# Signals of "New Physics" in High-Energy Cosmic-Ray Interactions

G. Domokos, B. Elliott, S. Kovesi-Domokos, and S. Mrenna
*Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218*
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In some composite models of quarks and leptons, leptons are expected to develop strong interactions at high energies. This hypothesis can be tested by studying the absorption of high-energy particles emitted by point sources in the sky on the cosmic microwave background. Data on Cygnus X-3 exhibit an anomaly in the absorption. A plausible interpretation of the anomaly is that some of the interactions are caused by neutrinos. We infer that the cross section of neutrino-nucleon interactions is approximately 6 mb at energies of a few PeV, significantly exceeding the prediction of the standard model.

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The existence of a substructure beyond the presently known quarks and leptons is likely to blur the distinction between them at high energies. In particular, leptons may acquire strong interactions,[1] if at least some of the subconstituents (henceforth, preons) carry a nontrivial representation of the gauge group of strong interactions.[2] Let $\Lambda$ stand for a characteristic energy scale of the preon model in question, e.g., the confinement scale of a model based on a gauged hypercolor group. At transverse momenta of the order of $\Lambda$ and higher, the colored preons are expected to begin exchanging gluons with the quarks in a lepton-hadron collision and the preonic contribution to the cross section of an inclusive process such as $\nu N \rightarrow \mu X$ can easily grow to a few millibarns (see the second paper of Ref. 1). The picture outlined above can naturally explain[1] the "muon-excess puzzle" arising from the study of the interactions of ultrahigh-energy (UHE) particles associated with point sources in the sky.[3]

In view of the potential importance of this problem from the point of view of the existence of some "new physics" going beyond the standard model, one should subject schemes purporting to explain the muon excess to further tests, even at this preliminary stage. Here we describe such a test; further, we use it to analyze currently available data on one source of UHE particles. The test is conceptually very simple: one attempts to determine the absorption coefficient of the primaries associated with any particular point source on the 3-K microwave background. The theory of the absorption of photons on a thermal radiation due to electron pair creation is well known.[4] We stress that the absorption is determined by "low-energy physics," where there is no doubt about the validity of the standard model. The absorption coefficient is given by Gould's formula, $L(E)^{-1} = 2\alpha^2 m(T/m)^3 f(\nu)$, where $\nu = m^2/ET$ and $m$ is the electron mass; $\alpha$ and $T$ stand for the fine-structure constant and temperature, respectively. The function $f(\nu)$ can be computed numerically; it has a broad maximum at $\nu \approx 0.5$, corresponding to $E_{\max} \approx 2$ PeV. The minimum of the mean free path is $L(E_{\max}) \approx 6$ kpc. It follows that if the differential spectrum of photons at the source is given by $dI_0^\gamma = f^\gamma(E)dE$, the observed spectrum is $dI^\gamma = f^\gamma(E)\exp[-d/L(E)]dE$, where $d$ is the distance to the source. Since the neutrino absorption coefficient is negligible, $dI_0^\nu = dI^\nu$. Analogous statements hold for the integral spectra. Assuming that every incident particle arriving from a given source is a photon, the differential event rate in an extensive-air-shower (EAS) detector is given by $dN = (\sigma_B + \sigma_\pi)dI^\gamma$, where $\sigma_B$ and $\sigma_\pi$ are the Bethe-Heitler cross section for pair production and the photoproduction cross section, respectively. Most calculations found $\sigma_\pi$ negligible compared with $\sigma_B$; see, e.g., Refs. 5 and 6.

In order to test the hypothesis that all primaries from a given source are photons (henceforth, hypothesis $H_0$) the source should satisfy several requirements. The spectrum has to be measured in as broad an energy range as possible; it must be at a distance from where absorption of the photons is noticeable, and, ideally, the flux has to be reasonably steady. Unfortunately, we do not know of a point source in the sky satisfying all these requirements.

