

TENTATIVE OBSERVATION OF A SIDEREAL  
ANISOTROPY NEAR 1500 GeV

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The underground muon flux produced by primary cosmic rays with a median rigidity of  $1.5 \times 10^{12}$  V has been monitored to search for periodic and transient rate variations. The detector has operated at an average rate of 4.47 Hz for most of the 1.2 yr interval starting 1978 Jan 1. A peak with relative amplitude  $(3.8 \pm^{1.4}_{0.9}) \times 10^{-4}$  is observed in the Fourier transform of data at the sidereal 0.9 frequency, where the errors are 68% confidence limits based upon an off-center Rayleigh distribution. After correction for solar motion the projected anisotropy ( $\hat{i} \cos \delta \cos \alpha$ ) is  $(4.9 \pm^{1.4}_{0.9}) \times 10^{-4}$  at right ascension  $2^{\text{h}}.8 \pm 1^{\text{h}}.2$ , where  $\cos \delta = 0.75$ . There are no discernible peaks at the solar or antisidereal frequencies. We observe a second sidereal harmonic of amplitude  $(3.8 \pm^{1.4}_{0.9}) \times 10^{-4}$  (the same size as the first harmonic) at right ascension  $0.99^{\text{h}}.8$  (or  $21^{\text{h}}.8 \pm 1^{\text{h}}.2$ ).

1. Introduction. We have monitored the underground muon flux produced by cosmic ray primaries with a median rigidity of  $1.5 \times 10^{12}$  V in an attempt to measure the sidereal anisotropy. The detector has operated 81% of the time since 1978 Jan 1; by 1979 May 1,  $1.52 \times 10^8$  counts had been recorded.

The experiment was motivated by an apparent contradiction between the observed high degree of cosmic ray directional isotropy and the substantial bulk streaming velocity implied by the short cosmic ray disc residence time inferred from isotopic abundance anomalies (1,2,3). There was reason to doubt the older air shower experiments (4,5) which are obscure in the literature. The more recent precision underground muon experiments (6,7,8) had such low energy thresholds that the parent cosmic rays were possibly subject to solar modulation.

Since then, the experimental and theoretical situations have both changed considerably. Solar modulation effects in the low-energy underground experiments were verified.(9) The isotopic abundance ratios were found to change with energy and even more significantly,  $\text{Be}^{10}$  ( $\tau = 1.6 \times 10^6$  yr) is nearly absent. (10) As a result, we now believe that the cosmic rays we observe were produced  $10^7$  years ago, a factor of 5 greater than was previously thought. "Halo containment" models were revived,(11) since the near-absence of  $\text{Be}^{10}$  may not be consistent with other isotopic abundances if the cosmic rays remain in the galactic disc for the entire time. Such models imply lower anisotropies than straightforward disc containment models, and in any case various plasma mechanisms may be operative(12) in reducing any anisotropy.

The need for precise higher energy measurements has partially been met. The Hobart group operated at Poatina at a primary rigidity just above  $10^{12}$  V for a four- year period. (13,14) Air shower detectors at Mt. Musala(15) and Mt. Norikura I have operated at rigidities just below  $10^{14}$ . All have obtained results near  $5 \times 10^{-4}$  for the projected anisotropy, and all agree that the right ascension is near  $1^{\text{h}}.5$ . The Utah detector has an order of magnitude larger aperture than that at Poatina, and the initial results from this detector are the subject of this paper.

2. The Detector. The detector and its performance characteristics are described elsewhere,(17) but for completeness we provide a brief summary here. It is located in the main drift of an abandoned mine near Heber, UT, at  $40^{\circ}37'N$ .

