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High-Statistics Study of the Low-Energy Cosmic-Muons Angular Distribution: Results from MICRO.

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Summary. — We present results from MICRO, a muon telescope with good angular resolution, which has collected more than $31 \cdot 10^6$ cosmic muons. Upper limits are given for the flux coming from point sources and for the periodic component from Cygnus X3.

PACS 91.10 – Geodesy and gravity.
PACS 94.40 – Cosmic rays.

1. – Introduction.

Wide-angle anisotropies in the arrival directions of high-energy cosmic muons have been reported by various experiments (1). The existence of narrow-angle anisotropies is however still an open question.

The aim of MICRO (monitor for intense cosmic-ray outbursts) is to give a high-statistics survey of the low-energy muon flux, with good angular resolution, to search for narrow peaks and time variations in the cosmic-muon distribution.

The apparatus has been operated since March 1986 through May 1987 in Frascati—latitude $= 41° 47'$, longitude $= -12° 40'$ at 300 m above sea level—collecting more than $31 \cdot 10^6$ muons whose arrival directions cover the range (in celestial coordinates) $-50° <$ declination $(\delta) < 90°$.

The μ arrival directions have been binned in (8×8) degrees (RA *vs.* δ) intervals. Minimum energy of detected μ's is ≈ 2 GeV, owing to absorption in the atmosphere. Selecting muons with zenith angle $\theta > 80°$ corresponds to a cut $E_\mu > 10$ GeV at 95% confidence level.

(1) O. C. ALLKOFER, W. D. DAN, H. JOKISH, G. KLEMKE, R. C. UHR, G. BALLA and Y. OREN: *Astrophys. J.*, **291**, 468 (1985), and references therein.

The data have been scanned searching for narrow (*i.e.* angular width < 1 bin) excesses, and an upper limit on the flux coming from the direction of known gamma-ray sources has been derived. The same search has been performed for each month looking for possible sporadic signals.

Searching for large-scale anisotropies requires a precise evaluation of the expected flux, taking into account the efficiency and acceptance of the apparatus in the observation period, and will be reported in a forthcoming paper.

Some underground experiments (2) have reported evidence for a periodic muon signal coming from the direction of Cygnus X3. In order to search for such an effect, a phase analysis has been performed using the known X-rays 4.8 h period, for the muons coming from a direction within 15 degrees in celestial coordinate around Cygnus X3. Upper limit on the flux is given.

2. – Experimental set-up.

The apparatus consists (fig. 1) of six 1 m^2 planes of 1 cm^2 steamer tubes of the same type as those used in the NUSEX experiment (3). The tubes are arranged in two groups, 95 cm apart. Within each group the distance between the planes is 1 cm with a 1 mm iron sheet in front to each group to allow recognition of electrons. The overall geometric angular resolution of the telescope is better than 1 degree.

The axis of the telescope is horizontal, in order to bring down the counting rate to a value acceptable to the acquisition system, and aimed at a direction maximizing the exposure to Cygnus X3. The absolute orientation of the apparatus is known to better than 1 mrad. The measured terrestrial angular distributions is reported in fig. 2 for part of the data set. We assume that no muons come from below the horizon, so that there is no front-back ambiguity.

The data acquisition system consists of the standard streamer tube electronics (3) read out by a Camac processor and sent to a nondedicated VAX

(2) G. Battistoni, E. Bellotti, C. Bloise, G. Bologna, P. Campana, C. Castagnoli, A. Castellina, V. Chiarella, A. Ciocio, D. Cundy, B. D'Ettorre Piazzoli, E. Fiorini, P. Galeotti, E. Iarocci, C. Liguori, G. Mannocchi, G. Murtas, P. Negri, G. Nicoletti, P. Picchi, M. Price, A. Pullia, S. Ragazzi, M. Rollier, O. Saavedra, L. Satta, P. Serri, S. Vernetto and L. Zanotti: *Phys. Lett. B*, 155, 465 (1985); M. L. Marshak, J. Bartlelt, H. Courant, H. Keller, T. Joyce, E. A. Peterson, K. Ruddick, M. Shupe, D. S. Ayres, J. Dowson, T. Fields, E. N. May, L. E. Price and K. Sivaprasad: *Phys. Rev. Lett.*, 54, 2079 (1985).

