COSMIC RAY OBSERVATIONS OF CYGNUS X–3: SOME THEORETICAL IMPLICATIONS

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ABSTRACT

We describe how the discovery of surface showers from Cygnus X-3 and other compact X-ray binaries may resolve the long-standing question of the origin of cosmic rays above 10^{15} eV. In contrast, we show how possible underground muon observations raise rather than answer questions.

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1. INTRODUCTION: γ-RAYS FROM COSMIC SOURCES AND IMPLICATIONS FOR COSMIC RAY PHYSICS

An incomplete compilation[1] of observations by surface experiments of signals from Cygnus X-3 is shown in Fig. 1. This source observed in radio, infrared, MeV γ- and X-ray experiments emits photons of energies all the way up to 10^5 TeV, with the Haverah park observations (open circles) suggesting a cutoff at that energy. It must be emphasized that the surface experiments do not detect the primaries directly but only their atmospheric cascades. The primaries are assumed to be photons because these are the only known particles that readily initiate air showers and that are also neutral and stable (and hence capable of traveling in straight lines for long distances from point sources). At this session underground searches for Cygnus X-3 have been extensively debated. Is it conceivable that both surface and underground signals could be induced by the same particles? We will summarize the theorems that make this very unlikely.

Also at this session surface as well as underground observations of Cygnus X-3 and other X-ray binaries have been criticized on statistical grounds. In comparison with X-ray data they indeed appear marginal. Moreover, the Frejus and Kamioka experiments have reported upper limits on an underground signal from Cygnus X-3 that are inconsistent with signals of the strength reported by NUSEX and Soudan I, though the measurements refer to different intervals of time. We have nothing definitive to add to this debate. We want to point out, however, that surface and underground experiments differ in an important way: whereas it has proved exceedingly difficult to find a consistent interpretation of underground results, the general outline of an interpretation of the surface signals has been known for several years.[2,3]

In Fig. 2 we sketch the general picture of a binary source of high energy photons. The system consists of a compact star in orbit with a star that has not yet collapsed. The

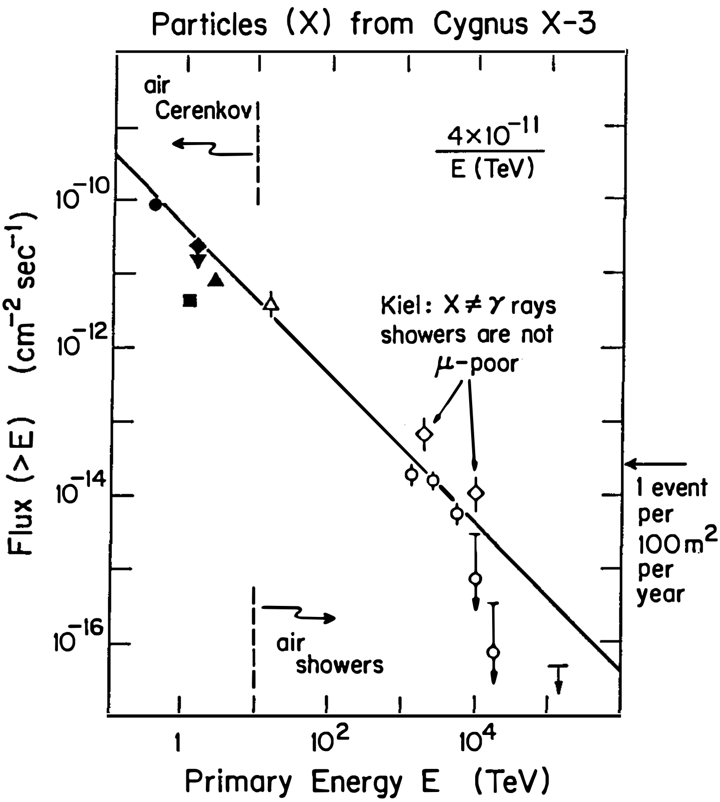

FIG. 1 Integral flux of very high energy particles from the X-ray binary Cygnus X-3. We will call these particles γ-rays although the Kiel experiment challenges this identification. Note the flatter E^{-1} dependence compared to the $E^{-1.7}$ fall off of the cosmic ray flux.

