QUARK NUGGETS, DARK MATTER AND PULSAR GLITCHES.

Jes Madsen
Institute of Astronomy
University of Aarhus
DK-8000 Aarhus C, Denmark.

ABSTRACT

Very tight constraints are put on the occurrence of stable lumps of quark matter (quark nuggets) in our Galaxy. Only nuggets heavier than 10^{15} grammes remain possible candidates for the dark matter. A suggestion for solving the solar neutrino problem is ruled out, and some restrictions are set on models trying to explain Centauro cosmic ray primaries or cygnets as quark nuggets. The existence of strange stars in binaries is questioned. The conclusions come from assuming that pulsar glitches can occur only in neutron stars, not in strange stars. As a consequence not a single quark nugget can have penetrated to the neutron drip region in a pulsar, and no quark nuggets can have been caught by the pulsar progenitor, since then the pulsar would have been converted to a strange star. This leads to limits on the galactic flux of quark nuggets many orders of magnitude better than limits from Earth-based detectors. The presentation is based on a recent publication[20], but unpublished results on the fate of nuggets during supernova explosions and during collisions with neutron stars are included as well.

I. PHYSICS AND ASTROPHYSICS OF QUARK NUGGETS

Quark matter composed of up, down and strange quarks in roughly equal proportions (*strange matter*) could be stable in bulk (i.e. stronger bound than ^{56}Fe) at zero temperature and pressure for significant ranges of strong interaction parameters and strange quark masses.[28),12)]

Quark nuggets (lumps of strange matter) could be the most bound state of baryonic matter for baryon number A in the range $10\text{-}100 \lesssim A \lesssim 2\times10^{57}$. Nuggets with masses above a few percent of a solar mass are significantly influenced by gravity and correspond to neutron stars - so called *strange stars*. Such objects could be the direct result of Type II supernova explosions, or be created by conversion of ordinary neutron stars. A Chandrasekhar-type instability limits A to be less than 2×10^{57}. Quark nuggets with $A \lesssim 10^{56}$ are bound by the strong interactions alone. Shell effects give a lower bound of order 10-100 on A for stable nuggets.

Nuggets where gravity is negligible have constant mass density throughout, typically of order $3.6\times10^{14}\,\mathrm{gcm^{-3}}$, and masses $m = A/6\times10^{23}\,\mathrm{g}$. The quark surface is well-defined and surrounded by an atmosphere of electrons. Nuggets with $A \lesssim 10^{15}$ have their outermost electrons in Bohr-like orbits out to a radius $\approx 10^{-8}\,\mathrm{cm}$, whereas larger nuggets with quark-radius exceeding this value have electrons up to 400 fermi above the quark surface.

Due to the extended electron atmosphere a typical nugget has a Coulomb barrier of order +10MeV at the quark surface, making it inert in low-energy collisions with ordinary matter, whereas free neutrons are efficiently absorbed and converted into quark matter.

The stability of strange matter is generally increased if a finite pressure is imposed, such as would be the case inside neutron stars/strange stars.[10)] On the other hand finite temperature effects tend to decrease the stability,[10),25)] so that even if strange matter is the most stable phase of baryonic matter at $T=0$, it may not be so at high temperatures. The details of stability as a function of temperature and pressure are even less secure than the situation at $T=0$. This is important since we shall in fact be looking at nuggets in hot environments such as the Big Bang and supernova-explosions. However as will be discussed in context later it is not only the overall thermodynamical stability of a nugget that matters, but also whether the lower energy state is accessible on the time-scales involved.

Quark nuggets have been looked for but not seen in laboratory-experiments.[9)] Very low-mass nuggets might appear as abnormally heavy isotopes of well-known elements. Another natural place to look is in ultrahigh energy heavy ion collisions, but it is not obvious that existing accelerators reach the interesting region, especially since the baryon number involved in collisions is low.

Instead it is interesting to look for extraterrestrial sources. Witten[28] suggested two astrophysical settings for quark nugget formation : The quark-hadron phase transition 10^{-5} seconds after the Big Bang, and the transformation of neutron stars into strange stars (with the possibility that strange star collisions may lead to further spreading).

Formation of quark nuggets during the quark-hadron phase transition in the early Universe could take place if neutrino cooling of regions in the quark phase was sufficiently fast compared to the transport of baryon number across the surface separating the quark phase from the hadron phase. Whether this is the case has been questioned by Applegate and Hogan[6], who prefer a less extreme scenario leading to full conversion of the quark phase, but with resulting inhomogeneities in the hadron phase and subsequent interesting consequences for Big Bang nucleosynthesis. In view of our present knowledge of QCD-physics it seems fair to leave all possibilities open and pursue the consequences of primordial quark nuggets further. (In particular since the nugget hypothesis is one of the few dark matter explanations that allows the relative amounts of dark matter and ordinary baryonic matter to be calculated - at least in principle. Witten found that the relative amounts might work out right).

