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STRANGE STARS, NEUTRON STARS AND PULSAR EMISSION

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RESUMEN. Se ha conjeturado que una partícula de dieciocho quarks, sin carga, sin espín y sin colar (quark-alfa) podría ser estable a bajas temperaturas y presiones aún con respecto a materia extraña. Presentamos en este trabajo la estructura de estrellas extrañas incluyendo los efectos y apariencia de partículas quark-alfa en las capas exteriores. La estructura interna ya no es homogénea del centro a la superficie, sino que muestra un centro de materia extraña, capas sólidas superfluídas y una costra delgada de materia normal en la superficie. La superficie de materia normal permite la formación de una magnetosfera, la que se piensa sea el sitio en donde ocurre la emisión del pulsar. La superficie de superfluído ayuda a explicar el fenómeno de 'glitch', el cual ha sido observado en muchos pulsares. Se discute también la ecuación de estado para materia quark-alfa relevante en este regimen.

ABSTRACT: It has been conjectured that an eighteen quark, uncharged, spinless and colorless particle (quark-alpha) could be stable at low pressures and temperatures even with respect to strange matter. We present in this work the structure of strange stars including the effects of the appearance of quark-alpha particles in their outer layers. The internal structure is no longer homogeneous from the center to the surface, but show a strange matter core, a solid and superfluid layers and a thin crust of normal matter at the surface. The normal matter surface allows the formation of a magnetosphere, which is thought to be the place where pulsar emission occurs. A superfluid layer helps to explain the glitch phenomenon, which has been observed in many pulsars. The equation of state for quark-alpha matter relevant in this regime is also discussed.

Key words: ELEMENTARY PARTICLES — EQUATION OF STATE — STARS-COMPACT

. INTRODUCTION

In a previous work we have conjecturated that strange matter formation in a Kelvin-lelmholtz timescale inside the collapsed core of a massive star can be the ultimate for the explosions known as type II supernovae. In this picture, the energy release from the process ι ---▸ u + d + s at high density drive a detonation fron whose hydrodynamical kinetic energy s enough to reproduce the energy output of these events (Benvenuto and Horvath, this Proceeding and references therein). It is apparent that the proposed scenario requires the remnant o be a strange star. Moreover, it is easily seen that neutron stars are only a short lived ($\sim$10 sec) metastable state, decaying quickly to the actual ground state of strong interactions. This means that we should address the full phenomenology of pulsars in the frame of strange stars, and this is the main purpose of this work.

Strange star models have been seriously questioned on the basis of two different bjections: first, a bare quark surface offers an enormous work function (10^{17} eV) to pull charged particles which can form a magnetosphere (Alcock, Farhi and Olinto 1986); second: the lack of a differentiated internal structure(a direct consequence of the form of the equation of state for strange matter) inside the star does not allow to accomodate glitches (Shapiro and

Teukolsky 1983) as a result of a sudden decoupling of some layer with moment of inertia $I_i / I = \Delta\Omega/\Omega \simeq 10^{-3}$. Although it has been shown (Alcock, Farhi and Olinto 1986) that strang stars can support a thin outer layer of normal material (which could solve the first problem) it is hopeless to postulate some relationship of this component with the glitch phenomenon because its moment of inertia is far too small ($I_i / I \simeq 10^{-5}$) to explain the observations (Alpar 1987).

Briefly stated, the problem is that normal matter can only exist in this picture o ly at densities up to 4 10^{11} gr/cm^3 when the neutrons begin to drip out of nuclei and thus can not survive in contact with strange matter. It seems that only internal structure of strange matter itself can help to overcome the glitch objection. In this view, strange matter is just crude model of high density bulk matter with s quarks (much in the same way as taking a Fermi gas equation of state for neutron matter) and we should properly refine it to include more com plex structures.

