SEARCH FOR MUONS FROM THE DIRECTION OF CYGNUS X-3

FREJUS Collaboration

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Muons and multimuons detected in the Fréjus underground nucleon decay detector between February 1984 and January 1986 have been analyzed No excess events are observed in the direction of Cygnus X-3, which yields a 90% confidence level upper flux limit of $0\,8 \times 10^{-12}$ cm^{-2} s^{-1}, for an average rock overburden of 5000 hg cm^{-2} corresponding to energies $\gtrsim 3$ TeV Using the 4.79 h periodicity of Cygnus X-3, no signal is found in any phase interval

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Cygnus X-3 has been observed in the X-ray, the infrared and radio range, and is usually interpreted as a binary system in which a compact object is orbiting around a more massive companion with a 4.79 h period. Several experiments have reported the observations of γ rays from Cygnus X-3 in the 30 MeV–1 GeV range, and at energies above 1 TeV [1]. Recently, two nucleon-decay-dedicated experiments reported evidence for underground muons from the direction of Cygnus X-3 with a characteristic 4.79 h period [2, 3]. This evidence was not confirmed in refs. [4,5].

The Fréjus nucleon-decay detector is installed in an underground laboratory [6] located in the middle of the Fréjus alpine road tunnel near Modane, France. The coordinates of the laboratory are 6.7° E and 45.1° N. The detector [7] weights 900 tons, is 6 meters high and presents a horizontal surface of $(6 \times 12.3)\ \mathrm{m}^2$. It is a very fine grain tracking calorimeter with (5 mm × 5 mm) cells and a calorimetric sampling of 3 mm of iron. One thousand vertical planes of flash chambers and Geiger tubes with alternately horizontal and vertical cells provide two orthogonal views. The 40 000 Geiger tubes are used to trigger the flash chambers which have $\approx 930\,000$ cells. The number of detected muons is $\approx 20/\mathrm{h}$ and corresponds to a flux of $4.9 \times 10^{-9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. By using the topological mountain map, the amount of rock crossed by each incoming muon can be determined.

Events were recorded between February 19, 1984 and January 3, 1986. One half of these data was taken after June 85, with the full-size detector. Before that date, the detector was gradually increased from 240 to 900 tons. The detector was active 78% of the time. Among the muons coming from the path of Cygnus X-3 a small fraction (5%) are almost parallel to the vertical detector planes and are lost because these muons do not satisfy the trigger requirements. In addition, short tracks with less than 8 flash chamber planes per view as well as tracks which undergo large multiple scattering have been removed. These cuts reduce the data sample by 11% and ensure that the angular accuracy of the muon angle is better than the mean scattering angle in the mountain rock. The final data sample contains 170 146 muons and 4 343 multimuons.

From the fitting procedure we calculate a 1 standard deviation error of 0.4° for the angles in the laboratory. From the study of the parallelism of multimuons we determine a 1 σ error of 0.9° in the initial angle of incoming muons due to scattering in the mountain rock. The orientation of the detector is known with an accuracy of 0.1° from the three independent measurements. First, with a maximum likelihood method, we adjusted the observed muon angular distribution to the known mountain profile. Secondly, the orientation of the detector was determined by gyroscopic measurements [‡1]. Finally, these measurements agree with the triangulation made during the construction of the Fréjus tunnel.

To look for a possible signal from Cygnus X-3 (right ascension $\alpha = 307.65°$; declination $\delta = 40.78°$ in the epoch A.D. 1950), we calculate the direction of each muon in equatorial celestial coordinates, α and δ. The overall angular resolution of the muon direction in celestial coordinates is 1.2°. The angular resolution and the accumulated statistics make it possible to consider a cone of half angle 2° centered on Cygnus X-3. We also present data in a 5° cone for direct comparison with ref. [3]. Fig. 1 shows the sky map of muons and multimuons in the vicinity of Cygnus X-3. No accumulation is seen.

