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Search for the solar diurnal and true sidereal modulations in MACRO

S. L. Mufson for the MACRO Collaboration

Indiana University

Abstract. We have analyzed 44.3M single muons collected by MACRO from 1991 through 2000 in 2,145 live days of operation. We have searched for the solar diurnal, apparent sidereal, and antisidereal modulation of the underground muon rate by computing hourly deviations of the muon rate from 6 month averages. We find evidence for statistically significant modulations with the solar diurnal and the sidereal periods. The amplitudes of these modulations are $< 0.1\%$, and are at the limit of the MACRO statistics. The antisidereal modulation is not statistically significant. The right ascension of the sidereal modulation is found at $\alpha = (23.7 \pm 1.3)^h$. The results of this investigation are consistent with the measurements made by other undergound and EAS experiments.

1 Introduction

The sidereal signal due to the solar system motion through an isotropic sea of relativistic cosmic rays in the Galactic halo was first described by Compton and Getting (1935). The Compton-Getting factor is expected to be a very small effect that modulates the total cosmic ray rate with a wave of amplitude $\leq 0.1\%$.

Previous investigations of this effect have given different results depending on the energy of the primaries. Underground muon observatories and air shower arrays (E $\geq$ 1 TeV) find sidereal wave amplitudes in the range $5 \times 10^{-4} - 10^{-3}$, consistent with a drift velocity of a few hundred km/s with respect to a halo distribution of cosmic rays (Munakata *et al.*, 1997). Shallow undergound muon telescopes and neutron monitors (E $<$ 1 TeV) observe statistically significant sidereal anisotropies that can be explained by solar wind effects and the influence of the sun (Hall *et al.*, 1996).

We searched the total MACRO data set for the first harmonic of the solar diurnal and true sidereal modulations in the underground muon rate using the method of Farley and Storey (1954).

2 Data analysis

2.1 Run/Event selection

In this analysis we included runs starting from the beginning of MACRO data taking with 6 supermodules in November 1991 through May 2000. The analysis proceeded by first dividing these runs into 17 run sets of approximately 6 months duration during which the detector acceptance remained constant. We then filtered the data to include only muons with single tracks in both views. Once filtered we compiled for each run set a histogram of the single muon rate/hour for all runs in that run set and then fitted a Gaussian to the resulting distribution.

We implemented run cuts as follows. A run was excluded from further analysis if:

- not all 6 supermodules were active, or
- the wire efficiencies were $<$ 90% and/or the strip efficiencies were $<$ 80% during the run, or
- its single muon rate was $> 5\sigma$ from the mean single muon ratex for that run set.

For the efficiency cuts, wire and strip efficiencies were determined for each run by computing the average number of wires and strips recording hits for all single muons crossing 10 planes.

There are 44.3M muons in the total data set. The total live-time for the included runs is 2,145 days. The average single muon rate in the total data set is 860.53 muons/hour/6 supermodules.

2.2 Histograms of deviations from the mean solar diurnal, apparent sidereal, and antisidereal muon rates

To search for the true sidereal modulation in the underground muon rate, we used the harmonic analysis method of Farley and Storey (1954). In this method, the observed or apparent sidereal modulation is assumed to be a superposition of two effects: a true sidereal modulation due to solar system motion and a faux sidereal modulation due to temperature variations in the atmosphere. To correct the apparent sidereal modulation to the true sidereal modulation requires the determination of the solar diurnal, apparent sidereal, and antisidereal

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Correspondence to: S. L. Mufson
(mufson@astro.indiana.edu)

