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Cygnus X-3: A source of highly symmetric quark bound states?

J. E. Horvath and O. G. Benvenuto
Departamento de Física, Facultad de Ciencias Exactas, Universidad Nacional de La Plata,
Calle 49 y 115, Casilla de Correo 67, 1900 La Plata, Argentina
and Facultad de Ciencias Astronómicas y Geofisicas, Universidad Nacional de La Plata,
Paseo del Bosque s/n, 1900 La Plata, Argentina
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The point source Cygnus X-3 continues to show puzzling features related to underground modulated muon signals and also an excess of hadron groups recently reported. We propose that the neutral particle responsible for these unusual facts could be a highly symmetric bound QCD state (quark α) recently hypothesized. Interactions of these primaries with ordinary matter and astrophysical expectations are addressed and it is concluded that this proposal is in principle capable of providing some desirable ingredients for an explanation of the data.

I. INTRODUCTION

Since its discovery more than 20 years ago the astrophysical point source Cygnus X-3 has become an exceedingly interesting object to watch because of several challenging features revealed by successive studies. Not only is this system emitting enormous amounts of energy in radio, x rays, and γ rays[1] but recently puzzling observations of underground muons coming from Cygnus X-3 coordinates and having arrival times modulated with its 4.8-h orbital period have been reported.[2,3] These observations also report a broad angular spread in the signal which is about $10° \times 10°$ in the nucleon stability experiment (NUSEX) and $3° \times 3°$ in the Soudan one. The muons should have mean energies $\bar{E}_\mu \simeq 5$ and 0.65 TeV, respectively, for reaching these underground detectors. Although the very strength of these data has been questioned[4] these reports have been seriously considered by several authors[5-7] as evidence for a new particle triggering air showers with a high muon content. This is motivated by the very low chance of explaining the events in terms of conventional photon- or neutrino-induced air showers: while the former are thought to produce an absolute flux of muons 2 or 3 orders of magnitude below the reported one, the latter would require an incoming neutrino flux far above the actual occurrence (charged particles are ruled out because they cannot preserve the direction relative to the source as they are deviated by interstellar magnetic fields).

As the initial excitement was decreasing and the negative reports of other experimental groups[8] put severe doubt on the significance of the muon observations, another striking report came to complicate considerably the very confusing preexisting situation. The Erevan (USSR) group claims to see groups of hadrons coming from Cygnus X-3 with fluxes around 2×10^{-11} cm^{-2}sec^{-1} for groups having more than four, five, or six hadrons.[9] Remarkably the signal also shows a large angular spread of $\sim 10° \times 10°$ as in the case of the NUSEX report, although it has some other peculiar features that remain to be analyzed. They also assign large significance to the signal, even increasing with the multiplicity of hadrons and reaching 5.5 σ for $n \geq 6$ groups. Undoubtedly this observation calls again for a theoretical explanation of Cygnus X-3 incoming primaries. Let us briefly state the constraints imposed on the parent particle (hereafter designated as "cygnet" following the terminology of Ref. 6). As already mentioned, it must be neutral in order to be unaltered by magnetic bending. It also must have a lifetime $\tau > 10^{12}/\gamma_L$ (where γ_L is the Lorentz factor) necessary to make the $\sim$10-kpc journey to Earth, which forces an energy of $\sim 10^9$ GeV for a neutron to be the primary, making it unlikely as a candidate. In addition to these constraints the primaries must produce muons locally at a rather high rate and finally they must interact semistrongly with ordinary particles, otherwise NUSEX would see signals at much larger zenith angles.[4]

