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Nature of the high-energy particles from Cygnus X-3

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If the published experimental results on both air showers and underground muons generated by particles from Cygnus X-3 are correct, then these particles cannot be any presently known elementary particles, neutral atoms, or micrograins of ordinary matter. The primary particles from Cygnus X-3 must be electrically neutral, relatively stable, strongly or electromagnetically interacting, and have rest mass less than 50 MeV/c^2.

Several experimental groups have recently reported[1-4] the observation of extensive air showers (EAS) initiated by high-energy particles ($3\times 10^2 \leq E \leq 2\times 10^7$ GeV) from the "cosmic accelerator" Cygnus X-3, lying at a distance $d \sim 40\,000$ light years from Earth.[5] Cygnus X-3 is believed to be a binary system consisting of a compact object (a neutron star or a black hole) and a main sequence star. It has been detected as a radio, infrared, x-ray, and γ-ray source, displaying a period $p \sim 4.8$ h associated with the eclipsing of the compact object by the companion star. The association of air showers with high-energy particles from Cygnus X-3 is based on both their direction and their time of arrival, which exhibits the characteristic period of the x-ray source. The high-energy particles initiating these air showers, which we shall denote by X, have been identified as high-energy photons[1-4] because (i) they must be electrically neutral, or the galactic magnetic field would have deflected and randomized their arrival directions, (ii) they must be relatively stable, with $\tau E/mc \geq 40\,000$ light years, in order to survive their trip from Cygnus X-3 to Earth, and (iii) they must interact strongly or electromagnetically in order to initiate the observed EAS high in the atmosphere.

Among the known elementary particles, only photons satisfy all these criteria. Consequently, it has been assumed that the excess of EAS from the direction of Cygnus X-3 is caused by interactions of high-energy photons in the Earth's atmosphere. The integral photon flux from Cygnus X-3 as deduced from both air-shower measurements at extremely high energies and direct measurement of lower-energy γ rays at the top of the atmosphere can be well described by a single power law:[2]

$$I(>E) = (6.4\pm 3.6)\times 10^{-7} E^{-1.108\pm 0.021}\ \mathrm{cm^{-2}\,sec^{-1}}\ , \quad (1)$$

where E is measured in GeV.

However, the identification of the X's as photons is inconsistent with surface-detector data,[6] indicating that the air showers they produce show essentially the same muon content as seen in hadron-induced showers. High-energy muons in EAS are produced mainly by meson decays in hadronic cascades. High-energy photons, however, are very inefficient in initiating hadronic cascades, because their total hadronic photoproduction cross section on air nuclei is about 300 times smaller than their cross section for e^+e^- pair production (the cross section for $\mu^+\mu^-$ pair production is much smaller still). Further support for this observation has been obtained recently by analyzing the muon background in deep-underground proton-decay detectors: at least two detectors, Soudan-1 (Ref. 7) and NUSEX (nucleon-stability experiment) (Ref. 8), have already reported seeing single-muon events from the direction of Cygnus X-3 which display the time modulation characteristic of the 4.8-h period of Cygnus X-3. The flux of the underground events as observed by both experiments is larger by several orders of magnitude than that expected from high-energy photons with a flux which is given by expression (1). The Soudan-1 group and the NUSEX group therefore have concluded[7,8] that if their observations are correct they either indicate misidentification of the primaries as photons or signal a new mechanism for very efficient muon production in high-energy photon-initiated air cascades.

Before invoking the existence of as-yet-undiscovered new particles[9,10] and/or interactions, it is important to examine the internal consistency of the observations and whether they can be explained by ordinary particles and interactions. In particular, can other known neutral "particles" such as neutral atoms or micrograins of ordinary matter,[11] which may be produced by shock acceleration[12] in Cygnus X-3, produce the observed signals? (Neutral atoms and micrograins of ordinary matter were claimed to be observed[13] in the high-energy jets emitted by the exotic galactic source SS-433.) Can high-energy protons from Cygnus X-3 be "channeled" through the galactic magnetic field (by an as-yet-unknown mechanism), retaining their original direction to produce the observed signals?

