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IS CYGNUS X-3 STRANGE?

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ABSTRACT

We discuss the recently reported measurements of the properties of high energy cosmic rays arriving from the direction of the compact binary X-ray source Cygnus X-3. We argue that the source of these events may be a strange quark star, and that the primary which directly produces them is a low baryon number neutral hadron with multiple strangeness which is stable up to (at least) simultaneous double strangeness changing weak decays.

Recently, the Soudan 1 underground proton decay detector has reported[1] observations of high energy muons from the direction of the compact binary X-ray source Cygnus X-3 (2030 + 4047), with a distribution of arrival times apparently modulated with its 4.8 hour orbital period, P. Preliminary results from the NUSEX detector,[2] as well as previously reported measurements from the Kiel air shower array,[3] tend to confirm these observations. The zenith angle dependence of the Soudan events indicates that the muons are produced in air showers originating in the upper atmosphere or the upper crust of the earth $(1-10^3 m)$. Such muons must have an energy at least .6 TeV to penetrate rock and reach the Soudan detector. The data suggest that the initiating particle might be a neutral hadron, for reasons which we shall soon discuss. In this paper, we shall assume that the experimental observations are correct and explore an unconventional hadronic source for the muons. We suggest that the muons are produced by metastable neutral strange dibaryons originating from the condensed star in Cygnus X-3, argue that for this to be the case most probably the condensed star must be entirely composed of matter with large strangeness fraction, and describe how such a strange star might be produced in a supernova explosion. Strange quark droplets, either arriving in large baryon number globs[4] or producing a large neutrino flux at the star,[5] have been considered previously as sources of the high energy muons. For reasons described below, neither is satisfactory.

As several authors have already noted,[4] the observation that the absolute flux of muons at the Soudan detector, $7\times10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$, is comparable to that of air showers from Cygnus X-3 extrapolated into this energy range indicates that the initiating particle is unlikely to be either a photon or neutrino, if the photon or neutrino cascade by conventional processes. The flux of muons is two to three orders of magnitude too large to be produced by such air showers initiated by high energy gamma rays. On the other hand, the overall neutrino and gamma ray fluxes from Cygnus X-3 should be comparable at high energies, if they are both produced by high energy hadronic interactions. If the air showers are assumed to be initiated by photons, then the absolute neutrino flux at the Soudan detector should be below the limit of detectability.[6] If the muons are produced by neutrino interactions, which do not generally produce air showers, the zenith angle distribution of produced muons would differ from that observed. The inference, therefore, is that the most likely candidate for the initiating particle is a hadron, and in order for interstellar magnetic fields not to alter its direction relative to that of the source, the hadron must be neutral. We shall refer to this particle here at the "cygnet".

In order that the cygnet may arrive from Cygnus X-3 without a tremendous reduction in flux due to decays, the cygnet must have a lifetime greater than approximately $d/\gamma c$, where $d \sim 12.5$ kpc. [This lower limit might be violated by perhaps as much as a factor of two and still allow for a reasonable flux of cygnets, but much more reduction forces the production rate of cyngets at the source to be unrealistically large.] The energy threshold for muons in the Soudan detector is about .5 TeV, corresponding to cynget primary energy of 5 - 10 TeV, or to $\gamma \sim 5$ - 10 TeV$/m$, with m the mass of the cynget. The NUSEX threshold is roughly 5 - 10 higher. In the Soudan detector, the pulses appear in an interval of $\sim$ .3 units of phase and in order that the dispersion in travel times not smear out the observed orbital modulation of the signal, γ must be $> (d/.6Pc)^{1/2} \sim 10^4$. For NUSEX, the signal is in $\sim .1$ units of phase, and the corresponding limit on γ is $\sim 2\times10^4$. If the cygnet is long lived enough so decay in flight is not important, then these limits on γ bound the cygnet mass to be below 1-2 GeV and the lifetime to be greater than $\sim$ 10 yr. If, on the other hand, the cygnet lifetime is short enough to affect the pulse shape (slow cygnets, which would be out of time, decay in flight) then the cygnet mass could be greater and the lifetime shorter by a factor of order unity. These computations should also be corrected for the shape of the cosmic ray spectrum as a function of energy, which could lower the limit on the cygnet lifetime by factors of order unity. Careful observations of the pulse shape as a function of phase and of the detector threshold energy can give detailed information about the cynget mass and lifetime. For example, if cygnets are massive, they should be delayed relative to the radio, X-ray, and high energy γ signals. For a stable particle, the delay (*i.e.*, width) of the signal is determined only by the energy threshold of the detector and provides a measure of the mass of the cygnet.[4] If the cygnet is unstable, none will arrive with energy below $E_{\min} \approx md/c\tau$, and the pulse shape will be independent of threshold energy for low thresholds.