The mass-spectrum of primordial nuggets (if they are created) is poorly constrained. Witten estimated a very tentative most likely range $10^{33}<A<10^{42}$. A reasonable upper bound is the mean baryon number within the horizon at the QCD-transition, $\approx 10^{49}$. A lower bound, $A \gtrsim 10^{20}\Omega_Q^3$, where Ω_Q is the present nugget density in units of the critical density, can be derived from Big Bang nucleosynthesis.[22] The efficiency of neutron absorption by nuggets means that many small nuggets present during nucleosynthesis could eat most neutrons, thus leaving no helium. A more thorough investigation of nucleosynthesis with nuggets is in progress.

Even if nuggets are created they do not necessarily survive until the present. Alcock and Farhi[1] argued that neutron and proton emission from the nugget surface at high temperatures would lead to evaporation of primordial nuggets with $A<10^{52}$-10^{55}. Madsen, Heiselberg and Riisager[21],[15] showed, that nuggets with $A \gtrsim 10^{46}$ survived the evaporation as a consequence of significant reductions in the emission rates due to u and d quark depletion in the surface layers (the emission rate is controlled by competition between kaon and nucleon emission). They also showed that much smaller nuggets might survive due to reabsorption of hadrons, but a detailed study of this process was not possible. Alcock and Olinto[4] have recently proposed that all primordial nuggets boil away in a manner that makes discussion of the surface evaporation irrelevant, unless the surface tension is rather high.

If nuggets survived from the Big Bang or were spread in our galaxy by secondary processes such as strange star collisions, there should be a potentially observable flux of nuggets hitting the Earth. De Rujula and Glashow[11] suggested "experiments" suitable for searching for these nuggets in the form of fast-moving meteors, special looking earthquakes, etchable tracks in ancient mica, etcetera. The only data actually investigated in their paper came from a negative search for tracks in ancient mica, and corresponded to a lower nugget flux limit of $8\times10^{-19}cm^{-2}s^{-1}sr^{-1}$, for nuggets with $A \gtrsim 1.4\times10^{14}$ (smaller nuggets are trapped in layers above the mica samples studied). For later comparisons it is useful to write this limit as an excluded region

$$1.4\times10^{14} \lesssim A \lesssim 8\times10^{23}\rho_{24}v_{250}, \tag{1}$$

where $v \equiv 250 kms^{-1} v_{250}$ and $\rho \equiv 10^{-24} gcm^{-3} \rho_{24}$ are the typical speeds and mass density of nuggets in the galactic halo. (The speed is given by the depth of the gravitational potential of our galaxy, whereas $\rho_{24} \approx 1$ corresponds to the density of dark matter.) In these units the number of nuggets hitting the Earth per cm^2 per second per steradian is $6.0\times10^5 A^{-1}\rho_{24}v_{250}$.

Later investigations utilizing cosmic ray-, proton decay-, and gravitational wave-detectors have improved these flux limits somewhat. The most stringent Earth-based flux-limits[24] are shown in Figure 1 as curves a, b, c, and d. It will be shown in the following, that a significant improvement of these limits can be achieved using much larger and longer-lived "detectors", namely radio pulsars and their progenitors.[20]

II. GLITCHING RADIO PULSARS - NEUTRON STARS, NOT STRANGE STARS

Because of the importance of gravity, strange stars with masses in the region of observed neutron star masses are hard to distinguish from ordinary neutron stars in terms of their radius or total moment of inertia.[28),14),2),3]

One important feature however seems to distinguish strange stars from neutron stars in a manner with observable consequences, and that is the distribution of the moment of inertia inside the star. Ordinary neutron stars older than a few months have a crust made of a crystal lattice or an ordered inhomogeneous medium reaching from the surface down to regions with density $2\times10^{14} gcm^{-3}$. This crust contains about 1% of the total moment of inertia. Strange stars in contrast can only support a crust with density below the neutron drip density

(4.3×10^{11} gcm^{-3}). This is because free neutrons would be absorbed and converted by the strange matter. Such a strange star crust contains at most 10^{-5} of the total moment of inertia. This is an upper bound, since the strange star may have no crust at all, depending on its prior evolution.

As pointed out by Alpar[5], and also partly by others[14),2], this difference in the moment of inertia stored in the crust of neutron stars and strange stars seems to pose significant difficulties for explaining the glitch-phenomenon observed in radio pulsars with models based on strange stars. Glitches are observed as a sudden speed-up in the rotation rate of pulsars. The fractional change in rotation rate Ω is $\Delta\Omega/\Omega\approx 10^{-6}$-$10^{-9}$, and the corresponding fractional change in the spin-down rate $\dot{\Omega}$ is of order $\Delta\dot{\Omega}/\dot{\Omega}\approx 10^{-2}$-$10^{-3}$. Regardless of the detailed model for the glitch phenomenon the jump in $\dot{\Omega}$ must involve the decoupling and recoupling of a component in the star containing a fraction $I_i/I\approx\Delta\dot{\Omega}/\dot{\Omega}\approx 10^{-2}$-$10^{-3}$ of the total moment of inertia. This role is played by the inner crust of an ordinary neutron star, but the crust around a strange star is much too small.