The present experimental results from surface detectors do not rule out the possibility that the X's are "channeled" protons, neutral atoms, or micrograins of ordinary matter (although some statistical information on the nature of the primaries could be obtained by measuring both the energy and the development of the showers in the atmosphere). However, we shall show that the reported underground muon fluxes do rule out protons, neutrons, nuclei, atoms, and micrograins of ordinary matter as possible candidates for the X's. Moreover, we shall show that the primaries must have a mass less than 50 MeV/c^2.

An underground detector at depth d can observe atmospheric muons at zenith angle θ if their energy is sufficient to penetrate the rock overburden. If the rock density above the detector is constant and the surface is level, then the overburden thickness $x(\theta)$ above the detector at zenith angle θ is given by

$$x(\theta)=x(0)\left\{\left[\left(\frac{R}{d}-1\right)^2\cos^2\theta+\frac{2R}{d}-1\right]^{1/2}-\left(\frac{2R}{d}-1\right)\cos\theta\right\}\simeq x(0)\sec\theta \ , \quad (2)$$

where R is the radius of Earth, and the approximation is valid for zenith angles $\theta\leqslant 65°$. Muons lose energy by ionization, radiation, pair production, and nuclear interactions according to

$$dE/dx=-\alpha-\beta E \ . \quad (3)$$

For standard rock ($\rho=2.6$ g/cm^2, $Z=11$, $A=22$), QED calculations yield[14] the values

$$\alpha=\{2.033+0.077\ln[E_\mu\ (\mathrm{GeV})]\}\ \mathrm{MeV\,cm^2/g} \quad (3a)$$

and

$$\beta=\{2.229+0.200\ln[E_\mu\ (\mathrm{GeV})]\}\times10^{-6}\ \mathrm{cm^2/g} \quad (3b)$$

for $E_\mu\leqslant 10^6$ GeV.

Since α and β vary rather slowly with E_μ, an approximate range-energy relation in rock can be obtained[15] by solving Eq. (3) for fixed average values $\bar{\alpha}$ and $\bar{\beta}$, i.e.,

$$E_{\min}=(\bar{\alpha}/\bar{\beta})(e^{\bar{\beta}x}-1) \ , \quad (4)$$

where $\bar{\alpha}=\alpha(E_{\min}/2)$ and $\bar{\beta}=\beta(E_{\min}/2)$. In practice $\bar{\alpha}$, $\bar{\beta}$, and $E_{\min}$ can be obtained by a few iterations of Eqs. (3) and (4). In Table I we list estimated values of $E_{\min}$ for selected zenith angles in the Irvine-Michigan-Brookhaven (IMB), Soudan-1, Homestake, and Kolar Gold Field (KGF) detectors, where $x(0)=1.5\times10^5$, 1.8×10^5, 4.2×10^5, and 7.0×10^5 g/cm^2, respectively. The total underground flux of atmospheric muons at vertical depth x and zenith angle θ now can be related to the integral flux of atmospheric muons at ground level with energy $\geqslant E_{\min}$ and in the same direction:

$$n_\mu(x,\theta)=\int_{E_{\min}}^{\infty}(dn_\mu/dE)\,dE=n_\mu(E\geqslant E_{\min},\theta) \ . \quad (5)$$

The ground-level flux of atmospheric muons can be calculated as follows.[15,16] Below 100 TeV the main known sources of atmospheric muons are $\pi\to\mu\nu$ and $K\to\mu\nu$ decays in cosmic-ray-induced atmospheric cascades. Accelerator experiments show that meson production in the beam fragmentation region obeys Feynman scaling up to at least 450 TeV, the equivalent laboratory energy of the CERN SPS collider. Therefore, we shall assume that the cross section for inclusive production of hadrons h in particle–air-nucleus collisions satisfy

$$\frac{1}{\sigma_{\mathrm{in}}}\frac{d\sigma}{dx}(NA\to h+\cdots)=f_{Nh}(x) \ , \quad (6)$$

