Time delay in the ultrahigh-energy signal from Cygnus X-3

B. A. Arbuzov and E. A. Razuvaev
Institute of High-Energy Physics

(Submitted 1 December 1986; resubmitted 17 February 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 6, 311–313 (25 March 1987)

The time delay in the signal from the source Cygnus X-3, detected from extensive air showers with $E \geqslant 3 \times 10^{14}$ eV and reckoned from the maximum of the radio burst from this source in October 1985, can be explained by an interpretation offered previously for the emission at ultrahigh energies from this source, as consisting of free gluons. This interpretation is shown to be consistent with the set of experimental data. The interaction energy of background-radiation gluons may be an important component of the density of the hidden mass in the universe.

Effects stemming from the ultrahigh-energy emission from the galactic source Cygnus X-3 continue to attract attention. The primary reason for the interest is that the body of data on extensive air showers and underground muons is difficult to interpret theoretically (see, for example, the paper by Berezinskiĭ *et al.*,[1] who also cite experimental studies). A recent experimental study by Alekseenko *et al.*[2] has furnished new information of a type qualitatively different from the earlier results. They established that there is a statistically significant effect in the emission from Cygnus X-3 at an energy $E \geqslant 3 \times 10^{14}$ eV, which is correlated in time with the intense radio burst in October 1985. The most important aspect of this result is that the extensive-air-shower signal is delayed several days with respect to the maximum in the radio emission. A reasonable suggestion is that the burst of radio emission and the burst of the unknown radiation that causes the extensive air showers have a common origin. In this case the time delay would completely rule out a photon nature for this puzzling radiation. Such an effect cannot be explained on the basis of suggestions regarding the nature of this emission from Cygnus X-3 which are being discussed in the literature, with the one exception of Ref. 3. That explanation, which is based on the possibility that states with an open color are produced at ultrahigh energies, identifies the unknown radiation as free gluons. The multiple scattering of such an ultrahigh-energy gluon by background-radiation gluons, which would have to be present in space for this mechanism to be valid, gives rise to an angular spread in the data on underground muons. Precisely this effect constitutes one of the major difficulties in other interpretations of the phenomenon.[1] The same multiple scattering introduces a time delay in the signal. Specifically, a multiple scattering due to a pronounced Coulomb interaction between gluons at distances $r > r_0 = 10^{-12}$ cm leads to the following mean square resultant scattering angle:

$$< \theta^2 > = nx \, \frac{225\, G^4}{256\Pi\, E^2} \ln \frac{1}{r_0 n^{1/3}} = \frac{A}{E^2}\,, \tag{1}$$

where $x = 3 \times 10^{22}$ cm is the distance to the source, $n = 10^3$ cm^{-3} is the density of gluons in the medium,[3,4] and the effective three-gluon interaction constant G, determined from the asymptotic behavior of the interaction of colored charges, is estimated to be $G^2 \cong 10^3$ in order of magnitude.[4,5] As was shown in an earlier paper, such parameter values lead to a correct estimate of the size of the angular spread, on the order of a few degrees, at an energy of 10 TeV. Since a high-energy gluon flies from the source to the earth along a broken line as a result of multiple scattering, a time delay is introduced. The mean value of this delay can easily be expressed in terms of the mean scattering angle in (1):

$$\overline{\Delta t} = \frac{x}{c}\,\frac{<\theta^2>}{4} = \frac{Ax}{4E^2c}. \tag{2}$$

We can also calculate the standard deviation of the time delay:

$$\sigma = \sqrt{\overline{\Delta t^2} - (\overline{\Delta t})^2} = \frac{x}{c}\,\frac{<\theta^2>}{\sqrt{24}}. \tag{3}$$

Using the data of Ref. 2, we find $\overline{\Delta t} \cong 5$ day $= 4.3 \times 10^5$ s for $E = 300$ TeV; then going back from (2) to (1), we find that at $E = 10$ TeV the mean angle is $\sqrt{\langle\theta^2\rangle} = 2.3°$, in complete agreement with the observations of Ref. 6. On the other hand, knowing $\overline{\Delta t}$ we can work from (1) and (2) to find the value of G^2; it turns out to be 2.5×10^3, again in agreement with the theoretical estimates of this quantity.[4,5] According to (3), the standard deviation is 4 day; this figure is compatible with the data of Ref. 2.