It therefore seems reasonable to conclude, that glitching pulsars must be ordinary neutron stars, not strange stars. Of course one might hope to invent a completely different model for strange star glitches[3], but with our present knowledge it does seem hard to circumvent the moment of inertia argument outlined above. We shall therefore assume that glitching pulsars are ordinary neutron stars.

If strange quark matter is stable, neutron stars can be converted to strange stars by a number of different mechanisms, such as pressure-induced transformation to uds-quark matter via ud-quark matter, sparking by high-energy neutrinos, or triggering due to the intrusion of a quark nugget.[2] As soon as a lump of strange matter comes in contact with free neutrons it starts converting them into strange matter. The burning of a neutron star into a strange star is therefore expected to take place on a rather small time-scale.[7),23] The transformation may even involve a detonation.[16]

Independent of whether the conversion takes place as a slow combustion or as a detonation the tlme-scale is sufficiently short, that any neutron star hit by a quark nugget capable of penetrating to the neutron drip region will quickly transform into a strange star. Furthermore, if the progenitor star during its lifetime has captured even a single nugget in its core, a strange star will result from the supernova explosion. The existence of glitching pulsars, that are neutron stars, not strange stars, can therefore be used to place limits on the flux of galactic quark nuggets.[20] To do this we shall first investigate the accretion rate and capture of quark nuggets hitting neutron stars and their progenitors.

III. STELLAR ACCRETION AND CAPTURE OF NUGGETS

For an infinite bath of positive energy nuggets with an isotropic, monoenergetic distribution function, the number accretion rate of nuggets onto the surface of a star of mass M and radius R is given by

$$F = 1.39\times10^{30}\mathrm{s}^{-1}A^{-1}\left[\frac{M}{M_\odot}\right]\left[\frac{R}{R_\odot}\right]\rho_{24}v_{250}^{-1}\left[1+0.164v_{250}^{2}\left[\frac{R}{R_\odot}\right]\left[\frac{M}{M_\odot}\right]^{-1}\right], \qquad (2)$$

where $M_\odot$ and $R_\odot$ denote the solar mass and radius.

For the Sun the second term in parenthesis (the geometrical term) contributes only slightly to the accretion rate, and the contribution is even less important for more massive stars and for compact objects like neutron stars. In the following we shall therefore only take the first term (gravitational) into account.

To convert a neutron star into strange matter a quark nugget should not only hit a supernova progenitor but also be caught in the core. Similarly, nuggets hitting a neutron star after its creation have to penetrate the outer layers and reach the neutron drip region. It is therefore important to consider the question of quark nuggets penetrating stars.

A nugget passing through matter will displace the matter in its path and suffer energy loss at a rate[11] $dE/dx=-\alpha\rho v^2$, where α is the effective surface area ($3\times10^{-16}\mathrm{cm}^2$ for nuggets with $A<10^{15}$ and $3\times10^{-26}A^{2/3}\mathrm{cm}^2$ for $A>10^{15}$ for interactions with charged matter; $3\times10^{-26}A^{2/3}\mathrm{cm}^2$ for all A for interactions with neutrons), ρ is the density of the medium, and v is the speed of the nugget. At low energies the displacement of matter takes place via elastic or quasi-elastic collisions due to the positive electrostatic potential at the quark-surface of the nugget.

If x denotes the (positive) distance below the stellar surface and ε is the structural energy density of possible crystalline material, the motion of the nugget is described by the equation :

$$m(x)v(x)\frac{dv(x)}{dx} = -\alpha(x)\rho(x)v^2(x) + \frac{GM(x)m(x)}{R^2(x)} - \varepsilon(x)\alpha(x) \qquad (3)$$

where R and M are the stellar radius and mass interior to that radius.

The first term on the right-hand-side of equation (3) describes the drag force due to removal of the mass $\alpha\rho dx$ encountered when moving the distance dx. The second term is gravity, and the third term is the structural resistance of an ionic lattice ($\varepsilon=0$ except in white dwarfs and neutron star crusts; in these systems it will be approximated by $\varepsilon(x)\approx n_i Z_i^2 e^2/a_i\approx 1\times10^{13}\mathrm{erg\,cm}^{-3}\rho^{4/3}Z_i^2A_i^{-4/3}$, where n_i and a_i denote number density and lattice spacing of ions with mass number A_i and charge Z_i).

The initial velocity $v(0)$ is mainly caused by gravitational acceleration of the nugget, $v(0) \approx (2GM/R)^{1/2}$. For the Sun $v(0) \approx 617 \mathrm{kms}^{-1}$, and it is higher for more massive main sequence stars and for compact objects. This means that nuggets to a good approximation can be assumed to move on radial trajectories. Nuggets hitting neutron stars are accelerated to kinetic energies of order 200 MeV per baryon, leading to inelastic collisions with ions (and of course with neutrons). We shall neglect relativistic corrections to the equations of motion, but will return to other consequences of the large impact energy later.