where $f_{Nh}(x)$ is a function of the scaled momentum $x=p_h/p_N$ of the produced hadron but not of the individual values of the momenta p_N and p_h of the projectile and fragment, respectively. The differential flux of atmospheric muons dn_μ/dE which is induced by a primary flux $dn_N/dE=kE^{-\Gamma}$ at the top of the atmosphere is then given by[15]

$$\frac{dn_\mu}{dE}\simeq\sum_{M=\pi,K}C_M[K_M(E)-K_M(m_M{}^2E/m_\mu{}^2)] \ , \quad (7)$$

where

$$K_M=kE^{-\Gamma}/[\Gamma+(\Gamma+1)\gamma_M E] \quad (7a)$$

and

$$C_M=[m_M{}^2/(m_M{}^2-m_\mu{}^2)]B_M g_{NM}^{\mathrm{atm}} \ . \quad (7b)$$

The decay coefficients γ_M for $M=\pi,K$ in the upper atmosphere are given by $\gamma_\pi{}^{-1}=(116\ \mathrm{GeV})\sec\theta^*$ and $\gamma_K{}^{-1}=(865\ \mathrm{GeV})\sec\theta^*$, respectively, where θ^* is the zenith angle at production. The branching ratios B_M for $\pi\to\mu\nu$ and $K\to\mu\nu$ decays are $B_\pi=1$ and $B_K=0.635$, respectively, and the production coefficients g_{NM}^{atm} are given approximately by

$$g_{NM}^{\mathrm{atm}}=\frac{1}{1-g_{NN}}[g_{NM}+g_{Nh}g_{hM}/(1-g_{hh})] \ , \quad (8)$$

where the summation extends over all "stable" hadrons h, and where

$$g_{ab}(x)=\int x^{\Gamma-1}f_{ab}(x)\,dx \ . \quad (9)$$

Similarly, the integral flux of atmospheric muons with energy larger than E, $n_\mu(\geqslant E)$, is given by

$$n_\mu(\geqslant E)\simeq\sum_M C_M[I_M(E)-I_M(m_M{}^2E/m_\mu{}^2)] \ , \quad (10)$$

where

$$I_M(E)=kE^{-(\Gamma-1)}/[\Gamma(\Gamma-1)+\Gamma(\Gamma+1)\gamma_M E] \ .$$

TABLE I. Minimum ground-level energy of penetrating muons at various underground experiments as function of zenith angle.

Zenith angle (degrees)	IMB (1.57×10^5 g/cm^2)	Soudan-1 (1.8×10^5 g/cm^2)	Homestake (4.2×10^5 g/cm^2)	KGF (7.0×10^5 g/cm^2)
	Minimum energy (TeV) of penetrating muons			
0	0.507	0.613	2.58	10.05
10	0.518	0.626	2.66	10.58
20	0.552	0.669	2.95	12.48
30	0.619	0.756	3.57	17.01
40	0.738	0.907	4.85	28.82
50	0.964	1.203	8.03	72.53
60	1.466	1.888	19.90	454.266
70	3.114	4.362	...	...
80	25.740	...	...	...

In the energy range $E \leq 10^6$ GeV the differential flux of primary cosmic rays at the top of the atmosphere is well represented by[15]

$$dN_p/dE = (1.6 \pm 0.2)[E \text{ (GeV)}]^{-2.7 \pm 0.03} \text{ nucleons/cm}^2 \text{ sr s GeV} .$$

Using accelerator data on hadron production and the value $\Gamma = 2.7$ we obtain $C_\pi = 0.29$ and $C_K = 0.0103$, while for the Cygnus X-3 spectrum with $\Gamma = 2.108 \pm 0.020$ we obtain the values $C_\pi = 0.75$ and $C_K = 0.0246$.

