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Underground Muons Observed in the Soudan 2 Detector From the Directions of X-ray Sources*

W. W. M. Allison[3], G. J. Alner[4], I. Ambats[1], D. S. Ayres[1], L. Balka[1], G. D. Barr[3], W. L. Barrett[1], D. Benjamin[5], P. Border[2], C. B. Brooks[3], J. H. Cobb[3], D. J. A. Cockerill[4], K. Coover[1], H. Courant[2], B. Dahlin[2], U. DasGupta[2], J. W. Dawson[1], V. W. Edwards[4], B. Ewen[5], T. H. Fields[1], C. Garcia-Garcia[4], R. H. Giles[3], M. C. Goodman[1], S. Heppelmann[2], N. Hill[1], J. H. Hoftiezer[1], D. J. Jankowski[1], K. Johns[2], T. Joyce[2], T. Kafka[5], J. A. Kochocki[5], P. J. Litchfield[4], N. Longley[2], F. V. Lopez[1], M. Lowe[2], W. A. Mann[5], M. L. Marshak[2], E. N. May[1], L. McMaster[5], R. Milburn[5], W. Miller[2], A. Napier[5], W. P. Oliver[5], G. F. Pearce[4], D. H. Perkins[3], E. A. Peterson[2], L. E. Price[1], D. Roback[2], D. B. Rosen[2], K. Ruddick[2], B. Saitta[5], J. L. Schlereth[1], D. Schmid[2], J. Schneps[5], S. Schubert[2], P. D. Shield[3], M. Shupe[2], N. Sundaralingam[5], M. A. Thomson[3], J. Thron[1], L. M. Tupper[3], S. Werkema[2], N. West[3]

[1] *High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439*
[2] *School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455*
[3] *Department of Nuclear Physics, University of Oxford, Oxford, U.K. OX1 3RH*
[4] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon U.K. OX11 0QX*
[5] *Physics Department, Tufts University, Medford MA 02155*

We report on observations of underground muons made with the Soudan 2 proton decay detector at a depth of 2090 mwe from the directions of the binaries Hercules X-1 and 1E2259+586 and the Crab pulsar.

I. Introduction

The question of whether cosmic ray muons observed deep underground can be associated with specific astrophysical sources remains perplexing[1]. On one side are the evidence of the Soudan 1 and NUSEX detectors relating deep underground muons to Cygnus X-3, the Kiel and CYGNUS detector observations of anomalous muon content in source-related showers, and, most recently, the Soudan 2 detector measurement of excess underground muons from the direction of Cygnus X-3 during the January 1991 radio flare of that source[2]. Contrary arguments include the absence of a known physical mechanism for producing muons in the observed quantities and published upper limits by the Frejus and Kamiokande detectors, which apparently conflict with at least some of the Soudan 1 and NUSEX results.

We have analyzed underground muon data from the Soudan 2 proton decay detector with the goal of providing further information concerning this question. We report here on analysis work in progress on the underground muon flux from the directions of 3 northern hemisphere objects, all of which have previously been reported as active at TeV and PeV energies[3]. Hercules X-1 is a binary with a well-determined orbital ephemeris, a somewhat erratic pulsar period and a not so well-determined 35-day precessional period. 1E2259+586 is apparently a binary with a very light companion mass. The pulsar period is well-defined and not significantly affected by an orbital Doppler shift. Flux modulation at all energies is only observed at the 2nd harmonic, not the fundamental period. The Crab pulsar is an isolated neutron star. 1E2259+586 and the Crab pulsar lie in the galactic plane.

We believe that resolution of the possible relationship between underground muons and sources requires simultaneous measurements by multiple detectors. Our goal here is to identify features of our data which appear worth checking in the existing data sets of other detectors. For this reason, we have chosen to use only simple, relatively insensitive, but clearly *a priori* tests for the purpose of determining the probability of the H_0 hypothesis (purely random events).

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These tests are as follows: (1) a d.c. analysis of the excess flux for the entire data sample for each of the three sources; (2) a d.c. day-by-day analysis for each of the three sources in which we calculate the Poisson probability that H_0 is correct; and, for 1E2259+586, (c) a day-by-day combination of the Poisson probability and a Rayleigh analysis of the arrival times for events (corrected to solar system barycenter), using *exactly* the known x-ray period for that day (2nd harmonic p=3.4893795 s, dp/dt=2.95 x 10^{-13}, t_0=JD 2446968.9). This combination uses the equation $pq(1 - \ln pq)$ for combining the results of independent tests. Although we have performed additional *a posteriori* tests as a means of exploratory data analysis, we do not derive any information from those tests about the probability of the correctness of H_0. We do restrict the day-by-day analyses to those days in which 5 or more events within the source cone are *expected*, as determined by the background calculation. We also correct the Rayleigh probabilities for small n, using the series of Durand and Greenwood[4].

