Underground Muons from the Direction of Cygnus X-3

Soudan 2 Collaboration

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We have measured the flux of underground muons from the direction of the binary Cygnus X-3 using the Soudan 2 proton decay detector. This time-projection calorimeter is located at a depth of 2200 m water equivalent in northern Minnesota at latitude 48° N, longitude 92° W. We then performed an analysis comparing both the total observed flux and the observed flux per transit with the number of events expected in the absence of a source. This expected number of events was determined by combining the detector acceptance as a function of time with the detector acceptance as a function of the local spatial coordinates. These functions were evaluated by use of off-source events. The direction of Cygnus X-3 was defined as a 2° half-angle cone, centered on the nominal source coordinates. This definition is consistent with the expected appearance of a point source in the Soudan 2 detector after consideration of track reconstruction errors, multiple scattering in the rock and possible systematic effects. Details of this analysis and the results are described in Ref. 1.

The integrated muon flux from January 1989 through February 1991 is consistent with the expected background, suggesting that Cygnus X-3 is not a steady-state source of particles which produce muons at a level observable by the Soudan 2 detector. The background calculation for the integrated flux was checked by comparing off-source observations with the background expectation. A folding of the total event sample using the Cygnus X-3 orbital ephemeris also indicated good consistency with background.

The validity of the daily background flux calculations is shown in Fig. 1, which plots the distribution of observed minus expected events for 41355 sources x days for fake sources located at the same declination as Cygnus X-3 but at differing right ascensions. The line is the expectation of a Poisson probability distribution. Fig. 2 shows events observed vs. events expected for 696 days of data for the Cygnus X-3 direction. The lines indicate Poisson probabilities of 10^{-3}. Two days are distinguished—20 and 23 January 1991. Both these days correspond to the major radio flux peak of one of 5 large radio flares of Cygnus X-3 which occurred between January 1989 and February 1991. Muon fluxes during the other radio flares showed no significant excess, although the Soudan 2 detector was smaller and had less sensitivity in 1989 and 1990. A subsequent analysis also indicated no significant deviation from background for the muon flux during the July 1991 Cygnus X-3 radio flare. Event arrival times within the days of 20 and 23 January 1991 are not significantly modulated either by time of arrival or by Cygnus X-3 orbital phase. The estimated muon flux for these two days is $\approx 7.5 \times 10^{-10}$ cm^{-2} s^{-1}. The estimated chance probability of this result is 5.5×10^{-4}.

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[1] M. A. Thomson *et al.*, Phys. Lett. **B269**, 220 (1991)

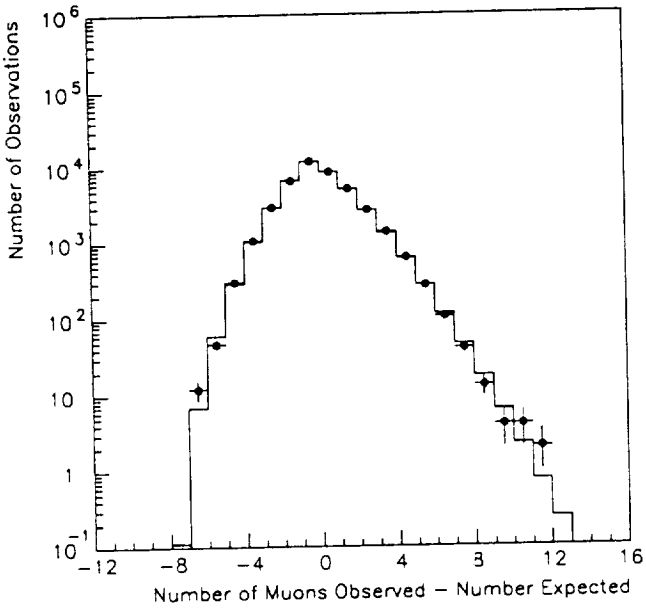

Fig. 1—The points are a histogram of the number of observed minus number of expected events for each live day for each of sixty 2.0° half-angle cones at the declination of Cygnus X-3. The solid curve is the prediction of Poisson statistics. A total of 41355 sources x days have been considered.

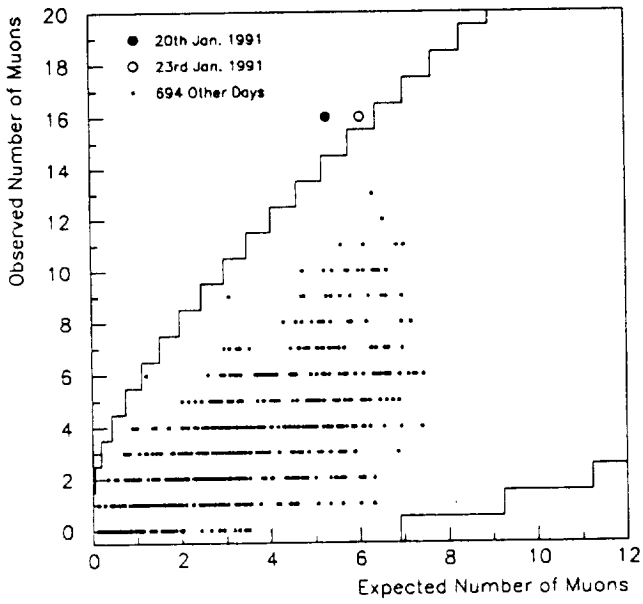

Fig. 2—A scatter plot of the number of muons observed from the direction of Cygnus X-3 on a given day vs. the number expected on that day for a total of 696 days. The lines show the 10^{-3} probability boundaries.