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What Can We Understand About the Muon Anomalies in High Energy Showers from Point Sources?

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Abstract

We consider here the muon anomalies which have been claimed to be seen in high energy air showers arising from point sources. We discuss what type of particle would be required to explain the experimental data and propose a generic class of models which can explain the data. Then we discuss accelerator experiment limits on the existence of such a particle. In particular, we argue that such a particle need not have been seen yet in either neutrino experiments or in beam dump experiments. We argue that neutrino experiments at 800 GeV provide perhaps the most sensitive test of our hypothesis in accelerator experiments. We present distinctive features of our model

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which should be observable in cosmic ray experiments. Finally we discuss the problem of making an acceptable flux of Cygnets at the compact X-ray source.

1 Introduction

There is a long standing controversy over the possible existence of muon anomalies in observations of high energy radiation (TeV and above) from stellar sources, Cygnus X-3 and, recently, Hercules X-1. Now it is a natural conjecture that the radiation consists of photons, since these are the only known particles that can reach the earth from such sources (a) without decaying first, (b) without losing directional information due to bending in the galactic magnetic field, and (c) with sufficient cross section to make them detectable. However, the muon anomalies in the data refute the conjecture.

One anomaly [1,2] is that air showers associated with both Cygnus X-3 and Hercules X-1 have a muon content consistent with that of hadronically induced showers and inconsistent with the much lower muon content of the electromagnetic showers normally induced by photons. Other anomalies appear in the observations in underground detectors of a signal from Cygnus X-3. First is that there is a signal at all: The underground experiments observe penetrating charged particles, which are presumably muons, and their flux is at least one or two orders of magnitude higher than what is expected from the known flux of high energy air showers from Cygnus X-3, even if the air showers are assumed to be hadronic. Secondly, the angular spread of the muons relative to the direction of the source is several degrees, instead of the expected spread of less than a degree. It has been deduced that the interactions responsible for the underground observations must therefore occur in the rock, not in the atmosphere [3,4].

In this paper, we shall assume that the muon production cannot be explained by photoproduction processes in photon induced showers. Photons have a very high cross section to interact electromagnetically; electromagnetic interactions predominantly involve low momentum transfers, of the order of the mass of the electron. This is well-established physics, and we see no possibility of turning these electromagnetic interactions off so as to unmask a new interaction with a substantially lower cross section. In a recent publication, it has been argued that the photoproduction cross section may grow rapidly at high energies due to semi-hard QCD processes [5]. We are not at present convinced by their arguments that a large photoproduction cross section is implied by a large inclusive cross section for the photoproduction of jets.

Several authors [3,4,6,7] have argued, correctly in our view, that the data require the introduction of a new particle, dubbed the Cygnet. We will summarize these arguments below. The Cygnet has a mass of at most about a GeV, it is electrically neutral, and in the energy range (probably several TeV) appropriate to the underground observations, its hadronic cross section is fairly large — of the order of $10\,\mu$b. However, a real dynamical model has not yet been given (*pace* Ruddick [6]). It is our purpose in this paper to provide such a model.

We will argue that if the Cygnet is a low mass, color singlet, electrically neutral particle which is coupled to color octet electrically neutral particles of mass about 1-10 GeV, then the air shower and underground data are explained, without an obvious contradiction with the results of accelerator experiments.

After summarizing the data in Sec. 2, we show, in Sec. 3, that there is room within ordinary QCD for extra particles (color non-singlet) of mass around a few GeV, provided that they are electrically neutral. The experimental constraints are surprisingly weak. In Sec. 4 we present our model for the Cygnets; it involves two of these new particles, X and X', in addition to the Cygnet. There is an approximately conserved quantum number carried by the Cygnet, which is also carried by the X'. The X and X' also presumably carry an approximately conserved quantum number. Our model is really a whole class of models. One way to imagine such a model is to suppose that Cygnets are bound states of the X and X' in a new technicolor-like interaction. The mass of the X and X' will be about 1 to 10 GeV.

In Secs. 5 and 6 we estimate the production and interaction cross sections of Cygnets. This enables us in Secs. 7 and 8 to show how we simultaneously satisfy both the constraints of the apparent non-observation of Cygnets in beam dump and neutrino experiments and the constraints derived from the cosmic ray observations of Cygnus X-3 and Hercules X-1. The important point here is that in the beam dump experiments there are enough threshold factors in the cross sections to keep the rate for observation of Cygnets low. Also needed is the wider angular spread of higher mass particles compared with that of charm. The strong energy dependence of the cross section enables us to avoid the conclusions of Berezinsky et al. [3], that would imply that our models cannot explain the data.

Section 9 contains some suggestions for experimental searches for these new particles in accelerator experiments, and distinctive features in cosmic ray experiments.

In Sec. 10 we give a few remarks on the production of Cygnets in X-ray binary stars. In Sec. 11, we summarize our results.

2 The data

We review here the data on high energy cosmic rays coming from Cygnus X-3 and Hercules X-1; we also review its interpretation [3,4,6,7]. Nagle, Gaisser and Protheroe [8] have recently reviewed the data on cosmic rays seen as extensive air showers associated with discrete astrophysical sources.

The original data from Kiel [1] showed that air showers from Cygnus X-3 have a muon content which is about the same as that from proton induced showers. The CYGNUS experiment [2] recently confirmed an excess of muons. The energy of the showers is about 1000 TeV. Now the large distance to Cygnus X-3, 13 kpc $= 4\times10^{20}$ m, means that any particle of this energy and of normal charge would be so deflected by the galactic magnetic field that all directional information would be lost. So the Cygnet must be electrically neutral. Its lifetime must satisfy $\tau \gtrsim (M_C/10^3\,\mathrm{TeV})\ 10^{12}$ sec, where M_C is the mass of the Cygnet. It is therefore very long-lived: a 1 GeV Cygnet would need a lifetime above about 10^6 sec, so that neutrons are ruled out. Photons are ruled out by the large muon content of the air showers. Therefore the Cygnet cannot be any known particle with known interactions. (Drees, Halzen and Hikasa [5] have argued that conventional estimates of the hadronic part of the photon-hadron cross section are substantially lower than the true value in this range of photon energy. They base this conclusion on calculations of the inclusive jet cross section, and find that the muon content of photon showers is consistent with the experimental observations that we have summarized. We are not convinced by their arguments. More work is necessary to resolve this issue.)

The timing of the arrival of the showers exhibits the 4.5 hour period of Cygnus X-3, so the mass of the Cygnet must be low enough to prevent this periodicity being washed out by dispersion. Specifically

$$M_C \lesssim 10^3\,\mathrm{TeV}\sqrt{1\mathrm{hr}/10^{12}\ \mathrm{sec}} \approx 60\,\mathrm{GeV}. \tag{1}$$

This is not much of a constraint. However, the Los Alamos experiment has also seen a signal from Hercules X-1. This source has a period of about 1.25 sec, and is at a distance also of about 10 kpc. The air showers from Hercules X-1 also have about the same muon content as those for average air showers at the same energy, that is, the muon content is about that for a proton induced shower. Further, the showers come in bursts, and the arrival time within each burst has a periodicity (1.236 sec) that is characteristic of the period of Hercules X-1.[1] This periodicity constrains the mass of the Cygnet to be less than about 1 GeV.

