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STRANGE QUARK MATTER FROM CYGNUS X-3

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ABSTRACT

We explore the possibility that the measured signals pointing at or toward the vicinity of Cygnus X-3 are produced by strange quark matter primaries. We show that for reasonable assumptions on the nature of the binary system the carrier signal can be nuggets of strange quark matter .

Photons with energies above 10^{15} eV have been observed through air showers pointing at the location of Cygnus X-3 and showing a period of 4.8 hour(1). A mechanism to account for this observation has been proposed by Eichler and Vestrand(2). Cygnus X-3 is assumed to be a binary system with a compact object pulsating with a period of 12 ms; charged particles (protons or nuclei) can be accelerated to $\sim 10^{17}$ eV giving rise to high energy interactions within the atmosphere of the companion star; neutral π's are produced and the subsequent decay can explain the high energy γ rays.

Underground experiments have recently reported muon signals with $E \sim 1$ TeV pointing towards the vicinity of Cygnus X-3 with the typical 4.8 hour phase(3) which are

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difficult to explain. The flux of γ's is insufficient to account for the underground muons due to the small photoproduction cross section. If the primaries are neutrinos (which will be produced in the decay of charged π's and K's with the same origin than the neutral ones), the number of μ's must grow with the zenithal angle (4). Experiments rule out this possibility; the μ's must be produced in the atmosphere or in the upper crust of the Earth.

The nature and properties of the signal carrier have been extensively discussed, speculating on the possibility that some form of stabilized quark matter constitutes the radiation from Cygnus X-3(5). Also it has been suggested that the primaries consist in doubly strange dihyperons, H, resulting from the stripping of strange quark matter with the atmosphere of the companion star(6). In this letter we study the possibility that the primaries are made by stable (or sufficiently long lived) neutral nuggets of strange quark matter.

Strange quark matter(7,8) consists of up, down and strange quarks in roughly equal proportion being stable for virtually any value of A. A defect in the strange quark content due to its greater mass, gives rise to a positive charge

$$Z \simeq 6 * A^{1/3} \tag{1}$$

in sharp contrast to $Z \simeq A/(1.98+0.015\ A^{2/3})$ of ordinary nuclei. The density estimate of this substance provides a value

$$\varrho \simeq 3.6 * 10^{14}\ \mathrm{gr\ cm}^{-3}$$

only somewhat larger from the density of usual nuclear matter. Ordinary quark matter is expected to exist in the high density interior of a neutron star. By changing its flavour composition via the weak interactions $u,d \rightarrow s$, ordinary quark matter can lower its Fermi energy, transforming itself into the most stable strange quark matter. In ref.(6) it has been studied the possibility that the remnant of a supernova explosion can be a strange quark star. In any case, the compact pulsar of the binary system Cygnus X-3 can be made, partially or totally, of strange quark matter.

We have studied the electronic properties of strange quark matter(9); as the strange quark matter is positively charged, in ordinary conditions it will be neutralized by electrons. The electron distribution, for atoms whose nucleus has been substituted by a strange ball, has been computed by the Thomas-Fermi statistical method. When the radius R of the strange quark nucleus is greater than $\sim 1\text{Å}$, the electrons move inside the nucleus like a plum-pudding; for $R \lesssim 10^{-2}$ Å practically all the electrons are outside the strange nugget, showing an atom-like structure; for the transition region $10^{-2}\ \text{Å} \lesssim R \lesssim 1\text{Å}$ the atmospheric electrons are partially inside and outside the nucleus.

Lumps of strange quark matter ejected from the neutron (or strange quark) star are ionized by high energy ambient photons in the system; this will happen if $R \lesssim 1\mathring{A}$ (*) The ionized nuggets, being charged, can be accelerated by the same mechanism that accelerate protons or ordinary nuclei.