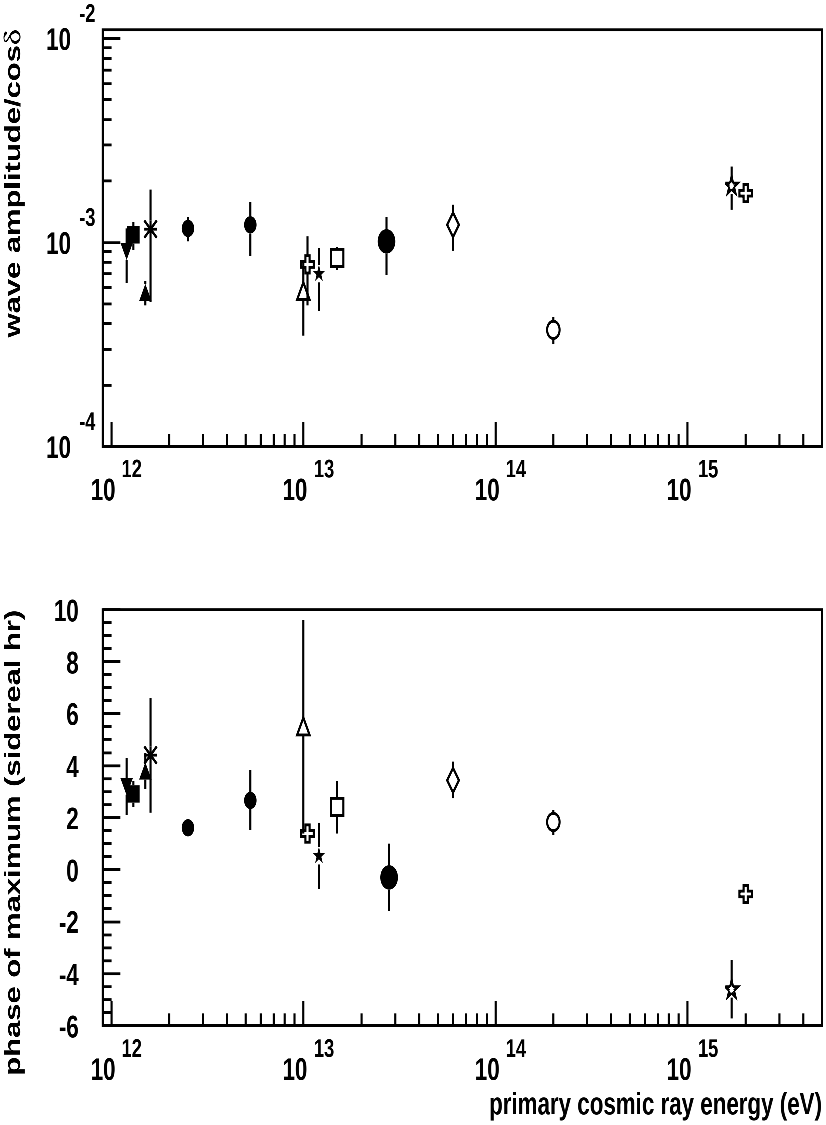

Fig. 4. Summary of sidereal wave searches at energies $\geq 10^{12}$ eV. Upper panel: measurements of the amplitude; Lower panel: measurements of the phase maximum of the first harmonic in the sidereal variations. Filled symbols represent underground experiments and open symbols represent EAS experiments. Symbol key: *large filled circle* = MACRO (this paper); *inverted filled triangle* = Poatina (Fenton, *et al.*, 1995); *filled square* = Matsushiro (Mori *et al.*, 1995); *filled triangle* = Utah (Cutler and Groom, 1991); *asterisk* = Hong Kong (Lee and Ng, 1987); *small filled circle* = Baksan (**?**); *open triangle* = Tibet (Munakata *et al.*, 1999); *open cross* = Baksan EAS (Alexeenko *et al.*, 1985,1993); *filled star* = Kamioka (Munakata *et al.*, 1997); *open square* = Norikura (Nagashima *et al.*, 1989); *open diamond* = Musala Peak (Gombosi *et al.*, 1975); *open circle* = EAS-TOP (Aglietta *et al.*, 1996); *open star* = Linsley (Linsley and Watson, 1977).

modulations. The periods of these modulations are: solar diurnal day = 86,400 seconds; sidereal day = 86,164.09892 seconds (Allen, 1973); the antisidereal day was assumed to be longer than a solar day by the same fraction that a sidereal day is shorter than a solar day, or 86,636.54693 seconds. The unphysical antisidereal modulation results from the beating of the solar diurnal modulation and the yearly (seasonal) modulation and its properties must be determined to correct the apparent sidereal modulation for this atmospheric effect (Farley and Storey, 1954).