The existence of muon rich air showers suggests that the Cygnet-hadron cross section at air shower energies, 10^3 TeV, be around $100\,\mu$b to 1 mb. If the cross section were much smaller then the necessary flux would be even larger. Since the flux is already rather high by the standards of the Eddington limit, we consider a higher flux rather hard to believe. The large cross section required to make an atmospheric air shower, combined with the high muon content suggests that the Cygnet fairly strongly produces hadrons. Photons can produce electron pairs with large cross section because of the small value of the electron mass, but the cross section for photons to produce muons is indeed very small.

The data from underground detectors put more constraints on the properties of Cygnets. Here the typical energy of a Cygnet appears to be 2-3 orders of magnitude lower [3,4,6] than that which is appropriate for the air shower experiments. There is no agreement among various experiments as to whether or not there is a signal. Mount Blanc (NUSEX) [10] and Soudan [11] have both claimed signals, but Fréjus [12] which is at the same depth as Mount Blanc, has seen nothing, and neither has Kamiokande. There appears to be a signal of marginal statistical significance in the data from IMB [13]. In view of the sporadic nature of all kinds of radiation from Cygnus X-3, it is perhaps not too difficult to understand the discrepancy as a result of the different on-times for detectors, and the different times at which Cygnus X-3 is overhead of the detector.

The lower energy of the primaries means that this data also provides an upper bound on the Cygnet mass, again of about 1 GeV. The lifetime of the Cygnet is constrained to be $\tau \gtrsim (M_C/1\,\mathrm{GeV})\,10^8$ sec. (Here we assume that the typical primary energy is around 10 TeV. This is consistent with the fact that only muons of energy greater than 500 GeV can reach

[1]This period is slightly different from the pulsar period, but is consistent with the period measured in a Cerenkov air shower experiment.[9]

the detector from the earth's surface, and that the leading muon carries about 1/10 of the energy of a hadron induced reaction.)

There are at least two puzzling features of the data, taken at face value. First the flux measured in Soudan and Mount Blanc is 1–2 orders of magnitude larger than what would be expected from ordinary air shower experiments extrapolated into this energy range, if it is assumed that the muons are the result of high energy air showers. Another very puzzling feature is the angular spread around the position of Cygnus X-3. This angular spread $\Delta\theta \approx$ 3–5 degrees is much larger than what might be expected from multiple scattering of muons produced by air showers above the rocks. Berezinsky, Ellis and Ioffe [3] showed that this angular spread can only occur if the muons have energy less than about 250 GeV. (Similar arguments were presented by Ruddick [6] and by Collins and Olness [4].) The minimum energy for a muon to penetrate from the surface to the detector is about 500 GeV for Soudan and several TeV for NUSEX. So the Cygnets producing the underground muons must have interacted in the rock, rather than in the atmosphere.

The zenith angle dependence of the underground signal shows that the Cygnet cross section must be above a few μb. In order that the rate of air showers and of underground muons be consistent, the Cygnets must not have too large a cross section, say above about 1 mb. Otherwise they would mostly interact in the atmosphere. We therefore agree with the conclusions reached by Berezinsky, Ellis and Ioffe [3] that results from the underground experiments require that the Cygnet-nucleon cross section be around 1 to 10 μb at the energies relevant for these experiments.

Needless to say, no known particle satisfies the above description, but it should surely have been seen in accelerator experiments. It is therefore very tempting to claim a no-go theorem. However, there have always appeared to be loopholes in the proof of the no-go theorem: "We would not be so foolish as to claim a no-go theorem, but almost." [3]

In addition to the above constraints on the properties of any Cygnet interpretation of the data concerning point sources of high energy radiation, one must explain why the Cygnets have a flux greater than or of the order of that for photons. The most reasonable explanation for the production of neutral particles at a stellar source is the acceleration of charged particles (presumably protons) followed by their collision with ordinary matter. By far the most common particles to result are of course pions. The stable neutral particles that are in their decay products are photons and neutrinos. Since neutrinos have a small interaction cross section, they should (apparently) be ruled out as Cygnets.

3 How well do we know the Lagrangian of QCD?

Hadron spectroscopy and experiments on e^+e^- annihilation to hadrons establish the existence of the light quarks, u, d, and s, each in three colors. To explain the binding of quarks into color-singlet hadrons a color octet of gluons is necessary: these of course also give us asymptotic freedom, which is necessary to explain the properties of hard scattering, and which is at least suggestive of color confinement. Higher energy e^+e^- experiments also give us the c and b quarks and a limit that other charged quarks, like the t, must be heavier than about 25 or 30 GeV. (There are similar limits, probably higher, but certainly less precise, from searches at hadron colliders.)

But if we hypothesized that there are other colored particles with a mass of as low as 2 GeV, there is remarkably little evidence to rule out that hypothesis, provided that these particles are electrically neutral. (Of course, the particles must not be absolutely stable, for otherwise stable particle searches would probably have revealed them, certainly if they can be bound into stable, electrically charged "wild hadrons".[14]) Indeed, current searches [15] for gluinos and squarks leave open a window of gluino mass between 2.5 GeV and 4 GeV. The most sensitive of these searches rely on specific signatures of supersymmetric models, for example that the gluinos decay into photinos, which experimentally have a similar signature to neutrinos, i.e., they are seen as missing transverse energy. Therefore the constraints are weaker on new particles that do not precisely match the characteristics of supersymmetric particles.

The cross section for making a colored particle of 1.5 to 2 GeV mass would be comparable to the cross section for charm, i.e., 10 to 100 μb at current accelerators. So plenty of them would be made, by the standards of many new physics processes that have been considered. But they would still constitute only 0.1% of the total cross section. Combinatorial backgrounds in picking out decays to many light hadrons make bump hunting hard, unless one has a very definite signature in mind. One only has to remember the long delay between the discovery of the J/ψ and the discovery of the D mesons, where the signatures were definite, to understand the difficulty in explicitly observing our new particles. (Our preferred masses are rather higher.)

Of course such new particles would change the cross sections for all kinds of hard scattering process, and specifically for jet production. But the current precision of theoretical calculations in perturbative QCD is low, normally only within a factor of two. Moreover, jet production is dominated by gluon-gluon scattering to gluons. Other subprocesses, including the production of our new particles, have cross sections that are at most comparable to the cross sections for known processes. So hard scattering experiments are not sensitive enough, at present, to readily give evidence of new particles.

4 The Model

4.1 General properties of models with new light particles

Let us suppose that in the QCD Lagrangian there is one or more extra matter fields. We will denote them by X. Each X is neutral under the usual electroweak interactions to prevent its detection in e^+e^- experiments and in W and Z decay. The spin of an X may be 0, $\frac{1}{2}$ or even 1. A spin-1 X would result from spontaneous breakdown of a larger color group to SU(3) (cf. Glashow's chiral color [16]). We propose that new electrically neutral particles in QCD be called snarks, since Lewis Carroll's definition of a snark seems appropriate:

For the Snark's a peculiar creature, that won't
Be caught in a commonplace way.
Do all that you know, and try all that you don't:
Not a chance must be wasted today.