We thus conclude that the interpretation of the ultrahigh-energy radiation from Cygnus X-3 as free gluons, which was offered in Ref. 3, agrees with both data on the angular spread and the new data on the time delay of the signal. We wish to call attention to the fact that the data of Ref. 2 contain absolutely no indication of any phase correlation. This circumstance is completely natural for the conditions of the given experiment, since the standard deviation $\sigma \cong 4$ day is substantially longer than the characteristic period of the source, 4.8 h. Since the time delay is inversely proportional to the square of the energy according to (2), we predict that as the energy of extensive air showers is increased by a factor of ten to 3×10^{15} eV, we will begin to see stable phase correlations in the presence of a signal from the source, since in this case we would have $\sigma \cong 1$ h. It is possible that this effect has been observed by the Kiel group.[7]

With regard to phase correlations, for which there are indications in the underground muon experiments, which correspond to lower energies, one should bear in mind that these correlations have a low statistical reliability. Furthermore, they are unstable in nature, as can be seen in the differences in the results found by different groups. In general, the mechanism which we are discussing here predicts that there will be no effect in the phase at the energies characteristic of these experiments, 10^{13} eV. However, unstable phase correlations—if confirmed—might be a consequence of collective effects in this gluon medium. Up to this point, we have assumed that there is no order of any type in this medium. Simple estimates show, however, that the interaction energy per gluon,

$$V = G^2 n^{1/3} = 1 \text{ eV}, \tag{4}$$

is several orders of magnitude greater than the thermal energy of a gluon. We would thus expect that the gluon medium would be an ordered system, a "gluon crystal," instead of a gas. The possibility of such a state of gluon matter has been suggested in the literature.[8] If the axes of the crystal are oriented in the appropriate manner, the signal from the source might arrive with an anomalously small time spread; this circumstance would be reflected in the presence of phase correlations. Such an effect could not be stable, however, since the relative positions of the source, the earth, and the medium are constantly changing.

There is another circumstance here which is not devoid of interest: The large interaction energy of the background-radiation gluon in (4) means that the gluon medium will represent a large component of the total density of matter in the universe. The values in (4) with $n = 10^3$ lead to an estimate of $\rho = 2\times 10^{-30}$ g/cm^3 for the density of gluon matter; this figure is not all that far from the critical density $\rho_0 = 5\times 10^{-30}$ g/cm^3. There are of course some strong theoretical[9] and observational[10] arguments to support the idea that the actual density of matter in the universe is equal to the critical density, since there must be a hidden form of matter representing the major component of the density. We would like to point out that the gluon medium may make an important, possibly governing, contribution to the hidden mass.

We wish to thank A. A. Logunov and A. E. Chudakov for useful discussions.

[1] V. S. Berezinskiĭ, B. L. Ioffe, and J. Ellis, Yad. Fiz. **45**, 132 (1987) [Sov. J. Nucl. Phys (to be published)].

[2] V. V. Alekseenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 255 (1986) [JETP Lett. **44**, 327 (1986)].

[3] B. A. Arbuzov, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 430 (1985) [JETP Lett. **42**, 532 (1985)].

[4] B. A. Arbuzov, Yad. Fiz. **42**, 542 (1985) [Sov. J. Nucl. Phys. **42**, 342 (1985)].

[5] B. A. Arbuzov, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 403 (1983) [JETP Lett. **37**, 479 (1983)].

[6] M. V. Battistoni *et al.*, Phys. Lett. **155B**, 465 (1985).

[7] M. Samorsky and W. Stramm, Astroph. J. Lett. **268**, L17 (1983).

[8] A. D. Linde, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 470 (1978) [JETP Lett. **27**, 441 (1978)].

[9] A. A. Logunov and M. A. Mestvirishvili, Prog. Theor. Phys. **74**, 31 (1985).

[10] J. E. Einasto, A. Kaasik, and E. M. Saar, Nature **250**, 309 (1974).

Translated by Dave Parsons