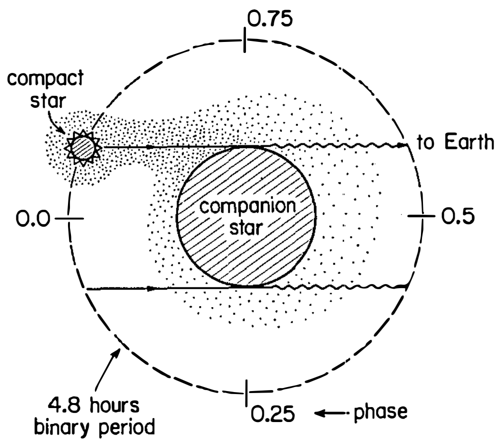

FIG. 2 The Cygnus accelerator beams neutral particles to earth produced in the beam dump. The dots represent accreting mattter and material blown off the companion.

compact partner somehow accelerates protons, perhaps by a pulsar mechanism[4] or more likely through conversion of energy from accretion of matter from the companion star.[5,6] These accelerated particles then interact with the companion and with the surrounding gas to produce a cascade of secondaries, the stable end products of which are photons, neutrinos, protons, anti-protons and electrons and positrons. The charged particles may be injected into the galaxy as cosmic rays (though the electrons and positrons especially will be much degraded in the source). Some fraction of the photons and neutrinos will escape the source and may be detected at Earth if their production is sufficiently prolific. As in any beam dump all particles for which the beam is above threshold will be produced, including any exotic, new stable neutral particles.

The energy output of Cygnus X-3 can be calculated[7] from the flux observed in our earth-based apparatus by making the following corrections to the observed flux of 10^{-10} erg cm^{-2} sec^{-1} above 10^{15} eV shown in Fig. 1:

(*i*) we only catch a fraction of the $4\pi R^2$ ($\geq 10^{46}$ cm^2) emission,

(*ii*) we have to take into account the duty cycle of the accelerator (≤ 0.02),

(*iii*) only a fraction of the energy goes into $p \rightarrow \pi^0 \rightarrow \gamma\,(0.1)$, and

(*iv*) γ's are absorbed on the 3° K background along the way.

Many of these corrections are model-dependent but Hillas estimates that

$$L > 10^{39} \text{ ergs sec}^{-1}, \tag{1}$$

i.e., more than 10^6 times the total energy output of the sun. This is above the Eddington limit for spherically symmetric accretion onto a one solar mass compact object.

The discovery of this point source in the very high energy spectrum might have solved[3,7] in part the old problem of the origin of high energy cosmic rays. The cosmic-ray spectrum can be understood up to perhaps 10^{14} eV in terms of shock wave acceleration in supernova remnants.[8] Although the spectrum shows a kink at 10^{15} eV (see Fig. 3), cosmic rays with much higher energies are observed and cannot be accounted for by this mechanism.[8] A compact accelerator with high magnetic fields concentrated over 10 km and possibly undergoing rapid flux changes and accreting matter could result in EMF's accelerating particles up to $\sim 10^{17}$eV.[4,5] The Cygnus accelerator's power of Eq. (1) is more than adequate by itself to supply the cosmic rays with energy in the interval $10^{15} - 10^{17}$ eV to the galaxy. One can estimate[3] the required power from Fig. 3 and the relation

$$\rho_E = \frac{4\pi}{c} \int_{10^{15}}^{10^{17}} EI(E)E \, dE \sim 4 \times 10^{-16} \, \frac{\text{ergs}}{\text{cm}^3} \tag{2}$$

together with an estimate[3] of the mean confinement time of $\sim 10^{16}$ eV cosmic rays in the galaxy, $\tau \sim 2 \times 10^5$ years. $I(E)$ is the integral flux shown in Fig. 1. The power required is