The gluino in supersymmetric QCD is a particular example of a snark. One peculiar feature of the gluino that is not shared by all possible snarks is its R-parity. R-parity is a conserved multiplicative quantum number that is 1 for all ordinary particles and -1 for their supersymmetric partners. Although R-parity appears to be a quantum number peculiar to supersymmetric models, it is a more general concept that follows from conservation of baryon and lepton number (B and L) and of angular momentum. Normal particles either have integer spin and zero lepton and baryon number or have half-integer spin and nonzero lepton or baryon number. Their supersymmetric partners violate this relation: for example, the gluino has spin-$\frac{1}{2}$ and zero baryon and lepton number. But any other new particle that has $B = L = 0$ and spin-$\frac{1}{2}$ would also have to be assigned $R = -1$. Even if lepton and baryon number were not conserved, R-parity would still be conserved if either $B + L$ or $B - L$ were conserved, as is true in many models. Conservation of R-parity provides a constraint on building models of snarks that do not have easily observable exotic decays.

The couplings of snarks to gluons are entirely specified by gauge invariance. A spin-0 snark will also have an X^4 interaction:

$$h(\bar{X}X)^2, \tag{2}$$

and may have a Yukawa interaction with quarks:

$$f\bar{\psi}t_\alpha\psi X_\alpha, \tag{3}$$

if the X is a color octet. Here t_α are the generating matrices of SU(3). An X^3 interaction may also be possible. We prefer to postulate that there is a symmetry reason to prevent the Yukawa interaction. For otherwise there is a danger of having too high a rate for the decay $K \to \pi + X + X$. Also the three jet distribution in e^+e^- annihilation to hadrons would be distorted. A spin-$\frac{1}{2}$ snark will have no non-gauge couplings in the QCD Lagrangian.

In general, a snark will participate in some generalization of the weak interactions, that will allow it to decay. (For example, a gluino can decay to two quarks and a photino: $\tilde{g} \to \bar{q} + q + \tilde{\gamma}$.)

In addition, snarks may participate in new strong interactions. Indeed, to explain certain of the characteristics of Cygnets, we will be forced to postulate such an interaction. We may suppose that this interaction is mediated by the gluons of a new symmetry group and we will denote the scale on which its interactions become strong by Λ_T, in analogy with $\Lambda_{\rm QCD}$. The new interaction shares some characteristics with technicolor [17], so we will call it 'TQCD' or just 'T'. We will find that Λ_T is probably low, perhaps a few GeV. Within this scenario, the snarks could be composites, just as hadrons are bound states of quarks. The Cygnet itself will be a Goldstone-like bound state under TQCD. On low mass scales, we will not see the compositeness. (Our discussion above about the possible couplings of snarks to quarks and gluons assumed that snarks can be treated as elementary particles for the purposes of doing QCD calculations at moderate energies.)

The gluons of TQCD are flavor-blind. Thus many of the bound states will be colored. It is quite likely that the lowest states will be color neutral, since color non-singlets would need to bind to gluons, and would therefore have a higher QCD energy than the color singlet states. It is the color nonsinglet states that we identify with snarks.

The same experiments that eliminate stable gluinos may also eliminate stable snarks. Thus it is likely that snarks are unstable against some kind of generalized weak or electromagnetic interaction. These decays may involve new particles with no strong interactions, such as the photino. But they need not. In that case we could get an effective weak interaction for snarks like

$$\bar{X}_\alpha \sigma^{\mu\nu} e \, G_{\alpha\mu\nu}, \tag{4}$$

where e is the electron field and $G_{\alpha\mu\nu}$ is the gluon field. This particular example assumes a color octet snark with spin-$\frac{1}{2}$ and lepton number 1. The interaction is non-renormalizable, as is appropriate for an effective low energy interaction.

In the scenario in which the snarks are technicolor-like composites, their decay pattern may be more complicated than in a model in which they are elementary. It would involve a combination of the usual QCD interactions, the technicolor-like interaction as well as some new effective weak interaction.

The constraints imposed by R parity on the decays of a snark with spin-$\frac{1}{2}$ and zero baryon and lepton number will be a significant subset of those imposed by supersymmetry on the decays of a gluino.

4.2 Cygnets

Cygnets themselves must be color neutral of course, because of color confinement in QCD. As we have reviewed, they are stable, or almost so, and have low mass – at most about a GeV. Moreover their cross sections must be in at least the μb range at cosmic ray energies. Any particle with these characteristics that couples directly to quarks or gluons would certainly provide an enormous signal in beam dump experiments and would also swamp the neutral current signal in conventional neutrino experiments. (This will be clear when we estimate rates for these experiments with indirect couplings and substantial thresholds.)

Therefore we will postulate that Cygnets couple directly to snarks, but not to quarks and gluons, and that the mass of these snarks is a few GeV. At low energies the Cygnet-hadron cross section will have a threshold suppression coming from the mass of the snarks, while at higher energies the cross section will be a normal QCD hard scattering cross section. The relatively light mass of the Cygnet can be explained by assuming that it is the Goldstone particle of some symmetry possessed by the snarks. But at the same time its interactions with hadrons will contain the threshold factors associated with the snark mass.

We now have a choice. Either the Cygnet is an elementary particle, probably a scalar, that has a coupling in the Lagrangian to snarks, or it is a bound state, just as the pion is a bound state of quarks. Since the Cygnet-snark coupling will turn out to be large, we prefer the second possibility. This of course leads us to postulate the TQCD interaction referred to earlier.

Let us assume that there are two kinds of snark X and X' to which the Cygnet couples, with an effective interaction:

$$g_C \bar{X}' X C. \tag{5}$$

We also assume that X' is heavier than X, with the predominant decay of the X' being $X' \to X + C$. Since the Cygnet, C, has a long lifetime, we must assume that X' and C carry some exactly or almost exactly conserved quantum number not carried by X. Under the color SU(3) of QCD both X and X' must transform in the same way. They must carry a zero triality representation like the octet to avoid exotic hadrons with fractional charge when the snarks are bound by QCD into color neutral states.

However, the elementary particles of TQCD may be in a triplet or other nonzero triality representation of color. For example, suppose that in TQCD we have elementary fields T and T' that are color triplet. Then a $\bar{T}'T$ bound state could only be a singlet or octet. So, in general, provided that the TQCD quantum numbers of the T and T' are appropriate, we can allow them to carry any representation of ordinary color. One can imagine that there are partners of the Cygnet with nonzero color, which will therefore be bound into higher mass hadrons.

It is not entirely clear to us whether the Cygnet may be absolutely stable. If it were, then we might fall afoul of cosmological constraints. We do know that the Cygnet lifetime must satisfy

$$\tau_C \gtrsim 10^8 \,\text{sec} \left(\frac{M_C}{1\,\text{GeV}}\right) = 2 \times 10^{32} \hbar c^2 \,\text{GeV}^{-2} M_C \tag{6}$$

in order that Cygnets of several TeV energy (as needed [3,4,6,7] for the underground muon observations) can travel the distance of order 10 kpc from Cygnus X-3 to the earth.

If the scale of interactions which violates the conservation of Cygnet number is of the Λ_C, then we expect the lifetime of the Cygnet to be of order

$$\tau_C \sim \frac{{\Lambda_C}^4}{{M_C}^5} \simeq 6 \times 10^{-9} \,\text{sec} \left(\frac{1\,\text{GeV}}{M_C}\right)^5 \left(\frac{\Lambda_C}{10\,\text{TeV}}\right)^4 \tag{7}$$

From the lifetime bound given by the underground experiments, we then have a bound on Λ_C:

$$\Lambda_C \gtrsim 10^8 \,\text{GeV}^{-\frac{1}{2}} {M_C}^{\frac{3}{2}}. \tag{8}$$

For example, if we take Λ_C to be of order 10 TeV, then $M_C \lesssim 1\,\text{MeV}$.