We examined data on the x-ray binary Cygnus X-3, since it is well studied and located at a substantial distance ($d \approx 12$ kpc). The disadvantage of this source lies in its erratic nature. Moreover, the observations have been performed over a span of several years and none of the detectors included in the sample have been active during the full span. We attempted to include in the sample as many observations as possible, while discarding those not containing a sufficient amount of quantitative information. To minimize contamination by various "soft" processes, we chose, somewhat arbitrarily, $E = 1$ TeV as a lower cutoff. These selection criteria resulted in a data sample containing twenty points; see Ref. 7. (The various experiments are listed according to increasing threshold energy.)

We assumed the following form of the spectrum: $f^\gamma(E) = N_0[E/(1\text{ eV})]^{-\alpha}\Theta(E_M - E)$. Under hypothesis $H_0$, we fitted the parameters $N_0$, $\alpha$, and $E_M$ but kept the distance fixed at 12 kpc. In order to parametrize possible deviations from $H_0$, we introduced the apparent distance $d^*$ in place of $d$. Under hypothesis $H_1$, $d^*$ was a parameter fitted to the data together with $\alpha$, $E_M$, and $N_0$. Thus, the deviation from $H_0$ is characterized by one parameter, $d-d^*$. (In view of the sparseness of the sample, this appears to be a reasonable way to search for deviations from $H_0$.) Clearly, $d=d^*$ means that hypothesis $H_0$ is correct, whereas $d^*<d$ signals either the presence of a component of the incident primaries not absorbed by the microwave background or an increase of the interaction cross section in the atmosphere. (A result $d^*>d$ would have signaled some internal inconsistency in the fitting procedure or in the data sample; however, we never encountered such a problem.) Using $T=2.756$ K from Ref. 8, a least-squares fit under $H_1$ resulted in the following values of the parameters: $\alpha=1.96$, $N_0=8.5\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, and $d^*=6.4$ kpc. The value of the fitted spectral index is in good agreement with values usually quoted, cf. Ref. 5. The cutoff energy $E_M$ is largely determined by the data point at the highest energy; it is found to be somewhat less than 1 EeV, with a substantial uncertainty. (With the exception of the point at 0.5 EeV, the rest of the data are insensitive to the exact position of the cutoff.) The goodness of fit is acceptable, given the sparseness of the sample; we obtained $\chi^2=0.77$ per degree of freedom under $H_1$. The data points together with the fits under hypotheses $H_0$ and $H_1$ are displayed in Fig. 1.

Given the smallness of the sample, it is more meaningful to test two hypotheses against each other. The likelihood ratio, $l=L(H_0)/L(H_1)$ tests $H_0$ against $H_1$, the best fit.[9] We obtained $l=4.3\times10^{-4}$, indicating that $H_0$ is unlikely to be true. On computing the power of the test[10] for $H_0$ against $H_1$, we obtained $P>0.95$ at the 90% confidence level; corrections to the noncentrality parameter due to the finite sample size amounted to about

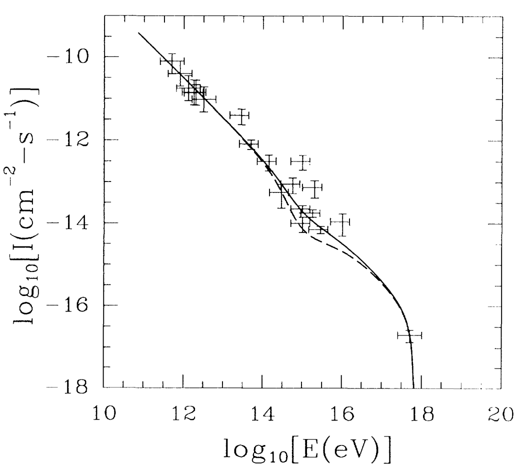


FIG. 1. Observed integral spectrum of Cygnus X-3 together with fits to the data. Dashed line: fit with fixed distance (hypothesis $H_0$). Full line: best fit (hypothesis $H_1$).