$$\rho_E V_{\text{Galaxy}}/\tau \sim 5 \times 10^{38} \text{erg/sec} , \tag{3}$$

and about 10% of this for the interval $10^{16} - 10^{17}$ eV. Thus the source need only be on at the rate measured over the past few years (Fig. 1) for a fraction of the time to supply all the galactic cosmic rays in a limited interval at high energy. Note that other identified TeV γ-ray emitters such as Hercules X-1, 4U 0115+63, the Crab pulsar, PSR 1953+29 and others are likely to play a role in this problem. The higher energy cosmic rays in Fig. 3 may be extragalactic, but also here point sources could be important with one source LMCX-4 already observed in the TeV-band.

It would be very instructive to see neutrinos from Cygnus X-3. Since they are much more penetrating than photons their escape from the source is much less model dependent.

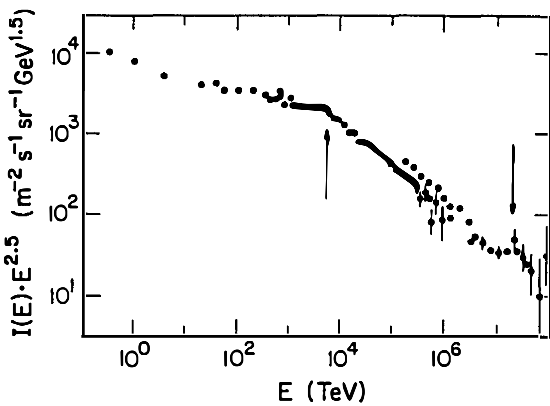

FIG. 3 Cosmic ray spectrum compiled by Hillas.

Estimates[9] based on the lower limit in Eq. 1, however, give a ν-induced-upward muon signal $\leq$ 1 event/1000 m^2/year. It is true that photon escape from the source is indeed model dependent. The duty cycle could therefore be much less than assumed in (ii) above with a consequent increase in luminosity and in the ν-induced signal. One cannot continue this increase indefinitely, however, without making the source so powerful it would blow itself away.[10] Perhaps an order of magnitude increase above the limit in Eq. 1 is conceivable. If the neutrinos could be detected, it would confirm the acceleration/beam dump scenario and give a rather direct measure of the luminosity of the source.

2. Muons from Cygnus X-3: Who Ordered That?

By last count 15 different experiments[1] have identified air showers in direction and with the characteristic time structure of the source Cygnus X-3. Some made repeated observations and found signals from astronomically similar binaries, *e.g.* Hercules X-1. Although a wealth of puzzling questions remain to be resolved (including especially the nature of the variability of the sources) a signal at the flux level given by Eq. (1) has much experimental support. Although γ-rays are ineffective at producing muons, the very high energy ones in the spectrum shown in Fig. 1 will generate some TeV muons and these will produce a calculable signal in underground (proton decay) detectors. A proton decay detector is therefore also an underground telescope. The signal is difficult to observe as γ-showers are muon poor[11] with $N_\mu/N_e \simeq 10^{-3}$, as opposed to 3×10^{-2} in a hadron shower where muons are generated abundantly by meson decay. In a γ-shower processes generating muons such as π photoproduction are associated with small cross sections. Assuming the atmospheric γ-flux shown by the line in Fig. 1 we computed the expected associated muon signal for the Soudan and NUSEX detectors. The $\gamma \rightarrow \mu$ signal is plotted at energy

$$E_\mu(\mathrm{TeV}) = 0.5\ [\exp\ (0.4x) - 1] \tag{4}$$

where x is the detector depth in km of water equivalent. The calculated muon fluxes are shown in Fig. 4 (labeled $X = \gamma$) where they are compared with the parent γ-flux and the published observations[12] of in-direction and in-phase muons from Cygnus X-3. The disagreement between calculated and observed flux is roughly three orders of magnitude for each experiment! It is possible that underground detectors rediscovered an old puzzle. The Kiel air shower array experiment,[13] after detecting a 4σ enhancement of the cosmic ray flux in the direction of Cygnus X-3, performed two tests to confirm the signal. They checked that on source showers indeed remember the 4.8 hour binary period but also found that the showers are not muon-poor as expected from γ-ray emission. The expected 2% muon content relative to the hadron induced background was observed to be 70%. Is our straightforward assumption that Fig. 1 represents the high energy tail of the electromagnetic emission spectrum to be questioned? Do cosmic accelerators emit particles (referred to as X from now on) other than photons?[14]