These considerations rule out the possibility that cygnets might be neutrons. For a neutron to arrive without decaying in flight, it must have $\gamma > 10^9$ corresponding to a primary energy 10^6 TeV. The neutron flux would have to be about 6 orders of magnitude larger than the flux expected for air shower initiating particles of the same energy, if the integral spectrum goes as $1/E$. The flux of high energy air showers from Cygnus X-3 has been studied for $E > 10^3$ TeV, and is consistent with an integral spectrum of $1/E$.

Let us now turn to the cygnet production mechanism. The observed 4.8 hr period of Cygnus X-3 has been identified with the orbital period of a binary system, thought to consist of a young pulsar and a $\sim 4M_{\odot}$ companion[7] possibly surrounded by a "cocoon" of diffuse matter. Vestrand and Eichler[7] have used these components to generate short pulses of $E > 1$ TeV radiation assuming the magnetosphere of the pulsar to be an efficient accelerator of charged particles[8] which then collide with the atomosphere of the comparison star. These hadronic interactions provide a source of high energy neutrinos and photons from π and K decays.[6,9] It is tempting to invoke this natural accelerator-target set-up of Cygnus X-3 to produce a flux of exotic cygnets which then produce the observed air showers and muons on earth. This mechanism fails because it requires too large a hadronic production cross section for cygnets, σ_c. The flux of neutrinos compared to the flux of cygnets should scale like σ_π/σ_c where σ_π is the production cross section for pions

$$N_{\nu_\mu}/N_c \sim \sigma_\pi/\sigma_c \quad . \tag{1}$$

On earth, this translates into the rate of of neutrino initiated muon events in an IMB-type detector compared to the rate of air showers,

$$\frac{\Gamma(\mu)}{\Gamma\ (\text{air showers})} \sim \frac{\sigma_\pi}{\sigma_c} \quad . \tag{2}$$

If the neutrino flux equalled the air shower flux it would produce 1 high energy muon event per year per 400 m^2 in an IMB type detector.[6,10] Since no flux of high energy neutrino produced muons associated with Cygnus X-3 has been seen in IMB[11], it is safe to conclude $\sigma_\pi/\sigma_c < 10^2$. Such a production cross section for a metastable particle of mass of order 1 GeV is sufficiently large that it is difficult to imagine that it would not have been detected in accelerator experiments. For example, at least particle-antiparticle bound states should appear in the inclusive photon decays of the ψ and Υ. It is, nevertheless, conceivable that such a neutral hadron might be produced and not detected, but in the remainder of this paper, we shall assume that this is not the case.

We propose instead that cygnets or rather their charged "parents" are already present in the flux of particles accelerated away from its surface of the pulsar. Since the time-modulated muon flux is comparable to that of electromagnetic showers, a large fraction of the high energy beam particles emerging from the pulsar must be parents of cygnets.

We picture then the cygnets originating as components of charged hadrons and being stripped by the interactions of such complexes with surrounding matter. The correlation in phase of the modulated muon events with the eclipsing seen in the X-ray (at phase ~ 0.7) suggests that the stripping occurs in the stellar atmosphere of the companion, rather than in the cocoon. The stripping process is expected to be similar to a high-energy nucleus-hadron collision (where the hadron is in the atmosphere of the companion),which efficiently fragments the nucleus.[12] A variety of nuclear fragments should be produced by the stripping. After production, weak single beta-decay processes and electromagnetic transitions should quickly return fragments to states which are stable or metastable. For example, if objects of zero charge are produced, which are unstable to single beta decay, the resulting charged particles will be produced quickly after stripping and bent in galactic magnetic fields. They would not follow a straight line trajectory to earth. Cygnets must be neutral and stable except for simultaneous multiple beta decays into states of the same baryon number but different charge.

