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STUDIES OF μ's UNDERGROUND WITH THE SOUDAN 2 TRACKER

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Abstract

During the period July 1987 through March 1988, a section of the Soudan 2 active shield known as the 'Tracker' recorded ~250,000 muon tracks. The detector is located in the Tower–Soudan State Park in Soudan, Minnesota USA at a depth of 2090 meters–water equivalent. We have analysed the data collected and searched for time–dependent astronomical sources. Distributions in azimuthal and zenith angles as well as declination and right ascension are shown.

<u>The 'Tracker'</u> The Tracker is a section of the Soudan 2 active shield that was installed as a muon tracking system. It consists of 128 proportional tube modules arranged in two planes. Each plane has crossed layers, separated by 10 m, with an effective overlap area of $\sim 35m^2$. The detector is shown in Figure 1. Each layer contains 32 proportional tube modules and each module has eight cells. Anode wires from the four cells in each of the upper and lower rows of a module are ganged together to form a detection element or channel. As measured on a cosmic ray test stand, individual channels are capable of responding to minimum ionizing radiation within 1 μs. The identification of a coincidence ($1\mu s$) between any adjacent upper and lower channels within a layer forms a trigger signal for that layer. The logical AND of the trigger signals generated by a set of three layers is used to form the event trigger for a penetrating muon in this experiment. Absolute timing information, accurate to 1 ms was provided by the WWVB signal generated in Fort Collins, Colorado.

Data were collected with the four layers of the tracker, L1-L4, from April 1987 through May of 1988. In December 1987, an extension to layer L3 was installed (L5). The trigger was $L1 \cdot L2 \cdot L3$. A sharp peak in the correct time buffer (Figure 2) for L4, the layer not in the trigger, is evidence that real penetrating muons were the bulk of the triggers.

There were about 250,000 recorded triggers. Table 1 shows how cuts were applied on the data. Electronics problems corrupted some of the data. There were 147,054 triggers which were passed to the pattern recognition and track fitting algorithms. At this point the track reconstruction is not heavily constrained. A single additional hit due to a delta ray or noise could cause an ambiguity in the track direction. Triggers for which there are no ambiguities in direction are called 'golden muons'. A golden single muon data sample and a golden multiple muon data

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sample were extracted from the data for further analysis.

The single muon distribution in zenith angle, θ is shown in Figure 3. The bin size in the plot is 1°. The average zenith angle is 15°, and no muons are observed for $\theta > 43^\circ$. The single muon distribution in azimuthal angle, A, is shown in Figure 4. The bin size in the plot (1°) was chosen to expose the inefficiencies in the trigger seen at the compass points where the probability for a muon to pass through undetected is highest (*i.e.,* through the crack regions). The distribution shows a minimum for muons from the northwest direction (-60°) and a maximum for muons from the southeast direction (150°). The asymmetry in this plot is due almost entirely to the acceptance of the Tracker and not to overburden. As can be seen in Figure 1, layer L1 is shifted north relative to layer L3 and layer L2 is shifted west relative to layer L4. This favors muons from the southeast direction.

Multiple Muons The muon multiplicity is shown in Figure 5 and the separation distribution between golden dimuons is in Figure 6. The average track separation (s) is 2.17 m with an rms width of 1.26 m.

Muon Flux The inability to reconstruct the angle for a large fraction of the muons causes an ambiguity in the vertical muon flux. However from the measured reconstructed triggers a lower limit can be set on the vertical muon flux:

$$(\frac{dN}{d\Omega})_\nu > 0.92\ 10^{-3} m^{-2} s^{-1} sterad^{-1} \tag{1}$$

The total trigger rate together with the measured angular distribution is then used to calculate an upper limit to the vertical muon flux:

$$(\frac{dN}{d\Omega})_\nu < 1.55\ 10^{-3} m^{-2} s^{-1} sterad^{-1} \tag{2}$$

Cygnus X-3 Possible previous observation of Cygnus X-3 using underground muons is a controversial subject. Using muons from the tracker, in the 3° cone around the direction of Cygnus X-3, the expected rate of cosmic ray background events is 301.3 ± 17 muons (corrected for detector sensitivity). The observed number was 311. A phase plot using the Van der klis Bonnet-Bidaud Bidaud 1988 ephemeris is shown in Figure 7. As might be expected with this size data sample, there is no compelling statistically significant peak in the Figure. Further analysis varying the cone size is in progress.[1]