II. BOUND STATES OF STRANGE MATTER (Q_α)

A suitable bound state candidate (high strangeness) has been recently proposed (Michel 1988) on the basis of typical nuclear symmetry arguments. The simple observation that binding energies go up as the symmetry of the state increases (e.g. ^{4}He vs. H) led this author to postulate the absolute stability of the maximally symmetric state composed of 6u + 6d + 6s quarks taken as fundamental entities. This state should have a large binding energy because it saturates (flavor (3) X spin (2) X color (3) = 18 particles) all available quantum numbers. Macroscopically it would behave like a chargeless, spin zero massive boson. Rough estimations of the mass tells us that it could be as low as 5 GeV, that is to say 0.6 GeV below the 6 neutrons state. Assuming the correctness of the hypothesis it is immediate to realize that pulsar interiors are the most conspicuous places where Q_α can form and survive. To see what extent they modify the stellar structure we have calculated the Gibbs free energy of this phase using the following scheme: first we have employed a bag-like model to write the mass of the Q_α as $M_Q = 4\pi R^3 B/3 + K/R$ where R is the radius of the Q_α, B an energy density related to the pe: turbative vacuum where partons live, and K a dimensionless quantity including all other forms (energy (which is the only possible form of the term in a theory with a single energy scale R^{-1}. While the conventional procedure has been to calculate perturbatively in the contribution to certain diagrams to K, this clearly would not work for Q_α's (a strongly bounded state cannot b investigated using perturbative interactions). Alternatively, we have chosen to fix K and R by imposing a mass value $\simeq 5$ GeV plus the condition of equilibrium $\partial M_Q / \partial R = 0$. is assumed to remain unchanged throughout the whole pressure range up to fusing Q_α's into the Fermi liquid. The result of the minimization yield are $K \sim 34 - 36$ and $R \simeq 1.7$ fm depending somewhat on the valı of M_Q.

III. FINITE DENSITY Q_α EQUATION OF STATE

We need to know the free energy expressions to see which phase is preferred at a given pressure. The most simple assumption on Q_α matter is to consider it as a collection of non relativistic Bose hard spheres. This model is suggested by the lack of any other interaction other than hard sphere **scattering**. The complicated quantum many body problem at finite density has been solved in Kalos, Levesque and Verlet (1974) where the energy per boson E/n vs. x = n : (with n the number density and a the Q_α scattering lenght) have been presented. By fitting suitble analytical expressions to the numerical curves we have calculated the pressure P for each phase (a fluid for $x \leqslant 0.25$ and a fcc solid for $x \geqslant 0.27$) and with it, the Gibbs energy per bary $g = (E + P) / n$. Plotting g_Q and g_{sm} vs. P we find a fluid solid transition at P_s = 0.06 and 0 MeV/fm^3 (for $K = 34$ and $K = 36$ respectively), and a solid - strange matter transition at P_m= 2 and 8.5 MeV/fm^3. Both results have been obtained using $\alpha_c = 0.3$, M_s = 150 MeV and B = 60 MeV/fm^3 for the **strange** matter side. It is important to note that if $M_Q > 5.5$ GeV (corresponding to K= : it is not possible to obtain any Q_α - strange matter transition because Q_α's would not be preferred at P = 0, contradicting the hypothesis. On the other hand if $M_Q < 5$ GeV (K= 34, extremely tightly bounded) the transition would occur at very high pressures $P \gtrsim 50$ MeV/fm^3 where analyti fits are not reliable anyway. This gives an idea of the uncertainties involved in the structur of the models presented below.

IV. STELLAR MODELS (STRANGE PULSARS)

In order to find the stellar models resulting from the inclusion of Q_α's to comple nent the strange matter picture we have integrated the Tolman - Oppenheimer - Volkoff equations of stellar structure (Shapiro and Teukolsky 1983) setting $M = 1.4\ M_\odot$ (as expected from formation arguments and available observations). A section of the models is presented in Fig. 1 for $K = 34$ and $K = 36$ on the left and right respectively. Before giving a detailed description of the models let us address how these objects may form because it will be crucial for understanding their final structure.