(3) G. Battistoni, E. Bellotti, C. Bloise, G. Bologna, P. Campana, C. Castagnoli, A. Castellina, V. Chiarella, O. Cremonesi, D. Cundy, B. D'Ettorre Piazzoli, E. Fiorini, E. Iarocci, G. Mannocchi, G. P. Murtas, P. Negri, G. Nicoletti, P. Picchi, M. Price, A. Pullia, S. Ragazzi, M. Rollier, F. Ronga, O. Saavedra and L. Zanotti: *Phys. Lett. B*, 155, 465 (1985).

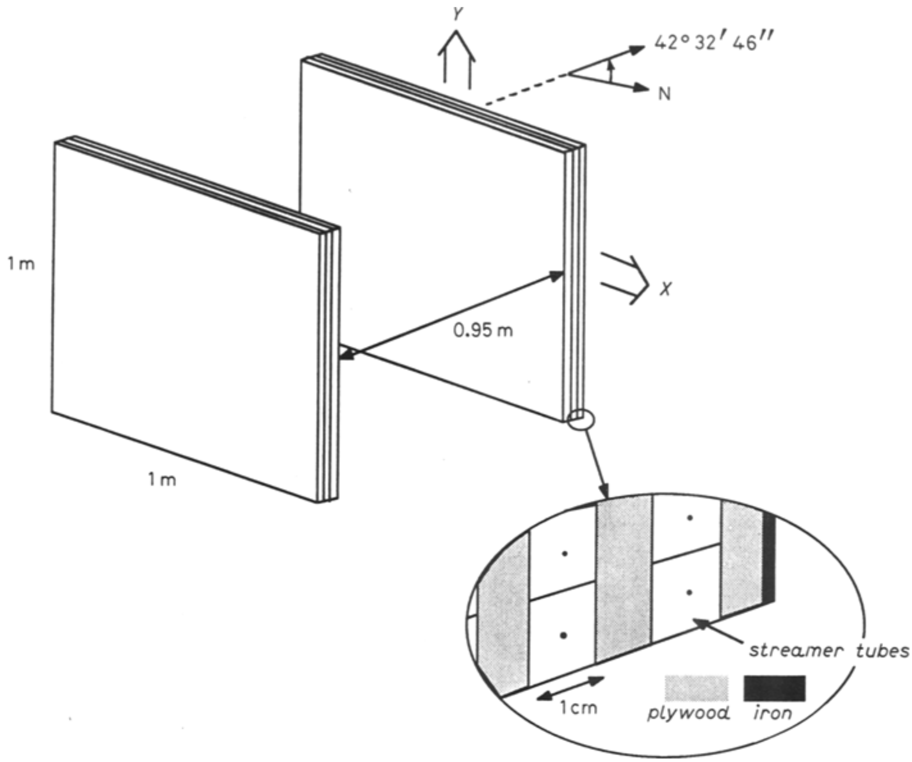

Fig. 1. – Experimental set-up.

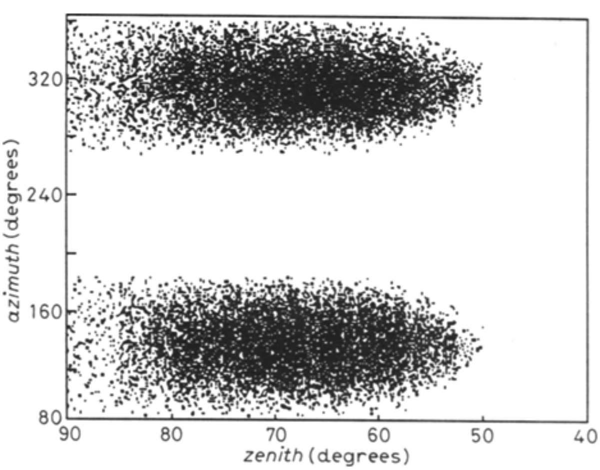

Fig. 2. – Zenith (θ) and azimuth (φ) distribution in the laboratory.

through an Apple II acting as interface. The trigger is made by the coincidence of at least 2 planes in each group, giving a trigger rate of 3 Hz. The acquisition system could register data at this rate with a dead time of 10%.

Typically a run consisted of 100 000 events, after which the data file was automatically closed and a new run started. At the same time a job residing on the host VAX automatically started for track reconstruction and histogram filling. The output of this program is a file containing the distribution in local and sideral time and local and celestial coordinates. Moreover the data coming within a 15° window around Cyg X3 have been analysed in phase, dividing the period in 20 intervals.