If the interaction that violates the Cygnet quantum numbers is the same as the one that violates the quantum numbers of the X, then we might expect that the lifetime of the X would be given by the same formula as that for the Cygnet, but with the mass replaced by that of the X. If the X has a mass in the range of 1-10 GeV, we therefore expect a lifetime of the order of $\tau_X \sim 10^{-8} - 10^{-12}$ sec Therefore the decay length of the X particle might easily be somewhere in the range of 10^{-4} m to 1 m.

5 Production of Cygnets

Production of Cygnets in hadron-hadron collisions goes by gluon fusion (fig. 1) to make X' pairs followed by the subsequent decay of the X's to $C+X$. This gives a pair of Cygnets plus a pair of Xs. We assume that the Xs then decay to ordinary particles. It is also possible to suppose that the Cygnets result not so much from the *decay* of X's as from the *fragmentation* of X's, just as pions result from the fragmentation of ordinary quarks and gluons. For our purposes the ultimate result is the same.

We will now derive an approximate formula for the QCD prediction for the cross section for X' pair production. It will apply to the production of any heavy particle, and will allow for the main physical effects that control the cross section as a function of energy and of the mass of the produced particle. The overall normalization will be controlled by the actual Born diagram at the parton level. We will see that the formula gives the cross section for heavy quarks to within better than a factor of two. So it should be adequate for our purposes, which are to estimate cross sections roughly and to understand the dependence of the cross section on the parameters of the problem, notably the mass of the X' and the energy. In the next section we will work out a corresponding formula for the interaction of Cygnets with hadrons.

Since for the moment we choose not to make a complete specification of our model, for example to fix the spin of the X and X's, we do not need to work to better precision. But it is crucial that we be able to check that the parameters of particular implementations of our scheme can be tuned to satisfy the experimental constraints.

For production of a pair of objects of mass m_Q by gluon fusion in a hadron-hadron collision, we write

$$\frac{d\sigma}{dy}(pp \to \mathrm{Pair} + \mathrm{anything}) = C_P C_H \left[\frac{\alpha_s(m_Q)}{\alpha_s(5.4\,\mathrm{GeV})}\right]^2 \frac{\sqrt{s}}{m_Q^3} \left(1 - \frac{3m_Q}{\sqrt{s}}\right)^\beta . \tag{9}$$

We have constructed this formula to give a reasonable approximation to the cross section at all energies. The powers of $\alpha_s(m_Q)$ are clearly from the hard scattering graphs; we have chosen to normalize them to b-quark production, for convenience. We next adjust the formula to give the correct large s behavior, which is governed by the small-x behavior of the parton distributions. Since a numerical check shows that these behave roughly like $1/x^{1.5}$ [18], the cross section must behave like $s^{0.5}$. Then the factor of $1/m_Q^3$ is needed to get the correct dimensions for the cross section.

The overall normalization is a product of two factors, $C_P C_H$. For ordinary heavy quark production, C_P is defined to be unity, and C_H is adjusted to fit perturbative calculations. For other processes, the value of C_H is left unchanged, and C_P is adjusted to reflect the correct value of the hard scattering subgraph. Group theory factors will be particularly important: for color octets, we expect C_P to be about 10.

There remains the factor $(1-3m_Q/\sqrt{s})^\beta$, which is meant to give the s dependence when $\sqrt{s}$ is not very much bigger than m_Q. The derivation of this factor starts by observing that the lowest value of the subprocess energy for the hard scattering is $2m_Q$ and that this corresponds to a parton x of $2m_Q/\sqrt{s}$. (It is sufficient for our purposes to consider the cross section at rapidity $y=0$ and to assume that both partons entering the hard scattering have equal x.) Typically, the subprocess must have more than the minimum energy, so we estimate the typical x to be $3m_Q/\sqrt{s}$. Now the large x behavior of parton distributions is as a power of $1-x$. Hence we get the last factor in (9). The exponent β is adjusted to fit low energy heavy quark production.

A rough fit to production (e.g., [19]) of b quarks gives the following parameters:

$$\begin{aligned} C_P &\equiv 1 \text{ (for heavy quark production)}, \\ C_H &\approx 0.2\,\mu\text{b-}\,\text{GeV}^2, \\ \beta &\approx 6.5. \end{aligned} \tag{10}$$

The value $\beta \approx 6.5$ for the exponent is appropriate for proton-proton collisions. It would be different for proton-antiproton collisions where the dominant subprocess at small s is the annihilation of valence quarks and antiquarks; valence distributions have a different large-x behavior from gluon distributions or quark-sea distributions.

We roughly estimate the rapidity range that is relevant to be

$$\Delta y = \max(1, 2\ln[\sqrt{s}/(3m_Q)]). \tag{11}$$

The formula (9) with the values given in (10) appears to be accurate to better than a factor of 2 for the case of heavy quark production, as we will now see.

5.1 CHECKS AGAINST HEAVY QUARK PRODUCTION

We have checked eq. (9) with the parameters (10) against Berger's calculations [19] of heavy quark production. For $b\bar{b}$ pairs at $\sqrt{s}=2\,\text{TeV}$, he gets $d\sigma/dy = 3\,\mu\text{b}$, while our formula with $C_P=1$ and $m_Q = 5.4\,\text{GeV}$ gives $2.4\,\mu\text{b}$. At 40 TeV, Berger gets $50\,\mu\text{b}$, as does the formula. Thus the overall normalization and energy dependence are correct when $\sqrt{s} >> m_Q$.

The exponent $\beta \approx 6.5$ of the large x correction factor can be checked by going to $\sqrt{s} = 30\,\text{GeV}$. Berger gets a total cross section of 0.2 to 0.4 nb, depending on his exact assumptions, while we get a $d\sigma/dy$ around 0.2 nb and a Δy of about 1.2, to agree with his cross section.

The previous checks just verified the choice of parameters in (10).

We now check the correctness of the form of (9) by checking it against production of top and of charm. Notice that we have no free parameters left. For top at $m_t = 40\,\text{GeV}$ and $\sqrt{s} = 2000\,\text{GeV}$, we get $d\sigma/dy = 2\,\text{nb}$ and $\Delta y = 6$, so that $\sigma_{tot}(pp \to t\bar{t}) \approx 10\,\text{nb}$. Berger quotes 10 to 20 nb. For charm at $\sqrt{s} = 39\,\text{GeV}$ and $m_c = 1.2\,\text{GeV}$, we get $\sigma_{\text{tot}} = 30\,\mu\text{b}$, and Berger gets $19\,\mu\text{b}$.

6 Interaction of Cygnets

We assume the total Cygnet-nucleon cross section is given by Cygnet-gluon fusion to $X' - X$ pairs (fig. 2). We construct a formula analogous to (9) for this case:

$$\sigma_{\text{tot}}(\text{Cygnet} + p \to \text{anything}) =$$

$$C_I \left(\frac{\alpha_C}{\alpha_s}\right) (1\,\mu\text{b-}\,\text{GeV}^2) \left[\frac{\alpha_s(m_{X'})}{\alpha_s(5.4\,\text{GeV})}\right]^2 \left(\frac{\sqrt{s}}{m_{X'}{}^3}\right) \left[1 - \left(1.5\frac{m_{X'}}{\sqrt{s}}\right)^2\right]^{\beta/2} . \qquad (12)$$

We will be assuming that the X is substantially lighter than the X'. Thus the typical subprocess energy will be $1.5m_{X'}$ instead of $3m_{X'}$. Now the hard scattering involves a photon, which has $x = 1$. Hence the typical x of the gluon is $(1.5m_{X'}/\sqrt{s})^2$. Moreover there is only one gluon distribution instead of two to give suppression at large x, so the exponent in the last factor is half what it is in eq. (9). Finally, we have changed the value of the overall constant from $C_P = 0.2\,\mu\text{b-}\,\text{GeV}^2$ to 1, because the $1/m_Q{}^3$ factor really comes from the subprocess energy, which is $3m_Q$ in eq. (9) and $1.5m_Q$ in (12). We have separated the overall unknown constant into two factors: C_I is to include the effects of group theory and the difference between the normalizations of the hard scattering, while α_C/α_s is to show the effect of the X-X'-C coupling, g_C.