What if X were a neutral hadron, *e.g.* a neutron? We can repeat the previous calculation assuming the atmospheric signal in Fig. 1 is due to hadrons (remember atmospheric experiments identify showers and not the nature of the primary particle). As expected, about 10^2 times more muons are predicted, but the assumption that X is a hadron falls short of accomodating the data by more than one order of magnitude for Soudan and two for NUSEX (see Fig. 4). To produce enough muons underground in this way would lead to more surface showers than observed.

An alternative candidate for a "conventional" explanation of the underground muon signal is that X is a neutrino. We already noted, however, that the expected signal is much too low. Moreover, it cannot be sufficiently increased by increasing the power of the source without causing instability of the companion. Given the Kiel and the underground muons results, the situation is now desperate. How desperate we will illustrate next by a

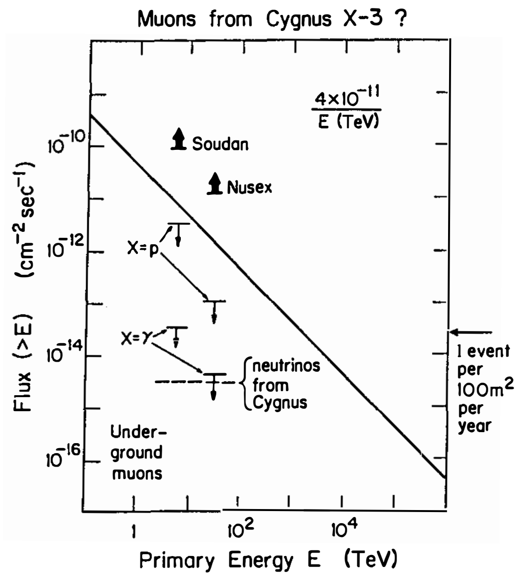

FIG. 4 Observed and calculated underground muon fluxes assuming that the source of the muons is γ-rays or hadron showers in the atmosphere or neutrinos directly from Cygnus.

series of theorems suggesting that X cannot exist!

Let us backtrack and list the properties of X implied by the observations:

(i) X is neutral: charged particles forget direction and time (phase) in the 3 μGauss intergalactic field. The 10^4 parsecs distance represents more then 10^4 gyroradii for particles with rigidity less than 10^3 TeV. This would exclude nuclei and protons anyway.

(*ii*) The 4.8 hours bunching of the Cygnus beam would be lost after $L^* = 10^4$ parsecs unless the γ factor is large enough. The time delay between the arrival of two particles with velocities v_1, v_2 which left Cygnus X-3 at the same time is

$$\delta t = \frac{L^*}{v_1} - \frac{L^*}{v_2}$$

or (5)

$$\delta t \simeq \frac{L^*}{2c}\left[\frac{1}{\gamma_1^2} - \frac{1}{\gamma_2^2}\right] \lesssim \frac{1}{2}\text{ hour}\,.$$

In Eq. (8) we imposed the condition that the muons arrive within a rather narrow time window, approximately half an hour as observed by the experiment. From (5) we conclude that the muon parents must be nearly monoenergetic (which is inconceivable in the type of models sketched in Fig. 2) or that the Lorentz factors must satisfy the bound

$$\gamma = \frac{E}{M(X)} > 10^4\,. \tag{6}$$

Therefore,

$$M(X) < 10^{-4}E\,. \tag{7}$$

As for Soudan $E \simeq 10^4$ GeV, we conclude conservatively that

$$M(X) \lesssim \text{a few GeV}\,. \tag{8}$$

(*iii*) The lifetime of X must be sufficient to cover the 10^4 parsecs distance, therefore

$$\tau(X) \gtrsim 10^8\text{ sec}\,. \tag{9}$$

This is about 10^5 neutron lifetimes.