We searched for the solar diurnal, apparent sidereal, and antisidereal modulations as follows. First event histograms for each run were constructed for the three periods by binning the arrival time of each muon according to its: (1) local solar diurnal time at the Gran Sasso; (2) local sidereal time; and (3) local antisidereal time. This antisdereal wave has zero phase at the autumnal equinox, when the sidereal time, the solar time, and the antisidereal time are coincident (Farley and Storey, 1954). In this analysis, the antisidereal time was computed relative to the 1988 autumnal equinox, September 22, 1988, 19^h 29^m UT. Second, the live time in each run was similarly binned into three histograms. The live time for a run was computed as the difference between the arrival times of the first and last muons. The live time was added to the histograms from the time of the first muon to the time of the last muon. The rate histograms for each run were then computed by dividing the contents of the appropriate event histogram by the contents of its corresponding live time histogram.

The rate histogram for each run was unpacked and the muon rate in each bin, r_i, was compared to the mean muon rate for that run set, $\bar{r}_j$, and its fluctuation from the mean was computed as $\delta_{ij} = (r_i - \bar{r}_j)/\bar{r}_j$. Each δ_{ij} for that run was then compared with the r.m.s of the distribution of fluctuations for the total data set and those $\delta_{ij} > (3 \times \ r.m.s)$ were cut from the analysis. This cut was made to exclude

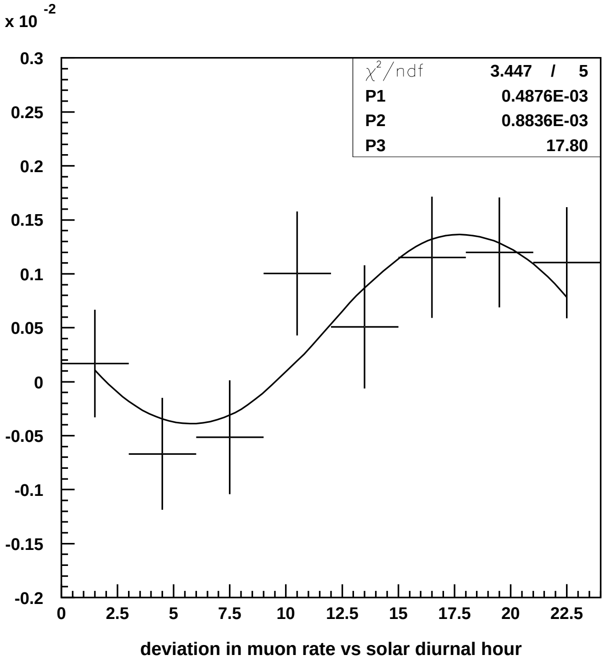

Fig. 1. Deviations of the muon rate from the mean muon rate binned according to the local solar diurnal time at the Gran Sasso.

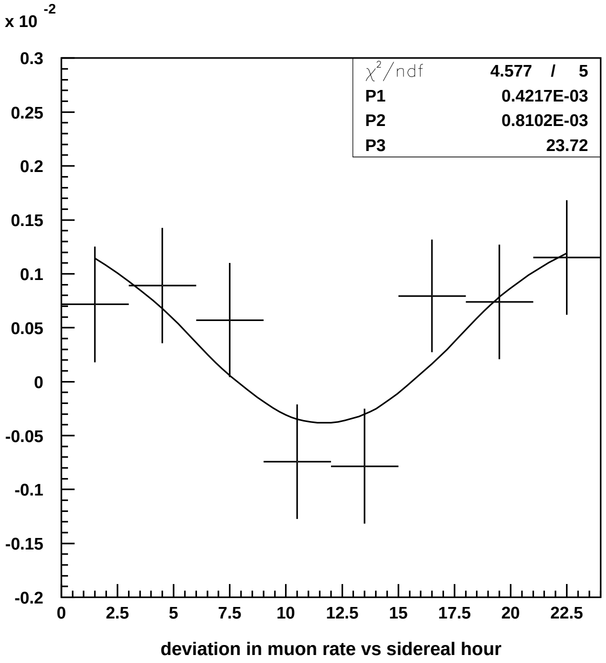

Fig. 2. Deviations of the muon rate from the mean muon rate binned according to the local sidereal time at the Gran Sasso.