3. – Search for narrow structures.

The energy threshold in MICRO is determined by the transparency of the atmosphere to muons of given energy. It has been determined by means of an analytic calculation (4) as well as a 3-dimensional Monte Carlo, based on the Hillas algorithm (5) for hadronic interactions, which takes into account muon energy loss and decay as well as the effect of the geomagnetic field. We derived in this way the relation between zenith angle and minimum muon energy; the selection of μ coming from $\theta > 80°$ implies $E_\mu > 10$ GeV.

The angular distribution of the muons with respect to the direction of the primary has been computed; this calculation takes into account the lateral spread of the shower due to the nonzero transverse momentum in hadronic interactions and the effect of the geomagnetic field.

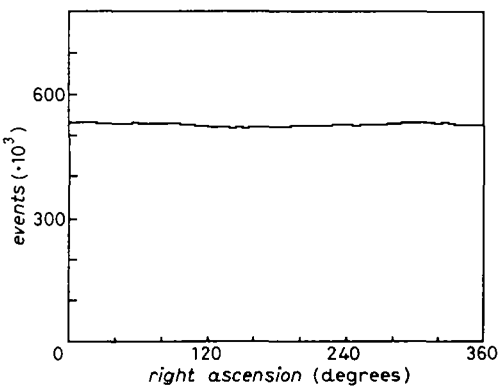

Fig. 3. – RA distribution of all the μ's (all θ).

(4) A. DAR: *Phys. Rev. Lett.*, **51**, 227 (1983).

(5) A. M. HILLAS: *Proceedings of the XVII International Cosmic Rays Conference*, Vol. 8 (Paris, 1981), p. 193.

On the basis of the above calculations the muons with $\theta > 80°$ have been binned in (8×8) degree intervals (RA *vs.* δ). The RA distribution of all the muons, summed over declination, is shown in fig. 3, that in δ in fig. 4, while a typical data plot at a given bin of declination is in fig. 5.

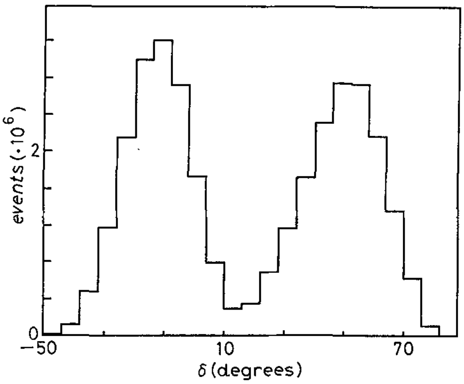

Fig. 4. – Declination distribution of all the μ's.

A detailed evaluation of the expected shape of the muon distribution, essential to reveal large-scale structures, requires a very accurate knowledge of the acceptance of the apparatus and local nonuniformities of the muon flux. In the case of the search for signals entirely contained in one angular bin this is not

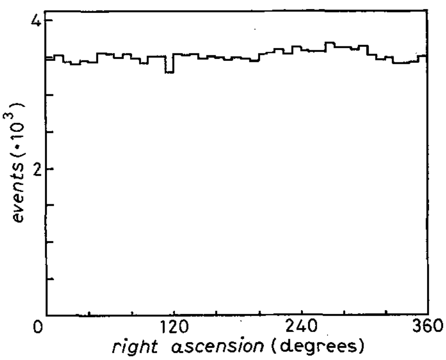

Fig. 5. – RA distribution for $-18° < \delta < -10°$ $(\theta > 80°)$.

necessary and a simpler procedure has been used. For each angular bin we have computed the expected muon flux by linearly fitting the measured contents of the six nearby RA bins. The significance of possible excesses has been computed with the following estimator (6):

$$T = (S - B)^2/(B + \sigma^2)$$

(where S is the measured signal, B the expected value and σ its standard deviation), which is distributed as $\chi^2(1)$, if there are no signals.

From this analysis we conclude that the number and distribution of the excesses are compatible with the expected ones. The same conclusion has been achieved subdividing the data in one month samplings. From the above result we can derive an upper limit (at 95% c.l.) for the μ flux as a function of declination, which is presented in fig. 6.

