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PROPOSED TEST OF A STRANGE MATTER PULSAR BY OBSERVATION OF THE NEUTRINO FLUX FROM CYGNUS X-3

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High energy γ 's observed from Cygnus X-3 have been explained by assuming that protons emitted by a pulsar are accelerated to 10^{17} eV in its polar field and then collide with the atmosphere of its companion star. Recognizing that ν 's are produced by this mechanism the IMB and other experimental groups are currently searching for them. It is shown how the hypothesis of the pulsar being strange matter might be tested by observation of the ν flux. Metastable strange droplets stripped from the pulsar (and accelerated) by electrodynamic fields yield ν 's, by decay and by collisions with the companion's atmosphere, with qualitatively different details than those produced by the proton collisions. Further, searching is suggested for ν 's produced by this decay mechanism from nearby pulsars with *no* companion in future, large detectors. The decays may be rapid enough to see the pulsar frequency in the neutrino signal.

Considerable theoretical interest [1–7] has focused on the intriguing possibility that not only may high-density multi-quark droplets (S droplets) with large strangeness be very long-lived, [3] but large bodies of strange matter (S matter) might be *absolutely stable*. Roughly, neglecting the strange-quark mass, the number of strange quarks n_s should be $\approx A$, the baryon number, since $n_s = n_u = n_d$ in order to lower the Fermi energies of the u and d quarks. Recently, Witten [5] suggested that not only might some neutron stars have strange matter in their cores but that one might imagine a star entirely made of S matter so that there is essentially *no* crust. The possibility of having S matter being the lowest state of extended, large A matter at nuclear density and *zero pressure* is truly exciting and of enormous importance. QCD calculations would need to be accurate to $\sim 1\%$ in order to make a definitive prediction. Thus experimental tests are crucial. Parallel to these ideas have been the very exciting results connected with Cygnus X-3: Ultra high energy (UHE) γ 's (up to 10^{16} eV) have been observed [8,9] ^{#1}. Cygnus X-3 has been understood [10–12], fig. 1, to be a pulsar revolving about a large (~ 4 solar mass)

companion star in a 4.8 h period. The UHE γ spectrum and phase peaks have been explained [10–12] ^{#2} by assuming that protons emitted by the pulsar are accelerated up to 10^{17} eV (in the electric field produced by the pulsar's corotating magnetic field) and then strike the atmosphere of the companion to produce γ 's. It is generally recognized that ν 's are also produced by this mechanism and the IMB proton decay collaboration and others are currently searching for them. Very recently, three of the proton decay groups [14–16] have reported (preliminary) observation of secondary shower muons from Cyg X-3 (phase locked to the 4.8 h period) which are not from neutrinos and have no conventional explanation.

This note points out how the hypothesis of a pulsar being mostly S matter may be tested by observation of the details of the ν events in present and future detectors. Metastable S droplets stripped from the pulsar (and accelerated) by electrodynamic fields yield ν 's by decay, and by collisions with the companion's atmosphere. This additional (extremely efficient) source of ν 's has *qualitatively* different features than those produced in the proton collisions. After completion

^{#1} See the list of references in the article of Samorski and Stamm [8] for the lower energy photon data from Cyg X-3.

^{#2} See fig. 2 of ref. [12] for an asymmetrical version of the atmosphere in the binary system.

Fig. 1. Following fig. 2 of Vestrand and Eichler [10], a schematic figure of how the UHE γ 's are generated from Cyg X-3. The pulsar, denoted by an emitting object orbits (4.8 h) in the outer circle. The lined region is the atmosphere [12] of the companion star which is denoted by the shaded region. The X ray minimum occurs at C and the narrow UHE γ bursts occur at phases when the pulsar is between A and B and between D and E. The high energy protons emitted by the pulsar produce π^0 's, decaying to γ 's in the atmosphere. In the optically thin regions AB and DE, the γ 's can emerge. In the model of Kolb, Turner and Walker [13], $\pi^\pm$, $K^\pm$ produced in the atmosphere by the protons decay to ν_μ 's, which then emerge through the companion from A to E (except for those ν with energy > 1 TeV which are absorbed and have a dip near region C). Our proposed S droplets from the pulsar, in addition to producing ν_μ 's by this collision process from A to E, will also produce mainly $\bar{\nu}$'s by S droplet decay from E to A.

of this work, two papers [17,18] appeared which explain the anomalous μ events [14–16] from Cyg X-3 on the basis of S droplet formation and breakup (in a very specific manner). These papers are complementary to ours. From our point of view of emphasizing neutrino detection to infer a strange matter pulsar, perhaps an even better situation than Cyg X-3 would be to search for ν 's from nearby, fast pulsars with *no* companion. Here no ν 's would be produced by collisions of accelerated particles with an atmosphere; they must come from the decay of the stripped and accelerated S droplets. Correlating the arrival time of such events (in large future detectors such as DUMAND) with the very accurately measured fraction of a sec-

ond period of the pulsar should distinguish any signal from background events. Since the dominant decay of the strange quarks in the S droplets will involve the emission of $\bar{\nu}_e$, observation of the details of the ν flux (μ and e production) from these companionless pulsars would give *very* accurate limits on ν oscillations in addition to *strong* evidence for the strange matter composition of pulsars.