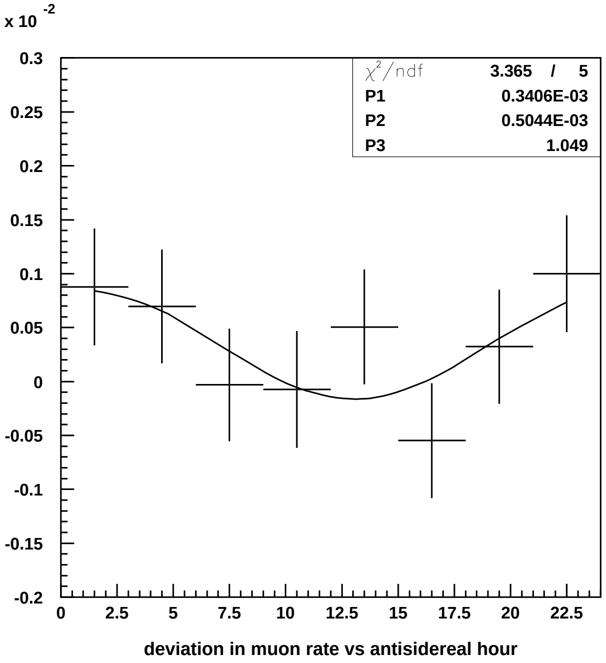

Fig. 3. Deviations of the muon rate from the mean muon rate binned according to the local antisidereal time at the Gran Sasso.

the effect of the fluctuations found in the long, asymmetric non-Gaussian tails in the distribution of fluctuations for the total data set. These outliers, which comprise much less than 1% of the data, mostly come about because of run starts, run stops, sudden data spikes, and other nonphysical effects. The results of the analysis are relatively insensitive to this cut over the range $(2.5 - 5) \times \ r.m.s.$. The δ_{ij} passing this cut were entered into summary histograms for the three periods.

At the end of this process, after all runs were analyzed, there resulted a set of three histograms with fluctuations from the mean muon rate binned in solar diurnal time, sidereal time, and antisidereal time. The contents of each bin in these summary histrograms were then normalized by the number of entries in that bin. The resulting histograms of the normalized fluctuations, Δ, for the three periods are shown in Figures 1-3.

2.3 Phase analyses

We searched for the first harmonics of the apparent sidereal, antisidereal, and solar diurnal modulations by fitting the histograms of the fluctuations to the form:

$$\Delta = < \Delta > + A \cos\left[2\pi(\phi - \phi_{max})/24\right], \quad (1)$$

where $< \Delta >$ is a constant, A is the amplitude of the modulation, ϕ is the phase in hours, and ϕ_{max} is the phase of maximum in hours. The results of this fitting procedure are given in Table 1. The fitted curves have been superimposed on the histograms in Figures 1-3.

2.3.1 Solar diurnal modulation

Table 1 shows that the solar diurnal modulation is a statistically significant effect. The origin of this modulation is the daily atmospheric temperature variations at approximately 20 km, the altitude of the primary cosmic ray interactions with the atmosphere. MACRO is the deepest experiment to report this effect.

Table 1. Results of Histogram Fits

Period	$< \Delta >$	A	ϕ_{max} (hr)	χ^2/DoF
Solar Diurnal	$(0.49 \pm 0.19) \times 10^{-3}$	$(0.88 \pm 0.26) \times 10^{-3}$	17.8 ± 1.2	3.4/5
Apparent Sidereal	$(0.42 \pm 0.19) \times 10^{-3}$	$(0.81 \pm 0.27) \times 10^{-3}$	23.7 ± 1.3	4.6/5
Antisidereal	$(0.34 \pm 0.19) \times 10^{-3}$	$(0.50 \pm 0.27) \times 10^{-3}$	1.1 ± 2.0	3.4/5

2.3.2 Sidereal modulation

Table 1 shows that the sidereal modulation is a statistically significant result. The amplitude is significantly larger than expected for the Compton-Getting effect due to the earth's motion around the sun at MACRO's latitude, $A = 3.4 \times 10^{-4}$; the maximum phase is also significantly different from the expected $\phi_{max} = 6^h$ (Aglietta *et al.*, 1996). This suggests there is an additional motion contributing to the Compton-Getting modulation that we have found.

2.3.3 Antisidereal modulation

As shown in Table 1, the fit to the antisidereal modulation does not yield a statistically significant result. This result is not unexpected. The antisidereal modulation is an atmospheric effect due to the beating of the yearly or seasonal modulation with the solar diurnal modulation (Farley and Storey, 1954). As reported by Ambrosio *et al.* (1991), the seasonal modulation of the underground muon rate seen by MACRO has an amplitude of $\sim 1\%$, and as shown here the solar diurnal modulation has an amplitude of $\sim 0.1\%$. Consequently, the amplitude of the antisidereal modulation is expected to be below the limit of MACRO statistics, consistent with our analysis.