7 Beam Dump and Neutrino Accelerator Experiments

7.1 400 GeV Beam Dump Experiments

We now apply these formulae to Cygnet production and interaction at the CERN beam dump [20]. The beam energy is 400 GeV and the distance from the beam dump to the target is 910 m, with most of this distance being through rock and earth. Consider Cygnet production at the target followed by Cygnet interaction at the detector. The signature at the detector is the same as for a neutral current neutrino interaction.

So we must compare the rate of Cygnet interactions to the rate of neutrino interactions. In a beam dump the neutrinos are predominantly prompt neutrinos, i.e., those produced in charm decay. Experimentally, the rate of charged current interactions of muon neutrinos is easily separated out; thence the rate of neutral current interactions of muon neutrinos can be deduced. Thus the background to Cygnet interactions is the rate of interactions of electron neutrinos.

Note that the interaction of Cygnets involves the production of at least one X' particle, which will decay to a Cygnet. So one or more Cygnets will be produced. Since the Cygnets have a low cross section to interact again, they will normally not do so, and there will be missing energy in the event seen in the detector, but not a second vertex. If the decay of the X' includes a muon as well as the Cygnet, it is possible to mimic a charged current interaction of a muon neutrino. This would complicate the interpretation of the experiment.

We will assume initially that for Cygnet production and interaction:

$$C_P = C_I = 1,\ \alpha_C = \alpha_s,\ m_{X'} = m_b \quad \text{(Initial parameters).} \tag{13}$$

The inclusive cross section for Cygnet production is then .2 nb. This is twice the cross section (9) for Cygnet pairs. Δy is about 1. The cross section for charm that decays to electron neutrinos is 1.5 μb. (We are quoting from Jonker et al [20] for the beam dump results and the deduced charm cross sections.) Thus there is a factor of $(0.2\,\text{nb})/(1.5\,\mu\text{b}) \approx 10^{-4}$ in the relative production rates between Cygnets and prompt electron neutrinos coming from charm.

Next, we must take account of flux factors. Because of the long path (910 m) between the beam dump and the target, the beam of neutrinos and Cygnets is much wider than the detector. The Cygnets come from decays of X's, and these are produced at higher transverse momentum 5 GeV than the charm quarks (1 GeV). The typical longitudinal momentum should be comparable, so the flux of Cygnets is multiplied by an extra factor of $1/5^2 = 1/25$, relative to the neutrinos.

The typical energy of both the Cygnets and the prompt neutrinos from charm (which has essentially the identical production mechanism) should be about 50 GeV or less. The cross section for interactions of Cygnets is then 1 nb from (12), while the neutral current neutrino cross section is around $2 \times 10^{-39}\,\text{cm}^2(E/1\,\text{GeV}) = 10^{-4}\,\text{nb}$. Thus the Cygnet interaction cross section is higher by a factor 10^4. This argument is of course very crude and sensitive to the details of the production processes. If the produced Cygnet energy is typically lower than above, the limits from accelerator experiments are much weaker. In the same vein, if we make the X or X' mass a bit larger, the limits are also weaker. The limits from the 400 GeV data are very sensitive to the mass, because we are so close to threshold for X-X' production.

Overall, the Cygnet to neutral current event rate is therefore $10^{-4} \times 0.04 \times 10^4 \approx .04$. The prediction for the neutral current rate without any new (non-charm) physics is not known with great precision, so that there should not be too much trouble accommodating an even higher Cygnet fraction, since the Cygnet interactions should not have any obvious distinguishing characteristics.

The rate just deduced is for the parameters given in (13). Let us now put in the overall factors C_I, C_P and α_C. This gives (for $m_{X'} = 5.4\,\text{GeV}$)

$$\frac{\text{Rate(Cygnet interactions)}}{\text{Rate(NC interactions)}} = .02\, C_P\, C_I\, \alpha_C/\alpha_s. \tag{14}$$

We will later need to increase α_C to give large enough cross section for the cosmic ray experiments. Since the cross sections are very sensitive to $m_{X'}$, we will be able to accommodate this increase without overwhelming the beam dump experiment by slightly increasing $m_{X'}$. The cross sections at higher energy are much less sensitive to $m_{X'}$, because the threshold factors become inoperative.

The important features in satisfying the constraint from the beam dump experiment with a very modest value of $m_{X'}$ are: the suppression of gluon distributions at large x and the flux factor from the higher transverse momentum. (In addition to these there is of course the wholly expected decrease of the hard scattering cross section with increase in $m_{X'}$.)

7.2 800 GeV Beam Dump Experiments

One experiment that we know of, E605,[21] has performed a beam dump experiment with the 800 GeV beam at the Fermilab Tevatron accelerator. This experiment is basically a Drell-Yan experiment, so the geometry is rather different to the 400 GeV beam dump experiments: The detector is much closer to the beam dump.

The statistics are low. The data is still being analyzed. In principle, this experiment may provide the most stringent limit on Cygnets since the production cross section is higher at 800 GeV, and since the production of energetic neutrinos from pion decays is no longer present.

7.3 Limits from Neutrino Experiments

In addition to limits arising from beam dump experiments, there are also possible constraints arising from neutrino experiments. As an example of the kinds of limits which arise in these experiments, consider the Fermilab beam neutrino experiment E616.[22] Here a neutrino beam is produced by bombarding about 5×10^{18} 400 GeV protons on a target which is about a proton interaction length thick. Neutrinos typically arise from π and K decays, which decay in flight. We shall later address the data from the 800 GeV run.

If there are Cygnets and X and X' particles, thete may be an observable flux of Cygnets at the target. To estimate the number of Cygnet induced events, we need the flux of Cygnets at the target. To compute this flux, we assume that the angular spread of the Cygnets is large compared to the target size. Recall, that the typical angular spread should be of order p_T/p_L. At Fermilab energies, we expect $p_L \sim 50\,\mathrm{GeV}$, and $p_T \sim 5\,\mathrm{GeV}$, so that the opening angle for produced Cygnet is about .1 rad. On the other hand, the distance to the target is 1300 m, and the Cygnets are spread over a transverse size of about 130 m which is large compared to the transverse dimensions of the target.

Under these conditions, the flux of Cygnets is

$$\Phi = 5 \times 10^{18} \frac{\sigma_{pp \to C}}{\sigma_{\mathrm{tot}}} \frac{1}{\pi (1300\,\mathrm{m})^2 \Theta^2} \tag{15}$$

where Θ is the opening angle for the Cygnets. We find therefore a total number of Cygnet induced events in the 500 ton detector of

$$N = 50 \frac{\sigma_{pp \to C}}{1\,\mathrm{nb}} \frac{\sigma_C}{1\,\mathrm{nb}} \left(\frac{.1}{\Theta} \right)^2 \tag{16}$$

At 400 GeV, our parameters give $\Theta \sim 0.1$, a production cross section of 0.1 nb, and an interaction cross section of .2 nb. We find therefore of order 10 events. Most of these events look like neutral current events at this energy, and would be hard to distinguish from ordinary neutral current interactions. In the experiment 5×10^4 neutral current interactions are observed.