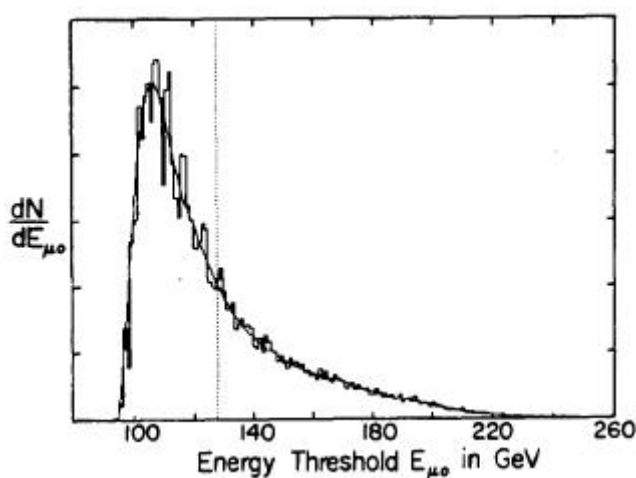


Fig. 1. The muon energy threshold distribution for the Utah detector.

average depth is  $507 \text{ hg cm}^{-2}$ , calculated by integrating the muon intensity over the aperture and the local topography. The muon energy threshold distribution is shown in Fig. 1; the average (dotted line) is at 128 GeV and the median is at 119 GeV. These numbers are slightly larger than previously reported because of improved calculations and because we now include several additional wide-angle channels in the analysis. The average muon arrival direction is  $1^{\circ}3'$  north of vertical, so that the effective latitude is  $41^{\circ}40'N$ , and  $\cos \theta = 0.747$ .

The detector consists of 300 plastic scintillation counters arranged in three layers separated by  $75 \text{ g cm}^{-2}$  of concrete. Most counters are  $25.4 \text{ cm} \times 154.4 \text{ cm}$ , and are arranged with long axes in the north-south direction to optimize right ascension resolution at about  $15^{\circ}$ . When loose 3-layer coincidence requirements are met, all discriminator outputs are latched for computer interrogation. The effective time resolution is 110 ns, and a hierarchy of latches and buffers reduces system dead time to 300 ns. Events with several simple topologies are recognized by the on-line computer and tallied in buffers representing the 1900 different ways muons can penetrate the apparatus with useful counting rates. These summaries are recorded every half hour, as are accurate times and a variety of maintenance information. More complicated events (multiple muons, very wide angle singles, etc.) are recorded verbatim. A number of "trouble flags" can be set by the computer, and the system's health is interrogated daily by a telephone call from campus. Tapes are retrieved every two weeks.

**3. Data Characteristics and Selection.** In spite of the loose trigger, 97.0% of the recorded events are unambiguous single muons. They fall into three topological categories:

- (i) "3-in-a-line" events: Events consisting of three triggers from counters through which a line can be drawn occur 87.8% of the time. 1.4% of the total occur at excessively large angles and are not used in the analysis; the remainder fall into 13 angular bins defined by the counter spacing.
- (ii) "ä-ray events." In 7.8% of the events four counters trigger, with the extra counter being adjacent to one of the three inline counters. From the relative occurrence frequency of various combinations we understand these events as about half due to ä-rays and about half due to locally produced pions. In the case of ambiguities, events are assigned to one of the two possible angular bins at random.
- (iii) "Noise events." In accord with calculation, a distant counter triggers along with three in a line 1.4% of the time. Such events can be treated unambiguously and provide a useful noise monitor.

The distribution of event rates and other characteristics of the 13 most important angular bins are summarized in Table 1. In principle, data cuts can be made on the basis of phase and energy; in practice, statistics do not yet

TABLE 1

Central angles, depths, energies, and fractional counting rates of muon angle intervals used in the analysis. Positive sectors are east of vertical.

Sector	Angle $\alpha$ (Degrees)	Rate (h) (%) (hg cm <sup>-2</sup> )	(E (GeV))
-6	-58.3	0.6 818	221
-5	-53.4	1.0 789	212
-4	-46.9	1.7 754	201
-3	-38.4	3.1 712	188
-2	-27.3	6.5 647	168
-1	-13.9	12.4 556	141
0		0.7 _____ 2	
		0.3 _____ 4	
		86 _____ 1	
		21	
1 15_1		20_1 451	111
2	27.9	16.1 449	110
3	38.6	9.2 470	116
4	46.9	5.2 501	125
5	53.3	2.6 536	135
6	58.2	1.4 577	147

