10^6 muons, we have searched for modulations consistent with the first harmonic of the solar diurnal, antisidereal, and sidereal periods. The method of Farley and Storey (1954) has been used to obtain the 'true sidereal' modulation. Preliminary results are presented.

INTRODUCTION

During the past 60 years, many searches have been made for a sidereal anisotropy in the arrival directions of cosmic rays. Compton and Getting (1935) initially looked for the sidereal signal arising from the Galaxy's rotational motion through a sea of extragalactic cosmic rays. They argued that a sidereal signal toward the apex of Galactic rotation would provide evidence for an extragalactic component of cosmic rays. Air shower array experiments, which typically are sensitive to cosmic rays with energies in excess of 50 TeV, have continued this search to the present with conflicting results (Kifune, et al. 1986; Nagashima, et al. 1989; Alexeenko, et al. 1993; Borione, et al. 1996). However, shallow underground muon telescopes and neutron monitors, which probe low energy cosmic rays ($E < 100$ GeV), have clearly observed statistically significant modulations with periods of a solar day and a sidereal day in their cosmic ray data (Hall, Duldig, and Humble 1996). These variations are well explained by the effects of the solar wind and interplanetary magnetic fields on lower energy cosmic rays.

MACRO is a large, deep underground detector that is well suited to search for a sidereal modulation of primary cosmic rays. Our sensitivity to weak periodic signals has already been demonstrated by the detection of seasonal variations in the underground muon rate (Ambrosio et al. 1997). MACRO's sensitivity to primary cosmic rays > 5 TeV suggests that the muon data are unlikely to be strongly affected by local interplanetary conditions.

DATA ANALYSIS

The effects we are searching for are smaller than the few percent seasonal variations already reported by the MACRO collaboration. It is therefore essential to define a very high quality data set that is as free of systematic effects as possible. The analysis procedure is based on the method of Farley and Storey (1954) that searches for the first harmonic of the sidereal modulation.

Data Sample

Data were collected during the period beginning in February 1989 and ending in December 1996. During this period, approximately 39.2×10^6 muons were recorded in approximately 5.2×10^4 hours of live time.

We first applied run cuts that ensured that the detector was operating efficiently. Run cuts include: all 6 supermodules in acquisition; streamer tube system operating efficiently; run rates within 3σ of the mean. Within a run individual events were required to cross all 10 horizontal streamer tube tracking planes. Such events have essentially almost 100% probability of resulting in a reconstructed track. These cuts therefore define a data set that requires no corrections for efficiency and they are the same cuts as those used in the search for seasonal variations (Ambrosio et al. 1997). This high quality data sample includes 13.2×10^6 muons.

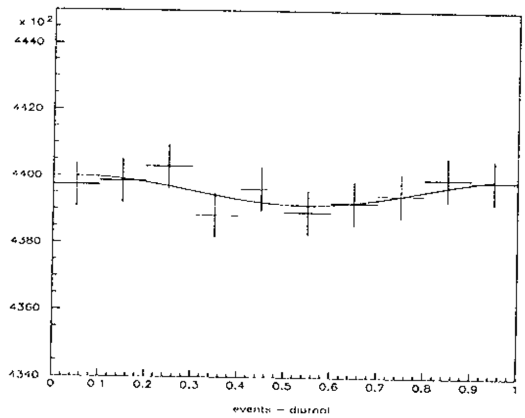

Fig. 1: Solar diurnal variations with fit superposed.

The search for the true sidereal modulation requires a correction for solar diurnal variations. However, solar diurnal variations can be masked by human activities on the detector like detector maintenance and repair, installation, calibration, etc., which typically takes place during the day. At night the detector is usually unattended. Additional cuts were developed to minimize this effect: (1) Gaps between runs were required to be ≤ 3.5 minutes. New runs begin automatically when the data buffers fill, and this proceedure usually takes less than 3.5 minutes. A longer gap between runs ordinarily indicates that a run was terminated manually. (2) Sets of runs with gaps < 3.5 minutes were required to be at least one whole day in length and muons were kept for further analysis only if their arrival times were within an integral number of whole days from the arrival time of the first event of that run set. Studies indicate that including runs with gaps longer than 3.5 minutes introduces significant solar diurnal variations. These cuts reduced the data sample to 4.4×10^6 muons.

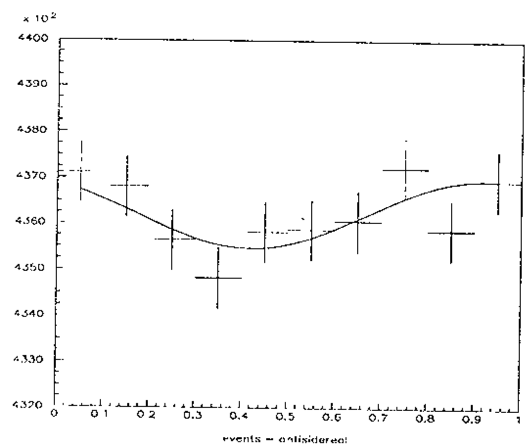

Fig. 2: Antisidereal variations.