If there was a substantial branching ratio for X into muons, these events would probably be detectable. If we forbid this, then presumably the Cygnet interactions are buried in the noise of neutral current interactions. At higher energies, in order to explain the underground cosmic ray experiments, we will need to invoke muon production. This we shall do by arguing there may be a large cross section for associated charm particle production. At this low energy where we are just above threshold for production of the X and X', there presumably is not much phase space for production of associated charm pairs.

At 800 GeV, the production cross section has risen to 5 nb, and the interaction cross section is $\frac{1}{2}\,\mu$b. The angle is decreased by a factor of two, so that the overall enhancement is four orders of magnitude. On the other hand at 800 GeV, the number of bombarding protons is 5×10^{17} resulting in an order of magnitude decrease. We therefore expect of order 10^4 cygnet induced events, while the total number of neutrino events at this energy is 10^6. The number of ordinary events increases so rapidly at higher energy because the momentum cut on the decaying pions and kaons is much less restrictive. The Cygnet interactions with our choice of parameters may therefore be safely hidden. If required, we also could raise the Cygnet mass by a GeV or so, and reduce these near threshold cross sections substantially, without much affecting the high energy behavior. We conclude therefore that the Cygnet interactions at even 800 GeV can be safely hidden, in a normal neutrino experiment. However, they should be easy to see in a beam dump experiment at this energy.

7.4 $K \to \pi + C + C$ DECAY

One of the best ways to reject models of new light particles is to use the upper limit on the decay $K^+ \to \pi^+ +$ missing energy. The limit is [23] a fraction 1.4×10^{-7}. In our case the missing energy can be carried by two Cygnets. (Because of conservation of the quantum number carried by the Cygnet, the decay to a single Cygnet, $K \to \pi + C$, is forbidden.) The decay is possible if $m_C < 180\,\text{MeV}$ and can be generated by diagrams like fig. 3, where a loop of the heavy X and X' particles couples gluons to Cygnets.

The process is suppressed because of the high mass of the X and X'. We estimate the relation between the amplitudes for $K^+ \to \pi^+ CC$ and $K \to 3\pi$ by:

$$A(K^+ \to \pi CC) = \alpha_s \alpha_C \left(\frac{\mu}{m_X}\right)^n A(K^+ \to 3\pi), \qquad (17)$$

where μ is some characteristic hadronic scale around m_π or Λ_{QCD}, and with our choice of parameters, given in (23) below, $\alpha_C = 30\alpha_s$ and $M_{X'} = 6\,\text{GeV}$. The exponent n is for the large m behavior of the loop. We have omitted numerical factors and logarithms associated with the loops.

Suppose for a moment that $m_C \approx M_\pi \approx \mu$. Then for the branching ratio we obtain:

$$B(K^+ \to \pi CC) \ = \alpha_s^2 \alpha_C^2 \left(\frac{\mu}{m_X}\right)^{2n} B(K^+ \to 3\pi)$$

$$= 0.45 \left(\frac{140\,\mathrm{MeV}}{6\,\mathrm{GeV}}\right)^{2n} 8\%. \tag{18}$$

If m_C is nonzero, then the branching ratio is even smaller. Even when $n = 2$, the branching ratio is less than 1.4×10^{-7}. The typical numerical factor, $1/16\pi^2$, from the loop also works in our favor. Because of the Goldstone nature of the Cygnet and with appropriate spin-parity combinations for the X and X', the exponent n may be even larger, so that the branching ratio is even smaller.

Hence, at least for some specific models, we feel that we are safely protected against the limit on $K \to \pi +$missing energy. Nevertheless, if the experimental upper limit on this decay can be improved by two order of magnitude, then they may well be a problem for models of the type we are discussing.

7.5 New particles in Υ decays

The Υ might decay to Cygnets and to Xs. (The X' is probably too heavy to be a decay product.) There are two possibilities that have been experimentally tested. The first is the decay of the Υ to a pair of Cygnets, by a diagram such as fig. 4.

The $\Upsilon \to C + C$ decay contributes to the branching ratio for $\Upsilon \to$ missing energy, since Cs escape from normal detectors around e^+e^-rings. The current limit is BR($\Upsilon \to$ missing energy) $< 2.3\%$, from the ARGUS experiment [24]. In our models the branching ratio is much lower, since the diagram contains more than one loop that involves short distances (i.e., of order $1/m_b$ or $1/m_t$).

If $m_X \lesssim m_\Upsilon/2$, then the decay $\Upsilon \to g + g + X + \bar{X}$ is possible with rather soft gluons which then combine with the Xs, after which the Xs decay. The branching ratio should also be less than 1 %.

8 Air Showers and Underground Muon Experiments

In this section, we show how to make our model compatible with the data from air shower experiments and underground experiments.

As regards the air shower experiments, there must enough cross section for Cygnets of sufficiently high energy to interact in the atmosphere and produce hadronic showers. Our model is set up to do this easily. What we must also do is to simultaneously satisfy the constraints explained in the previous section that come from accelerator experiments that have not detected the Cygnet.

If there is sufficient cross section for the air shower data, the danger is that is an insufficient signal in the underground experiments: muons produced in the atmosphere will not penetrate to the detectors. This is the usual problem [3,6,4] in explaining the data from the underground experiments. However, with our model, the strong energy dependence of Cygnet cross sections means that lower energy Cygnets will typically not interact in the atmosphere. The lower energy goes in the direction of explaining the wider-than-expected angle of the muons detected in the underground experiments.

8.1 Cygnet interactions in atmosphere

With the parameters used above, the Cygnet-nucleon cross section (12) at a beam energy of 1 TeV is .2 μb, which is clearly too small for the data in cosmic ray experiments. Even at 1000 TeV, the cross section is only 9 μb. So we must tune the parameters. First of all, if we assume that the X and X' are color octets, then C_P and C_I are larger, perhaps 10 and 3 respectively. Next, we can increase α_C. This all results in a substantial increase in the cosmic ray cross section but also in the ratio of Cygnet events to ordinary neutral current events at the beam dump. We now find suitable values of the parameters.

Let R be the ratio of rates at the beam dump. Then

$$R = .02 C_P C_I \frac{\alpha_C}{\alpha_s} \left(\frac{5.4\,\mathrm{GeV}}{m_{X'}}\right)^8 U. \tag{19}$$

Here U is the ratio of the threshold factors to those with $m_{X'} = 5.4\,\mathrm{GeV}$. The variation in the QCD coupling with mass is negligible for our purposes. The factor U,

$$U = \left[\frac{1 - 3m'_X/28\,\mathrm{GeV}}{1 - 3 \times 5.4/28}\right]^{\beta} \left[\frac{1 - (1.5 m_{X'}/10\,\mathrm{GeV})^2}{1 - (1.5 \times 5.4/10)^2}\right]^{\beta/2}, \tag{20}$$

is very sensitive to $m_{X'}$. At 1 TeV we have

$$\sigma_{\mathrm{tot}}(\text{Cygnet-nucleon}) = .25\,\mu\mathrm{b}\; C_I \frac{\alpha_C}{\alpha_s} \left(\frac{5.4\,\mathrm{GeV}}{m_{X'}}\right)^3, \tag{21}$$

so that

$$R = .02\, \frac{\sigma_{\mathrm{tot}}(\text{Cyg-nucl})}{.25\,\mu\mathrm{b}}\, C_P \left(\frac{5.4\,\mathrm{GeV}}{m_{X'}}\right)^5 U. \tag{22}$$

Let us assume that $C_P = 10$, as seems appropriate, and require that the Cygnet-nucleon cross section at 1 TeV is 20 μb, as is appropriate for the underground cosmic ray experiments. If we ignore the variation of U with $m_{X'}$, then we would need $m_{X'} > 10\,\mathrm{GeV}$ to keep R below 1. However if we increase $m_{X'}$ to 6.5 GeV, then we get all the suppression we need at the beam dump.