It can be further shown that if the cygnets are required to maintain the phase coherence observed in the signals one can get a lower bound on the Lorentz factor $\gamma_L = E_c/m_c > 10^4$, with E_c and m_c the energy and the mass of the cygnet, respectively. All these features make it difficult for an elementary particle already known to satisfy them simultaneously. In several attempts to explain the data glueballinos ($\tilde{G}$), photinos ($\tilde{\gamma}$), and free gluons (g) have been proposed (see Refs. 5 and 10), none of them being fully satisfactory.[11] Another class of candidates which are not truly elementary particles has also been suggested. They consist of stable or quasistable bits of matter with a high-strangeness content. Two specific candidates are strange-quark nuggets (an almost symmetric plasma bubble with the mass number of u, d, and s quarks[12,13]) investigated in Ref. 7, and the lowest-mass droplet of strange matter (the dihyperon H) proposed in Ref. 6. While the high strangeness per baryon has the desirable feature of yielding a large muon content because of the intermediate production of Λ's or K's with their subsequent decays, one still has to face some problems not easy to solve in order to explain the data. Regarding the quark nuggets, it is important to point out that they are thought to be charged[13] (which helps their acceleration) but a neutral beam should be supplied by whatever the production and emission mechanism would be, and it is more likely that they can be associated with other more spectacular events

(Centauros[14]) having a higher hadronic multiplicity. To our knowledge there is no clear reason for expecting different types of behavior in each case, although, as will be evident below, we believe that Centauros and Cygnus X-3 signals are certainly related. It also appears that the dihyperon H has a lifetime too short[15] to solve the puzzle, although this point is not still completely well established.

We would like to propose in this work another likely candidate which has several features that can potentially give a satisfactory explanation of the observed muon and multihadron events, and in addition arises consistently from a specific astrophysical scenario. This is the quark-α particle (Q_α) first proposed in Ref. 16, which we address in the following sections.

II. QUARK-α'S FROM CYGNUS X-3 AND THEIR ATMOSPHERIC INTERACTIONS

It is well known from conventional nuclear physics that binding energies are highly dependent on the symmetry of the state under consideration. This observation is the basis of the proposal of Michel who speculates that the most symmetric possible configuration in a shell model of "strange nuclear physics," with quarks u,d,s as fundamental entities, could lead to a tightly bound object referred to as the quark-α particle because it is evidently parallel with the ^{4}He nuclei. The wave function symmetric in color, spin, and flavor spaces contains eighteen quarks which build up a spin-0 chargeless boson having a mass ~ 5 GeV, that is to say, a large binding energy of ~ 100 MeV/baryon.[16] These features would make Q_α the most stable known particle, and the bulk strange matter should necessarily be metastable against the formation of Q_α's at low enough pressures or temperatures.[17]

In this sense we can expect that Q_α's can arrive at Earth as the final state of the high-energy process associated with strange-matter formation in the death of stars (see the next section). It is also a better candidate than H particles concerning its binding energy as we expect an absolutely stable object (if it exists at all). It is very important to note that, in fact, a relatively heavy particle such as Q_α can satisfy the constraint on the Lorentz factor γ_L because as it is built up of A baryon units (albeit possibly with different qualitative properties due to its peculiar binding structure) it will satisfy $AE_c/Am_c = \gamma_L > 10^4$. This means that muons are indeed fragments of a larger system breakup (see Ref. 18).

Let us consider the fate of an incident Q_α particle as it collides with normal matter penetrating the atmosphere. In the following, we refer all the calculations to the rest frame of Q_α. At typical incident energies the quarks inside Q_α will see the incident air nucleus contracted with a cross section $\sigma \simeq 2A^{2/3}10^{-25}$ cm^2, where the $A^{2/3}$ factor accounts for the shielding of the interior nucleons in the air. We take $A = 14$ as the typical component of the atmospheric gas (nitrogen). It is necessary to note that there exists an important dynamical reduction factor to σ coming from the following: For scattering to occur a quark should be given enough energy to reach at least the first excited state because the ground-state shell has all its quantum numbers saturated. In this higher state the energy of the quark will be of the order $E_r \sim 5.4/R$ (corresponding to the simple MIT bag model[19]), with R the radius of the Q_α estimated as ~ 1.7 fm.[17] If we denote by p the transferred impulse and k_0 the energy of the quark in the ground state, the reduction in σ is given by the factor