6% only. This analysis suggests that the presence of a nonabsorbed component in the radiation emitted by Cygnus X-3 is a likely possibility.[11]

A plausible objection to this claim could be based on the variability of the source. The majority of data in the region around $E_{\max}$ may have been taken during a period when the source was particularly active. Thus faking a nonabsorbed component. Although tests against such a hypothesis are hard to conduct at the quantitative level (mostly due to the small size of the sample), we found no correlation between deviations from the fit under $H_1$ and the midpoint of the observation period or the threshold energy of the detector.

If the effect is real, the question of its interpretation arises. If the compositeness effects dominate and the excess around $E=2$ PeV is mostly due to an emerging strong interaction of neutrinos, one can obtain a crude estimate of the magnitude of this effect from the value of $d^*$ obtained before. For this estimate, we assume $\sigma_\pi \ll \sigma_B$ and $f^\gamma(E_{\max})\approx f^\nu(E_{\max})$, which is probably a fair assumption.[12] (The calculations in Ref. 12 predict a higher flux of neutrinos than photons due to photon absorption within the binary system. However, an increased neutrino cross section leads to an increase of neutrino absorption at the source too: Hence the assumption $f^\gamma\approx f^\nu$.) Assuming further that the cross sections are slowly varying functions of $s$, one deduces the approximate equality, valid near $E_{\max}$:

$$\sigma_B\exp(-d^*/L)=\sigma_B\exp(-d/L)+A\sigma_\nu\,,$$

where $A$ stands for the effective atomic number of air. Using $\sigma_B\approx420$ mb, the cross section of neutrino-nucleon interactions at $E_{\max}$ is found to be $\sigma_\nu\approx6$ mb. (This is an acceptable value in view of the estimates given in the second paper of Ref. 1; it exceeds the prediction of the standard model[13] by several orders of magnitude.) In order to get a better feeling about the meaning of the results, we tested two simple models.

In model A, we added to the photons a nonabsorbed component with the same incident flux; in order to minimize the number of unknown parameters, we assumed that the interaction turns on suddenly. This gives an observed EAS event rate

$$dN=dI_0\{\sigma_B\exp[-d/L(E)]+\Theta(s-\Lambda^2)\sigma_0\}\,,$$

where $\sigma_0$ is the neutrino-air cross section. This model is a crude representation of the interactions due to compositeness turning on at the characteristic energy, $\Lambda$.

Model B is a crude representation of the ideas expressed by Drees and co-workers.[14] These authors attempt to explain the muon excess in EAS by means of an increasing photoproduction cross section. In the same spirit as in model A, we estimate the differential event rate in an EAS detector as

$$dN=dI_0^\gamma[\sigma_B+\Theta(s-\Lambda^2)\sigma_0]\exp[-d/L(E)]\,.$$

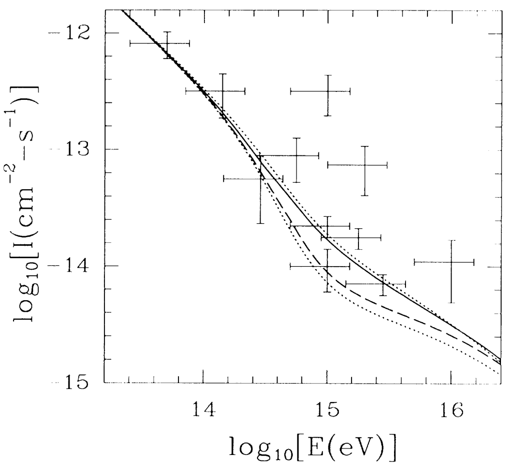


FIG. 2. Data and fits in the absorption region. Upper dotted line: fit under hypothesis $H_1$. Lower dotted line: fit under hypothesis $H_0$. Full line: fit with model A. Dashed line: fit with model B.