We can now deduce from (19) that α_C/α_s is about 30. The Cygnet must be strongly coupled to the X and X'. This is at first sight unsettling. But if we postulate a new kind of strong interaction that is responsible for binding X-type particles and postulate that the Cygnet is a Goldstone particle for these new interactions, then the model may even be plausible: not only does it fit in with the required size of the Cygnet coupling, but it provides an explanation of the low mass of the Cygnet, which is to be regarded as a pion-like bound state of X-type particles. (Note that we have α_C around 2 and g_C around 4, and recall that the pion-nucleon coupling is around 10.) This strong interaction could be the

TQCD interaction referred to in the sect. 4. In any event, we have a set of numbers that are reasonable as regards cross sections.

We will therefore take the following set of parameters:

$$C_P = 10,\ C_I = 3,\ m_{X'} = 6.5\,\mathrm{GeV} \text{ and } \alpha_C = 30\alpha_s \tag{23}$$

to be our canonical set of parameters for the model.

For a beam energy of 1000 TeV, the Cygnet nucleon total cross section is then around 0.4 mb, which should be plenty.

8.2 Angular distribution in underground experiments

The cross section we have derived for the Cygnet-nucleon interaction is of the right order of magnitude to give the signal observed in the underground experiments, if the Cygnet energy is several TeV. However, we must be able to get enough muons out of the interactions and show how they can be given a sufficient angular spread. Now, the most common source of muons in hadronic interactions is the decay of ordinary hadrons. But in a solid material the hadrons reinteract before they decay, so we must get the underground muons from prompt production.

One obvious possibility is that the decays of the X include muons with a significant probability, since when Cygnets interact, they produce $X - X'$ pairs. (The X' decays to a Cygnet and an X.) Such muons would carry a large fraction, e.g., 0.1 or 0.2, of the beam energy. Thus they would easily be able to penetrate to the detector. Such muons would have a very small angle to the beam: If the transverse momentum of the muon is about 5 GeV, we get an angle of around $5\,\mathrm{GeV}/(E/5)$ radians. For a beam energy $E = 1\,\mathrm{TeV}$ this gives 25/1000 radians, about 1 degree. This angle is uncomfortably low. We can increase it only by decreasing the beam energy, but then we lose too much cross section.

Another possible mechanism is that the muons come from charm decays, rather than from X decays. There will be a much larger fraction of charm in Cygnet interactions than in normal hadronic interactions because we necessarily have a hard interaction with a virtuality of many GeV. Instead of being suppressed by the ratio of a hard scattering cross section to the total hadronic cross section, charm production is only suppressed by $(\alpha_s/\pi)^2$ times at least one logarithm, corresponding to the available rapidity range. Since the hard scattering will be in the extreme forward direction, the rapidity range is exceptionally large. The charm will carry a small fraction of the beam energy. If we say that the transverse momentum of the charm is increased by the existence of the hard scattering to about 2 GeV and that the beam energy is 1 TeV, then charm with a fraction .05 of the incident momentum will come out at an angle 2/50 radians, which may be sufficient. (There will be a range of rapidities of the charm, and therefore a range of angles. The muon in the charm decay keeps the angle of the charm particle, at high energy.)

9 Consequences for Accelerator Searches

Since we have no complete model for Cygnets and their heavy strongly interacting companions, it is difficult to give with precision a clear experimental signal. As we have noted, due to the rapid rise of the cross section for Cygnet interactions at fixed target energies, the best place to look seems to be in 800 GeV beam dump or neutrino experiments. The number of such events was estimated in previous sections, and there appears to be no lack of such events. For most purposes, these events look like neutral current interactions. The classic beam dump signal is an excess of such events over the expectation from the standard model.

There may be several features which allow one to disentangle these events from neutral current interactions. When a Cygnet interacts, a Cygnet of lower energy, and hence of reduced cross section, is an end product of the collision. This Cygnet might further interact downstream, and there would be double simultaneous neutral current events. If the heavy X particle is long lived, hadrons formed from it might also propagate fairly far downstream from the interaction. Due to its larger mass, it is presumably more penetrating than light mesons. The cross section for the interactions of these hadrons is presumably comparable to, but somewhat smaller than, the cross section for the interaction of ordinary hadrons.

If the X particle is long lived, it should be produced at some level in jets in high energy $p\bar{p}$ colliders, and in e^+e^- colliders. The threshold for this X particle production to turn on is rather high, and could only be looked for in the highest energy e^+e^- collider events, and at high p_T in hadron colliders. Its identification may be difficult if the X has decay modes which involve missing neutral energy. At some level, the Cygnet interactions will affect all perturbative QCD predictions, and sufficiently high precision experiments will be able to detect their effects.

The Cygnet might appear in either $\pi^0 \to$ nothing or rare kaon decay modes into missing neutral energy. This might be disallowed if the Cygnet were massive enough. Even for a small mass Cygnet, if the Cygnet is an approximate Goldstone boson, our estimates indicate the rates are below current published limits.

10 Production of Cygnets in X-ray binaries

In view of the uncertainties in both the nature of the production of a beam of any kind of very high energy particle at an X-ray binary, and in the detailed parameters of our models for Cygnet interactions, we have chosen not to attempt an explanation of the production of our Cygnets. In this section we will merely summarize some of our ideas on the subject.

The canonical model of production of a high energy beam of neutrinos and photons at Cygnus X-3 assumes that a beam of protons is dumped in the companion star. This could not be the case for Hercules X-1 where the observed periodicity reflects the rotational period of the compact X-ray source. In this case, the secondaries must be produced nearby the X-ray source, probably in an accretion disk. It is also fair to say that one cannot rule out the possibility that the beam at Cygnus X-3 is produced near to the compact X-ray source, and not in the companion star. Even if the beam of secondaries is produced in the companion star, the heating of the companion by the large energy deposition must surely strongly distort the companion star's dynamics.

The problems we face in making a beam of Cygnets are many fold. First, we must have a Cygnet flux larger or comparable to that of photons. We will assume the source of Cygnets is a secondary beam produced by dumping a primary beam into matter. We might evade this assumption if for example one might have long lived bound states of $X - X'$ particles with charged particles, for example $X - X'$ particles bound in nuclear fragments. In this case, the charged fragment is accelerated, and the X' particle decays in flight, producing some Cygnets. Such a scenario is difficult to realize however since we must forbid long lived bound states with quarks for compatibility with accelerator data. Therefore the only bound states allowed are with nuclei. If the lifetime of the X-particle is 10^{-4} to 10 m/c, then at this energy, the distance traveled is 10^2 to 10^7 m, and the bound X particle would have time to be accelerated before decaying. We must of course here invoke some as yet unknown mechanism for enriching the beam of hadrons with a component which contains $X - X'$ particles. Perhaps this might be possible if more massive particles were preferentially accelerated.

