Model for the Underground Muons Associated with Cygnus X-3

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A phenomenological model is presented which can explain all aspects of the observations of undergound muons associated with Cygnus X-3. A long-lived, light neutral particle produced at Cygnus X-3 interacts in the earth with a cross section in the range 10 to 20 μb. This interaction produces a massive secondary particle with mass 10 to 40 GeV/c^2, which decays to at least one muon. It is possible that the primary particles are produced hadronically at Cygnus with a very small cross section.

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Underground muons from the direction of Cygnus X-3 have been observed in both the Soudan I and NUSEX nucleon-decay detectors.[1,2] These observations have not yet been confirmed at other underground detectors,[3], but, if correct, have important consequences for particle physics. No explanation of the effect is possible in terms of conventional particle physics. Several less conventional explanations have been offered, but none has been able to explain all aspects of the data.[4,5]

The arrival of the muons within a narrow phase interval of the 4.8-h period of the Cygnus X-3 system can be used to set a limit on the mass and lifetime of the primary particles coming from Cygnus.[4,6] The system is at least 11.6 kpc from Earth.[7] Thus, relativistic primaries must have a transit time greater than 1.2×10^{12} s. During a recent (October, 1985) burst,[8] muons were observed in Soudan I within a limited interval of less than 400 s during successive periods. In order to maintain coherence of this signal, the fractional velocity spread of the primaries must be less than 3.3×10^{-10}. Equating of this to $1/2\gamma^2$, where γ ($=E/m$) is the Lorentz factor for primaries of mass m with some minimum energy E, yields $\gamma > 4\times10^4$. The lifetime of the primaries must thus exceed 3×10^7 s, and their mass m must be less than $2.5\times10^{-5}E$. In the model presented in this paper, primary energies must exceed 100 to 1000 GeV, approximately, corresponding to primary masses less than a few tens of megaelectronvolts. These primary particles, which have been called cygnets,[9] must be neutral to have avoided significant deflection in the galactive magnetic field.

An important aspect of the data which has not been confronted previously is the finite angular spread of up to 5° in the observed muon arrival directions relative to the actual direction of Cygnus X-3. Figure 1 shows data from Soudan I during the recent burst,[8] where the signal-to-background ratio is significantly enhanced over the earlier data, and from the NUSEX experiment. The angular resolution in each detector is better than 1° while multiple Coulomb scattering of the muons is less than 0.5°. The spread is suggestive of the production of a massive particle with its subsequent decay to at least one muon. Any model involving direct muon production by the cygnets would produce too many muons at very small angles.

Consider an incident particle interacting with a target particle of mass m to produce a final state including a massive secondary particle (which we call S) of mass M. For a steeply falling spectrum of primary energies E_0, most of the production will occur near threshold, at a center-of-mass energy squared $s = 2E_0m = (kM)^2$, where $k = 1$ for resonant production and $k < 2$ for typ-

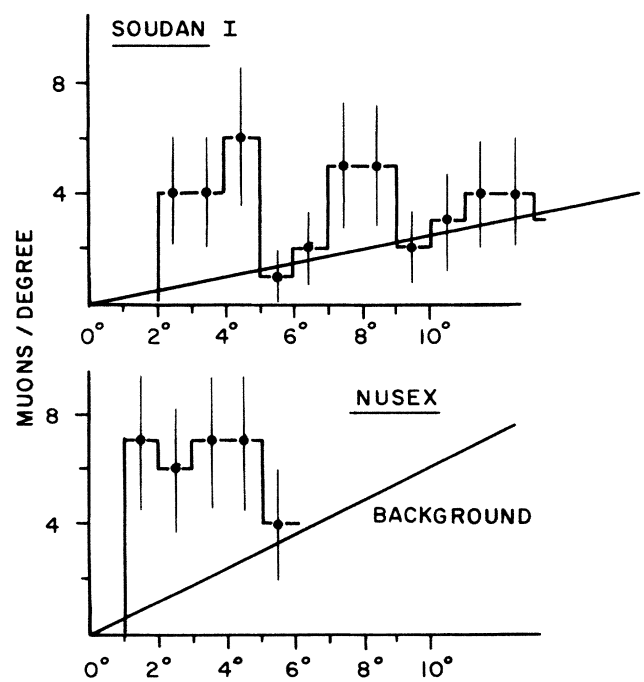

FIG. 1. Angular distributions of muons associated with Cygnus X-3. (The NUSEX data have been corrected from the celestial coordinates used in Ref. 3 to local coordinates.)