As shown elsewhere (Benvenuto and Horvath, this Proceedings and references therein) the complete conversion of the proto - neutron star into a strange star occurs after the expulsion of the stellar mantle and envelope by the detonation wave fueled by n ---► u+d+s+ energy. This fast combustion mode does not, however, reach the edge of the compact core (which would be disastrous for nucleosynthesis), but becomes a standard shock wave at $R \simeq R_{cut}$ (see Benvenuto and Horvath, this Proceedings). Due to the high Reynolds numbers of the left-over fluids after the passage of the front, turbulent convection is expected to mix strange and nuclear matter and this greatly enhances the conversion of the nuclear material. Q_α formation when the turbulent transient begins to settle down does help to add some normal "residual" nuclear particles to the object because s quarks are massive and assembling equal numbers of u, d, and s quarks will leave u's and d's which are known to be the building blocks of proton and neutrons. After a short transient, the normal matter will settle forming the most exterior layer (outer crust). However as it stands, it is extremely difficult to calculate the amount of normal matter surviving after all these processes, and we shall treat this quantity as a free parameter.

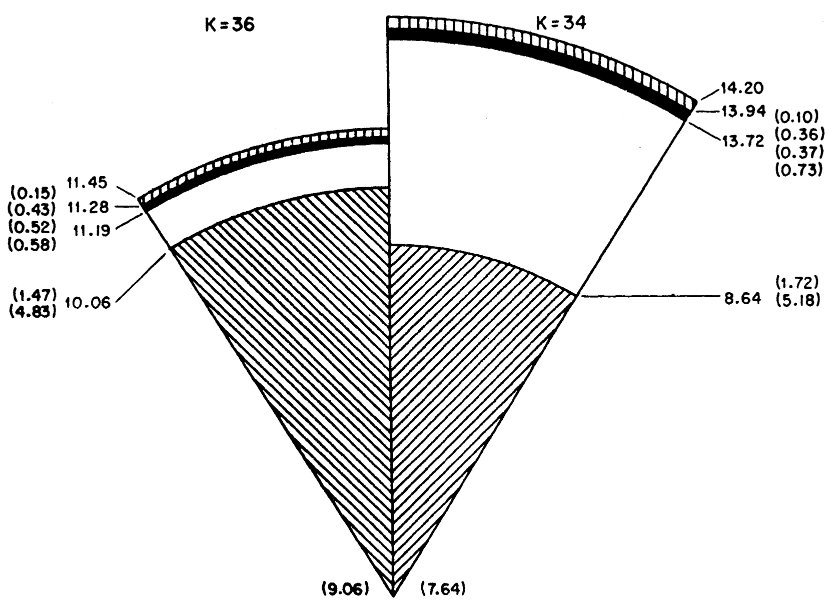

Fig. 1: Cross sections of a 1.4 $M_\odot$ strange stars showing the internal structure due to the inclusion of Q_α. The corresponding layers are strange matter (oblique hatched), Q_α solid (white), Q_α fluid (black), and normal matter (vertical hatched). Numbers quote the values of the radius in Km at which each interphase occurs. The densities on both sides of each interphase (in units of 10^{14} gr/cm^3) are given in brackets.

There is however an important constraint on this amount of normal matter if the models are required to reproduce the observed pulsar behaviour. Fig. 1 shows that, below the outer normal matter crust, a layer of Q_α matter is present. As the low energy excitation spectrum must be phononic in this layer, the Q_α will behave as a superfluid, and then this is the layer that should be identified as the suddenly decoupled component when a glitch occurs. The very existence of this thin layer depends on the amount of normal matter present in the outer crust, and so to reproduce the pulsar glitch observations, the normal matter should not exceed 10^{-2} of the total baryon number. We nevertheless believe that 10^{-2} is still a large number and we have used 10^{-3} in our models.

Inmediatly below the superfluid Q_α layer, there is a region of solid Q_α matter rigid ly coupled to the central core containing bulk (liquid) strange matter. The coupling is provic by residual normal charged particles trapped among the Q_α solid because their diffusion timesca is far in excess the age of the Universe. It is amusing to note that the very different values $\Delta\dot{\Omega}/\dot{\Omega}$ (and so of I_i/I) observed in the cases of Crab and Vela pulsars can be attributed in this picture to slightly different values of normal matter surviving the conversion.

Due to the hardness of the solid Q_α region, our stellar models present a relatively large radius, a circumstance which is known to disfavour the stability at high rotation rates. We are presently studying the compatibility of our models with the observations reported by Kristian et al. (1989) of a submillisecond pulsar inside SN 1987A. While it is known that naive strange stars can rotate so fast (Frieman and Olinto 1989), to refine the models as proposed he would require large K and / or large values of the constant B.

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