Conclusion The Soudan 2 tracker has been run and has given an initial data sample of muons and multiple muons for the Soudan 2 experiment. Final results from the above analyses will be reported in a journal article which is in preparation.[1]

References

1. J. Kochocki et al., to be submitted to Physical Review, 1989.

DISCLAIMER

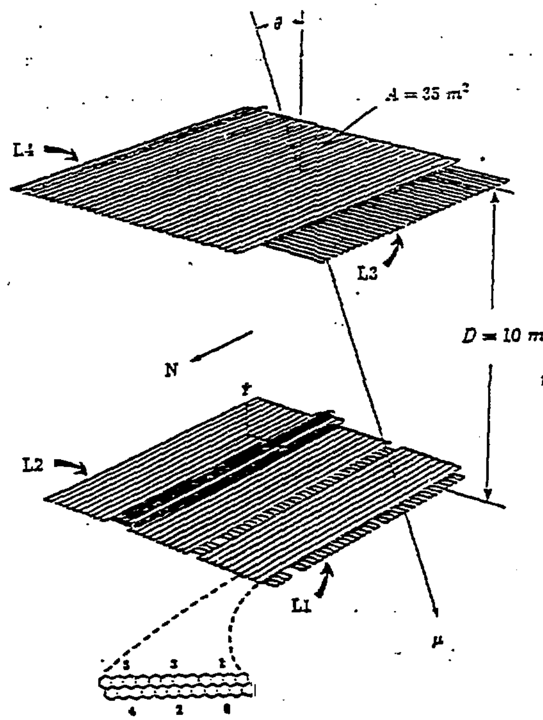

Figure 1. The tracker consists of four layers of 32 proportional tubes each, arranged in two crossed planes as shown.

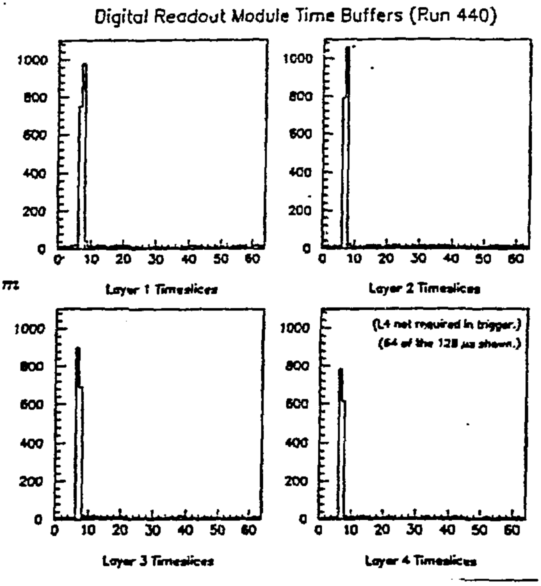

Figure 2. Readout module time buffers. L1, L2 and L3 were in the trigger. The sharp peak in L4 is evidence for a μ.

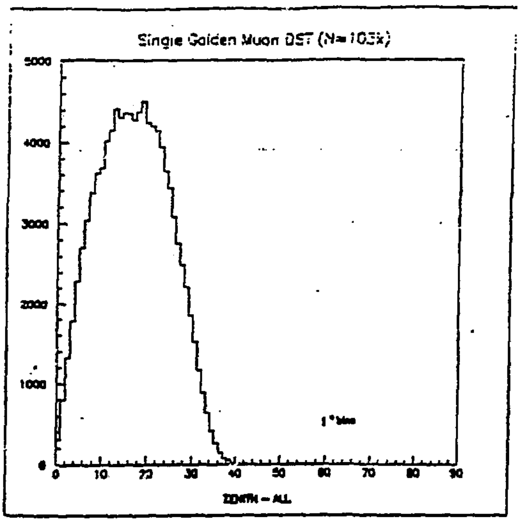

Figure 3. Zenith angle distribution for all of the golden single muon data sample.

