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On the Anatomy of Hybrid Stars in the Bag Model[1]

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Abstract. We construct a simple two-phase picture for the strongly interacting matter within the scheme of the MIT bag model. The results obtained for the equation of state are analytical and show the possibility of first or second order phase transition for reasonable values of the bag constant, central density and pressure. A neutron star model is obtained by integrating the general relativity Tolman-Oppenheimer-Volkoff equation. On the basis of available observational data for maximum masses and central density the model predicts the existence of hybrid stars.

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1 Introduction

The possibility of existence of a quark core inside certain neutron stars was first suggested by Ivanenko and Kurdgelaidze [1]. After this pioneering work much effort has been devoted to the crucial issue of deriving an equation of state for strongly interacting matter and to obtain the critical densities at which the phase transition should occur. The presently available equations of state vary from very simple phenomenological models up to lattice QCD calculations (for a recent review see ref [2]).

Neutron star models are constructed from a given equation of state by integration of Tolman-Oppenheimer-Volkov equation. Most of the calculations are concerned with global quantities such as the resultant gravitational mass and radius for given central densities.

The purpose of the present contribution is to provide for a detailed analysis of the anatomy of neutron stars, giving particular emphasis on the properties of hybrid stars, i.e, stars consisting of quark matter surrounded by ordinary neutron matter. Our study deals with the inner crusts of the star, where, for densities in the range $2.4\text{x}10^{14} g/cm^3 < \rho < \rho_{core}$ it is believed to be composed of superfluid neutrons with a smaller concentration of superfluid protons and normal electrons. Also a core region $\rho > \rho_{core}$ may or may not exist and depends on whether there is a transition to quark matter.

Although the issue of the existence or not of such phase transition is rather controversial and model dependent, it is of enough importance to deserve detailed analysis based on a model which is sufficiently simple as to allow for analytical results including phase transition and which contains what are believed to be the essential physical ingredients. The basic issue in the phase transition is the property of quark confinement.

In the bag model [3] the confinement effect is atributed to the bag pressure which is exerted by the physical vacuum on the region containing the perturbative system. It has been demostrated that above the critical temperature the results derived by using the bag model with an appropriate choice of the bag parameter are in full agreement [4] with those obtained by lattice calculations. It seems, therefore, that in the phenomenological considerations of the quark-hadron phase transition, the bag parameter should be of crucial importance and the perturbative calculations should play a minor role. In fact this has been pointed out in ref [5], where the temperature dependences and energy densities are calculated within the scope of the simplest model containing such physical input. We pursue these calculations further, exploring the consequences of the model's equation of state for the anatomy of the neutron stars. This is done by integrating the general relativity equation of hydrostatic balance, the Tolman-Oppenheimer-Volkoff (TOV) equation for central densities and by using values for the bag constant which are nowadays believed to be reasonable.

Our results together with the presently available empirical results support the suggestion of Ivanenko and Kundgelaidze [1] on the existence of hybrid stars.

This paper is divided as follows: in section II we present the model; in section III the results of the TOV equation for our equation of state. Conclusions can be found in section IV.

2 The Model: Criteria for Phase Transition

In this model the hadronic phase is taken to be an ideal gas of nucleons. One theoretical motivation for this assumption is the fact that for the densities of interest, interacting relativistic nucleon models such as Walecka's model [6] or the Linear Sigma model [7] exhibit the behavior of a free gas. The quark-gluon plasma is described as an ideal gas of gluons and massless u and d quarks.The confinement effects, as mentioned, were taken to be independent of the thermodynamical parameters. The transition between the two phases is determined on the basis of the Gibbs criteria. Stability considerations constrain the range of allowed bag constant values and critical chemical potential, so that we can say there are no free parameters in the calculation, since the bag constant value is known from hadronic spectra.

Hadronic Phase: In this phase we have a completely degenerate Fermi gas of nucleons, whose pressure, energy density and baryon number density are given by [5, 8]:

$$P_h(T=0,\mu) = \frac{M^4}{6\pi^2}\left\{\frac{\mu}{M}\left(\frac{\mu^2}{M^2}-1\right)^{1/2}\left(\frac{\mu^2}{M^2}-\frac{5}{2}\right)+\frac{3}{2}ln\left(\frac{\mu}{M}+\left(\frac{\mu^2}{M^2}-1\right)\right)^{1/2}\right\} \quad (2.1)$$

$$\epsilon_h(T=0,\mu) = \frac{2\mu}{3\pi^2}\left(\mu^2-M^2\right)^{3/2} - P_h(T=0,\mu) \quad (2.2)$$

$$n_{Bh}(T=0,\mu) = \frac{2}{3\pi^2}\left(\mu^2-M^2\right)^{3/2} \quad (2.3)$$

where M is the nucleon mass and μ the chemical potential.

