Cygnus X-3 as a source of high-energy free gluons

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An interpretation is proposed for the unusual properties observed experimentally for the ultrahigh-energy muons that are produced by radiation from the galactic source Cygnus X-3. Specifically, it is suggested that these properties result from the production of these muons by free gluons. This interpretation is supported by the angular spread of the muons around the direction to the source. This spread is attributed here to a multiple scattering of ultrahigh-energy gluons by a thermal gluon gas.

The galactic object Cygnus X-3, which is an intense source of photons over the energy range from radio frequencies to 10^{16} eV, has recently been attracting interest (see the review by Vladimirskiĭ *et al.*[1]). Recent papers[2,3] have reported the results of measurements of the fluxes of muons with energies $\gtrsim 1$ TeV which clearly result from radiation from the Cygnus X-3 source, since their momenta are directed away from it, and their intensity varies with a period of 4.8 h, which is characteristic of that source. It turns out that the muon intensity detected is at least 20 times what it should be under the assumption that these muons are produced by many-TeV γ rays from the Cygnus X-3 source.[4,5] It should thus be assumed that ultrahigh-energy particles of some species other than γ rays are arriving from that source. The great distance from the earth to the object, $x = 10 \pm 1.5$ kpc, i.e., 3×10^{22} cm, means that these particles must be neutral and stable and must have a zero mass (or a small mass, $\lesssim 1$ GeV). Discussions of the various possibilities[2–5] lead to the conclusion that no known particles qualify as candidates. In the present letter, which is based on the possibility of an incomplete color confinement,[6–8] we suggest that the particles which are arriving from the Cygnus X-3 source and which produce (with a high probability) ultrahigh-energy muons might be interpreted as free gluons.

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In proposing and defending this interpretation, we are working from the following considerations.

1. Cygnus X-3 is a natural accelerator which is producing beams of particles with energies of up to at least 10^{16} eV. In the collisions with slow protons that necessarily occur in and near the object, the energy in the c.m. frame ranges up to 4 TeV, which is well above the threshold for the production of unconfined color, according to the concept of incomplete color confinement in quantum chromodynamics.[6–8] The plasma in the source (see the models discussed in Ref. 1) may thus contain some unneutralized color charges which, in particular, emit free gluons. If an incomplete color confinement is indeed possible, Cygnus X-3 would thus be completely capable of being a source of free gluons.

2. Let us assume that gluons with an energy on the order of 10 TeV emitted from the Cygnus X-3 source reach the earth. It follows from the estimates in Refs. 6 and 8 that the region in which the color charges interact with nuclei is determined by the radius $r_0 = 10^{-12}$ cm, which leads to an interaction cross section $\sigma = 10^{-23}$ cm^2. These estimates, in particular, agree with data on anomalous nuclear fragments.[8] Such a large cross section means that the gluon would interact in the upper atmosphere. The probability for the splitting of a gluon into a quark-antiquark pair, $g + A \to \bar{q} + q + A' +$ hadrons, must be significant, since in the resultant octet state there is no high potential barrier to provide an effective confinement of quarks in a colorless state. The gluon does not distinguish among the flavors of quarks, so the pairs $\bar{u}u$, $\bar{d}d$, $\bar{s}s$, $\bar{c}c$, $\bar{b}b$, $\bar{t}t$,..., are produced at comparable probabilities at such high energies. The last three of these pairs will decay before they interact in the atmosphere, and muons will be emitted in about 20% of the cases. There is accordingly a large probability (possibly on the order of 1%) that the interaction of a gluon with a nucleus will produce a high-energy muon. At the same time, the probability for the production of such a muon in showers caused by γ rays is much smaller, leading us to the conclusion that the effect cannot be explained by that mechanism.[5] In our model, the muons that are observed result from the decays of heavy quarks or of heavy particles that contain them and that are produced in the interactions of high-energy gluons in the atmosphere. We note that the muon should retain the direction of the gluon that produced it. The ratio of the transverse momentum of the muon to its longitudinal momentum can be estimated from the ratio m_q/p, which, even for a t quark with a mass of 40 GeV, would be 4×10^{-3}; i.e., the angle would be 0.2°. Experimentally,[2,3] on the other hand, the deviations of the momenta of the muons from the direction to Cygnus X-3 are substantially larger (on the order of several degrees). This circumstance, which is exceedingly important to our interpretation, is explained as follows.