We have compared the distributions of rock thickness crossed by muons coming from the direction of Cygnus X-3 and by muons coming from the entire

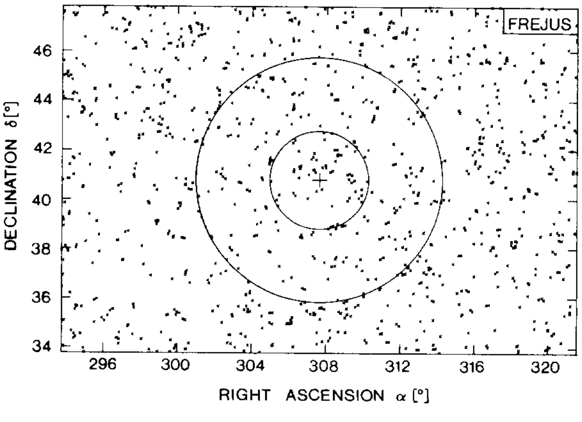

Fig. 1. Sky map of detected muons and multimuons. The inner circle shows the projected cone of half angle 2° centered on Cygnus X-3. The outer circle is for 5°. The position of Cygnus X-3 is indicated by the cross.

[‡1] We are grateful to W. Coosemans and C. Fisher from CERN-LEP who performed these gyroscopic measurements.

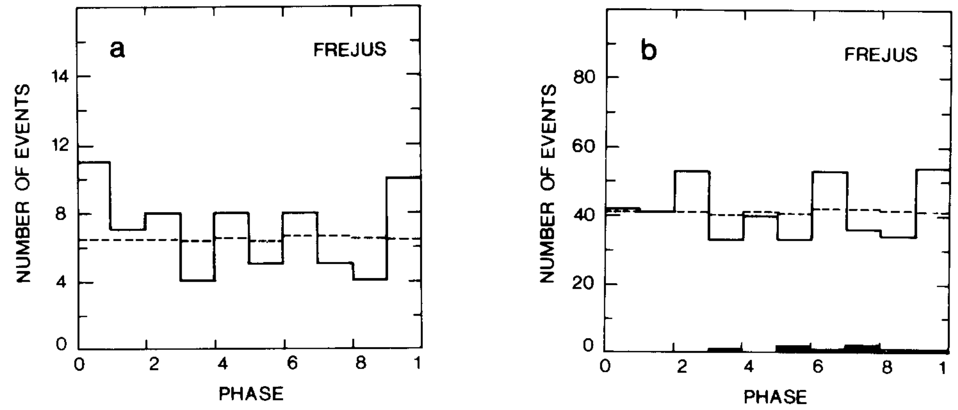

Fig 2 Phase distribution of muons and multimuons in cones of half angle 2° (a) and 5° (b) centered on Cygnus X-3 The solid line corresponds to the detected muons and multimuons. The contribution of multimuons is shown by the shaded area. The dashed line represents the expected number of atmospheric muons and multimuons (see text)

path followed by Cygnus X-3. We found good agreement. The average thickness, 1835 m or 5000 hg/cm^2, corresponds to muon energies $\gtrsim 3$ TeV It is larger than the average amount of rock (1780 m) crossed by the entire sample of muons from all directions.

The phase of each event is calculated from the arrival time t after heliocentric correction, the Cygnus X-3 period P_0 at a reference time T_0 and its time derivative $\dot{P}$ according to

$$\Phi = (t - T_0)/[P_0 + \dot{P}(t - T_0)/2] \text{ modulo } 1$$

with [8] T_0 = Julian Day 2440949 8986, P_0 = 0.1996830 day and $\dot{P} = 1.18 \times 10^{-9}$ The phase histograms are shown in fig 2 for 2° and 5° windows centered on Cygnus X-3.

In order to analyze these data in terms of an excess signal, one has to determine the expected background of atmospheric muons. One must take into account the variation of the rock thickness and the detector acceptance along the path of Cygnus X-3, the increasing size of the detector and the periods during which the detector was not active. Since the Cygnus X-3 period is very close to 1/5th of a sidereal day, the strong correlation between the phase and the rock thickness crossed by muons from the direction of Cygnus X-3 may produce systematic effects if the time distribution of recorded events, modulo 174 days, is not uniform.