Plasma Phase: In this phase, the Equations of State are given by:

$$P_p(T=0,\mu_q) = \frac{1}{2\pi^2}\mu_q^4 - B \quad (2.4)$$

$$\epsilon_p(T=0,\mu_q) = 3P_p(T=0,\mu_q) + 4B \quad (2.5)$$

$$n_{Bp}(T=0,\mu_q) = \frac{2}{3\pi^2}\mu_q^3 \tag{2.6}$$

We can now construct the phase transition using the Gibbs criteria:

$$P_p = P_h \tag{2.7}$$

$$3\mu_q = \mu = \mu_c \tag{2.8}$$

$$\epsilon_p - \epsilon_h \geq 0 \tag{2.9}$$

One can find solutions for the chemical potential in the interval

$$M \leq \mu_c < \sqrt{\frac{9}{8}}M \tag{2.10}$$

And, consequently, the value of the bag constant is in the (narrow) interval

$$\frac{1}{2\pi^2}\left(\frac{M}{3}\right)^3 \leq B < \left(\frac{3}{8} - ln\sqrt{2}\right)\frac{M^4}{4\pi^2} \tag{2.11}$$

where the lower(upper) limit corresponds to the lower(upper)limit in (10).

We now consider the following physical situations corresponding to different values of B and μ (see Fig 1).

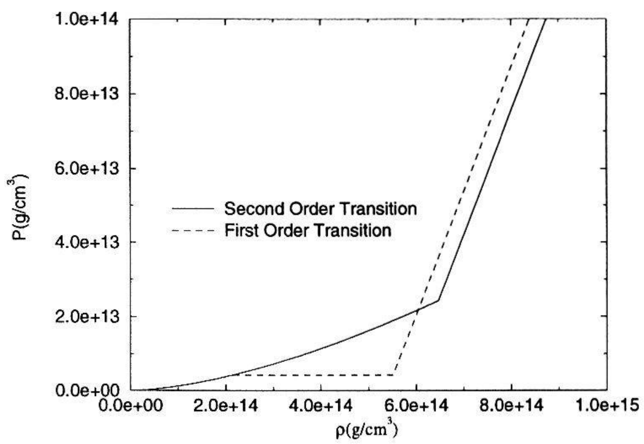

Figure 1: First and second order phase transition.

The dashed line corresponds to $B = B_1 = 5.319\text{x}10^{-4}GeV^4$ and $\mu_c = 0.98GeV$, for which the system undergoes a first order phase transition from the plasma phase at densities $\approx 2.3\text{x}10^{14}g/cm^3$. The coexistence of the two phases is established until the normal matter density is reached. For lower densities a noninteracting neutron gas will be found. The solid line corresponds to $B = B_2 = 6.155\text{x}10^{-4}GeV^4$, $\mu_c = 1.036GeV$ and the system undergoes a second order phase transition.

3 Solutions of the T.O.V equation:

Assuming an isotropic mass distribution and the validity of Einstein's General Theory of Relativity, with the Tolman-Oppenheimer-Volkoff equations [9, 10]

$$\frac{dP}{dr} = -\frac{[G/r^2][\rho(r) + P(r)/c^2][M(r) + 4\pi r^3 P(r)/c^2]}{1 - 2GM(r)/rc^2} \tag{3.1}$$

and

$$\frac{dM}{dr} = 4\pi r^2 \rho(r) \tag{3.2}$$

where P(r) is the pressure, $\rho(r)$ the mass density, M(r) is the gravitational mass inside r, G is the gravitational constant and c the speed of light, we obtain the following curves: $M/M_\odot$ as a function of the central density and $M/M_\odot$ as a function of the total radius of the star, R.

In fig.2 we display the curves of $M/M_\odot$ as a function of the central density for the chosen B values. We observe that the second order phase transition can only occur for stars with $\rho_c > 7\text{x}10^{14}g/cm^3$.