ical production cross sections. The energy of the massive particle is $E_s = \gamma M = kM^2/2m$. This then decays to a muon plus other particles at a median angle $\theta = M/E_s$. Thus, $M = 2m/k\theta$. For θ in the range of 0.05 to 0.1 radian, $k = 1$ to 2, M must lie in the range 10 to 40 GeV/c^2 for a nucleon target, 5 to 20 MeV/c^2 for an electron target. If the S particles are produced in pairs, they would have half the mass. The energies E_S, corresponding to the maximum possible for a decay muon, are hundreds of gigaelectronvolts for nucleon targets, hundreds of megaelectronvolts for electron targets. The detector masses are sufficient to stop muons up to about 1 GeV. Since no stopping muons are observed, we conclude that production of the S particles only occurs in hadronic interactions. This conclusion is unchanged if allowance is made for the finite velocities of atomic electrons.

The similar angular spread observed in both experiments implies that the cygnets must interact in the rock above the detectors. The Soudan detector is at a depth of 1.8×10^5 g/cm^2 and NUSEX is at 5×10^5 g/cm^2. Muons produced in the atmosphere require at least 0.65 and 4.0 TeV, respectively, to reach the detectors. Thus, for atmospheric production, the angles observed at NUSEX should be much smaller than at Soudan. The NUSEX flux is approximately ten times less than at Soudan, and can only be explained by attenuation of the cygnet beam in the rock. Thus, an average interaction length must be (1 to 2)$\times10^5$ g/cm^2, corresponding to cross sections about 10 to 20 μb. Such interaction lengths will also explain the zenith angle distributions of the muons, which are similar to the background produced by normal cosmic-ray interactions in the atmosphere.

A more refined analysis has been performed by means of Monte Carlo calculation, taking into account the trajectory of Cygnus X-3 above the detectors, and assuming a differential cygnet energy spectrum E^{-2} and production cross sections parametrized as $\sigma = \sigma_0(M^2/s)^p(1-M^2/s)^q$, with $p = 0,1$, $q = 1,3$. (We have also considered diffractive-type cross sections, which rise more slowly above threshold, and find that solutions are possible with S masses in the range 1 to 4 GeV/c^2, but the primary energy spectrum must be at least as steep as E^{-3}, and muon energies are in the range of 5 to 20 GeV, which are almost excluded by the present data.) Some typical results for the decay angular distributions are shown in Fig. 2(a). The data are best reproduced by S masses in the range 15 to 30 GeV/c^2, more conservatively 10 to 40 GeV/c^2. Monotonically rising cross sections ($p = 0$), causing earlier interaction of the higher-energy primaries, lead to a lower average interaction energy at the deeper detector, with slightly larger decay angles. The predicted zenith-angle distributions [Fig. 2(b)] are too similar to that of the background to be distinguished in the present data. Figure 2(c) shows that muon energy measurements would be useful to check the model. None are possible in present detectors. As illustrated in Fig. 2(d), the model predicts a characteristic variation of the muon signal with depth; the optimum depth for observing the muons is at their average range. Detectors on the surface of the Earth should observe muons only near the horizontal, because of the large interaction length of the primaries. However, such detectors would have to be very large to detect a signal.

The flux of gamma rays observed over many decades of energy by surface detectors is of the form $dN/dE = 6.4\times E^{-2.11}$ (E in GeV),[10] although there is evidence that this average flux may be decaying with a half-life of about one year.[4] (This, plus the fact that the Cygnus X-3 system is inherently very unstable,