Two independent methods of determining the expected background are used. One method relies solely on data and therefore automatically includes all the effects mentioned above. We first determine, for each detector size, the atmospheric background flux variation during one sidereal day using all the muons in the declination band (± 5°) centered on the Cygnus X-3 position. This distribution, shown in fig 3, illustrates the effect of the mountain profile as well as the experimental acceptance The null flux corresponds to the time during which Cygnus X-3 is near and below the horizon. In order to correct for the time during which the detector is not active, we

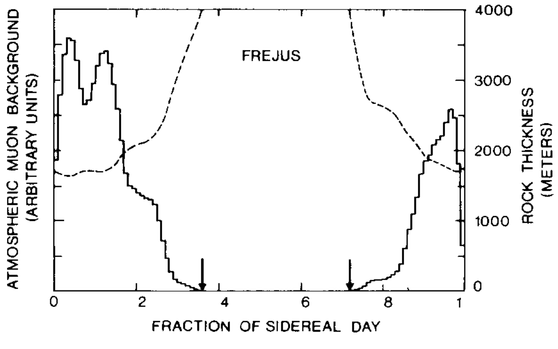

Fig. 3. Cygnus X-3 daily background of atmospheric muons and multimuons (full line). The events come from the path of Cygnus X-3 35.78° < δ < 45 78° The dashed line shows the rock thickness (in meters) crossed by these muons. The origin of the horizontal axis corresponds to the culmination of Cygnus X-3 The arrows define the time interval during which Cygnus X-3 is detectable

proceed as follows: for each detected muon from any direction, which signals that the detector is alive, we calculate the position and the phase of Cygnus X-3 at this time. The phase plot is then incremented with a weight proportional to the corresponding daily background muon flux (fig. 3). A similar procedure applied to 35 off-source windows centered every 10° of right ascension in the same declination band provides the absolute background normalization.

The second method of determining the expected background uses a complete Monte Carlo of all experimental effects. A crucial input in this simulation is the muon spectrum, i.e. the number of muons traversing a given rock thickness. With the empirical formula which we used [9], the observed azimuth-and zenith-angle distributions are well reproduced. According to this simulation the average rock thickness seen by muons from the path followed by Cygnus X-3 as well as the thickness seen by all muons are in good agreement with the observed values. Both background determinations agree with each other in absolute value and in their shapes. The background is essentially flat as indicated by the dotted line in fig. 2.

The phase distribution in the 2° window (fig. 2a) is compatible with the background expectation. The number of observed muons is 70 and the expected background 65.3. Using a Monte Carlo simulation of the likelihood function, we obtain a confidence level of 65% for the background hypothesis.

In the 5° window (fig. 2b), the number of detected muons and multimuons is 419 whereas the expected background is 414.5. The chi-squared for the background interpretation is 15.3 for 10 degrees of freedom (12% confidence level). The confidence-level distributions for all 36 windows shown in fig. 4 are uniform, as expected if the background distributions are in agreement with the majority of the 36 observed experimental distributions. We have checked that the sky map of events in the most populated phase bin (0.9–1.0) does not show any accumulation near Cygnus X-3.

Finally we calculate upper limits for a possible excess muon flux from the direction of Cygnus X-3. The 90% CL flux limits corresponding to the 2° and 5° windows are given in table 1 for 10 phase intervals.

Table 1
90% confidence level upper flux limits for the 2° and 5° windows in 10 phase bins. The limits are calculated by considering that Cygnus X-3 is not detectable between 0.36 and 0.72 of sidereal day as illustrated by the arrows in fig. 3. This arbitrary convention is very similar to the one used in ref. [3].

Phase	90% CL flux limits in units of 10^{-12} cm^{-2} s^{-1}	
	2° window	5° window
0.0–0.1	0.48	0.51
0.1–0.2	0.25	0.46
0.2–0.3	0.30	1.08
0.3–0.4	0.08	0.04
0.4–0.5	0.30	0.37
0.5–0.6	0.13	0.04
0.6–0.7	0.30	1.04
0.7–0.8	0.12	0.12
0.8–0.9	0.06	0.04
0.9–1.0	0.43	1.14
All phases	0.8	1.5