The solution of equation (3) is discussed elsewhere.[20] The important point here is that nuggets are stopped after sweeping up a mass comparable to their own. This happens for $A \leq A_{stop}$, where

$$A_{stop} = \begin{cases} 5.8 \times 10^{-6} D^3 & A \geq 10^{15} \\ 1.8 \times 10^8 D & A \leq 10^{15} \end{cases} \tag{4}$$

with column density $D \equiv \int_0^x \rho(x) dx$.

IV. CAPTURE IN PRE-SUPERNOVA STARS

The total column density encountered by a nugget moving the distance $2R$ on a radial orbit through a star described by a γ=4/3 polytrope is $5.0M/R^2$, so that $A_{stop} \simeq 5.0 \times 10^{31} (M/M_\odot)^3 (R/R_\odot)^{-6} \simeq 5.0 \times 10^{31} (M/M_\odot)^{-1.8}$, where the last equality comes from $R \sim M^{0.8}$ for upper main sequence stars. Nuggets with $A > A_{stop}$ pass unhindered through main sequence stars, whereas nuggets with $A \ll A_{stop}$ are effectively stopped and will settle near the center.

The Sun would in this way accrete $3.7 \times 10^{-20} \rho_{24} v_{250}^{-1} M_\odot$/year, or a total of $10^{-10} \rho_{24} v_{250}^{-1} M_\odot$ in its total lifetime on the main sequence. Very low-mass nuggets collected near the solar center in this manner might have an impact on the energy production,[17] but the effect is negligible unless the electrostatic barrier at the nugget surface is much smaller than expected, or unless very special circumstances allow nuggets to catalyze nuclear reactions.[26] It was originally suggested to study the impact of quark nuggets on solar structure and in particular on solar oscillations[19], but according to Thompson[27] the mass of a quark nugget core in the Sun must exceed 10^{-4}-$10^{-3} M_\odot$ before the dramatic change in the central gravitational potential of the Sun leads to observable consequences with the present quality of helioseismological data. This mass limit is orders of magnitude above the maximally accreted mass of nuggets in the solar lifetime, so solar oscillations are only capable of tracing a strange matter core (or neutron star) in the Sun in the rather unlikely case where the Sun formed by condensation around a pre-existing very massive nugget. The situation may improve if g-mode oscillations probing the central parts of the Sun are observed.

In any case the results of the present investigation rule out that the Sun has accreted any nuggets at all in its lifetime.

Conversion of a neutron star into a strange star will happen if even a single nugget is present near the stellar center at the time of neutron star formation. According to equation (2) a nugget has hit the star if $Ft>1$, or $A<A_1$, where

$$A_1 = 4.4\times10^{37}(t/\mathrm{years})(M/M_\odot)(R/R_\odot)\rho_{24}v_{250}^{-1}. \tag{5}$$

Approximating the main sequence lifetime of massive Population I stars by $t_{MS}(\mathrm{years})\approx 3.7\times10^{9}(M/M_\odot)^{-1.9}$, it follows that $A_{stop}\ll A_1$ for $\rho_\infty\gg\rho_{min}\approx 3.0\times10^{-40}\mathrm{gcm}^{-3}(M/M_\odot)^{-1.7}v_{250}$, so that A_{stop} is the relevant capture limit. For $\rho_\infty<\rho_{min}$ the capture limit is $A<A_1\approx 1.6\times10^{47}(M/M_\odot)^{-0.1}\rho_{24}v_{250}^{-1}$.

The total column density of a star increases when it leaves the main sequence, due to central density concentration. Immediately prior to a supernova explosion of Type II, the central region of a massive Population I star resembles a γ=4/3 white dwarf with $M_{cent}\approx 1.4M_\odot$ and $R_{cent}\approx 10^{-2}R_\odot$, corresponding to $A_{stop}\approx 10^{44}$. Since in this case $A_{stop}\gg A_1$, the neutron star will contain quark nuggets if nuggets with $A<A_1\approx 10^{35}\rho_{24}v_{250}^{-1}$ are present in our Galaxy. Nuggets with slightly higher baryon number may be caught between the main sequence phase and the explosion.

For the pre-supernova rates of nugget capture to be used for limiting the nugget flux, the nuggets must survive in the stellar core during the explosion, so that they are available for converting the nuclear matter to strange matter. As discussed in section I, quark nuggets in the early Universe may evaporate partially by emission of hadrons (mainly neutrons, protons and kaons) from a thin surface layer. A similar effect might be expected in the hot interior of a (proto-)neutron star during the initial stage of a supernova explosion. Temperatures may reach 10-30 MeV for a few seconds following core collapse, resulting in high surface emission rates of hadrons. Formation of a strange star would be prevented if nuggets could dissolve.