Calculations to explain the energy dependence and phase (see fig. 1) of the UHE γ 's from Cyg X-3 proceed [10–12] by assuming that protons are emitted from the magnetic polar cap of the pulsar. Electrically driven flow from the polar cap, along the magnetic field of a pulsar has been studied in detail for some years ^{#3}. There is however no consensus on the acceleration mechanism. Thus Eichler and Vestrano [11] consider two possibilities for acceleration of ions of mass Am_p and charge Ze : The maximum energy from a large amplitude Deutscher wave [20] is

$$E_{\max} \sim 10^{16} A^{1/3} Z^{2/3} B_{12} (10^3 P)^{-4/3} \times [\ln(R_B/R_L)] \text{ eV}, \quad (1)$$

where B_{12} is the surface magnetic field in units of 10^{12} G, P the period of the pulsar in s, and R_L and R_B radii of the light cylinder and the binary orbit. Alternately, [21–24] acceleration in the near zone in a gap (of height h in units of 10^6 cm) near the polar cap gives

$$E_{\max} \sim 10^{18} Z B_{12} (10^3 P)^{-5/2} h \text{ eV}. \quad (2)$$

Either mechanism can give energies $\sim 10^{17}$ eV for protons from Cyg X-3 if the pulsar has ms rotation period (*no* direct observation of P has been made) ^{#4}. Colli-

^{#3} See e.g. the review by Michel [19].

^{#4} Acceleration from accretion disk electrodynamics is also possible [25], and would operate *separately* from our mechanism. This would not extract S-matter from the pulsar, but it could supply the protons which yield the $\sim 10^{38}$ erg/s X-rays. Exceptionally close binaries like Cyg X-3 may not permit the classic accretion disk formation, however, so energy yield estimates from such pictures are at best qualitative. The ultimate energy source is probably accretion from the companion, which may well have spun up the pulsar to a ms period, as is suspected for the other ms pulsars [26]. Thus while these accretion disk processes may be present (and probably necessary for the complete picture), our acceleration picture, eqs. (1) and (2), is complementary and necessary for stripping the S droplets from Cyg X-3. No such accretion disk process is necessary for slower pulsars, and is clearly not present for pulsars not in binary systems.

sions of these protons with the atmosphere of the companion star produce π^0 's which decay rapidly to UHE γ 's. In the phase of the pulsar's 4.8 h rotation (see fig. 1) for which the γ 's passage through the atmosphere is $\sim 100 \text{ gm/cm}^2$ thick (so that protons produce π^0 's but the decay γ 's will not be absorbed) a narrow phase pulse of UHE γ 's will emerge.

Recently, detailed calculations [13,27] have been made of the ν_μ 's expected by a similar mechanism of $\pi^\pm$, $K^\pm$ produced in the companion's atmosphere by the interaction of the UHE protons from the pulsar. The calculated ν_μ flux and phase plot depend both on whether the $\pi^\pm$ and $K^\pm$ decay before interacting (in the high temperature atmosphere) and on the absorption of the ν 's in the central core of the companion star (see e.g. fig. 3 of Kolb, Turner and Walker [13]).

Now we turn to an alternative or second component of high energy ν 's from Cyg X-3 arising from the possibility that the neutron star is made essentially of S matter [5].

There is a positron-electron cascade over at least one magnetic pole; this is the plasma which produces coherent radio emission in pulsars, and may be related to the radio bursts seen by Molnar et al. [28]. Ion emission must accompany this cascade and is not prevented by it. Ion emission occurs from spiky peaks on the polar cap, about 1 mm to 1 cm high [22]. The parallel electric field concentrates on these peaks, lowering the effective work function well below the binding energy. S-matter present on a peak will be ejected along with protons. In addition, all locally self-consistent acceleration models demand that TeV electrons bombard the cap. This causes bremsstrahlung and pair creation showers in the crust, which can liberate S-matter clumps or S droplets without necessarily breaking them up. These S droplets would perhaps have $30 \lesssim A \lesssim 10^4$ with lifetimes $[3] \gtrsim 10^{-4} \text{ s}$.