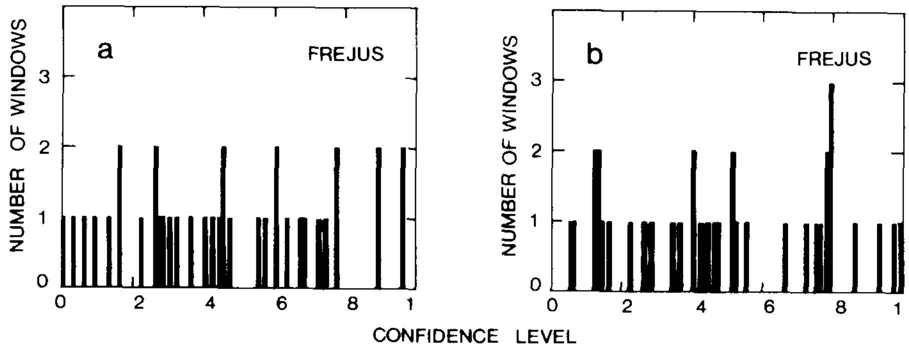

Fig. 4. Confidence-level distribution of the background hypothesis for 36 windows of half angle 2° (a) and 5° (b) along the path of Cygnus X-3.

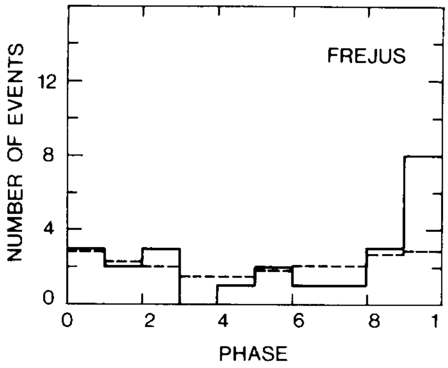

Fig. 5 Phase distribution of muons and multimuons detected between September 26 and October 19, 1985 in the 5° window centered on Cygnus X-3 The dashed line represents the expected number of atmospheric muons and multimuons

When considering all events regardless of their phase, the 90% CL flux limits are 0.8×10^{-12} and 1.5×10^{-12} cm^{-2} s^{-1} for the 2° and 5° windows, repectively.

In September and October 1985, a very large radio burst from Cygnus X3 was recorded [10]. In order to check if there is a correlation between this radio flare and high-energy particles from Cygnus X-3, we analyzed the muons recorded in the Fréjus detector during this time period in the smae way as our total data sample. No accumulation is seen at the position of Cygnus X-3 Furthermore, the phase distribution of events lying in a 5° window which is shown in fig. 5 contains a total of 24 events (all of them are single muons) when 21 8 are expected. Even with the large Fréjus detector, the sensitivity in such a short observation period is poor. There is no evidence for a signal; the confidence level for the background hypothesis is 38%. It is also important to realize that for such a short observation time, the expected background phase distribution is not flat.

In conclusion, analysis of the Fréjus data yields new upper limits on the excess muon flux from the direction of Cygnus X-3 The positive signals reported in refs. [2,3] are not confirmed. It should be noted that, except for the observation period. the experimental conditions, in particular the rock thickness traversed by muons from the direction of Cygnus X-3, were very similar to those in ref. [3].

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References

[1] A.A. Watson, Rapporteur talk, 19th Intern Conf of Cosmic ray physics (La Jolla, 1985), and references therein
[2] M.L. Marshak et al , Phys Rev. Lett. 54 (1985) 2079, 55 (1985) 1965.
[3] G Battistoni et al., Phys Lett B 155 (1985) 465
[4] See Ch Berger, in Search for high energetic muons from Cygnus X-3 with the Fréjus detector, Proc. EPS Conf. (Bari, July 1985).
[5] Y. Oyama et al., Phys. Rev. Lett. 56 (1986) 991.
[6] A Rousset, Ph. Delcros, M Levy and J.M. Demorieux, in TRAVAUX (février 1983) p 9
[7] See J Ernwein, in Early results from the Fréjus experiment, Proc Sixth Workshop on Grand Unification (University of Minnesota, April 1985).
[8] M. van der Klis and J M. Bonnet-Bidaud, Astron. Astrophys 95 (1981) L5
[9] S. Miyake, J. Phys. Soc Japan 18 (1963) 1093, FREJUS Collab , Ch Berger et al., to be published.
[10] K Johnston, private communication (Naval Research Laboratory)