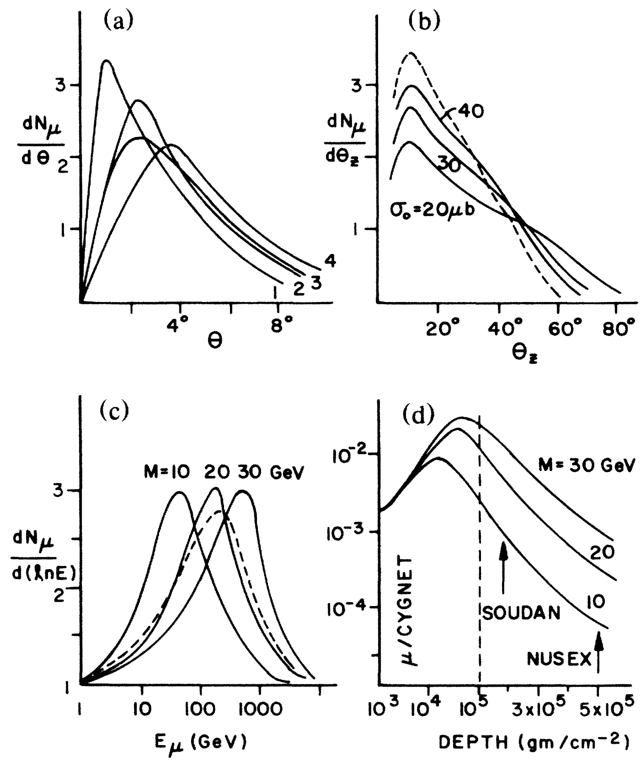

FIG. 2. Typical results of Monte Carlo calculation. (a) Muon angular distributions at Soudan for $M = 15$ GeV, $\sigma = (30\ \mu\text{b})(1-M^2/s)$. The curves labeled 1–4 are for isotropic decay from rest in the c.m. backward production in the c.m. with isotropic decay, primary spectrum E^{-3}, and spectrum E^{-3} with backward production, respectively. (b) Zenith-angle distributions for $M = 15$ GeV, $\sigma = \sigma_0(1-M^2/s)$. The dashed line is the background distribution. (c) Muon energy distributions at Soudan, on the assumption of two-body decay of the S particles. The dashed line is background. (d) Depth dependence on the assumption that $\sigma = (30\ \mu\text{b})(1-M^2/s)$, E^2 cygnet spectrum. (Units on the ordinates of (a)–(c) are arbitrary.

may explain the nonobservation of the effect in more recent experiments.) The cygnet flux required to explain the data is dependent upon the assumed mass of the S particles. In the energy range of interest, 100 to 1000 GeV, the flux must lie within an order of magnitude of the gamma flux. In order to decide if this is likely, or even possible, we must consider models of the star system.

Cygnus X-3 is presumed to consist of a neutron star in close association with a large companion star, with the orbital plane lying close to the line of sight. The strong electric fields associated with the rotating magnetic fields near a neutron star are capable of accelerating protons to energies 10^6 to 10^7 GeV. Vestrand and Eichler[11] have suggested that such a proton beam, interacting in the atmosphere of the companion star, would produce a neutral pions whose decays lead to electromagnetic showers; this would produce gammas over just a narrow portion of the 4.8-h period of the system, as observed. Hillas[12] has shown that a monochromatic 10^8-GeV proton beam is capable of producing the observed gamma flux. (The overall flux of protons from Cygnus X-3, as estimated by Hillas, is likely responsible for most of the cosmic rays with energies in excess of 10^6 GeV which are observed at the Earth).

We have used a crude model of hadronic and electromagnetic cascades to investigate under what conditions the requisite cygnet flux can be obtained. The development of a hadronic cascade is dominated by pion production at low Feynman $x = E_\pi/E_0$. To a sufficient approximation we can assume that the produced pion energy spectrum is of the form $dN/dE_\pi = 1/x$. The π^0 source spectrum at depth n interaction lengths is then found to be $dN/dE_\pi = (\ln E_0/E_\pi)^n/(E_\pi n!)$. (Integration over the full hadronic shower leads to an energy spectrum E^{-2}, close to that which is observed.) A similar approximation is used for electromagnetic showers: At each successive radiation length, a photon becomes two electrons with uniform energy spectra, an electron becomes a photon and electron with uniform energy spectra. The energy spectrum of photons emerging after m radiation lengths is then $dN/dE_\gamma = (2.\ln E_\pi/E_\gamma)^m/(E_\pi m!)$. For hadronic interaction length and a radiation length of 25 and 65 g/cm^2, respectively (the interaction medium is taken to be hydrogen), maximum production of teraelectronvolt gammas occurs for column densities between 200 and 600 g/cm^2, with negligible flux emerging after 1200 g/cm^2. It is possible that the electromagnetic shower may propagate via synchrotron radiation in a small local magnetic field,[12] but this will have no material effect on the magnitude of the fluxes we estimate, and will only reduce the effective column densities estimated above. For cygnet production, we assume a source spectrum the same as for pions, but the cygnets have an interaction length between 1 and 2×10^5 g/cm^2.