A surface gap in charge density must exist and emit a current to supply the corotation charge. This outward flowing ion beam excavates matter at a rate [23]

$$F \approx 2 \times 10^{-3} A Z^{-1} B_{12} P^{-1} \text{ g cm}^{-2} \text{ s}^{-1} \quad (3)$$

from the gap. The cap radius is

$$R_c \approx 1.4 \times 10^4 R_6^{3/2} P^{-1/2} \text{ cm} \quad (4)$$

with the pulsar radius R_6 in units of 10^6 cm . The current flow will have oppositely charged species and thus the mass flow will exceed this estimate. The strong B

retards resupply of this matter, so any crust would be steadily broken up by TeV electrons and stripped. Thus S droplets would form a component in the ion beams which contribute to the global magnetospheric picture.

The charge ratio Z/A of the S droplets should be small compared to a nucleus since the strangeness ratio n_s/A of S matter would be ~ 1 . Further, the ratio Z/A of the droplets might vary not only from droplet to droplet, but also with time after the formation of an individual droplet. As described by Chin and Kerman [3]^{‡5}, the S droplet after formation (perhaps in an excited state) can be rapidly driven by several strong processes to $n_s/A \gtrsim 2$. At this point, the expected decay of the S droplet is by the weak quark decay

$$s \rightarrow u + e^- + \bar{\nu}_e. \quad (5)$$

Proper lifetimes $\gtrsim 10^{-4} \text{ s}$ are expected [3]. This is long enough for an S droplet to pass through the accelerating region above the pulsar surface to reach its full energy given by (1) or (2). These high energy S droplets will then have lifetimes $\gtrsim 1 \text{ s}$. Thus large fluxes of high energy, metastable S droplets may flow from the pulsar, although not as high in energy/ A as the 10^{17} eV protons needed to produce the observed UHE γ flux.

The crucial point of the speculative scenario is that these S droplets would produce ν 's with *qualitatively* different features from those made by the protons, as summarized in fig. 1. These include:

(a) ν 's during the *entire* period. Some are produced in the ACE region of the pulsar orbit by collision of S droplets with the atmosphere to make $\pi^\pm$ and $K^\pm$ which then decay to ν_μ 's. Others are produced in the EA portion of pulsar orbit from decay of metastable S droplets.

(b) $\bar{\nu}$'s during the unoccupied path EA. Since S droplets have large strangeness ratios $n_s/A > 1$, the decays will be preferentially via process (3) which emits $\bar{\nu}_e$. Although oscillations to $\bar{\nu}_\mu$ are possible (and would

^{‡5} We have carried out [29] detailed analyses of the decay of strange globules with parameters consistent with the hypothesis of stable strange quark matter in bulk [5] and unstable globules due to a surface energy. The parameters and formalism are consistent with those of Farhi and Jaffe [6]. At the end of the decay sequences we find for most sets of parameters a number of $\bar{\nu}_e/A \sim O(1)$.

test Δm_ν^2 to 10^{-16} eV² for 10 GeV ν 's) the major component of $\bar{\nu}_e$'s would persist. $\bar{\nu}_\mu$ will also be emitted during the chain of decays of an S droplet if $s \rightarrow u + \mu^- + \bar{\nu}_\mu$ is energetically allowed. We expect $\sim A$ $\bar{\nu}$'s from the sequential decay of a S droplet with baryon number A (and $n_s/A \gtrsim 1$). We envision that proton and neutron emission would be involved in the sequential decays of the S droplet in addition to (5).

Tests of these two features in the present and future proton decay and neutrino detection experiments should be feasible since they each have striking signatures. An excess of $\bar{\nu}$'s versus ν 's, as suggested in (b), could be detected through the use of large magnets to distinguish between μ^+ and μ^- . The prediction of a large component of $\bar{\nu}_e$'s is so striking an indicator of S droplets that future detectors should be instrumented so as to be able to observe them.

Now we examine a situation which might be better than Cyg X-3 for seeing evidence for a strange matter pulsar. The idea is to look for $\bar{\nu}_e$ fluxes from nearby young, fast pulsars which are *not* in binary systems. Thus no ν 's would be produced in the conventional collision scheme [13,27] and they would have to come from the decay of the (stripped and accelerated) S droplets. We show qualitatively that strange matter pulsars that are within a few hundred parsecs and that have periods $P \sim 0.1$ s will emit $\bar{\nu}$ fluxes that could be detected in future large detectors such as DUMAND [30].