If the parents of cygnets are already present in the flux leaving the neutron star then they must be present in some form in the neutron star itself or be created by surface bombardment by counter-accelerated particles in the high energy beam. The latter probably requires too large a production cross section to be consistent with laboratory data. It has long been suggested that neutron stars could be largely composed of strange quark matter.[13] If this is true, it suggests a natural candidate for the cygnet, namely the doubly strange dihyperon, H, first proposed in Reference [14].

The H has the quantum numbers of two lambdas, and is a tightly bound 6-quark state. Careful theoretical estimates of the mass of the H range from 2[15] to 2.24[16] GeV corresponding to binding energies of 230 to -10 MeV. The binding is special to the flavor $SU(3)$ singlet 6 quark state because its color-spin wavefunction is the most symmetric possible, thereby maximizing the attractive QCD hyperfine interaction. The binding is rather model independent, indeed the same state appears in topological models of baryons in QCD.[17] If $m_H < m_p + m_\Lambda$, then the particle can only decay by doubly weak processes, and can have a lifetime in the requisite range. Two reported observations of double hypernuclei in emulsion exposures to negative hyperon beams might seem to rule out a tightly bound H since the Λ's appear to undergo $\Lambda \to p\pi^-$ decays forbidden if $M_H < M_p + M_\Lambda$.[18] The interpretation of these experiments is, however, controversial and the dynamics of $\Lambda\Lambda \rightarrow H$ in a nucleus are not well-understood. A direct search for H production in $pp \rightarrow K^+K^+X$ did not have sufficient sensitivity.[19] [When the acceptance bracketed the threshold, continuum $\Lambda\Lambda$ production was not seen.] We regard the existence of a light dihyperon as an open issue. A recent proposal to look for it in $\Xi^- d$ capture ($\Xi^- d \rightarrow Hn$) should be given high priority.[20]

It has been proposed that strange quark matter exists in the core of the star and is somehow brought up to the surface.[5] We are unable to find any mechanism which efficiently transports matter from the core to the surface by diffusion, convention, or excavation. The other possibility, which we now explore, is that this exotic matter exists stably up to the stellar surface.[21] This scenario is based on the possibility that strange quark matter is absolutely stable, *i.e.* the energy per baryon of quark matter in equilibrium with the weak interactions, with strangeness per baryon f_s, is less than that of ordinary nuclear matter. Ordinary nuclei cannot decay into strange matter because conversion to stable quark matter would require a very high order weak interaction,[21–22] with a lifetime far in excess of the age of the universe. If strange matter is stable at all it is stable in bulk and for all baryon numbers above some $A_{\min}$.[22] $A_{\min}$ cannot be too small lest light nuclei decay by first or second order weak processes into strange matter. A strangelet (a droplet of strange matter of nuclear dimensions) with $A < A_{\min}$ would decay by sequential first order weak processes and by α particle and nucleon emission.

Strange matter must have positive electric charge on the quarks. Otherwise, without a Coulomb barrier, a single strangelet would rapidly gobble up all ordinary matter with which it come in contact.[22] For generic values of model parameters the Coulomb barrier of strange matter, while lower than that of ordinary matter, suffices to prevent strangelets from absorbing ordinary nuclei at ordinary steller temperatures. In particular, we have considered the effect that stable strange droplets might have on the companion star in the Cygnus X-3 system. It is necessary to take into account the $\sim$ 1 KeV temperatures in stellar cores and the droplet density dependence of the droplet-proton interaction rate. If each strange droplet accelerated from the neutron star produces a cygnet upon interaction with the companion and these cygnets are entirely responsible for the air shower flux, a droplet to proton ratio as large as 10^{-6} could be established in the companion's core over the 10^4 year it would take a system such as Cygnus X-3 to radiate a substantial fraction of a solar mass. [This is probably a gross overestimate, since most of the strangelets which arrive from the neutron star have small A and probably are unstable with weak interaction lifetimes.] At this concentration, strangelets with Coulomb barriers below $\sim$ 1.5 MeV would grow. It is unlikely that strangelets with so low a charge ($\sim$ 4 or 5) would be stable.[22] but in any event the Coulomb barrier of strange matter grows with A and saturates at $\sim$ 5 - 15 MeV,[23] high enough to prevent consumption of the core.