$$\Delta = \int \rho(k)\Theta(|\mathbf{p}+\mathbf{k}| - E_T)\delta(k-k_0)dk \Big/ \int \rho(k)dk \,, \tag{1}$$

where $\rho(k)$ is a suitable smoothed density of states for the bag. For a cavity containing massless fermions we have the expression[13]

$$\rho(k) = \frac{gVk^2}{2\pi^2} - \frac{g}{48}\int_S d\sigma \left[\frac{1}{R_1} - \frac{1}{R_2}\right] + \cdots \,, \tag{2}$$

with $g = 18$ as the degeneracy of the quarks, V the volume, S the area, and R_1,R_2 the local radii of curvature of the cavity (note the lack of a term proportional to S). In Eq. (1) the upper limits of the integrals are set by an energy scale E_M beyond which enough energy would have been given in the scattering to trigger the breakup of the Q_α. An estimate based on the energetics for Q_α decays, which would be preferably into 6Λ or $3H$ states, yields values of $E_M \sim 1$ GeV and thus $\Delta \simeq (k_0/E_M)^3 \simeq \frac{1}{64}$. We should then have a cross section $\sigma_{Q\text{-air}} \sim 1.7 \times 10^{-26}$cm^2 corresponding to a semistrong interaction. Note that the consistency with the multihadron production seen at the Erevan experiment requires $\sigma_{Q\text{-air}}$ to be $\gtrsim 3 \times 10^{-26}$cm^2,[9] contradicting previous estimations on upper bounds.[11] An interesting quantity to estimate is the mean number $\bar{n}$ of collisions for each Q_α-air interaction. According to the model of Ref. 20 this quantity is given by

$$\begin{aligned} \bar{n} &= 2\pi A^{2/3}\sigma_{Q\text{-air}}\rho_R \int_0^{R_A} 2r(R_A^2 - r^2)^{1/2} dr/\pi R_A^2 \\ &= \tfrac{4}{3} A^{2/3}\sigma_{Q\text{-}N}\rho_R R_A \,, \end{aligned} \tag{3}$$

where $\sigma_{Q\text{-}N}$ is the Q_α-nucleon cross section, ρ_R is the number density of particles inside the nucleus, and R_A the radius of the air nucleus. In addition to the multiplicative factor Δ we should also correct for an incomplete overlap factor in an average non-head-on collision which gives a factor of order $\frac{1}{5}$ for comparable sizes of the Q_α and the nucleus. Inserting appropriate values $\bar{n}$ turns out to be ~ 1.3 indicating that multiple scattering is unlikely in our problem.

We turn now to the problem of the Q_α breakup. When a collision is such that a quark is given an energy $|\mathbf{p}+\mathbf{k}_0| > E_M$ this will be enough to trigger the fragmentation of the Q_α. One can expect this to be the case in almost every collision due to the very high energies of the incoming projectiles. Although it would appear as if the dominating mode is $n + X + \pi^0$ (where X has the quantum numbers of 5Λ) this fragmentation would cost a lot of energy because the strange fragment would be uphill from the strangeness barrier,[16] so that it is not only a matter of paying the energy cost I of liberating one n (this is to be contrasted with the reaction $A+1+I\to A+n$ in bulk strange matter, where the remnant lump has A particles and it is also energetically preferred). The same argument holds for the reaction Q_α+energy$\to H+X'$, with X' having quantum numbers of a 4Λ state, and so on. This indicates that the dominant modes for Q_α fragmentation are Q_α+energy$\to 6\Lambda$ and Q_α+energy$\to 3H$. The $3H$ mode will dominate if the H particle is below the Λn threshold (although it has been argued to be above the nn state[15]). The dominant fragmentation chains would be