Since $n_s/A \sim 1$, we expect $\sim A$ decay $\bar{\nu}_e$'s from each S droplet stripped from the pulsar. Thus from (3), a minimum ν flux at the pulsar cap is

$$F_c \sim 1.2 \times 10^{21} (AZ^{-1} B_{12} P^{-1}) \nu's \text{ cm}^{-2} \text{ s}^{-1}. \quad (6)$$

For pulsars with periods $\gtrsim 0.1$ s, a more realistic estimate than (1) or (2) for the maximum energy of each ion (coming from detailed consideration of the gap process) is [23]

$$E_{\max}/A \sim 1.5 \times 10^{12} Z A^{-1} R_6 (P B_{12})^{-1/7} \text{ eV}. \quad (7)$$

We will assume that each droplet reaches this maximum energy/ A and each ν has an energy $E_\nu \sim 1/9$ of this value (7). The flux of $\bar{\nu}$'s received at the earth from a pulsar at distance d (in cm) is

$$F_r = F_c \theta_p (10^6 R_6/d)^2, \quad (8)$$

where $\theta_p = (\text{pulse width}/P)$. Note the calculated θ_p , given by the opening angle of the cap [23]

$$\theta_c \sim 1.4 \times 10^{-2} (R_6/P)^{1/2} \quad (9)$$

are close to the observed values. Assuming a *large*, *fully* instrumented water detector (such as DUMAND), the number of expected $\bar{\nu}$ events in one year is

$$N_\nu \sim 1.7 P^{-1.5} B_{12} R_6^{3.5} d_p^{-2} V, \quad (10)$$

where V is the effective value of the detector in cubic kilometers and d_p is d in units of 10^2 pc. [We used a $\bar{\nu}N$ cross section of $3 \times 10^{-39} E_\nu$ (in GeV) cm².] Thus a signal of ~ 50 events in a year would be expected for a $P \sim 0.1$ s strange matter pulsar having "unit" values for the other parameters in (10). (There are several observed pulsars having roughly "unit" values for B_{12} , R_6 and d_p and $P \sim 0.1$ s. For example, PSR 0950+08 has $d_p \approx 100$ pc, $\theta_p = 0.4$ and $P = 0.25$ s.) This signal should be readily discernible from the background by correlating the timing of the events in the detector with the precisely known period of the pulsar.

Although (10) appears independent of the energy E_ν (and thus Z/A of the S droplets), there is a minimum ν_e energy for detectability which is purely dependent on the spacing between photomultipliers in the water. If we assume e.g. a heavily instrumented array for which an electron neutrino with $E_\gamma \gtrsim 6$ GeV can be detected, this implies a corresponding $|Z/A| \gtrsim 0.03$ for the droplets stripped off the pulsar and accelerated. Further restrictions are that the effective lifetime τ_s of an emitted S droplet (before it emits a considerable number of $\bar{\nu}$'s be (a) long enough to traverse the ~ 100 m gap for acceleration and (b) short enough so that the dispersion in arrival time of the ν 's from the pulsar is within $\theta_p \sim 0.02$ in order to use arrival time to reject background. We readily estimate that (a) and (b) require $10^{-7} < \tau_s < 1$ s.

Whereas the energy required to maintain this S droplet emission and acceleration for a ms pulsar is *very* large (see footnote 4) it is quite small for the $P \gtrsim 0.1$ s pulsar (which is *not* in a binary system). In fact, the energy expended in accelerating the S droplets in the polar cap is for the slow pulsar, $P \gtrsim 0.1$ s, [estimated from (3), (4) and (7)] a *negligible* fraction of the energy loss in the (observed) slowing down [31] of the pulsar due to the dipole radiation from rotating the B_{12} field [31]:

$$dE/dt \sim -10^{32} (B_{12})^2 P^{-4} \text{ ergs s}^{-1}. \quad (11)$$

This illustrates what an enormously efficient system a strange matter pulsar would be for producing a detectable pulsed $\bar{\nu}_e$ beam.

If indeed strange matter pulsars exist and can be detected by observation of the pulsed $\bar{\nu}_e$ beam, a *very* significant bonus follows: Since we expect the dominant composition of the ν beam to be $\bar{\nu}_e$, the separate measurement of μ and e events would present an extremely sensitive test of neutrino oscillations. Not only would the appearance of $\bar{\nu}_\mu$'s test Δm_ν^2 to $\sim 10^{-16} \text{ eV}^2$, but would simultaneously be sensitive to quite small mixing angles. Quantitative values would depend greatly on the volume and instrumentation of the detector. Note that the unit size detector $\sim \text{km}^3$ in (10) is ~ 30 times the presently planned array dimensions for DUMAND [30]. Also, the spacing of the optical sensors is planned to optimize ν_μ detection rather than ν_e . Clearly, if further developments [14–18] concerning Cyg X-3 point to the possible emission of strange droplets, then a larger, fully instrumented version of the presently planned DUMAND should be built.

We conclude these speculations by emphasizing the importance and relevance of searching for S droplets produced in the scheduled (1986) fixed-target high-energy heavy-ion accelerators at BNL and CERN, as proposed in fig. 1 of ref. [7]: Relativistic S droplets produced in the primary heavy-ion collisions pass through a spectrometer-trigger that both separates out and identifies (on-line) S droplets having $A > 10$ and small or negative Z/A , and then triggers counters surrounding a secondary target. The observation of multiple Λ 's emitted in the interaction of a S droplet in the secondary target would be a striking, readily identified signature.

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