CONSTRAINTS ON COSMIC-RAY OBSERVATION OF CYGNUS X-3

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Two experimental groups[1,2] working at different minimum energies have reported underground muons coming from the direction of Cygnus X-3 with rates that vary in synchrony with its binary period. At the Mont Blanc detector[2] the events are, within statistics, uniformly spread over a 5-degree circle around the position of Cygnus X-3, even though the angular resolution is significantly better than this. The ratio of events in the phase peak to total muons observed rises as a function of minimum muon energy. The Soudan experiment also sees an excess in the number of pairs of codirectional multiple-muon events arriving within about 5000 seconds of each other, the excess events coming from a direction about 20 degrees away from Cygnus X-3.[3]

Cygnus X-3 is at least 10 kpc from Earth. Charged particles cannot travel this distance and maintain the required coherence in direction and time. If these events were caused by neutrons with enough energy to reach the earth from this distance their flux would be easily observable in high-energy cosmic rays, where they have not been seen. Similarly, gamma rays are ruled out as primaries because there are too many muons observed for them to have been generated by an acceptable number of gammas[4] (unless gammas at high energies have unexpectedly high probabilities of producing muons). Neutrinos are eliminated as a possible primary by the substantial zenith-angle dependence of the experimental rates. Therefore, if the effect is real it must be caused by some rather exotic primary.

The muons in the peak arrive within a rather narrow time period, approximately half an hour. Maintaining this time correlation gives another constraint on the particles. The time delay between the arrival of two particles which left Cygnus X-3 at the same time is

$$L*(\gamma_1^{-2} - \gamma_2^{-2})/(2c).$$

Since this time difference cannot exceed half an hour, the

primaries must either be nearly monoenergetic or else the Lorentz factor must exceed 10^4. As one increases the minimum energy of the observed particles, the last particles must be arriving earlier and the width of the peak should get smaller if the mass is near the limit. There is even some indication of such a tendency in the data.[1,2] If the underground signal is due to muons produced in the atmosphere, the minimum energy per parent hadron must be sufficient to produce muons that can penetrate to the detector. Unless the energy is much greater than this minimum, the above constraint on the Lorentz factor then requires the mass of the parent to be less than or of order 1 GeV. It is difficult to believe that a long-lived particle of this mass, capable of producing muons in atmospheric interactions, would have been overlooked in accelerator experiments.

One possibility that we have suggested[5] is that the parent primaries might be nuggets of quark matter. There are theoretical reasons for believing that such objects might exist and be stable for certain ranges of mass.[6] Furthermore, they might be produced in high energy processes around a compact quark star. One would then expect comparable numbers of up, down and strange quarks. Some fraction of such nuggets would be neutral and thus a possible signal-carrier. A high content of strange quarks would lead to enhanced kaon production in the atmosphere and thus to a relatively high yield of muons. Quark globs of the right mass could penetrate deep in the atmosphere and explode to give rise to Centauro events.[7] A specific version of a stable ensemble of quarks has been suggested some time ago which could be relevant in the context of underground signals from Cygnus X-3.[8] This is the di-lambda, a bound dihyperon state of 2u, 2d, and 2s quarks.

Hillas[11] has pointed out that the surface air shower signal from Cygnus X-3 puts a significant constraint on models which would produce the muons by interactions of nucleon-like objects in the atmosphere: Assume such parent "nucleons" are bound in aggregates of mass number A. These particles will also produce air showers. To be consistent with the observed air shower signal, $dF_{surface}/dE$, one then requires

$$\text{Cyg X-3 underground signal} < \int_{AE_\mu}^{\infty} N_\mu(>E_\mu)\,[dF_{surface}/dE]\,dE,$$

where N_μ is the number of muons per primary of total energy E that have sufficient energy to penetrate to the detector. The differential surface flux is roughly $4\times10^{-8}/E^2$ $cm^{-2}s^{-1}GeV^{-1}$. Using an Elbert formula[9] for underground muon yield from incident nuclei[10], we find a bound on the underground signal from Cyg X-3 of $1.3\times10^{-6}(E_{GeV})^{-2}cm^{-2}s^{-1}$, where E_{GeV} is the minimum muon energy for the underground detector. For Soudan (E_{GeV}=650) this bound is 3×10^{-12} $cm^{-2}s^{-1}$ and for Mont Blanc (E_{GeV}=3400) 10^{-13} $cm^{-1}s^{-1}$. In contrast, the reported signal at

Soudan is about 7×10^{-11}. A flux is not stated for the signal at Mt. Blanc, but an estimate can be obtained from a comparison of signal/background ratio with the background flux of single atmospheric muons in the angular region around Cygnus X-3. Such an estimate gives of order 10^{-11} $cm^{-2}s^{-1}$. Thus the underground signal appears to be at least a factor 20 too high to be induced by nucleons. Conversely, the parent hadrons must be at least 10-20 times more prolific at producing muons relative to air showers than nucleons are. In view of the quark matter suggestion (for which kaon and hence atmospheric muon production should be enhanced), we ran the cascade simulation of Ref. 10 for incident lambda hyperons, forcing production of a leading kaon at each lambda interaction. The muon production was enhanced by a factor less than two relative to nucleons, so even in this case there is a problem of consistency with the surface air shower fluxes.

A conceivable way out is to arrange the interaction length of the parent to be comparable to or greater than the thickness of the atmosphere so that production of the signal occurs too low for air shower production (i.e. mostly in the Earth). In this case, however, muon production must be prompt.

One can in principle use the energy-dependence of the signal implied by the different depths of the experiments to determine whether the muon production is prompt or atmospheric via pion and kaon decay. In the latter case the signal should be suppressed by an extra power of E_{GeV} as the depth increases due to time dilation of the parent pions and kaons. If the spectrum of the carrier from the source is E^{-2} (differential) one would expect the ratio Soudan/NUSEX underground signal = 5 for prompt and = $(5)^2$ for atmospheric pion and kaon decay. The ratio of the observed fluxes quoted above is closer to 5, but the analysis is not conclusive because we have not taken account of the complex variation of the overburden in the line of sight to Cygnus X-3 as it passes across the sky at Monte Bianco.

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