(*iv*) The observations also restrict the interaction cross section of X with matter. An upper limit is obtained from our previous observation that the muons do not originate in conventional hadronic air showers, see Fig. 4. A way out of this is to arrange the interaction length of X to be comparable or greater than the thickness of the atmosphere so that production of the signal occurs too low for regular air shower production. This requires $\sigma(X\text{-nucleon}) \lesssim 1$ mb. However, if the cross section is made too small, the zenith angle distribution becomes very different from that of muons originating in atmospheric showers and the X particles penetrate so deep that they can interact inside the detector resulting in "contained" events. Both of these results disagree with observations. Calculations[14] relevant to the Soudan detector are shown in Fig. 5. A comparison with the data suggest that the cross section cannot be made smaller than 10μb. We therefore conclude

$$10\mu\text{b} < \sigma(XN) < 1 \text{ mb} . \tag{10}$$

Also, this discussion eliminates the possibility that neutrinos (or photinos) are the underground muon parents.

This concludes the theorem: a particle with the properties (i) – (iv) should have been discovered by accelerators. If you can imagine that such a particle has been overlooked, consider this as a challenge.

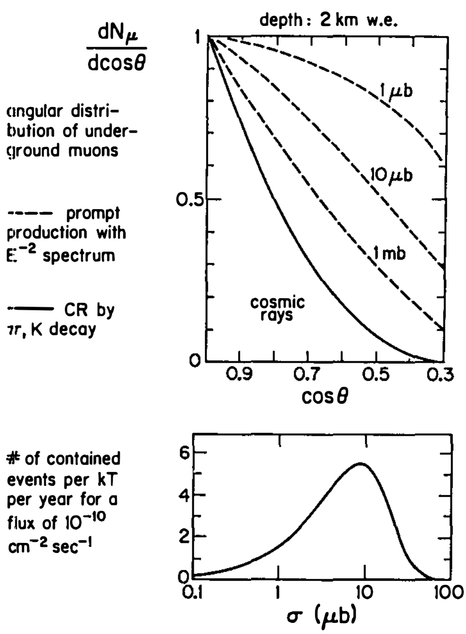

FIG. 5

The no-go theorem doesn't even exploit the puzzling fact that both experiments observe[16] an angular spread of 3° of the muon's arrival direction. This cannot be understood without adding some large mass or transverse momentum as an ingredient of the problem. In summary one can conservatively state that although pathological scenarios[17] can be dreamed up without contradicting accelerator information, none of these scenarios fit into the standard model or any of its extensions (*e.g.*, compositeness or supersymmetry) that have been proposed.

3. CONCLUSIONS

Non-accelerator experiments now have their great accelerator(s) in the sky. The field has undoubtedly a long and promising future whether the Cygnus muon puzzle survives further scrutiny or not.

—Cygnus muons are at present the only challenge to the standard model of quarks and leptons. One should, however, keep in mind the possibility of a "garbage" solution of which quark matter is an illustration,[14] as an alternative to new particles or interactions if the underground signal does not fade away.

—As regards surface experiments, the highest priority is to confirm the data. We count as many as 10 new air Cherenkov and 5 new or upgraded extensive air shower arrays which will be operating in the near future. This amount of effort testifies to the potential importance of the subject.

—New experiments will bring better statistics, hopefully understanding of the variability, but most importantly simultaneous confirmation of signals by independent detectors. This has at present not been achieved. A good possiblilty exists for coincidence measurements between Utah's Fly's Eye and the Los Alamos array which are only 6° apart and have therefore virtually the same field of view at the same time. Another important disign goal of many of the new experiments is to establish the photonic nature (or otherwise) of the signal by measuring the muon content of the showers.

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