$$Q_\alpha+\text{energy}\begin{cases} 6\Lambda\to 6p+6\pi^-\to 6p+6\mu^-+6\nu\,, \\ 3H\to 3\Lambda+3n\to 3n+3p+3\pi^-\to 3n+3p+3\mu^-+3\nu\,, \end{cases}$$

where possibly kaons can also contribute in other chains not shown. The proposed chains have the nice feature that they lead to an important π^0 suppression, which is known to initiate electromagnetic cascades via $\pi^0\to\gamma\gamma$ incompatible with the observations as they would far outnumber the hadronic components (this suppression of π^0 should also be true for any other model of Cygnus X-3 events). Production of π^0 is contained in some decay chains (not shown above) which comprise *a priori* ~30% of the decays. Unfortunately, until detailed interactions of Q_α objects with nucleons are understood there is no hope of accounting for this feature properly.

Another puzzling feature of the data that should be explained by the theoretical picture is the angular spread of the signal, reported in Soudan, NUSEX, and Erevan experiments. Let us address the specific case of the muons detected at NUSEX because this experiment is well documented and has the largest angular spread.

There have been essentially three possibilities considered in the literature to explain the observed spread. These are direct muon production in the atmosphere by the reaction $c+n\to\mu+X$, muon production through secondaries with high $P_\perp$, and prompt muon production in the neighboring rock. From the physical features of the Q_α particle we can safely exclude prompt production because of the large $\sigma_{Q\text{-air}}$ (see also the criticisms of rock-produced muons in Ref. 1). Regarding atmospheric direct production we note that Q_α's increase somewhat the final angular spread quoted in Ref. 11 by a factor $(m_c/m_n)^{1/2}\sim 2.2$, which still falls short by a factor of ~2 to agree with NUSEX observations. Finally, if muon production through high-$P_\perp$ secondaries were taking place, this would require secondary particles with $P_\perp>350$ GeV, which is enormous for any hadronic interaction.[1] Unless Q_α-nucleon interactions are completely different from ordinary nucleus-nucleon collisions, it seems that such high values pose a serious constraint on this muon production mechanism. In this sense, our proposal has no great advantage to offer over some other works concerning a compelling explanation of the angular spread.

It might be useful to draw a parallel with other puzzling events which we believe to be closely related, as will be explained in the next section. The Centauro events[21] have been seen to yield a high multiplicity of baryons ~100 particles having a high average $P_\perp$ approximately five times the ordinary nucleon-induced one, and more importantly π^0 and e^- multiplicities consistent with zero. In our opinion Cygnus X-3 events are similar to Centauro ones but have smaller multiplicities and higher transverse momenta, features which can be related to the structure of the primaries. We turn now to address the problem of the origin of the primaries.

III. ASTROPHYSICAL SCENARIO

Independently of the specific Cygnus X-3 observations, any primary particle coming from a compact point source should have a reasonable expectation of being produced and accelerated if we observe it in terrestrial experiments. This in turn depends on the very nature of the source and environment, a point that deserves attention being as important as the detection themselves for guiding us to understand exotic new phenomena. Let us now examine the expectations for Q_α production and acceleration in the Cygnus X-3 system.

Cygnus X-3 is widely thought to be a binary system composed by a nondegenerate star of $M\sim 4M_\odot$ and a compact star (possibly a pulsar) companion with a 4.8-h orbital period. From this period observation we conclude that the distance between the two stars is approximately $d\sim 1.5\times 10^{11}$ cm. "Standard" formation arguments dictate that the compact object would have been formed after gravitational collapse of a massive progenitor star which exhausted its nuclear fuels, although another formation mechanism might be possible. We shall assume that a type-II supernova explosion indeed happened and the event did not disrupt the companion star, as seems to be required by the binary picture.