However due to the extreme density of the nucleon gas surrounding the nugget, no such evaporation takes place. On the contrary, net neutron absorption by the nugget is quickly initiated. To see this one may compare the rates of neutron emission, λ_{em}, and neutron absorption, λ_{abs}, per nugget in the neutron star. These rates are (for a non-degenerate gas)[21)]

$$\lambda_{em} = \frac{2m_n(kT)^2}{\pi\hbar^3} e^{(\mu_n - m_n)/kT} r^2 \tag{6}$$

$$\lambda_{abs} = n_n v_n 4\pi r^2 = \frac{\rho_n}{m_n}\left[\frac{kT}{2\pi m_n}\right]^{1/2} 4\pi r^2, \tag{7}$$

where m_n, v_n, ρ_n and n_n are the neutron mass, speed perpendicular to the nugget surface, mass density and number density respectively. The radius of the quark part of a nugget is r, and μ_n is the neutron chemical potential given as $\mu_n = \mu_u + 2\mu_d$, where μ_u and μ_d are the up and down quark chemical potentials in the nugget surface layer.

Thus the ratio of the rates is independent of r,

$$\frac{\lambda_{em}}{\lambda_{abs}} = \frac{m_n^{5/2}(kT)^{3/2}}{2^{1/2}\pi^{3/2}\rho_n\hbar^3} e^{(\mu_n - m_n)/kT}$$

$$= 7.94\times 10^{-3}\left[\frac{T}{\text{MeV}}\right]^{3/2}\left[\frac{10^{14}\text{gcm}^{-3}}{\rho_n}\right] e^{(\mu_n - m_n)/kT} \tag{8}$$

In the limit where the effective neutron binding energy, $I_n = m_n - \mu_n$, goes to zero one finds that $\lambda_{em} < \lambda_{abs}$ for $T \lesssim 40\text{MeV}$, assuming $\rho_n \gtrsim 2\times 10^{14}\text{gcm}^{-3}$. Thus nuggets present grow rather than evaporate.

In case of complete degeneracy the neutron absorption rate is increased relative to the non-degenerate rate by the factor $(3\pi^{1/2}/8)\left[\varepsilon_F/kT\right]^{1/2}$, where $\varepsilon_F \approx 30\text{MeV}\left[\rho_n/10^{14}\text{gcm}^{-3}\right]^{2/3}$ is the neutron Fermi-energy. At the same time the emission-rate of neutrons is decreased since the low-energy part of neutron phase space is occupied. The emission rate of protons is not influenced in the same amount by phase space blocking, so it is more relevant to compare the (non-degenerate) proton emission rate with the (degenerate) neutron absorption rate. In any case the conclusion is unchanged : Nuggets absorb nucleons faster than they are emitted, even at the high temperatures in proto-neutron stars.

Whether nuggets are stable at $T \approx 10\text{-}30\text{MeV}$, or whether it is energetically favorable to dissolve nuggets into a gas of hadrons, is another matter that depends on poorly constrained QCD-parameters. Studies of this question for bulk quark matter in weak equilibrium indicate, that stability is probably retained, assuming stability at T=0, P=0, especially at the high pressures present in neutron star interiors.[10)]

Thus it seems, that nuggets absorbed by a pre-supernova star are able to survive the heating of the stellar interior during the explosion.

V. CAPTURE IN NEUTRON STARS

A nugget capable of reaching layers in a neutron star with densities exceeding the neutron drip density ($4.3\times10^{11}\mathrm{gcm}^{-3}$) will convert the neutron star to a strange star. An upper bound to the baryon number of nuggets hitting a neutron star of age t is given by equation (5), but several events may hinder the nugget from ever reaching the free neutrons.

Neutron stars are too hot to build up a solid crust during the first few months of their lifetime. In this molten phase $\varepsilon=0$, and any nugget hitting the star and surviving the impact will convert it to strange matter. An upper bound to the baryon number of nuggets hitting the star in this phase of its life is $A<A_1\approx6.3\times10^{32}(t_m/\mathrm{years})(M/M_\odot)R_{10}\rho_{24}v_{250}^{-1}$, where t_m is the duration of the molten phase, and R_{10} is the neutron star radius in units of 10km. A lower bound on A stems from the stopping of small nuggets by the expanding supernova shell: $A_{min}=4.6\times10^{10}(M_{sh}/M_\odot)v_{250}^{-2}(t_m/\mathrm{years})^{-2}\approx10^{12}$.

Whether these nuggets can convert the neutron star into strange matter depends crucially on their ability to survive the collision with the neutron star. Due to the strong gravitational potential, nuggets reach the star with kinetic energies of order 200A MeV. Therefore the collisions with ions (and in deeper layers with neutrons) are inelastic. Ions easily penetrate the electrostatic barrier of a nugget, until the nugget has lost most of its kinetic energy. As $A_{stop}\gg A_1$ nuggets are stopped above the neutron drip layer, and they absorb a mass comparable to their initial mass during the stopping.

The absorption of ions destabilizes the nuggets in two ways. First the nuggets are significantly heated, which reduces their stability. Secondly ion absorption increases the amount of u and d quarks relative to s quarks, which also reduces the stability. A detailed study of the kinetics of such collisions has not been attempted, but consideration of the time-scales involved gives an impression of the physics involved.