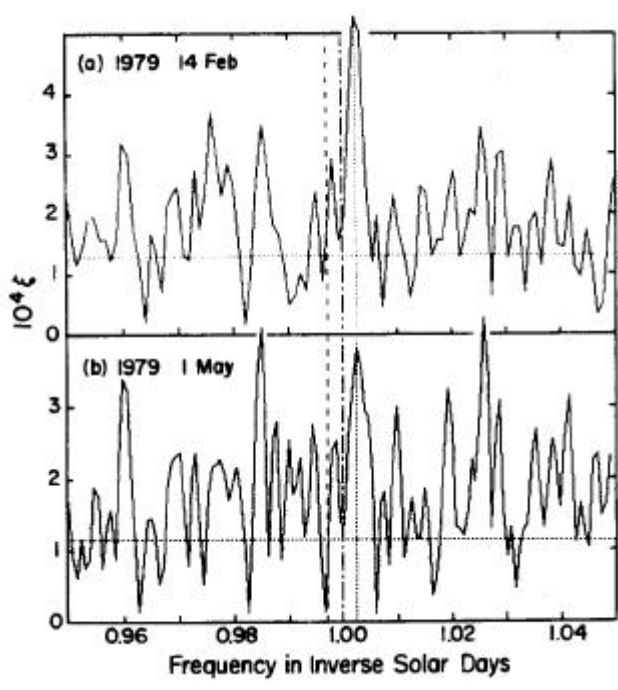


Fig. 2. Fourier amplitude spectra for the data starting 1978 Jan 1 to the cutoff dates shown in the vicinity of 1 day<sup>-1</sup>. The dotted vertical line is at the sidereal frequency, and the dashed line at the antisydereal frequency.

justify such cuts. The peaking of the rate into the near-vertical channels results in an East-half versus West-half (defined by the dotted line in the Table) average phase difference of only 2°.4, or 2.8.

**5. Response Function.** The controversial problem of relating the muon energy threshold to a primary rigidity distribution finally appears to have been resolved. Three groups(18,19,20) have made calculations based upon ISR data which spans the region of interest. Their functional shapes are nearly identical, and after removal of minor numerical errors in two of the calculations(18,19) the authors also obtain essentially the same median primary energies. Gaisser (21) concludes that residual uncertainties due to particle physics are at the 5% to 10% level. New data is not likely to change this conclusion. Following Gaisser, we take 10.4 as the factor relating muon threshold energy  $E_{i0}$  to proton median energy  $E_{med}$  at our energy. If 79.4% of the nucleons arrive as protons, the response functions all yield a median primary rigidity  $R_{med}$  equal to  $1.17 E_{med}$ . The muon energy distribution of Fig. 1 thus implies a median primary rigidity of  $1.5 \times 10^{12}$  V for the Utah detector. (The distribution of Fig. 1 will be folded with the fixed- $E_{i0}$  response function to obtain the detector response function in the near future.)

For the reported average depth of 360 hg cm<sup>-2</sup> at Poatina, we obtain  $E_{uo} = 87$  GeV,  $E_{med}/E_{i0} = 10.5$ , and  $R_{med} = 1.1 \times 10^{12}$  V.

**6. Results and Discussion.** Our analysis methods are discussed in Paper II, MG7-7. Typical discrete Fourier transform (DFT) amplitude spectra in the vicinity of 1 solar day<sup>-1</sup> are shown in Fig. 2, where the sidereal frequency at 1.0027 day<sup>-1</sup> is indicated by the vertical dotted line. Fig. 2(b) is identical with Fig. 3(c) Paper II, while Fig. 2(a) represents the data as of 9 weeks earlier.

Data from the 13 angular intervals have been combined with the appropriate phase shifts in calculating the DFT's, although this correction makes very little difference in practice because of the heavy weight given to the near-vertical intervals. It is particularly interesting to note the "Greisen effect" between Fig. 2(a) and Fig. 2(b); i.e., the loss of significance as more data is accumulated. A change of this magnitude is not improbable, and the surrounding noise behaves as expected.