Which then is the expected connection between a supernova explosion and the presence of strange complexes? There exists a model of a type-II supernova explosion[22] based precisely on the appearance of bulk strange matter at high pressure during the early stages of the Kelvin-Helmholtz phase of a protoneutron star. In this picture the remnant is converted to strange matter entirely by the passage of a detonation wave fueled by $n\to uds$ decays at densities of approximately a few ρ_0 (where ρ_0 is the nuclear matter saturation density $\sim 2.4\times 10^{14}$ g cm^{-3}). This energy source is hypothesized to be the very cause of the observed explosions and preliminary calculations support the energetics outcome expectations.[22] The important point is that some ejection of strange matter seems to be *required* by the model[23] as a result of turbulent convective mixing with normal matter in the tail of the velocity distribution. The amount of ejected strange matter has been estimated to be $\sim 10^{-4}$–10^{-5} $M_{\odot}$ per event. The fragmentation of the strange fluid as it expands and cools will give rise to a spectrum of droplets which would be metastable against the production of Q_α and nuclear particles. However, the decay to these states need not be instantaneous. They obviously depend on the unknown dynamics of the processes strangelets $\rightarrow Q_\alpha +$anything. For example, substantial supercooling of the strangelets may occur with latent heat determined by the natural energy scale of the bag $B \simeq 60$ MeV fm^{-3}, which would retard them and leave us with ejected strange matter in bulk form floating around the system. This belief is reinforced by noting that strange matter is ejected with $v \sim v_{\rm escape}$ (Ref. 23) and could indeed be retained by the dynamics of the binary system.

We then picture a contamination of strangelets in the accreted matter onto the compact star. This object should have a net positive charge at this stage because (as its size is smaller than the electronic Compton wavelength) it can be easily ionized by the standard mechanisms. Strangelets can thus be accelerated by any mechanism that can accelerate accreting charged particles, as seems to be suggested by the near-Eddington luminosity measured in Cygnus X-3. Our scenario does not require accelerating strange matter stripped from the pulsar as in Refs. 6 and 24. The latter process is constrained by the Eddington limit and thus may need a complementary acceleration from accretion-powered sources.[24] The need of a homogeneous strange pulsar can be avoided in this proposal where all the primaries coming from the system could originate at the same accelerator. A very suitable specific acceleration mechanism is the disk dynamo of Chanmugam and Brecher,[25] but others can work as well.[26]

We turn now to the fate of accelerated strangelets. As in the models of Refs. 6 and 24 we believe that the beam accelerated away from the compact star will suffer substantial interactions in the atmosphere of the companion, as seems to be suggested by the correlation in phase at $\phi \sim 0.7$ measured in underground muon signals and x-ray eclipse. The picture (already discussed in Ref. 24) arising is the breakup of strangelets by high-energy collisions with free protons in this atmosphere. After the collision, the variety of strange fragments produced would quickly decay to metastable or stable states via weak and electromagnetic interactions. Q_α's would be a natural product of these interactions, and it is interesting to note that no flavor-changing decays are needed to form these bound states, so Q_α formation would render γ rays (but not neutrinos) coming from these processes that might be detectable under favorable circumstances. A flux of neutrinos coming from strangelet decays (before colliding in the atmosphere) and decays of unstable produced fragments could also be measurable, as discussed for example in Ref. 24.

Note that some small fraction of strangelets can avoid the decay and would seed the Galaxy with strange matter.[23] Strangelets striking the atmosphere would be observed as Centauros, although it is not possible to detect them coming from point sources because they are bent by interstellar magnetic fields. The acceleration and survival of strangelets might happen in isolated neutron stars accreting interstellar material contaminated by strange matter ejected in their own formation events. In this sense, the possibility of ejected strange matter could be an important ingredient to unify the picture of exotic primaries coming to Earth.

In summary, the report of the Erevan calorimeter together with the already existing evidence give support to the idea of a hadronic primary. While in principle it is not impossible to find some other solution to the puzzle, we believe that the Q_α hypothesis is a promising proposal to explore in view of the advantages given by the preexisting formation scenario, suitable physical characteristics, and the possibility of direct experimental detection with existing techniques.