Let us concentrate on large nuggets ($A>10^{15}$) hitting neutron stars with $R_{10}=M/M_\odot=1$. For these the stopping time-scale, t_{stop}, can be approximated as $t_{stop}\approx x_{stop}/v(0)\approx2.92\times10^{-12}\mathrm{s}A^{2/15}$. Quarks moving at the speed of light inside nuggets at temperature T can equilibrate the temperature across a nugget radius on the diffusion time-scale $t_{diff}\approx10^{-28}\mathrm{s}A^{2/3}T_{MeV}^2$. One notes that t_{diff} exceeds t_{stop} as long as $A>10^{31}T_{MeV}^{-15/4}$, which means that heat is distributed inefficiently through a large, hot nugget (t_{diff} is an increasing function of T because Pauli blocking prevents scattering at low temperatures).

The neutrino emissivity of strange matter is of order $2\times10^{31}T_{MeV}^6\mathrm{ergcm}^{-3}\mathrm{s}^{-1}$.[13] This cooling rate is much too low to remove the heat distributed in a nugget when the nugget loses 200AMeV of kinetic energy in a time t_{stop}.

A hot nugget emits hadrons, in particular neutrons, from the surface. With the emission rate λ_{em} given from equation (6) an estimate of the evaporation time of a nugget is $t_{em} = A/\lambda_{em} = 4.3\times 10^{-20}\mathrm{s}A^{1/3}T_{\mathrm{MeV}}^{-2}\exp(I_n/kT)$. For typical neutron star parameters t_{em} is small compared to t_{stop} as long as $A < 1.3\times 10^{39}T_{\mathrm{MeV}}^{10}\exp(-5I_n/kT)$. This comparison assumes isotropic emission from an isothermal nugget, but it seems clear, that significant evaporation will take place for nuggets in the mass-range likely to hit young neutron stars.

The most likely outcome of the inelastic collisions involved when nuggets are stopped in the outer layers of a neutron star is, that the nugget is severely damaged. It probably starts to disintegrate, beginning in the direction of motion. However since characteristic weak interaction time-scales are long compared to t_{stop} for $A \lesssim 10^{35}$-10^{40} a large number of s-quarks have to be incorporated in the fragments, so it is quite possible, that smaller lumps of strange matter are among the disintegration products.

Only a small fragment of a nugget has to survive in order to finally convert a molten neutron star, so it seems likely that the nugget flux limit derived for molten neutron stars is relevant in spite of (partial) disintegration.

The situation is more uncertain when it comes to neutron stars older than a few months. After the crust solidifies, it becomes difficult for a nugget to reach the region where free neutrons are available for conversion. The column density of the 5×10^{28}g solid crust above the neutron drip region is $D_{crust}\approx 4\times 10^{15}\mathrm{gcm}^{-2}$. Only nuggets with $A > A_{stop} \approx 4\times 10^{41}$ penetrate this outer crust freely. Smaller nuggets are slowed down and perhaps destroyed. Fragments will only be able to reach the neutron drip region if gravity exceeds lattice resistance for fragments surviving collision. This happens for $A_f > 2.5\times 10^{36}\varepsilon_{28}^{3}(M/M_\odot)^{-3}R_{10}^{6}$, where A_f is the baryon number of surviving nugget fragments. For neutron star age t this excludes nuggets with $10^{36} \lesssim A_f \leq A \lesssim 10^{33}(t/\mathrm{years})\rho_{24}v_{250}^{-1}$. For the glitching pulsars Crab and Vela we may use $t \approx 10^3$ and 10^4 years respectively. (The age of Vela has recently been questioned[8]). Strong glitches have been observed in the pulsar PSR0355+54, which has a characteristic age derived from its period and period derivative of 6×10^5 years.[18] Assuming the characteristic age to be a good measure of the true age, PSR0355+54 excludes the highest A-values. Higher values of A may be excluded if glitches are found in those millisecond pulsars, which are presumably old neutron stars spun up by accretion from a binary companion.