If we make the conventional assumption that the Cygnets arise as a secondary beam from primary interactions, we must decide whether the primary beam is protons, or more exotic particles. If it is a beam of $X - X'$ particles, then the previous analysis goes through as before. If it is a proton beam, we must deal with the problem that protons produce a large number of neutral pions which decay to photons. If the matter into which the beam dumps is thick for the penetration of photons, that is, it is a beam dump, this problem is solved. Further, at these energies, the distance a 10^4 TeV pion goes before weak decaying is of the order of 10^4 km, so that is not too difficult to imagine that the matter is in fact a beam dump as regards neutrino production. If these conditions are satisfied, there are two sources for the radiation from the X-ray source: neutrinos from charm production, and Cygnets. Asymptotically, the production cross section for charm is a factor of 50 larger than that for Cygnets with our parameters, and therefore, we believe the flux of Cygnets and the consequent flux of neutrinos does not present insurmountable problems.

The energy transfer to the beam dump is however enormous. In comparison with π_0s, only rarely is a Cygnet produced. This energy deposition must therefore strongly perturb the matter of the dump. In some way this energy must be recycled back into the X-ray source companion system. We lack any dynamical model of how this might occur.

Of course with a potentially new particle with its own interactions, much that is unexpected might happen. It might be conceivable that the Cygnet carries with it some U(1) charge, and ordinary matter is neutral under this U(1) charge. If it is possible to set up a strong, long range U(1) field at the source, it might be possible to pair produce and accelerate the Cygnets. While this idea is clearly extremely speculative, it does prove the point that without a more detailed understanding of the nature of the Cygnet and its friends, assuming it exists, not much can be said about Cygnet production.

We of course have no dynamical mechanism for generating the Cygnet beam, but it seems that it does not obviously violate any basic physical principles to generate this beam.

11 Conclusions

We have presented here a model for a particle which may explain the muon anomalies in high energy cosmic rays arriving from point sources. This model seems to be consistent with current results from accelerator experiments, and the particles it predicts are likely to be detectable in 800 GeV beam dump and neutrino experiments.

In our opinion, this model suffer from two drawbacks. First it is contrived not for reasons of aesthetics, but simply to try to squeeze between limits from accelerator experiments in order to attempt to explain accelerator experiments. Of course it would not be the first time that nature chose perhaps not the most aesthetic way to manifest itself.

The second drawback is that we have no credible model of the production of the Cygnet beam at the source. We have been able to show that our model does not violate any basic physics which might prevent its production. Nevertheless, the uncertainties in the astrophysics and the particle physics involved should allow us the necessary freedom to make an acceptable model. This we have not been able to do.

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List of Figures

Figure 1: Gluon fusion to make Cygnets

Figure 2: Cygnet-gluon fusion.

Figure 3: $K \rightarrow \pi + C + C$ decay.

Figure 4: $\Upsilon \rightarrow C + C$ decay.

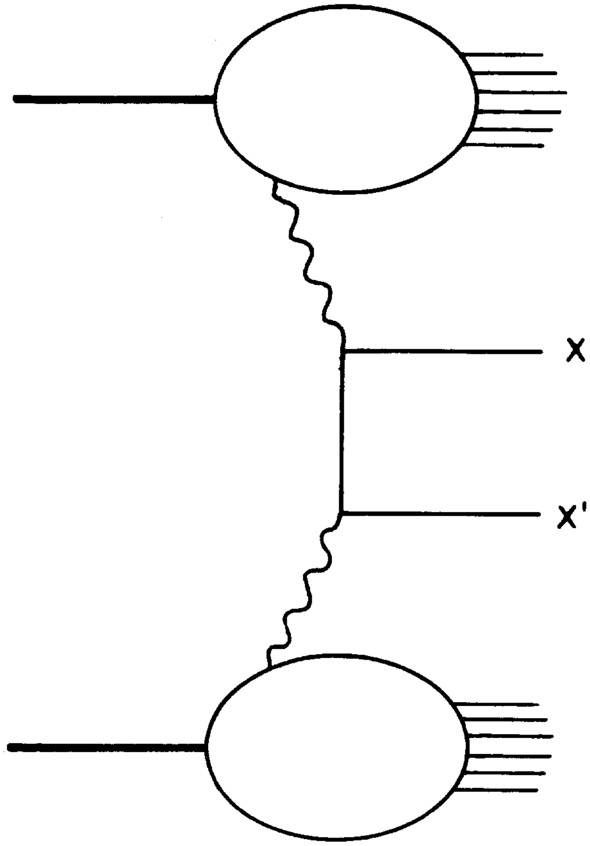

Fig. 1

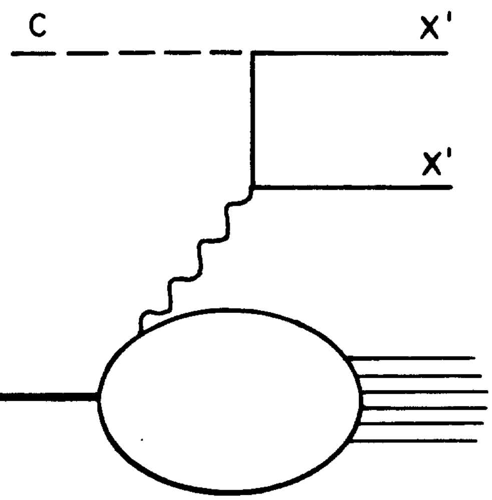

Fig. 2

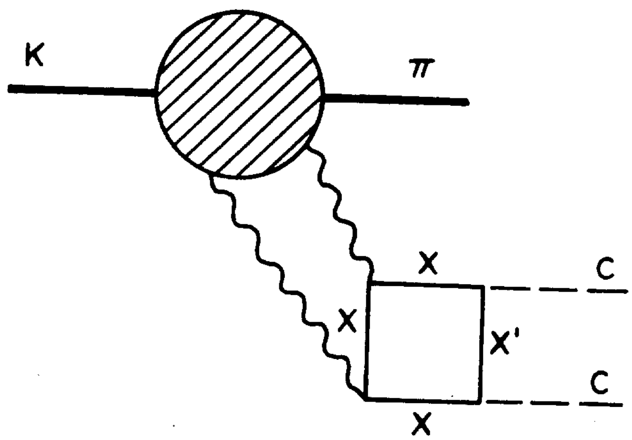

Fig. 3

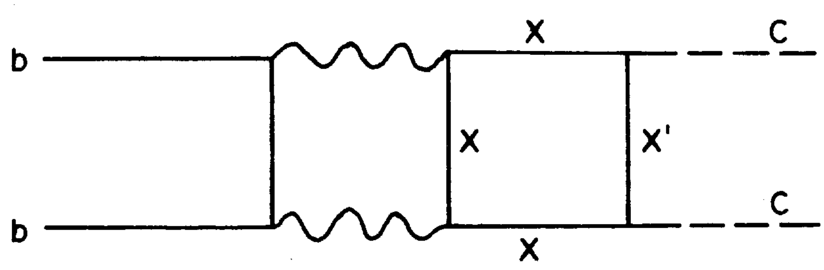

Fig. 4