We would like also to point out that, in addition to providing a nice candidate for Cygnus X-3 observations, Q_α's are expected to play a major role in pulsar structure[17] and possibly in the dark-matter problem as well.[16]

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[1] For a general review, see J. M. Bonnet-Bidau and G. Chardin, Phys. Rep. **170**, 302 (1988), and references therein.

[2] M. L. Marshak *et al.*, Phys. Rev. Lett. **54**, 2079 (1985).

[3] G. Battistoni *et al.*, Phys. Lett. **155B**, 465 (1985).

[4] J. Rich *et al.*, Phys. Rep. **151**, 241 (1987).

[5] K. Ruddick, Phys. Rev. Lett. **57**, 531 (1986); G. Auriemma, L. Maiani, and S. Petrarca, Phys. Lett. **164B**, 179 (1985); V. S. Berezinskii and B. L. Ioffe, Report No. IETP Nro. 127, Moscow, 1985 (unpublished).

[6] G. Baym, E. W. Kolb, L. McLerran, T. P. Walker, and R. L. Jaffe, Phys. Lett. **160B**, 181 (1985).

[7] M. V. Barnhill, T. K. Gaisser, T. Stanev, and F. Halzen, Nature (London) **317**, 409 (1985).

[8] Frejus Collaboration, in *Proceedings of the International Europhysics Conference on High Energy Physics*, Bari, Italy, 1985, edited by L. Nitti and G. Preparata (Laterza, Bari, 1985); Harvard-Purdue-Wisconsin Collaboration, *ibid.*

[9] V. V. Avakyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 235 (1988) [JETP Lett. **48**, 255 (1988)].

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

[11] V. S. Berezinskii, B. L. Ioffe, and J. Ellis, Yad. Fiz. **45**, 16 (1987) [Sov. J. Nucl. Phys. **45**, 8 (1987)].

[12] E. Witten, Phys. Rev. D **30**, 272 (1984).

[13] E. Farhi and R. L. Jaffee, Phys. Rev. D **30**, 2379 (1984).

[14] J. D. Bjorken and L. D. McLerran, Phys. Rev. D **20**, 2353 (1979).

[15] I. B. Kriplovich and E. V. Suryak, Report No. INP Nro. 85-

117, Novosibirsk, 1985 (unpublished).

[16] F. C. Michel, Phys. Rev. Lett. **60**, 677 (1988); Astrophys. J. Lett. **327**, L81 (1988).

[17] O. G. Benvenuto, J. E. Horvath, and H. Vucetich, Universidad Nacional de La Plata report, 1989 (unpublished).

[18] F. Halzen, Ann. N.Y. Acad. Sci. **490**, 237 (1987).

[19] A. Chodos, R. L. Jaffe, K. Johnson, C. Thorn, and V. Weisskopf, Phys. Rev. D **9**, 3471 (1974).

[20] G. F. Bertsch, in *Nuclear Physics with Heavy Ions and Mesons,* Proceedings of the Les Houches Summer School, Session XXX, edited by R. Balian, M. Rho, and G. Ripka (North-Holland, Amsterdam, 1978).

[21] T. K. Gaisser and G. B. Yodh, Annu. Rev. Nucl. Part. Sci. **30**, 475 (1980), and references therein.

[22] O. G. Benvenuto and J. E. Horvath, Phys. Rev. Lett. **63**, 716 (1989); Int. J. Mod. Phys. A **4**, 257 (1989).

[23] O. G. Benvenuto and J. E. Horvath, Mod. Phys. Lett. **4**, 1085 (1989); J. E. Horvath and O. G. Benvenuto, Phys. Lett. B **213**, 516 (1988).

[24] G. Shaw, G. Benford, and D. Silverman, Phys. Lett. **169B**, 275 (1986).

[25] G. Chanmugam and K. Brecher, Nature (London) **313**, 767 (1985).

[26] D. E. Nagle, T. K. Gaisser, and R. J. Protheroe, Annu. Rev. Nucl. Part. Sci. **38**, 609 (1988), and references therein.