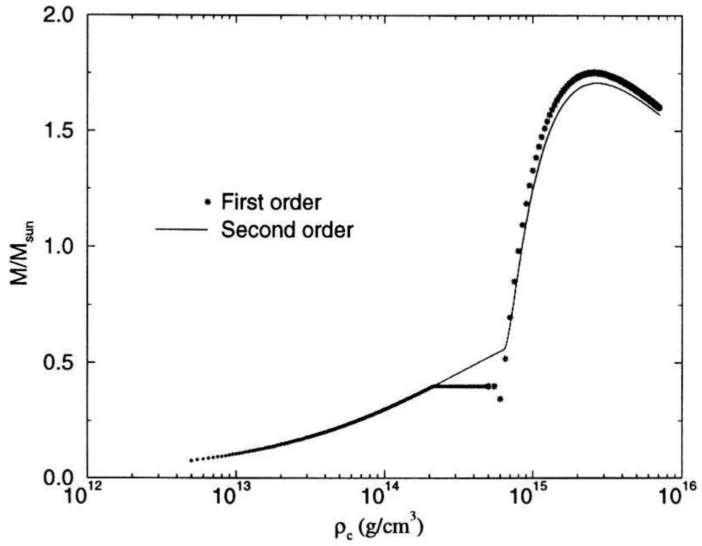

Figure 2: $M/M_{\odot}$ as a function of central density for the two values of B in the text. In this Figure M_{sun} corresponds to $M_{\odot}$.

Stars with smaller central densities do not undergo the transition. In this case, stars with adequate central densities will be partly composed by hadrons and partly by quarks. As the central density is increased the proportion of quarks to hadrons increases until the central density has reached the maximum value corresponding to maximum star mass.

More detailed information can be obtained by studying the matter distribution in some chosen neutron stars as follows. For example, the most favorable case are Hybrid Stars: the central densities shown are $2\text{x}10^{15} g/cm^3$. Such stars occur for the Bag constant values given by B_1 or B_2. In Figs.3 and 4 we display an example where a first order phase transition occurs at a radius of about 9 km. The total mass of the star is 1.7 $M_{\odot}$. This corresponds to a quark core star with a small neutron layer. It fits well with phenomonological expectations.

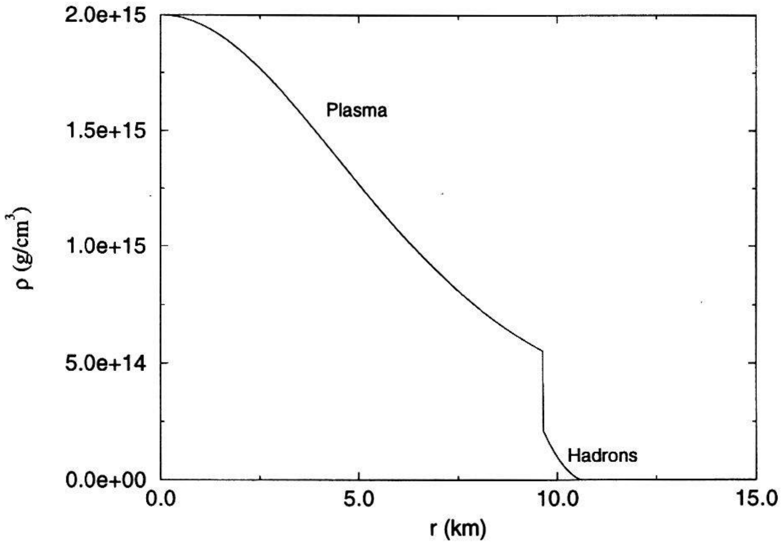

Figure 3: Density as a function of the star radius r, for a hybrid star in which a first order phase transition occured. The total radius of the star is about 11km and it's central density is $2\text{x}10^{15} g/cm^3$.

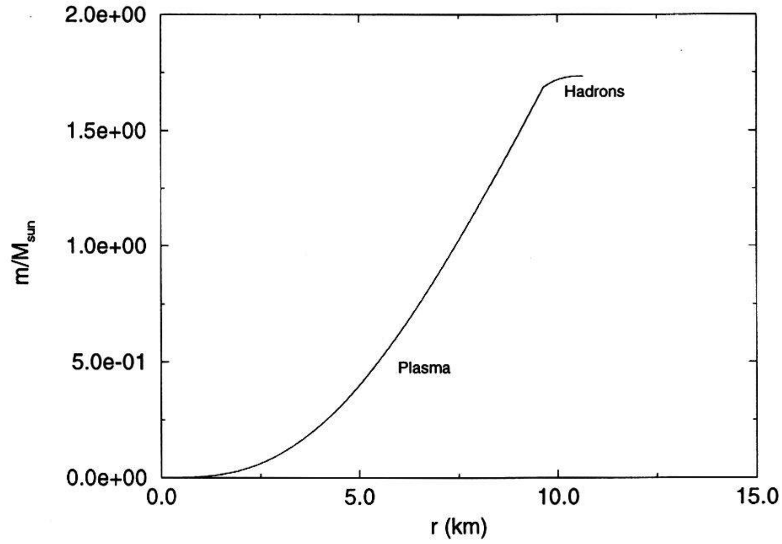

Figure 4: $m/M_{\odot}$ as a function of r for the same star of Fig.3.