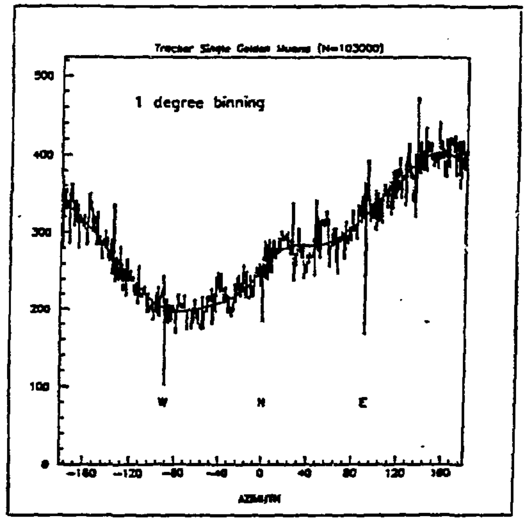

Figure 4. Azimuth angle distribution for all of the golden single muon data sample.

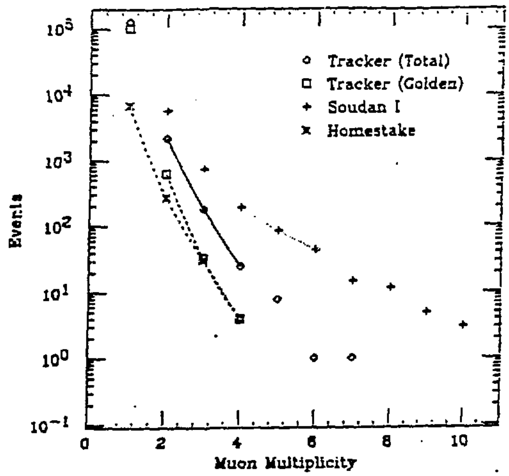

Figure 5. Observed muon multiplicities for golden multiple muons and two other experiments. No acceptance corrections are made.

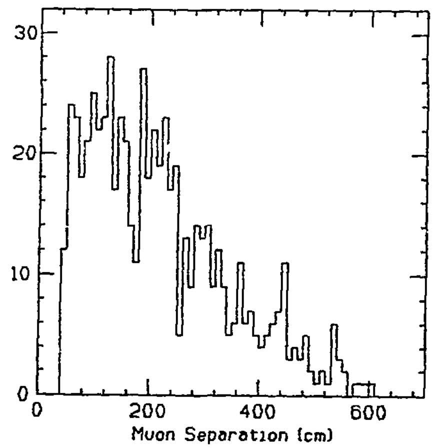

Figure 6. Two muon separation. The mean separation was 2.17 m.

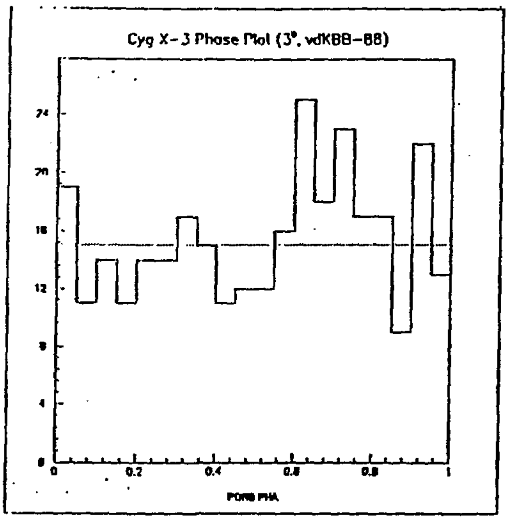

Figure 7. Phase plot for muons in a 3° cone around the direction of Cygnus X-3 using the van der Klis Bonnet-Bidaud 1988 ephemeris.

Table 1

CUTS APPLIED TO THE DATA

248,576	RECORDED TRIGGERS
- 2,980	NON-COSMIC RAY TRIGGERS
-17,153	DATA BUFFER ERRORS
- 1,010	READOUT ERRORS (CAMAC)
- 6,977	NO IN-TIME HITS
-57,164	MISSED LAYER L4
- 3,814	FALSE TRIGGERS
- 8,534	NOISE TRIGGERS
- 3,775	MISSED LAYER L3 (POST-EXTENSION)
- 115	TIME ERRORS
147,054	TRIGGERS ENTERED THE PATTERN-RECOGNITION AND TRACK-FITTING ALGORITHMS

~ 103,000	~ 900	~ 43,000
GOLDEN SINGLE MUON SAMPLE	GOLDEN MULTIPLE MUON SAMPLE	AMBIGUOUS OR BLOB-SIZE TOO BIG OR > 100 TRACKS