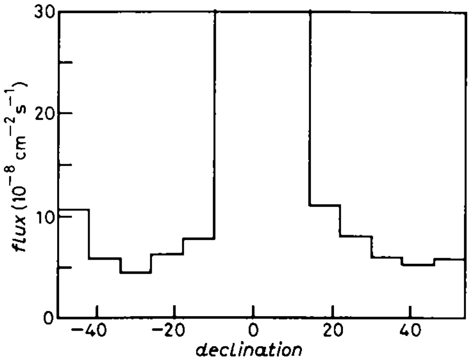

Fig. 6. – Upper limit (95% c.l.) to the μ flux *vs.* δ.

TABLE I. – 95% c.l. *upper limits for the flux coming from known* X- *and* γ-*ray sources.*

	RA (degrees)	δ (degrees)	95% UL (10^{-8} cm^{-2} s^{-1})
Cyg X1	299.1	35.1	5.1
Cyg X2	325.6	38.1	3.3
Her X1	254.0	35.4	1.2
Sco X1	244.3	− 15.5	3.7
Geminga	97.7	17.8	8.2
4U1758-25	269.5	− 25.1	2.1
Crab	82.9	22.0	9.8
AM Her	273.3	50.0	5.0
Kepler	261.9	− 24.4	3.5
IC443	93.5	22.6	5.4

(6) W. T. EADIE, D. DRIJARD, F. E. JAMES, M. ROOS and B. SADOULET: *Statistical Methods in Experimental Physics* (North Holland, Amsterdam, 1977).

At $\delta = (9 \pm 6)°$ and $AR \approx 48°$ where a 4σ excess in higher-energy muons was reported in ref. (1), our data present a small excess of 2σ, while the negative anisotropy at $AR = 120°$ reported in the same reference does not appear.

In table I we report the 95% c.l. upper limit for flux coming from the directions of some known X- and γ-ray sources, and some other interesting objects. These results should be compared with those in ref. (7), taking into account the different energy thresholds.

4. – Cygnus X3.

Cygnus X3 has been reported as a periodic source in X (8), high and UHE γ-rays (9) with a very well-known period (in the X emission) $P = 4.792392$ h. The period is not constant but its derivative $dP/dt = 1.18 \cdot 10^{-9}$ is also known. An underground μ signal has also been reported (2). Common feature of all high-energy signals from Cyg X3 (and similar very-high-energy emitters) is that the source is «on» in a small part of the period, typically 1/10 to 1/20.

To search for such a signal, we have selected the μ ($\theta > 80°$) coming from a region of $(15 \times 15)°$ centred on the position of Cyg X3, which has been divided in 25 (3×3) degree bins. Due to the effect of the geomagnetic field, muons pointing to the source are spread in more than one angular bin: this deflection has ben computed with our Monte Carlo and collected data have been corrected

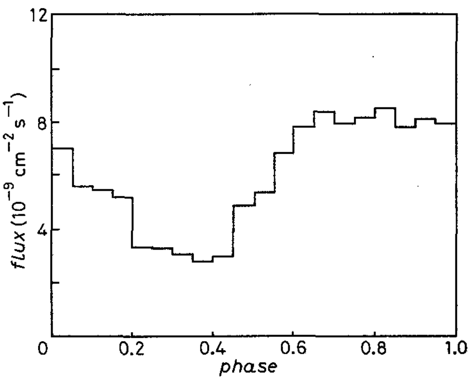

Fig. 7. – Phase plot for muons pointing to Cyg X3, after correction for geomagnetic effect («on source»). Fluxes are averaged over a period.

(7) V. D. Ashitkov, T. M. Kirina, A. P. Klimakov, R. P. Kokoulin and A. A. Petrukhin: *Proceedings of the XX International Cosmic Rays Conference* (Moscow, 1987), HE 4.3-6,240.

(8) M. Van der Klis and J. M. Bonnet-Bidaud: *Astron. Astrophys.*, **95**, L-5 (1981).

(9) J. Lloyd Evans, R. N. Coy, A. Lambert, J. Lapikens, M. Patel, R. J. O. Reid and A. A. Watson: *Lett. Nature*, **305**, 784 (1983).

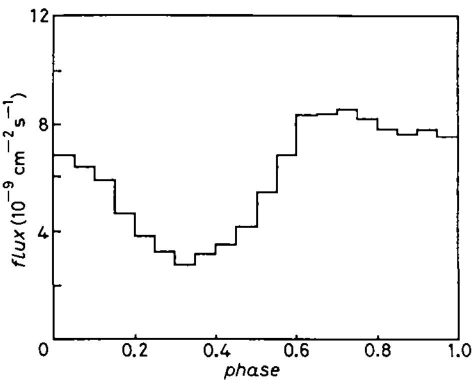

Fig. 8. – Evaluated background phase plot («off source»).

accordingly. Although in principle this correction depends on the assumed source spectral shape, we have found this dependence to be marginal, at least for differential spectral indices in the range $2.1 \div 2.7$ which are appropriate for point sources.