II. Detector and Analysis Procedure

The Soudan 2 detector is a time-projection, ionization calorimeter located at a depth of 700 m (2090 m water equivalent) in northern Minnesota U.S.A. (47.82° N, 92.25° W). The data reported here consist of 5.5 x 10^6 muon events observed between January, 1989 and June, 1991. During this time interval, the detector size increased from 4 m by 8 m by 5 m high to 10 m by 8 m by 5 m high, which resulted in a steady increase in the rate of observed muons. Data collection was frequently interrupted during the day Monday through Friday for detector installation. Data recording was generally continuous at other times.

The Soudan 2 detector measures three spatial coordinates and deposited ionization for each charged track gas crossing. Crossings are tubes with a nominal inner diameter of 15 mm separated by 1.6 mm of steel. Spatial resolution in the time-projection coordinate is <1 cm. A typical muon track in the Soudan 2 detector is several meters in length, consists of more than 100 gas crossings and penetrates >25 cm of steel. Although the identity of tracks is generally unambiguous, the directionality of tracks is sometimes confused by delta rays and bremsstrahlung. A study of multimuon events and a consideration of all detector systematics suggests an overall, absolute track angular resolution of ≈1.2°. If the angular errors are approximately gaussian, a 2° half-angle cone cut will yield the best signal-to-background ratio. This cut was used for this entire analysis.

The data reported here were first analyzed by a geometry program which sorted events by topology. Apparent muon events were reconstructed in two 2-dimensional projections. The projections were then correlated and transformed to right ascension and declination using a clock synchronized to the national time standard via radio station WWVB. Event arrival times were transformed to the solar system barycenter using the JPL ephemeris. The data sample contains both single and multimuon events. Each event has been counted once, regardless of the number of contemporaneous muons.

The determination of the background flux which would be observed in the absence of a source is an important aspect of this analysis. For a detector such as Soudan 2, the background flux is determined by a convolution of the geometric acceptance in local coordinates with the recorded detector ontime and efficiency. For the analysis here, we have determined both of these acceptances by sampling actual events. Thus, we have done a Monte Carlo calculation which randomly pairs event arrival times with track geometries from other events. The paired events are required to occur within 0.5 days (so that detector characteristics are similar) but not within 0.1 days (to remove a possible source fluctuation from the background determination). We have performed this random pairing 500 times for each real event (and divided the resultant numbers of events by 500) to make negligible any statistical error in the background calculation.

Finally, we have checked both the data sample and the analysis procedure for systematic effects by applying the same analysis to 7 background cones for each source.

These cones are centered at the same declination as the source and spaced in right ascension at 45^0 intervals.

III. Observations

The d.c. excesses for the entire sample for each of the three sources are listed in the table below. The data suggest that none of these objects are long-term sources at a level more than a few percent of the cosmic ray background:

Source	Observed	Expected	Excess (%)	Sigma (%)
1E2259+586	4776	4812.5	-0.8	1.4
Crab	3069	3120.0	-1.7	1.8
Hercules X-1	3533	3551.8	-0.5	1.7

For the day-by-day analyses, we have identified the most anomalous days for each source. No day for any of these sources deviates significantly from the uniform background hypothesis. However, an exploratory analysis yields some intuitively interesting features of the data which appear worth checking in other data samples. The next table lists the minimum value of test probability multiplied by the number of days tested found in each of the day-by-day tests.

Source	Days Tested	Poisson (probability of excess)	Combined Rayleigh and Poisson
1E2259+586	486	0.84	0.14
Crab	273	0.39	
Hercules X-1	332	0.09	

The most unlikely day for muons from the direction of 1E2259+586 is 20 September 1989, which has a combined test (Poisson for d.c. excess and Rayleigh for modulation) probability of 2.9×10^{-4}, which multiplied by 486 days tested yields 0.14. The analysis of the 7 off-source directions showed one day with an equally small combined probability and no days with a smaller combined probability, which confirms the accuracy of the probability estimate. On 20 September 1989, 11 events were observed, with 5.9 expected. The Rayleigh power for the 11 events was 7.1 at the exact x-ray 2nd harmonic period for that day of 3.48940004 s. The phase plot is shown in Fig. 1. Even the background is phase-peaked, which is not surprising since the day was selected, in part, for strong modulation.