Different mechanisms of acceleration of charged particles in the vicinity of a neutron star have been proposed(10). One of them use the presence of a Deutch wave associated with the variation of the magnetic dipole of the rotating pulsar to accelerate charged particles(11). By this mechanism, the maximum energy available is

$$E_{max} = 6*10^{14} A^{1/3} Z^{2/3} \left(\frac{Bs}{10^{12}G}\right)^{2/3} \left(\frac{P}{10ms}\right)^{-4/3} \ln\left(\frac{r_{max}}{r_i}\right)^{2/3} \text{ eV} \tag{2}$$

where r_i and r_{max} are the radii between which a particle is accelerated, A is the atomic number of the charged particle, Z is its charge, Bs is the surface magnetic field of the pulsar and P is its rotation period. The atom-like nuggets, once ionized, have a positive charge given by (1), so they will be accelerated to a maximum energy of the order

$$E \simeq 3 * 10^3 A^{5/9} \text{ TeV.} \tag{3}$$

An alternative mechanism is DC acceleration in the polar regions of the magnetosphere of the pulsar(12). The maximum potential drop is given by

$$\Phi_{max} = 7 * 10^{16} \left(\frac{Bs}{10^{12}G}\right) \left(\frac{P}{10ms}\right)^{-2} \left(\frac{R}{10km}\right)^3 \text{ V} \tag{4}$$

where R is the radius of the pulsar. The maximum energy available for an ionized nugget is, according to (1)

$$E \simeq 4 * 10^5 A^{1/3} \text{ TeV.} \tag{5}$$

because the radiation shows the 4.8 hour phase of the source, the γ factor of the nuggets must be greater than $\frac{1}{3} 10^5. \gamma (\simeq \frac{E}{M}) \gtrsim \frac{1}{3} 10^5$ assures us, that different signal carriers, with a dispersion of the energy at generation of the order of E, arrive at Earth with a time delay of 1/10 of the phase (the separation of the Earth from the

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(*) In fact, there will be a rearrangement of the electron distribution of the system, giving strange quark lumps partially ionized in the transition region 10^{-2} Å $\lesssim R \lesssim 1\mathring{A}$ Howerer this happens only if the typical time of reorganization of the electrons is less than the corresponding of ionization for usual photon densities surrounding a neutron star; our estimates show that this is not the case.

source being 10 Kpc). By (3) and (5), and by taking the mass of the nugget $M \simeq A$ GeV, the restriction in the γ factor implies that the nuggets baryon number must be less than a certain value for each of the two mechanisms of acceleration commented above; namely,

$$A \lesssim 10^{9/2} \qquad \text{(Deutch wave acceleration)} \qquad (6\text{-a})$$

$$A \lesssim 10^{6} \qquad \text{(D.C. acceleration)} \qquad (6\text{-b})$$

This means that only nuggets with baryon number restricted by (6-a,b) can give the observed phase. The maximum energy per quark will be $E(p.q.) \simeq 10^3 A^{-4/9}$ TeV (Deutch wave acceleration) and $E(p.q.) \simeq 10^5 A^{-2/3}$ TeV (D.C. acceleration). We must say that the above results are valid for $A \gtrsim 10^2$ when relation (1) applies; nuggets with $A \; 10^2$ show a positive charge less than $6 * A^{1/3}$(8).

The rigidity of strange quark nuggets satisfying (6) are by far less than 10^{12} GeV/c. This is the minimum value that prevents the charged nugget to disperse from both time and direction, traveling the 10 Kpc distance from Cygnus X-3, into the magnetic galactic field(5). Consequently, the nugget must be neutral.

Neutral nuggets can be produced when the original charged ones interact the atmosphere of the companion star. When a nugget interacts with the hadrons of the companion star atmosphere, it can be completely destroyed into ordinary matter, losing its original nature and yielding, therefore, nucleons, hyperons and dihyperons H. In addition, high energy photons and neutrinos, from pion and kaon decay, are produced. The H'^s are the only possible responsible for muon signal. It is also feasible that when interacting with the atmosphere, the nuggets do not lose their strange quark matter nature. Being the interaction deeply inelastic, when a nugget of strangeness S collides with a hadron, many π'^s and K'^s will be produced, remaining a nugget with strangeness $S' < S$; because of the conservation of the baryon number, this nugget will be unstable (i.e. being its strangeness reduced, the final strangeness will be less than approximately A/3 which is what makes strange quark matter stable); the unstable residual will explode or will be stabilized by evaporating baryon number in the form of nucleons. Again in this second case, only H'^s can give the correct signal. However, it seems more probable that for $A \gtrsim 10^3$, the interaction with the atmosphere results in a breakdown of the nugget, like a spallation process, with residual mesons and baryons. We will study with more detail this last possibility.