In fig. 7 we report the phase plot at the Cyg X3 position («on source»), corrected as described above, for spectral index 2.1. Figure 8 is the weighted average of the bins which do not contain muons coming from the source direction («off source»), while in fig. 9 we have the ratio «on source»/«off source». The fluxes in fig. 7, 8 are averaged over a period.

It has to be noted that, by selecting muons with $\theta > 80°$, the direction of Cyg X3 is observed for 1.53 h, *i.e.* only a fraction of its period. This implies that we do not expect to see a flat phase distribution in our data, even in the absence of signal.

The comparison of «on source» with «off source» data shows that there is no significant difference, giving a χ^2 of 20.35 (19 degrees of freedom) for the

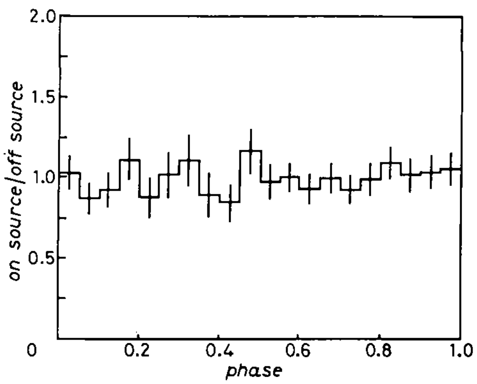

Fig. 9. – «On source»/«off source» phase plot.

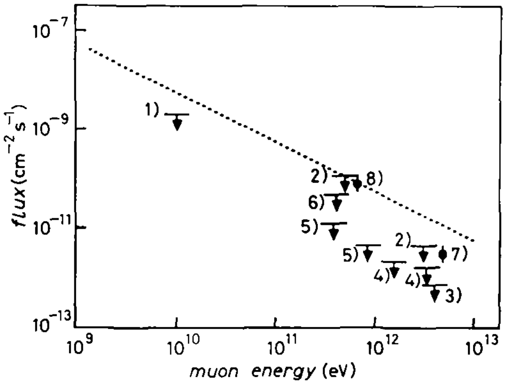

Fig. 10. – Upper limits for the flux from Cyg X3. The dotted line is the γ flux extrapolated from UHE experiments (10). 1) This experiment, 2) IMB, 3) Frejus, 4) Kamioka, 5) Baksan, 6) HPW, 7) NUSEX, 8) Soudan.

hypothesis that the plots are compatible. Taking the largest difference between on-source and off-source phase plots we have computed the 90% c.l. upper limit on the flux: $\varphi < 1.7 \cdot 10^{-9}\,\text{cm}^{-2}\,\text{s}^{-1}$ which is also reported in fig. 10, together with the results from other experiments (10). If we instead consider the phases $0.2 \div 0.4$ and $0.6 \div 0.8$, where signals have been reported, the limits are $5.8 \cdot 10^{-10}$ and $3.6 \cdot 10^{-10}\,\text{cm}^{-2}\,\text{s}^{-1}$, respectively.

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We wish to thank Dr. S. Torres who helped us in setting up the data acquisition system, and G. Mazzenga who built the mechanical structure of the apparatus.

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(10) G. CHARDIN: Talk given at Moriond (1987) and references therein.

● RIASSUNTO

In questo articolo presentiamo i risultati di MICRO, un telescopio per muoni cosmici ad elevata risoluzione angolare, che ha raccolto più di $31 \cdot 10^6$ eventi. Vengono riportati i valori dei limiti superiori per il flusso di muoni da note sorgenti puntiformi; in particolare viene dato un limite per la componente periodica in direzione di Cygnus X3.

Исследование углового распределения космических мюонов низких энергий с высокой статистикой. Результаты, полученные из MICRO.

Резюме (*). — Мы приводим результаты, полученные из MICRO, мюонного телескопа с высоким угловым разрешением, на котором было собрано более $31 \cdot 10^6$ космических мюонов. Приводятся верхние пределы для потока мюонов из точечных источников; в частности, указывается предел для периодической компоненты из направления от Лебедя X3.

(*) *Переведено редакцией.*