Equations (3), (4), and (10) have been shown to reproduce remarkably well[15] the world data on the "background" of atmospheric muons at ground level and deep underground. When these formulas are used to estimate the underground muon fluxes at NUSEX, we find that for a depth $x = 6200$ g/cm^2, Eqs. (3), (4), and (10) predict that the minimum energy of penetrating muons is 6.84 TeV and the flux of cosmic-ray muons is 3.05×10^{-10}/cm^2 sr s, in good agreement with the observed muon flux of $(3.12 \pm 0.28) \times 10^{-10}$/cm^2 sr s at this depth. However, if we assume that the X's are nucleons, we find that the expected resulting muon flux at a depth of 6200 g/cm^2 is 6.4×10^{-14}/cm^2 s, which is smaller by a factor of about 30 than the observed flux $(2.5 \pm 0.5) \times 10^{-12}$/cm^2 s.

A similar problem is posed by the results reported from the Soudan-1 detector: In Table II we list our theoretical estimates for the underground muon fluxes at Soudan-1 due to normal cosmic rays and due to "nucleons" from Cygnus X-3. The integrated flux of the cosmic-ray muons is 2.23×10^{-7}/cm^2 s, in good agreement with the measured flux 2.49×10^{-7}/cm^2 s. The integrated flux of muons from air showers induced by nucleons from Cygnus X-3 is obtained by integrating over the range of zenith angles θ of Cygnus X-3, given by

$$\cos\theta = \sin\phi \sin\delta + \cos\phi \cos\delta \sin(2\pi t/p_s) ,$$

where p_s is the sidereal period (23.93 h), $\delta = 40.9°$ is the declination of Cygnus X-3, and $\phi = 44.5°$N is the latitude of the Soudan-1 detector. The expected flux is 3.2×10^{-12}/cm^2 s, while the observed flux of muons from the direction of Cygnus X-3, 2.4×10^{-11}/cm^2 s, is a factor of 10 larger.

If the X's are atomic nuclei, neutral atoms, or micrograins of mass number A then they behave essentially like a beam of A nucleons with energy E/A per nucleon. The effective nucleon flux is therefore given by $dN/dE = A^{1-\Gamma} dn/dE$, where $dn/dE = kE^{-\Gamma}$ is the differential flux of the primary particles. Consequently, muon production by nuclei, atoms, or micrograins of matter is suppressed by a factor $A^{1-\Gamma}$ compared to muon production by nucleons with the same energy spectrum, and thus cannot explain the observed enhancement of muons from the direction of Cygnus X-3.

The atmospheric muons which are produced in collisions of X's with air nuclei must have a hard spectrum, or their flux would not be comparable to that of the incident X's as reported by the Kiel,[2] Soudan-1,[7] and NUSEX (Ref. 8) detectors. Consequently, a significant number of muons are produced with momenta similar to that of the primary X's. If the X's have mass m and energy E, then their arrival time at Earth is delayed by an amount

$$\Delta t = t - t_\gamma \simeq \left(\frac{d}{2c}\right)\left(\frac{mc^2}{E}\right)^2$$

compared with the arrival times of photons (or ultrahigh-energy X's) which were emitted at the same time and site. Thus the maximum time delay that will be shown by muons with energy $E_{\min}$ is

$$\Delta t_{\max} = \left(\frac{d}{2c}\right)\left(\frac{mc^2}{E_{\min}}\right)^2 .$$

However, $\Delta t_{\max}$ must be equal to or smaller than the width w of the pulse (phase enhancement) of the underground muons which are produced by the X's, because part of the observed pulse width is due to the natural width of the source, and part of it may be due to experimental resolution. We thus obtain

$$mc^2 < \left(\frac{2cw}{d}\right)^{1/2} E_{\min} . \quad (11)$$

The Soudan-1 proton-decay detector reported[7] a total width $w \simeq 0.25p = 1.2$ h for the phase enhancement. The minimum ground-level energy of muons that survive down to the Soudan-1 detector is $E_{\min} = 613$ GeV. We therefore obtain the upper limit $mc^2 < 50$ MeV. Thus it is unlikely that the X's are double-strange dibaryons with mass $\sim 2m_p$ produced by the decay of strange droplets which originate

TABLE II. Underground muon fluxes at Soudan-1 proton-decay detector due to normal cosmic-ray nucleons ($dn/dE = 1.6E^{-2.7}$/cm^2 sr s GeV) and due to nucleons from Cygnus X-3 ($dn_p/dE = 7.1 \times 10^{-7} E^{-2.108}$/cm^2 s GeV). The time-averaged fluxes are 2.23×10^{-7}/cm^2 s normal background muons and 3.2×10^{-12}/cm^2 s muons induced by nucleons from Cygnus X-3.