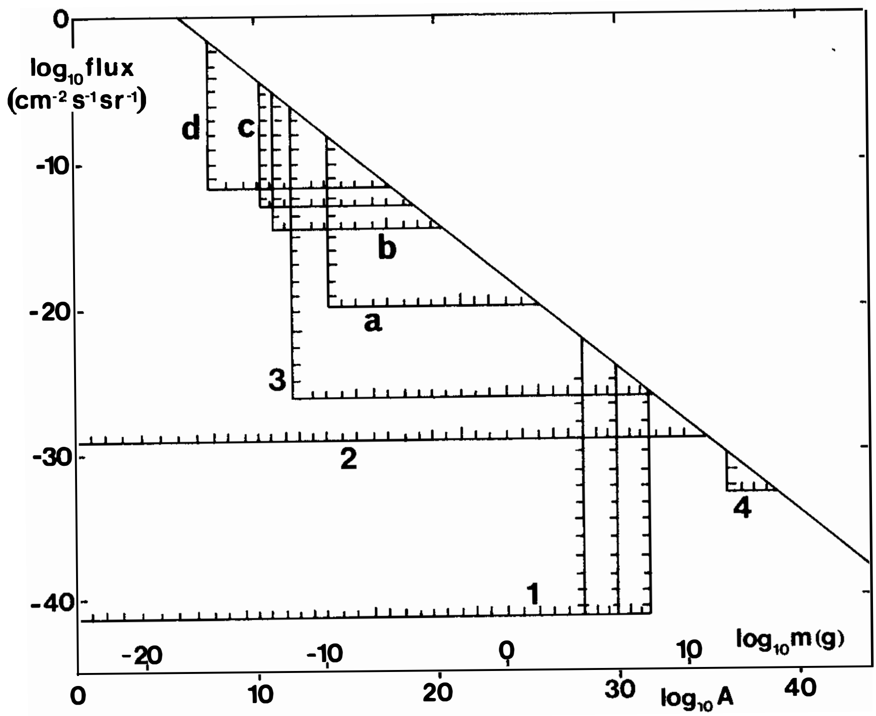

Figure 1 :

Limits on the flux of nuggets reaching the Earth as a function of nugget mass and baryon number. Regions on the hatched side of lines are excluded. Curves a, b, c, and d are the best Earth-based limits[24]. Curves 1 correspond to nugget capture in the main sequence phase of supernova progenitors with masses of 100, 10, and $1 M_{\odot}$. Curve 2 shows capture in supernova progenitors after the main sequence phase. The area surrounded by curve 3 is excluded by nugget capture during the molten neutron star phase, provided that just a tiny lump of strange matter survives the impact. Finally the region denoted by 4 is excluded by capture in the solid crust neutron star phase for the pulsar PSR0355+54, provided that nugget fragments with baryon number exceeding 10^{36} survive the impact. The diagonal curve is the upper flux limit corresponding to the galactic dark matter. Astrophysical limits are shown for $v_{250}=1$.

VI. CONCLUSIONS

Figure 1 illustrates limits on the flux of quark nuggets hitting the Earth (or rather its upper atmosphere). Curves a-d are the best ground-based detector-limits,[24] and the curves 1-4 show the astrophysical limits derived here and in ref.20). The diagonal curve is an upper flux limit given by the total density of galactic dark matter.

Most of the astrophysical flux-limits depend on the parameter $\rho_{24}v_{250}^{-1}$, which enters in the gravitational accretion rate in equation (2). Limits derived with Earth-based detectors depend on the geometrical accretion term, which is proportional to $\rho_{24}v_{250}$. The astrophysical limits in Figure 1 have therefore been plotted assuming $v_{250}=1$.

Throughout the investigation it has been assumed that only nuggets with a single value of A contributed to the flux. If a distribution of A-values is involved the *upper limits* on excluded A at a given $\rho_{24}v_{250}^{-1}$ remain valid if the density is hidden in nuggets with a distribution of A below that limit, but above the *lower limit*, when that exists. If the distribution extends to values of A exceeding the upper boundaries of the excluded regions, the density ρ_{24} should be interpreted as the density contribution from nuggets in the excluded region.

With these reservations it is easily seen from the figure that the astrophysical nugget flux-limits are many orders of magnitude better than those derived from experiments on Earth. Neutron stars and their progenitors are very sensitive quark nugget detectors.

The dark halo around our Galaxy is expected to have $\rho_{24}v_{250}^{-1}\approx 1$, so Earth-based experiments exclude nuggets with $3\times 10^{7}\lesssim A\lesssim 5\times 10^{25}$ as being responsible for the dark matter. For comparison capture in pulsar progenitors during the main sequence phase excludes $A\lesssim 10^{30}$. Stopping of nuggets in the giant phase rules out $A\lesssim 10^{35}$. Capture during the molten phase of the neutron star life could exclude $10^{12}\lesssim A\lesssim 10^{32}$ if a tiny fraction of the incident nugget survives the collision, and capture in solid crust neutron stars may exclude nuggets as large as $A\lesssim 6\times 10^{38}$, if the age of PSR0355+54 is estimated correctly, and if fragments with baryon number $A_f\gtrsim 10^{36}$ survive. Only very large nuggets may explain the dark matter.

The pulsar glitch argument excludes nuggets with $A\lesssim 10^{28}$ even at fluxes 18 orders of magnitude below that of the halo dark matter, since these nuggets would have been absorbed by the neutron star progenitor in its main sequence phase. At even lower fluxes the excluded region due to main sequence capture is approximately $A\lesssim 10^{47}\rho_{24}v_{250}^{-1}$. This seems to rule out the suggestion[26] that nuggets of very low A accreted in the Sun could catalyze nuclear reactions, thereby reducing the solar neutrino problem. If such nuggets were around in our Galaxy they would have been accreted by neutron star progenitors as well.

Furthermore the very existence of strange stars may be questioned on the basis of these flux-limits. If strange stars exist our Galaxy almost inevitably contains a background flux of quark nuggets due to mass ejection in strange star collisions (in systems like the binary pulsar). A single event releasing $0.1M_{\odot}$ of nuggets would correspond to a mean density in the galactic disk of 10^{-35}gcm^{-3} under the (rather unlikely) assumption that the nuggets are spread evenly in the disk. At this density and even at densities of 10^{-42}gcm^{-3} nuggets with $A \lesssim 10^{28}$ are excluded. Thus strange stars probably never existed in compact binaries unless most of the nuggets spread by stellar collisions have $A > 10^{28}$, or the orbits of the nuggets avoid the galactic disk.