In this scenario, the lowest energy configuration of the star would contain strange matter out to its edge; the problem is to understand how the star could reach this state. Let us first look at the high density core. In the cases discussed,[21, 22] non-strange quark matter becomes stable relative to nuclear matter at some sufficiently high density, ρ_{crit}. If, in the formation of the neutron star during a supernova, the central density exceeded ρ_{crit}, then the core would form quark matter over strong interaction time scales and later relax to finite strangeness fraction via first order weak processes. These processes should be rapid ($\sim 10^{-10}$ sec, or longer, for strangeness-changing decays in dense matter) compared with deleptonization times for the supernova core, and so the rate at which the initially degenerate neutrinos leave the core determines the timescale for formation of a strange core. [Until the neutrinos have left, the matter is diffuse and not at sufficiently high density to rapidly form quark matter.] On the other hand, if the mean baryon densities reached are not above ρ_{crit}, a strange quark region can still form through fluctuations in the local density. Once formed, it would be absolutely stable and expand by converting the neighboring normal matter – either quark matter or neutrons – to strange quark matter. For example, if a neighboring neutron crosses the surface of the strange region, it would disassemble into its component quarks; an up or down quark would be converted to strange matter either by a direct semi-leptonic process or by purely hadronic weak interactions. Eventually, the entire core would be turned into a strange quark core. The conversion process releases an energy of order tens of MeV per baryon; however, because the core after deleptonization is bound with $\sim$ 100 MeV per baryon, the burning should not lead to explosive disassembly of the core.

After the core has been converted to strange quark matter, the strange matter begins to eat its way outward. At the interface between the strange matter and ordinary nuclear matter, ordinary matter is absorbed through the interface and is converted to quark matter, provided the matter encountered is sufficiently neutron rich, or if the temperature of the star remains sufficiently high that there are some particles in the nuclear matter with kinetic energies sufficient to overcome the Coulomb barrier of strange matter. As the strange quark matter burns its way outward, it may preheat the matter in front and generate enough particles with kinetic energies above the Coulomb barrier to maintain burning. Our estimates indicate that this is indeed possible.

Just inside the moving surface ("formation front") which divides the quark matter from the neutrons or nuclei, the quark matter must have finite strangeness fraction since non-strange quark matter is not bound. Because strangeness changing weak decays are relatively slow, non-strange quarks must diffuse away from the formation front. The time it takes to achieve the required strangeness fraction at the formation front limits the speed, V, at which it moves. If τ is the time scale for strangeness changing weak processes, then

$$X = V\tau \tag{3}$$

is the width of the region over which conversion to strange quark matter is accomplished. The chemical potential difference across the conversion region, equal to the binding energy of strange quark matter, $\Delta\phi$, sustains the diffusion of non-strange quarks away from the formation front. The problem is analogous to electrical conduction in a resistive medium. Taking the quarks to be relativistic ($v_q \approx 1$),

$$\frac{\Delta\phi}{X} = \frac{\Delta p}{\lambda/v_q} \sim \frac{P_f V}{\lambda} \tag{4}$$

Δp is the change in momentum due to scattering, p_f is the Fermi momentum ($\approx$ 300 MeV) and λ is the quark interaction mean free path. The quark mean free path is much longer than the typical particle separation (λ_0) because of Pauli blocking. Eliminating X in Eqs. (3) and (4) we obtain

$$V \sim \left\{\frac{\Delta\phi}{p_f}\right\}^{1/2} \left\{\frac{\lambda_0}{\tau}\right\}^{1/2} \left\{\frac{\lambda}{\lambda_0}\right\}^{1/2} . \tag{5}$$