In order to estimate the relative production of cygnets and photons, we must make some assumptions about the distribution of hydrogen in which the proton beam interacts. It is probable that the intense proton beam incident on the surface of the companion star lifts off a significant amount of material in the form of a fountain of gas,[12] as shown in Fig. 3(a). There are obviously large uncertainties in the modeling of such a distribution, which is also likely to be time variable, to estimate the resultant photon and cygnet fluxes. By way of illustration, however, we have assumed that, during the neutron star's orbit, the line-of-sight proton beam passes through a spherical region of uniform gas density, as in Fig. 3(b). If the column density of the gas cloud rises to more than a few times 10^5 g/cm^2, before the proton beam is completely absorbed in the companion star, our simple cascade model shows that cygnets need only be produced at the rate of about 10^{-4} the pion production rate to produce the necessary flux. It is not difficult to imagine gas distributions which could produce the necessary cygnet flux via very small production cross sections: The neutron star must spend a large time behind column densities in the region 10^3 to 10^5 g/cm^2, relative to the time spent behind lesser column densities, where the gamma flux is generated. The short times during the 4.8-h period over which the cygnet flux is observed will exceed those over which the gamma flux is observed. If this model of cygnet production is correct, it may yield a very useful probe of the structure of the gas clouds

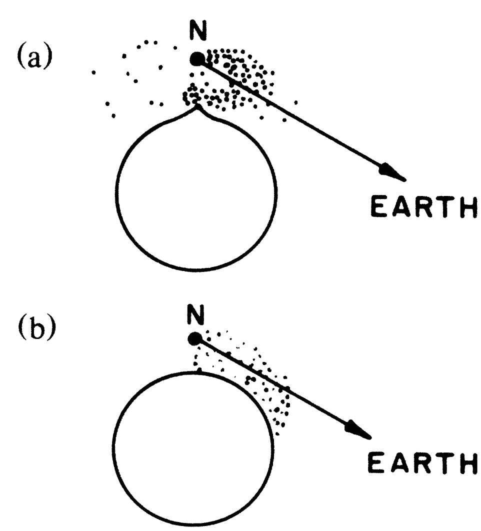

FIG. 3. (a) Possible distribution of gas in the Cygnus X-3 system, as suggested by Hillas. (The asymmetry is due to rotation in the system.) (b) The distribution assumed for calculation.

surrounding such objects.

Neither of the objects described in this Letter has been seen in the accelerator experiments. It has been remarked that the underground experiments and accelerator beam-dump experiments are very similar, and that the nonobservation of cygnets in such experiments must pose difficulties for any model of their production and interaction.[13] However, those authors assumed that the muons are produced directly in cygnet-nucleon interactions. We have shown that such a source for the muons cannot explain their observed angular distributions. At present, the highest incident energy used in beam-dump experiments has been 400 GeV ($\sqrt{s} = 27$ GeV). If the cygnet is only observable through its interactions leading to S particles, its nonobservation sets a lower limit of about 20 GeV/c^2 for the S mass. This assumes that a 400-GeV primary beam can produce observable cygnet fluxes at up to 200 GeV. A better estimate requires assumptions about its x distribution at production. Of course, if the cygnet is produced only in association with massive particles (possibly even the S particles?), then this mass estimate is not valid. Collider experiments have achieved much higher center-of-mass energies. In such experiments, the cygnets should result in missing visible energy; if their production cross sections are small enough they would not yet have been seen.

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[1]M. L. Marshak *et al.*, Phys. Rev. Lett. **54**, 2079 (1985), and **55**, 1965 (1985).

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

[3]K. Oyama *et al.*, Phys. Rev. Lett. **56**, 991 (1986).

[4]F. Halzen, in Proceedings of the International Europhysics Conference on High Energy Physics, Bari, Italy, July 1985 (to be published), p. 408.

[5]A. De Rújula, in Ref. 4, p. 1109 (this paper contains an extensive review, with references).

[6]M. V. Barnhill, T. Gaisser, T. Stanev, and F. Halzen, Nature (London) **317**, 409 (1985).

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

[8]M. L. Marshak *et al.*, to be published.

[9]G. Baym, E. W. Kolb, L. McLerran, T. P. Walker, and R. L. Jaffe, Phys. Lett. **160B**, 181 (1985).

[10]M. Samorski and L. Stamm, Astrophys. J. **268**, L17 (1983); J. Lloyd-Evans *et al.*, Nature (London) **305**, 784 (1983).

[11]W. T. Vestrand and D. Eichler, Astrophys. J. **261**, 251 (1982).

[12]A. M. Hillas, Nature (London) **312**, 50 (1984).

[13]V. S. Berezinsky, J. Ellis, and B. L. Ioffe, CERN Report No. TH.4343/85, 1985 (to be published).