As of 1979 Play 1 the height of the sidereal peak was  $(3.8 \pm 1.4_{0.9}) \times 10^{-4}$ . The errors are 68% confidence limits, and are determined from the appropriate off-center Rayleigh distribution, as discussed in Paper II. The peak has been persistent, as is indicated by a stationary phase (Fig. 4 in Paper II) corresponding to right ascension  $\alpha = 1^h.5 \pm 1^h.2$ .

After removal of the Compton-Getting component due to solar motion ( $19.5 \text{ km sec}^{-1}$  at  $\alpha = 18^h$ ,  $\delta = 30^\circ$ ), the result becomes  $(4.9 \pm 1.4_{0.9}) \times 10^{-4}$  for the projected anisotropy  $\hat{I} \cos \delta \cos \alpha$ , so that  $\hat{I} \cos \alpha = (6.6 \pm 1.9_{1.2}) \times 10^{-4}$ . The declination is in principle unknowable in such an experiment, but if the streaming apex should be on the galactic equator then the galactic longitude is near  $130^\circ$  and  $\cos \alpha \sim 0.5$ .

There is no evidence for peaks at the antisidereal or solar frequencies. The latter is worrisome in view of our sensitivity to upper air temperature effects at this energy. For an upper air diurnal wave of amplitude  $\Delta T$ , we would have expected a solar frequency contribution of  $27 \times 10^{-4} \Delta T / 1^\circ\text{K}$ . It is expected to be  $\pi$  out of phase with the Compton-Getting contribution due to the earth's motion about the sun ( $3.5 \times 10^{-4}$  at our latitude), but since  $\Delta T$  was expected to be about  $0.3^\circ\text{K}$ , a nearly exact cancellation would be surprising. We have attempted to correct the data using telemetry tapes from bidaily weather balloon flights at Salt Lake City, but jitter in the atmospheric data (presumably instrumental) is prohibitively large. Longer term weather effects of  $\pm 1.5\%$  also exist, but have no Fourier components at frequencies of interest.

The DFT amplitude distribution near  $2 \text{ day}^{-1}$  is shown in Fig. 3. The peak near the second sidereal harmonic (vertical dotted line at  $2.0055 \text{ day}^{-1}$ ) has an amplitude of  $(3.8 \pm 1.4_{0.9}) \times 10^{-4}$ , which by coincidence is the same as that of the first harmonic for this particular data string. The right ascension of the apex is  $9^h.8$  (or  $21^h.8$ )  $\pm 1^h.2$ . If the peak is real,

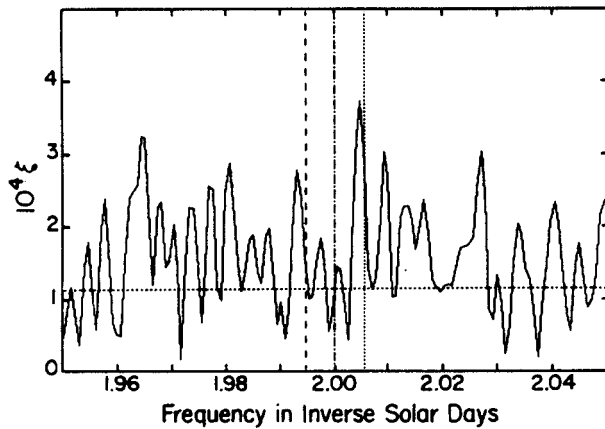


Fig. 3. Fourier amplitude spectrum for data through 1979 May 1 in the vicinity of  $2 \text{ day}^{-1}$ .