Both d and s quarks participate in the drift. The problem is analogous to the calculation of the transport coefficients in liquid He-3.[24] The mean free path, is proportional to $(\sigma\rho)^{-1}$, where σ is the cross section, about 13 mb for quarks, and ρ is the density of matter from which the quarks may scatter. This matter is composed of those quarks which are at the Fermi surface, and $\rho \sim (T/\mu)$,[2] where μ is the quark Fermi energy, $\mu \sim p_f \sim 0.3$. Using $\lambda_0 \sim 1$ fm, (corresponding to baryon density $(125\ \mathrm{MeV})^3$), $\Delta\phi = 20$ MeV and $\tau \sim 10^{-5}$ sec, a typical time of $\Delta S = 1$ weak process at this energy scale, we find that

$$V \sim 10^{-5}\ \mathrm{cm/sec}\ (\mu/T) . \tag{6}$$

If the temperature during the time the burning takes place ranges from 0.1 to 1.0 MeV, the drift velocity ranges from $10^{-2} - 10^{-1}$ cm/sec, and the outer crust of the star would be reached in a time of a month to a year. In this time, the temperature would still be $\sim$ 100 KeV's, and there should be sufficiently large numbers of particles with energies above the Coulomb barrier to penetrate the interface between nuclear matter and quark matter. To see this, note that the interface travels a fermi in a time $\sim 10^{-12}$ sec, compared to $\sim 10^{-24}$ sec for light. A typical particle has $\sim 10^{12}$ chances to make it across the barrier, and even with exponential suppressions due to Boltzmann factors, there should be sufficient flux to maintain burning. In addition to the heat from the supernova explosion, preheating of the nuclear matter in front of the formation front should also help to maintain burning. We estimate that diffusion of electrons takes place with sufficient speed to precede the burning front, and to maintain a high enough temperature to that there are particles which can penetrate the Coulomb barrier. We should also note that as the burning front nears the surface, the typical particle separation in the nuclear matter increases, and the burning front should move more rapidly through this diffuse matter. As yet unstudied faster burning mechanisms such as detonation may also be important.[25] Although our naive estimates indicate that the star would burn in a month to a year, much smaller times of perhaps hours to minutes might be possible, and this problem deserves more careful study. After the star is born, the cooling should proceed by the mechanism proposed by Iwamoto for the cooling of neutron stars with quark interiors.[26]

The structure of a strange quark star is remarkably different than that of an ordinary neutron star. The surface of an ordinary neutron star consists of nuclei in a Coulomb lattice. At greater depths, the nuclei become neutron rich and finally merge into uniform nuclear matter. Perhaps the neutron star contains a quark matter core. A strange quark star would have a sharp surface $\sim 10^3$ fermis thick, corresponding to a halo of electrons which surround the matter, followed by strange quark matter at a few time nuclear matter density. The matter is qualitatively similar all the way to the core, with a central density of perhaps 10 - 20 times that of nuclear matter.

It is essential for our scenario that quark matter be present all the way to the surface. If matter accreted gently onto the surface of the quark star from its companion, it would cover the surface with a crust of ordinary matter. We must assume this has not happened on Cygnus X-3. Since the accreting matter acquires an energy $\sim$ 100 MeV/nuclear from gravity and, if charged, is probably accelerated to much larger energies in the electric fields surrounding the star, it would appear to have enough energy to cross the Coulomb barrier at the surface. The heat generated this way may suffice to burn what ordinary matter may have gently accreted.

Accreting matter, if sufficiently energetic, will eject material from the quark star's surface. The matter emitted would consist of strangelets of relatively low baryon number (including H's) in addition to the expected mix of nucleons, hyperons, and mesons. Strangelets that are so light as to be unstable via strong interaction processes decay rapidly away. Those that are stable and many which decay weakly survive long enough to be accelerated outward, stripped in the atmosphere of the companion yielding nucleons, hyperons, and H's in addition to high energy photons and neutrinos (from meson decay). The strangelets which decay in flight from the surface of the strange quark star might provide a source of high energy neutrinos with a flux not constrained by the photon flux, and might be measurable.[5] Stable strangelets which miss the companion seed the galaxy with stable quark matter. Such matter, in the form of large baryon number globs, may be the source of Centauros[27,28] and explain a number of cosmic ray anomalies.[29] In addition, the stable quark matter produced in this manner by Cygnus X-3 like objects in the past would have seeded the solar nebula and led to a substantial terrestrial abundance of strange matter. To obtain a crude estimate of its abundance, we assume 1 - 10 Cygnus X-3 like objects active at any time in our galaxy. We suppose that a fraction X of the 10^{-5} $M_\odot$/yr accreting onto Cygnus X-3 is converted via the processes we have described into stable strangelets and are emitted. Over 10^{10} years, $10^5 - 10^6$ X $M_\odot$ of strange matter are spread through the galaxy giving a fractional abundance by mass of $10^{-(7-8)}X$ in population I stars such as the sun. X is hard to estimate, but even as low a fraction as 10^{-10} would be detectable using mass spectroscopy and $X > 10^{-4} - 10^{-5}$ would be observable using heavy ion activation methods.[23]