3. We need to consider what happens to a gluon on its path from the source to the earth. The number of hydrogen atoms on this path is small, 3×10^{22} atoms/cm^2, so that with a cross section $\sigma = 10^{-23}$ cm^2 the distance to the source would be only a third of an interaction length; i.e., the interaction with interstellar hydrogen would have essentially no effect on the propagation of gluons. These cosmic gluons, however, must interact primarily with the thermal gluon gas which necessarily exists if incomplete color confinement is valid.[8] As was pointed out in Ref. 8, if the temperature and the density of the gluon gas are equal to the corresponding properties of the known

photon gas of the background radiation, $T = 4$–5 K and $n = 10^3\ \mathrm{cm}^{-3}$, the presence of gluons in the medium will not affect the motion of colorless objects. A high-energy colored gluon, however, will be scattered repeatedly in the gas, so that the direction of its motion will change. In our estimates on multiple scattering, we use the expression for the differential cross section for small-angle scattering of a gluon with a large momentum p by a soft gluon:

$$\frac{d\sigma}{d\theta} = \frac{225 G^4}{256 \pi p^2 \theta^3}. \tag{1}$$

Here the effective infrared constant (G) of the three-gluon interaction is determined by the coefficient of $1/r$ at $r \gg r_0$ in the interaction potential of color charges.[6,8] From the condition for the joining, at the point $r_0 = 10^{-12}$ cm, of the region of a Coulomb decrease with a region of a linear increase, $V(r) = a^2 r$, where $a = 428$ MeV, we find $G^2 = 3\pi a^2 r_0^2 = 4.3 \times 10^3$. The mean-square deflection angle can be estimated from (1) by the method of Ref. 9:

$$\langle \theta^2 \rangle = nx \int_{\theta_1}^{\theta_2} \frac{d\sigma}{d\theta} \theta^2 d\theta = nx \frac{225 G^4}{256 \pi p^2} \ln \frac{1}{r_0 n^{1/3}}. \tag{2}$$

The minimum angle, θ_1, is determined by the average distance between gluons in the gas, while the maximum angle, θ_2, is determined by the radius (r_0) bounding the region of the Coulomb interaction. Substituting this value of G^2 into (2), along with the parameter values $n = 10^3\ \mathrm{cm}^{-3}$, $r_0 = 10^{-12}$ cm, and $x = 3 \times 10^{22}$ cm, introduced above, we find $\sqrt{\langle \theta^2 \rangle} = 0.12$ rad $= 7°$ for $p = 10$ TeV. Precisely such deviations from the direction to the source, on the order of several degrees and substantially greater than the resolution of the apparatus,[2,3] are characteristic of the muons in question.

This interpretation thus leads to an explanation for the most puzzling properties of the muons associated with the Cygnus X-3 source, specifically, the large probability for the production of ultrahigh-energy muons in a single interaction event and the comparatively large angular spread of the momenta of these muons around the direction to the source. The latter circumstance seems to be the most important to an explanation of the nature of the phenomenon. An experimental confirmation of the properties of the angular spread described by the multiple-scattering law[2] would not only confirm the validity of the gluon interpretation of this effect but also prove the existence of a thermal gluon gas.

Since this phenomenon may provide conclusive information on the problem of the observability of color states, I wish to emphasize the importance and desirability of further experiments with underground (or underwater) muons of ultrahigh energies which are linked by direction and temporal variations with the Cygnus X-3 source.

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