Analysis Procedure

Our 'harmonic analysis' procedure (Farley and Storey 1954) first searches for variations in muon arrival times modulated by the solar diurnal period, the sidereal diurnal period, and the antisidereal diurnal period. The length of a solar diurnal period is the mean solar day, t_{sol}; the length of a sidereal diurnal period is the sidereal day, t_{sid}. Let T_{trop} be the length of a tropical year. Then there are $N_{sol} = T_{trop}/t_{sol}$ solar days in a tropical year and $N_{sol} + 1$ sidereal days in a tropical year. The antisidereal diurnal period is then given by $t_{anti} = T_{trop}/(N_{sol} - 1)$. The data are modulated with the antisiderial period because the solar diurnal period beats with the seasonal period, T_{trop}, and a 'sideband' with the period t_{anti} appears. This same beating effect also introduces a 'sideband' with the sidereal period, t_{sid}. It is this faux sidereal modulation that must be removed from the data to find the true sidereal effect (Farley and Storey 1954).

Three phase diagrams were constructed using the data set described above. These phase diagrams differed only in the length of the day used. For the solar diurnal modulation, the Julian day fraction of its arrival time was used to bin each muon; this implies that the zero point of phase is 12^h UT. For the apparent sidereal modulation, the right ascension of its arrival direction was used to bin each muon. The zero point of phase for the antisidereal modulation was arbitrarily chosen as the arrival time of the first muon in the data set. These three (zero-suppressed) phase diagrams are shown in Figures 1, 2 and 3. The error bars are statistical. Since only whole days of data are used, no corrections were necessary for changes in the detector configuration.

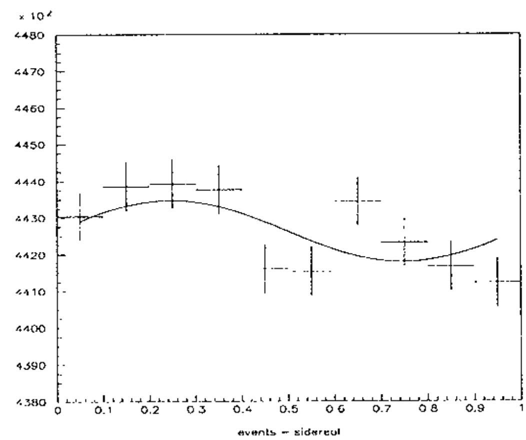

Fig. 3: Apparent sidereal variations.

We searched for the first harmonic of the modulation in the three phase diagrams by fitting the binned muon data to the form:

$$N = < N > + A \cos\left[2\pi(\phi + \phi_{max})\right], \tag{1}$$

where $< N >$ is the mean per bin, A is the amplitude of the modulation, ϕ is the phase, and ϕ_{max} is the phase of maximum. The fit parameters are given in Table 1. The curves representing these fits have been superposed on the binned muon data in Figures 1, 2, and 3.

Table 1: Results of Fitting Binned Muon Data

	$< N >$	A	ϕ_{max}	χ^2/dof
Solar Diurnal	4.40×10^5	430 ± 290	$0.05 \pm .11$	0.345
Antisidereal	4.36×10^5	750 ± 280	$0.08 \pm .06$	0.841
Apparent Sidereal	4.43×10^5	840 ± 280	$0.25 \pm .06$	2.26

RESULTS

Vector methods can now be used to extract the first harmonic of the 'true sidereal modulation.' The fit to the solar diurnal data in Table 1 directly yields the fit parameters in the relation: $K_1 \cos\left[2\pi(N_{sol}t + \phi_1)\right]$, where K_1 is the solar diurnal amplitude and t is the arrival time of the muon. Since the antisidereal modulation results from the solar diurnal modulation beating against the seasonal modulation, the fit to the antisidereal diurnal data gives the parameters in the relation: $K_2 \cos\{2\pi[(N_{sol} - 1)t + \phi_1 - \phi_2]\}$. In this fit, ϕ_{max} in Table 1 was shifted to account for the arbitrary zero point of phase used in constructing Figure 2. As shown in Ambrosio et al. (1997), the phase of maximum modulation for the seasonal variation is $\phi_2 \approx 0.6$, which implies that $\phi_{max} \approx 0.45$ for the antisidereal modulation. Finally, the sidereal modulation seen in Figure 3, parameterized as $K_3 \cos\{2\pi[(N_{sol} + 1)t + \phi_3]\}$, is the 'apparent sidereal modulation' and represents the sum of two terms,

$$K_3 \cos\{2\pi[(N_{sol} + 1)t + \phi_3]\} = K_4 \cos\{2\pi[(N_{sol} + 1)t + \phi_4]\} + K_2 \cos\{2\pi[(N_{sol} + 1)t + \phi_1 + \phi_2]\}.$$

The amplitude, K_4, and the phase, ϕ_4, of the 'true sidereal modulation' can be found from the fits in Table 1. The results of this analysis, including the correction for the zero point of antisidereal phase and the converstion from Julian days to solar time, are given in Table 2. The errors on K_4 and ϕ_4 were computed by combining the errors in quadrature.

Table 2: Analysis of Underground Muon Data

	Amplitude (%)		Phase of Maximum (hr)	
Solar Diurnal	0.093 ± 0.063	(K_1)	13.2 ± 2.6	(ϕ_1)
Antisidereal	0.17 ± 0.05	(K_2)	10.8 ± 1.4	$(\phi_1 - \phi_2)$
Apparent Sidereal	0.19 ± 0.06	(K_3)	5.9 ± 1.3	(ϕ_3)
True Sidereal	$0.34 \pm .26$	(K_4)	4.8 ± 3.2	(ϕ_4)

CONCLUSIONS

We have used the method of Farley and Storey (1954) to search for the first harmonic of the sidereal modulation in the underground muon data collected by MACRO. The result at this time must be considered preliminary. In order to achieve a result with high statistical significance, several more years of MACRO data must be analyzed.

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