In order to relate the flux of cygnets to the flux of muons, the detailed properties of cygnet-hadron interactions much be understood. If the cygnet is an H particle, its interactions are similar to those of a proton with an energy equal to that of an H. The cross section for $H - p$ interactions is somewhere midway between that of a proton and that of a deuteron. The fractional energy loss for the H, so long as the H holds together should be roughly half that of a proton, since the mass is twice as large and the energy loss per collision should be about the same. After several interactions, the H particle might fall apart into two Λ's or protons and kaons. The Λ's and kaons are in the projectile fragmentation region, and should quick decay, generating fast muons. Kaons have shorter lifetimes and larger mean free paths than pions, and therefore, are more likely to product fast muons.

Estimates of the total flux of hadronic primaries necessary to produce muons at the rate seen by Soudan are about a factor of twenty larger than the flux observed in air showers extrapolated into this energy range. This presents a problem for our scenario. Because the H particles may shower somewhat differently than a proton primary (yielding more muons), this discrepancy may not be so severe. Also, since the flux from Cygnus X-3 may be variable, and the measurements were not made at the same time, and since the air shower measurements are not at exactly the same energy as the Soudan measurements, this discrepancy, which deserves more study, may not be as severe as first estimated.

There is a puzzling feature of the NUSEX data which is not explained by our proposal. The NUSEX detector sees the muon signal from a region many degrees on a side around Cygnus X-3. We have no mechanism for dispersing H particles over such a large angular range. This result seems difficult to explain by any mechanism since the NUSEX experiment sees a wider angular dispersion than Soudan, although it measures higher energy particles, so one would expect that the dispersion at Soudan would be larger. For example, if there was production of a new particle high in the atmosphere with high tranverse momentum, the spread at Soudan should be larger by a factor of about 5 - 10 compared to NUSEX since the energy of particles detected is lower by about this amount. Two plausible, although unattractive, explanations for the increased angular broadening would be either multiple muon scattering in the rock beyond that expected from multiple Coulomb scattering Monte-Carlo computations, or an improper determination of the detector orientation.

If as we have suggested, Cygnus X-3 is a strange quark star, the H particle as well as possibly strange quark matter for larger values of A might be made in the collisions of ultra-relativistic nuclei. In such collisions, matter at densities as large as those found in neutron stars are produced in regions of large spatial volume, and in rare events stable or metastable strange quark matter fragments might be formed.