Here $\sigma_0$ represents the increased photoproduction cross section on an "air nucleus."

In both models A and B we chose the same values for $\Lambda$ and $\sigma_0$; in this way, we can assess the importance of absorption on the microwave background. For purposes of illustration we chose $\sigma_0 = 100$ mb, $\Lambda = 1$ TeV, which is a reasonable compromise between the estimates quoted in Refs. 1 and 14. The values of $N_0$, $\alpha$, and $E_M$ were fitted under $H_0$. In energy regions where absorption on the microwave background is negligible, all four assumptions ($H_0$, $H_1$, model A, and model B) give indistinguishable results. In Fig. 2 we show the region where the absorption is significant. The resulting likelihood ratios for models A and B are $L(\text{model A})/L(H_1) = 0.62$ and $L(\text{model B})/L(H_1) = 4.0 \times 10^{-3}$. We stress that the values of $\sigma_0$ and $\Lambda$ were not fitted; thus a likelihood ratio of 0.62 means a very good agreement with the data. Because of the fact that in model B one cannot escape from the absorption losses, much bigger values of $\sigma_0$ and/or much lower values of $\Lambda$ would be required in order to achieve a reasonable fit.

To summarize, the absorption characteristics of the radiation emitted by Cygnus X-3 reveal an anomalous behavior. Although one cannot entirely exclude the hypothesis that the anomaly is caused by a particle which so far escaped detection, this appears to be a remote possibility. The anomaly can be naturally explained in terms of strong interactions developed by neutrinos, as it is likely to be the case if presently known "fundamental" particles have a preonic substructure. On theoretical grounds, some increase of $\sigma_\pi$ due to QCD effects[14] is likely to contribute; however, it appears to be hard to explain the entire anomaly with the standard model alone. The UHE observation[15] of the galaxy NGC 5128 ($d \approx 6$ Mpc) supports this conclusion: As discussed in Ref. 15 (cf. also Protheroe, Ref. 4), it is difficult to give a plausible explanation of this observation if all primaries are photons.

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[2]Such preon schemes are, e.g., H. Harari and N. Seiberg, Phys. Lett. **100B**, 41 (1981) and I. Bars, in *Proceedings of the International Workshop on Superstrings, Cosmology and Composite Structures,* edited by S. J. Gates and R. N. Mohapatra (World Scientific, Singapore, 1987), to mention but two.

[3]The puzzle is, in essence, that extensive air showers (EAS) associated with x-ray binaries contain a substantial number of muons. In view of recent results [B. L. Dingus *et al.*, Phys. Rev. Lett. **60**, 1785 (1988)], the primary is neutral, light ($m < 60$ MeV), and its interaction cross section in the atmosphere is at least a few mb/nucleon. It is unlikely that a particle with such properties was missed in accelerator-based experiments, unless it is one previously known, e.g., a photon. A straightforward extrapolation of photoproduction cross sections, however, gives too few muons in the EAS. There are similar difficulties in interpreting underground data on "muon bursts." See, e.g., R. Morse, in *Very High Energy Gamma Ray Astronomy,* edited by K. E. Turver (Reidel, Dordrecht, 1986) and R. J. Protheroe, in *Proceedings of the Twentieth International Cosmic Ray Conference, Moscow, 1987,* edited by V. A. Kozyarivsky *et al.* (Nauka, Moscow, 1987), for a review.

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[6]Protheroe, Ref. 3.

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[10]From an intuitive point of view, the *power* of a test is the probability of correctly rejecting a hypothesis; it is the probability of rejecting $H_0$ assuming that $H_1$ is true. Compare Kendall and Stuart, Ref. 9.

[11]The possibility of an absorption anomaly was pointed out earlier on the basis of the Kiel data (Samorski and Stamm, Ref. 7) alone. R. J. Gould, Astrophys. J. Lett. Ed. **274**, L23 (1983).

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