Quark nuggets have been suggested as candidates for the Centauro cosmic-ray events. Centauro primaries may have a flux as high as $10^{-14}\text{cm}^{-2}\text{s}^{-1}$ and $A \approx 10^{3}$. Since Centauro primaries move at relativistic speeds they are destroyed by inelastic collisions when hitting a star, so the flux-limits given in this paper cannot directly be used to rule out quark nuggets as Centauro primaries. However the mechanism producing the primaries must be tuned so that it only produces relativistic quark nuggets in order not to conflict with the flux-limits for non-relativistic nuggets. Similar arguments constrain attempts[7)] to invoke nuggets in explanations of cygnets.

In summary the allowed occurrence of quark nuggets in our Galaxy is very tightly constrained. Only very massive nuggets remain possible dark matter candidates. A suggestion for solving the solar neutrino problem is ruled out, and some restrictions are set on models trying to explain Centauro primaries or cygnets as quark nuggets. The very existence of strange stars is questioned, at least as members of systems resembling the binary pulsar. The lack of strange stars may be taken as an indication that strange matter is *unstable* in bulk. This would have significant implications for the range of QCD-parameters allowed.

The basic assumption underlying these conclusions is, that pulsar glitches can not occur in strange stars. This assumption seems to be well motivated. Should a mechanism for glitches in strange stars nevertheless be shown to work, the conclusions mentioned above would not hold. No limits on the galactic flux of quark nuggets could then be set from the glitch argument, but the "excluded region" in Figure 1 could then instead be interpreted as the combinations of nugget flux and baryon number capable of converting *all* neutron stars into strange stars. Some of the flux limits presented above may in fact still be applicable (regardless of the validity of the glitch argument) if the consequences of neutron star conversion turn out to be more dramatic than any events observed. This may in particular be the case if a detonation rather than a slow combustion is involved.

Thanks are due to the organizers for a very interesting workshop.

REFERENCES

1) Alcock, C., and Farhi, E. 1985, *Phys. Rev.*, D32, 1273.
2) Alcock, C., Farhi, E., and Olinto, A. 1986a, *Ap. J.*, 310, 261.
3) Alcock, C., and Olinto, A. 1988, *Ann. Rev. Nucl. Part. Sci.*, 38, 161.
4) Alcock, C., and Olinto, A. 1989, *Phys. Rev.*, D39, 1233.
5) Alpar, M. A. 1987, *Phys. Rev. Letters*, 58, 2152.
6) Applegate, J. H., and Hogan, C. J. 1985, *Phys. Rev.*, D31, 3037.
7) Baym, G., Kolb, E. W., McLerran, L., Walker, T. P., and Jaffe, R. L. 1985, *Phys. Letters*, **160**B, 181.
8) Bignami, G. F., and Caraveo, P. A. 1988, *Ap. J. (Letters)*, 325, L5.
9) Brügger, M., *et al.* 1989, *Nature*, 337, 434.
10) Chmaj, T., and Slominski, W. 1987, preprint.
11) De Rujula, A., and Glashow, S. L. 1984, *Nature*, 312, 734.
12) Farhi, E., and Jaffe, R. L. 1984, *Phys. Rev.*, D30, 2379.
13) Haensel, P. 1987, *Acta Phys. Pol.*, B18, 739.
14) Haensel, P., Zdunik, J. L., and Schaeffer, R. 1986, *Astr. Ap.*, **160**, 121.
15) Heiselberg, H., Madsen, J., and Riisager, K. 1986, *Physica Scripta*, 34, 556.
16) Horvath, J. E., and Benvenuto, O. G. 1988, *Phys. Letters*, 213B, 516.
17) Jändel, M. 1988, *Z. Phys.*, C40, 599.
18) Lyne, A. G. 1987, *Nature*, **326**, 569.
19) Madsen, J. 1986, in *Second ESO-CERN Symposium - Cosmology, Astronomy and Fundamental Physics*, ed. G. Setti and L. Van Hove (München: ESO), p. 279.
20) Madsen, J. 1988, *Phys. Rev. Letters*, **61**, 2909.
21) Madsen, J., Heiselberg, H., and Riisager, K. 1986, *Phys. Rev.*, D34, 2947.
22) Madsen, J., and Riisager, K. 1985, *Phys. Letters*, 158B, 208.
23) Olinto, A. V. 1987, *Phys. Letters*, 192B, 71.
24) Price, P. B. 1988, *Phys. Rev.*, D38, 3813.
25) Reinhardt, H., and Dang, B. V. 1988, *Phys. Letters*, 202B, 133.
26) Takahashi, K., and Boyd, R. N. 1988, *Ap. J.*, 327, 1009.
27) Thompson, M. J. 1987, Ph.D. thesis, Cambridge (unpublished).
28) Witten, E. 1984, *Phys. Rev.*, D30, 272.