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References

1. M. L. Marshak, J. Bartlet, H. Courant, K. Heller, T. Joyce, E. A. Petersson, K. Ruddick, M. Shupe, D. S. Ayres, J. Dawson, T. Fields, E. N. May, L. E. Price and K. Sivaprasad, *Phys. Rev. Lett.* **54**, 2079 (1985).
2. G. Battistoni, *et al.*, CERN Preprint, to be published in *Phys. Lett. B*, and NUSEX Collaboration, Talk presented at the 1st Symposium on Underground Physics, Saint Vincent, Italy, April (1985).
3. M. Samorski and W. Stamm, *Astrophys. J.* **268**, L17 (1983).
4. M. V. Barnhill, T. K. Gaisser, T. Stanev and F. Halzen, University of Wisconsin Preprint MAD/PH/243 (1985).
5. G. L. Shaw, G. Benford and D. J. Silverman, University of California at Irvine Preprint 85-14 (1985).
6. E. W. Kolb, M. S. Turner and T. P. Walker, Fermilab Preprint, (1985); T. Gaisser and T. Stanev, Bartol Preprint BA-85-12 (1985).
7. W. T. Vestrand and D. Eichler, *Ap. J.* **261**, 251 (1982).
8. M. A. Ruderman and P. G. Sutherland, *Ap. J.* **196**, 51 (1975).
9. F. W. Stecker, *Ap. J.* **228**, 919 (1979); V. J. Stenger, *Ap. J.* **284**, (1984).
10. K. Brecher and R. Chanmugan, Boston University Preprint (1985); G. Cocconi, CERN Preprint (1985); V. S. Berezinsky, C. Castognoli and P. Gabeotti, Instituto de Fisica Generale dell' Universita di Torino, Preprint (1985).
11. R. M. Bionta, Proceedings of the 5th Moriond Astrophysics Meeting (1985).
12. J. Finnet *et al.*, *Phys. Rev. Lett.* **49**, 1321 (1982).
13. G. Baym and S. A. Chin, *Nucl. Phys.* **A262**, 527 (1976); G. Chapline and M. Nauenberg, *Nature* **264**, 23 (1976); B. A. Freedman and L. D. McLerran, *Phys. Rev.* **D16**, 1169 (1976) and *Phys. Rev.* **D17**, 1109 (1978); K. Brecher, *Astrophys J.* **215**, 117 (1977); W. Fechner and P. Joss, *Nature* **274**, 347 (1978).

14. R. L. Jaffe, *Phys. Rev. Lett.* **38**, 195 (1977).

15. M. Soldate (unpublished).

16. K. F. Liu and C. W. Wong, *Phys. Lett.* **113B**, 1 (1982).

17. A. P. Balachandran, A. Barducci, F. Lizzi, V. J. G. Rogers and A. Stern, *Phys. Rev. Lett.* **52**, 887 (1984); R. L. Jaffe and C. Korpa, MIT Print MIT-CTP-1233 (1985); C. Nappi and S. Yost, Princeton University Preprint Print-85-0278.

18. M. Danysz, *et al.*, *Nucl. Phys.* **49**, 121 (1963); *Phys. Lett.* **11**, 29 (1963); see also J. Prowse, *Phys. Lett.* **17**, 782 (1966) for the report of the double hypernucleus ${}_{\Lambda\Lambda}{}^{6}He$.

19. A. S. Carroll, *et al.*, *Phys. Rev. Lett.* **41**, 777, 1002(E) (1978).

20. P. D. Barnes and G. Franklin, Brookhaven proposal (1985), unpublished.

21. E. Witten, *Phys. Rev.* **D30**, 272 (1984).

22. R. L. Jaffe and E. Farhi, *Phys. Rev.* **D30**, 2379 (1984).

23. E. Farhi and R. L. Jaffe, MIT Preprint MIT-CTP-1276, June 1985.

24. G. Baym and C. Pethick, in *The Physics of Liquid and Solid Helium*, K. H. Bennemann and J. B. Ketterson, eds., (Wiley-Interscience, New York, 1978).

25. M. Gyulassy, K. Kajantie, H. Kurki-Suonio and L. McLerran, *Nucl. Phys.* **B237**, 477 (1984).

26. N. Iwamoto, *Phys. Rev.* **D28**, 2353 (1983); *Phys. Rev. Lett.* **44**, 1637 (1980).

27. J. D. Bjorken and L. D. McLerran, *Phys. Rev.* **D20**, 2353 (1979); S. A. Chin and A. Kerman, *Phys. Rev. Lett.* **43**, 1292 (1979); A. K. Mann and H. Primakoff, *Phys. Rev.* **D22**, 1115 (1980); F. Halzen and H. C. Liu, *Phys. Rev. Lett.* **48**, 771 (1982), *Phys. Rev.* **D25**, 1842 (1982); J. Elbert and T. Stanev, University of Utah Preprint UU-HEP82/4 (1984).

28. C. M. G. Lattes, Y. Fujimoto and S. Hasegawa, *Phys. Rept.* **65**, 151 (1980).

29. H. C. Liu and G. Shaw, *Phys. Rev.* **D30**, 1137 (1985).