By themselves, the data for muons from the direction of 1E2259+586 on 20 September 1989 are not remarkable. However, this day is amidst a multiday interval with excess flux. Since the TeV atmospheric Cerenkov observation of 1E2259+586 involved an 8 day interval, it seems reasonable to consider a multiday interval. The contiguous interval which includes 20 September and which maximizes the "significance" of the dc flux excess is 0h U.T 19 September to 0h U.T. 27 September. For this interval, 62 events are observed and 39.2 are expected. As plotted in Fig. 1, the event arrival times for the entire 8 day interval show a strong peak in phase with the modulation on 20 September at the *a priori* period of 3.4894004 s. The Rayleigh power of this peak is 5.4, probability 0.005 (Rayleigh power of 2.3, probability 0.10 if 20 September is not included) The real probability of finding an 8-day interval such as this one in the data cannot be determined, since the test is *a posteriori*. The absolute phase is such that an event which arrived at JD 2447789.79838279 (actual arrival time before barycentering) has a phase of 0.55. The estimated flux over the eight day interval from the phase plot is 54 ± 15 percent of the cosmic ray background within a 2^0 half angle cone.This estimate is somewhat biased upward by the procedure described above for choosing this 8 day interval.

The most unlikely day for Hercules X-1 is 31 December 1990. This day has 18 events observed, 7.1 events expected. The trials modified probability is 0.09. The 7 background directions yield one equally unlikely and one slightly more unlikely day, so the probability calculation is consistent with off-source data. The orbital phase (period=1.70

days) for almost all the events on this day is between 0.60 and 0.70, a phase at which TeV emission has been observed. Seven of the 18 events come in two bursts of less than 400 s each, one with 3 events at an orbital phase of 0.63 (near 15.0 h U.T.) and one with 4 events at an orbital phase of 0.67 (near 16.9 h U.T.). Approximately 0.2 events are expected within 400 s. The 35 day phase is ≈0.55, corresponding with the beginning of the "short on" portion of the cycle. We have searched for modulation at the pulsar period for these data; however, the low data rate and an imprecise knowledge of what period to use makes a definitive answer difficult.

No notable deviations from the hypothesis of a uniform, random background are observed for any day for muons from the direction of the Crab.

IV. Conclusions

We have identified in a very preliminary analysis one time interval each during the past 2.5 years for 1E2259+586 and Hercules X-1 that appear worthy of checking in the data of other detectors. If these episodes are not random fluctuations, they suggest somewhat different behavior for the two sources—stable radiation at a fixed period for more than a week for 1E2259+586 and multiple, short bursts of less than an hour each for Hercules X-1. Future analyses might use these characteristics *a priori*, in order to increase the sensitivity of an analysis.

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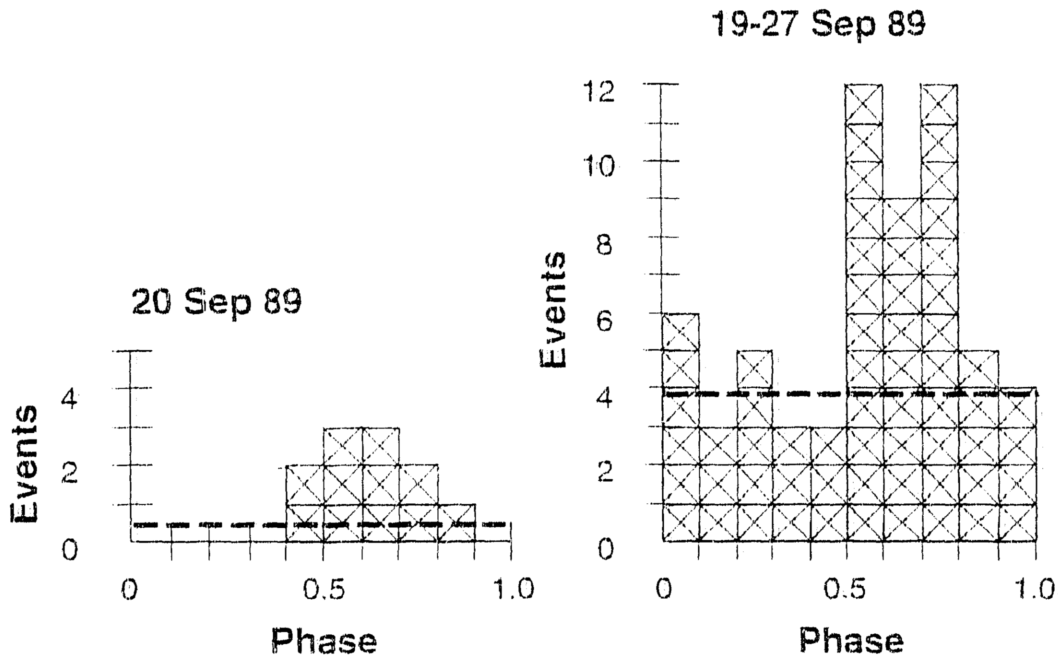

Fig. 1—Phase plots for muons from the direction of 1E2259+586 at the known pulsar period. The left plot is for the most anomalous day in the data sample; the right plot is for an 8 day interval including that day.

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