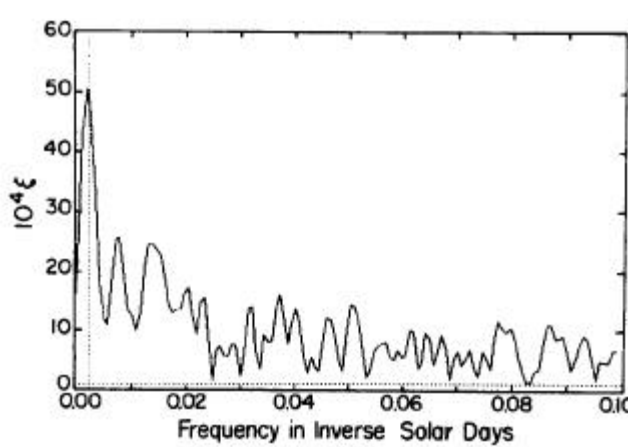


Fig. 4. Fourier amplitude spectrum at low frequencies for data through 1979 May 1. Vertical dotted line is at  $1 \text{ yr}^{-1}$ .

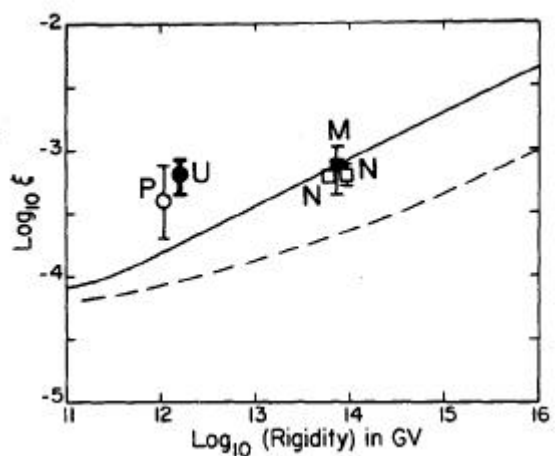


Fig. 5. Projected sidereal anisotropy first harmonics  $E \cos \delta$  as measured at Poatina, Utah, Mt. Musala, and Mt. Norikura. Curves are for halo containment model of Owens and Jokipii.

the small frequency shift could be due to sidelobe interference.

The region near zero frequency is shown in Fig. 4. The 0.5% wave at  $1 \text{ yr}^{-1}$  is of the expected size and phase. However, there is evidence for a  $1/f$  noise component below  $0.7 \text{ day}^{-1}$ , perhaps due to the long-term weather effects, and so we can attach little significance to the annual wave.

Our present sidereal amplitude is plotted in Fig. 5, together with measurement from Poatina(14), M Musala(15), and Mt. Norikura.(16) All stations obtain phases near  $\hat{\alpha} = 1^{\text{h}}.5$ . In all cases, we have divided the published results and errors by  $\cos \delta$ , so that  $\hat{\alpha} \cos \delta$  is plotted. The curves represent two predictions of halo containment models.(11) If  $\hat{\alpha} \sim 60^\circ$ , then all points should be moved upward by 0.3. For the first time in the history of the subject, experiments agree in amplitude and phase and the amplitudes are at or above theoretical expectations.

We hope to quadruple the running time before dismantling the apparatus, in order to decrease the error by a factor of two and permit a variety of data cuts which the present statistics do not support. Peaks should then be four times sharper, resulting in a much cleaner separation of solar and sidereal effects.

7. Transient Searches. The on-line computer keeps running tallies of the number of coincidences in time intervals  $\Delta t_k = 3^k \times 12 \text{ msec}$ ,  $k = 0, 1, \dots, 8$ . These tallies are kept for 30 intervals into the past and are updated every time there is a coincidence. If the current total in a bin for  $k = 1$  exceeds a preset significance level, all 30 bins for each time interval are recorded on tape. The significance levels are set so that the probability of exceeding these levels is the same for each time interval and are scaled to yield a total rate of triggers of about 1 per day. For the data segment analyzed in this way (200 days from 1978 Oct 13 to 1979 May 1), 191 triggers have been observed having a distribution consistent with Poisson statistics.

8. Acknowledgments. This work was supported by the National Science Foundation (USA). We are indebted to J. West and A. Larsen for invaluable technical assistance, and to the other five dwarfs who helped make a high energy laboratory out of a very unpromising mine.

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Number of Pages: 6  
Number of Words: 2,338 (approx.)  
Number of Characters: 13,330 (approx.)