We know by (1) that the charge per nucleon of a strange ball is $Z/A \simeq 6 * A^{-2/3}$. A nugget of baryon number A, will suffer a number of quark-quark scatterings, breaking it succesively, and will leave the atmosphere of the companion star with a different baryon number A'. Because we are interested in neutral primaries, let us suppose the charge of the residual nugget is practically zero, so

$$A'(6*A^{-2/3}) \simeq 10^{-1}$$

that is, $A' \simeq A^{2/3}/60$ is the baryon number of a residual neutral nugget, the parent having a baryon number A. We need to know how many collisions a nugget of baryon number A must suffer in order that the residual nuggets have baryon number $A^{2/3}/60$ with a great probability of being neutral. Let us suppose that at each collision the strange ball breaks into two approximatelly equal parts. In fact this is possible: being the surface energy of a strange quark ball $E_s^i \sim 50\ A^{2/3}$ MeV, the energy needed to break it into two equal sized nuggets, with surface energy $E_s^f \sim 2\left[50(A/2)^{2/3}\right]$ MeV, is $\Delta E = E_s^i - E_s^f \simeq 50\ A^{2/3}$ MeV, that is 500 GeV for $A = 10^6$. Assuming this way of spallation, the number N_c of encounters quark-quark, that results in a neutral strange ball, will be

$$A/2^{N_c} \simeq A^{2/3}/60 \qquad (7)$$

which gives N_c between 8 and 12 for the interacting baryon numbers; we will take $N_c = 10$ to concrete.

Now we must look at the conditions of the atmosphere of the companion star that can give the appropriate residual nuggets (the neutral ones). The mean free path of a nugget of baryon number A will be

$$L \simeq (\sigma_T\ n)^{-1} \qquad (8)$$

where $\sigma_T \simeq \sigma_{qq}(3A)$; $\sigma_{qq} \simeq 13$ mb being the quark-quark cross section and n the number of hadrons per cm^3 in the atmosphere. Because we need a number of collisions of the order of ten, the distance the nugget must travel is

$$D \simeq N_c L \simeq 10^{-27}\ A^{-1}\ n^{-1}\ \text{cm} \qquad (9)$$

which will be of the order of the radius of the companion star $R \simeq 10^{11}$ cm. The appropriate number density of the atmosphere will be

$$n \simeq 10^{16}\ A^{-1}\ \text{cm}^{-3}. \qquad (10)$$

Normal values assigned at the density of the atmosphere of the companion star of Cygnus X-3 are around 10^{15} cm^{-3}(10,13) in the vicinity of the surface, decreasing exponentially with the height. It seems that there is a window in the eclipsing and anti eclipsing phase of the binary, which will allow the existence of neutral nuggets of strange quark matter leaving the atmosphere.

The stability of strange quark nuggets is a matter of controversy for small baryon number. Strict stability seems to hold for $A \gtrsim 100$ while for $A \gtrsim 10$ strange quark matter can be metastable. For $A \gtrsim 100$ strange matter is stable having a positive char ge $Z \simeq 6*A^{1/3}$. For small baryon number the charge will be smaller(8). Neutral nuggets with baryon number of a few tens can be stable or sufficiently long lived to reach the Earth. If the baryon number of the primaries is less than ten they will decay during their trip; depending on their mean life they can give the appropriate signal or give an additional contribution to the background. Between the strange quark matter primaries, the dihyperon A = S = 2, H, which seems to be stable(8), can play a significan role(6).

In this connection, a possible explanation of the Centauro-like events(14) deserves a special comment. If the compact component of Cygnus X-3 is a strange quark star it will emit fundamentally strange quark drops, the power of the pulsar being $L > 1.3*10^{39}$ erg $\sec^{-1}$(2). This flux can acount for the Centauro events which consist in a flux of $\sim 10^{-4}$ primaries per cm^2 per year with baryon number $\sim 10^3$ and with energy 1-10 TeV per baryon(7).

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