3 Results

Since the antisidereal modulation is of low statistical significance, the correction to the apparent sidereal modulation for the faux sidereal modulation (Farley and Storey, 1954) does not need to be applied. This implies that the observed sidereal modulation is the true sidereal modulation to the underground muon rate.

The comparison of the result found in this investigation with the results of other experiments in the primary cosmic ray energy range $E_p \geq 1$ TeV are shown in Fig. 4. In the upper panel the amplitude of the modulation is shown. To compare the results of different experiments, the reported amplitude is corrected for the effective declination of the experiment (Linsley, 1983). The MACRO result is consistent with other experiments. In the lower panel the sidereal hour of the phase maximum of the modulation, or the right ascension of the maximum signal, is compared with results from other experiments. In this figure, the y-axis labels for 18^h to 24^h have been replaced by -6^h to 0^h. The result found in this investigation is again consistent with other experimental determinations.

After correcting for the earth's motion around the sun (Aglietta *et al.*, 1996), the sidereal modulation of the underground muon rate has an amplitude $A_{sid} = 8.6 \times 10^{-4}$ and a phase $\phi_{max} = 22.7$. The right ascension of the residual sidereal wave is consistent with the direction of the solar system motion about the Galactic center toward $l = 90°$, $b = 0°$, where l and b are the Galactic latitude and longitude and we ignore the small peculiar motion of the solar system with respect to the Local Standard of Rest compared with its Galactic rotation speed of 250 km/s (Mihalas and Binney, 1981). Transforming from Galactic coordinates to equatorial coordinates gives $\alpha = 21.2^h$ (Duffet-Smith, 1988) for the direction of Galactic rotation, a value 1σ from the right ascension of ϕ_{max} we found in our sidereal analysis.

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References

Aglietta, M. *et al.*, *Astrophys.J*, **470** (1996) 501.

Alexeenko, V.V., and Navarra, G., *Lett.Nuovo Cim.*, **42** (1985) 321; Alexeenko, V.V., *et al.*, *The 23rd International Cosmic Ray Conference*, Calgary, **2** (1993) 483.

Allen, C.W. *Astrophysical Quantities, 3rd ed.* (The Athalone Press: London) 1973.

Aglietta, M. *et al.*, *Astrophys.J*, **470** (1996) 501.

Ambrosio, M., *et al.*, *Astropart.Phys.*, **7** (1997) 109.

Compton, A., and Getting, I.A., *Phys.Rev.*, **47** (1935) 817.

Cutler, D.J., and Groom, D.E., *Astrophys.J.*, **376** (1991) 322.

Duffet-Smith, P., *Practical Astronomy with your Calculator, 3rd ed* (Cambridge University Press: Cambridge) 1988.

Farley, F.J.M., and Storey, J.R., *Proc.Phys.Soc.*, **67** (1954) 996.

Fenton, K.B., *et al.*, *The 24th International Cosmic Ray Conference*, Rome, **4** (1995) 635.

Gombosi, T. *et al.*, *Nature*, **255** (1975) 687.

Hall, D.L., Duldig, M.L., and Humble, J.E., *Space Sci.Rev*, **78** (1996) 401.

Lee, Y.W., and Ng, L.K., *The 20th International Cosmic Ray Conference*, Moscow, **2** (1987) 18.

Linsley, J., *The 18th International Cosmic Ray Conference*, Bangalore, **12** (1977) 135.

Linsley, J., and Watson, A.A., *The 16th International Cosmic Ray Conference*, Plovdiv, **12** (1977) 203.

Mihalas, D., and Binney, J., *Galactic Astronomy, 2nd ed* (Freeman: San Francisco) 1981.

Mori, S., *et al.*, *The 24th International Cosmic Ray Conference*, Rome, **4** (1995) 648.

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Munakata, K. *et al.*, *Phys.Rev.D*, **56** (1997) 23.

Munakata, K. *et al.*, *The 26th International Cosmic Ray Conference*, Salt Lake City, **7** (1999) 293.

Nagashima, K. *et al.*, *Il Nuovo Cim.*, **12C** (1989) 695.