θ (deg)	$E_{\min}$ (TeV)	Background (10^{-7} cm^{-2}s^{-1}sr^{-1})	Cygnus X-3 (10^{-12} cm^{-2}s^{-1})
0	0.613	1.39	9.37
10	0.626	1.33	9.10
20	0.669	1.17	8.32
30	0.756	0.919	7.00
40	0.907	0.640	5.42
50	1.203	0.361	3.59
60	1.888	0.141	1.81
70	4.362	0.0223	0.464

from strange neutron stars,[9] or that they are the supersymmetric partners of ordinary particles[10] whose masses are constrained to the multi-GeV region by experimental and by cosmological arguments.[17]

Finally, we comment that stronger upper bounds on the mass of the X's perhaps can be obtained by analyzing the ground-level muon spectra measured with the large muon detectors, such as the Kiel–Tel Aviv spectrometer[18] or the MUTRON (Ref. 19) spectrometer.

Note added. After we had submitted this paper for publication, it was brought to our attention that Hillas[20] has independently pointed out the significant constraint placed by the EAS data on models which seek to explain the underground observations.

[1]S. Danaher *et al.*, Nature **305**, 784 (1981), and references therein.

[2]M. Samorski and W. Stamm, Astrophys. J. **268**, L17 (1983).

[3]J. Lloyd-Evans *et al.*, Nature **305**, 784 (1983), and references therein.

[4]R. M. Baltrusaitis *et al.*, University of Utah Report No. 85-0332, 1985 (unpublished); in *Proceedings of the 19th International Cosmic Ray Conference, La Jolla, 1985,* edited by F. C. Jones *et al.* (NASA, Washington, D.C., 1985), Vol. 1, p. 234.

[5]J. M. Dickey, Astrophys. J. **273**, L71 (1983).

[6]M. Samorski and W. Stamm, in *18th International Cosmic Ray Conference, Bangalore, India, 1983, Conference Papers,* edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 11, p. 244.

[7]M. L. Marshak *et al.*, Phys. Rev. Lett. **54**, 2079 (1985).

[8]G. Battistoni *et al.*, Phys. Lett. **155B**, 465 (1985).

[9]G. Baym *et al.*, Phys. Lett. **160B**, 181 (1985).

[10]R. W. Robinett, Phys. Rev. Lett. **55**, 469 (1985).

[11]S. Nussinov (private communication).

[12]D. Kazamas and D. C. Ellison (unpublished).

[13]R. Ramaty, B. Kozlowsky, and R. Lingenfelter, Astrophys. J. **283**, L13 (1985).

[14]See also E. V. Bugaev and L. B. Bezrukov, in *17th International Cosmic Ray Conference, Paris, 1981, Conference Papers* (Centre d'Etudes Nucleaires de Saclay, Gif-Sur-Yvette, France, 1981), Vol. 7, p. 102.

[15]A. Dar, Technion Report No. 84-41 (unpublished).

[16]A. Dar, Phys. Rev. Lett. **51**, 227 (1983), and references therein.

[17]See, for instance, J. Ellis, in *Proceedings of the Sixth Workshop on Grand Unification, Minneapolis, 1985,* edited by S. Rudaz and T. Walsh (World Scientific, Singapore, 1985), and references therein.

[18]O. Allkofer *et al.*, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977,* edited by B. Betev (Bulgarian Academy of Science, Sofia, 1977), Vol. 9, p. 62.

[19]T. Mitsui *et al.*, Nucl. Instrum. Methods **169**, 97 (1980).

[20]A. M. Hillas, in *Proceedings of the 19th International Cosmic Ray Conference, La Jolla, 1985* (Ref. 4), Vol. 2, p. 296.