The same qualitative behaviour is obtained for a similar star in which a second order phase transition occurs. This is shown in Figs.5 and 6. We thus conclude that the presently available inclusive data can not distinguish between the two types of transitions, although from our model calculations they are both possible.

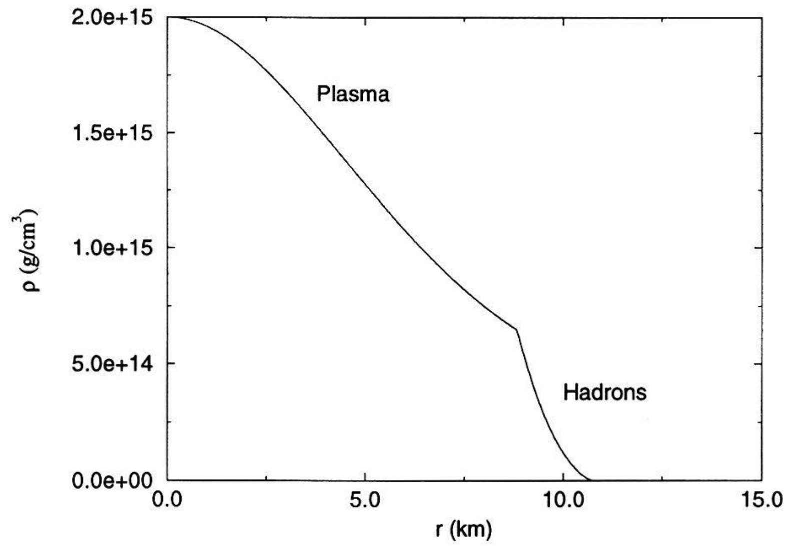

Figure 5: Density as a function of the star radius r, for a hybrid star in which a second order phase transition occured. The total radius of the star is about 11km and it's central density is $2x10^{15} g/cm^3$.

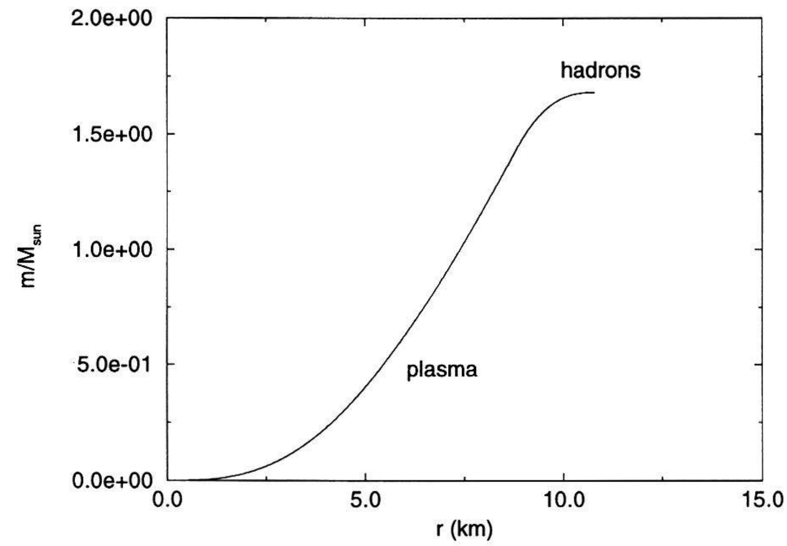

Figure 6: $m/M_{\odot}$ as a function of r for the same star of Fig.5.

4 Discussion:

We have constructed a simple model for the phase transition by using an ideal gas description for the quarks and hadrons and a bag constant parametrization of the confinement effects. Although the inclusion of n-n interactions or resonances in the hadronic phase and perturbative QCD interactions in the plasma phase would very likely alter parameter values, we do not believe the qualitative results should change.

Our results seem to strongly favour the possibility of existence of hybrid stars for central densities of the order of $2\text{x}10^{15} g/cm^3$ which is within our expectations. The phase transition responsible for such stars could be of first as well as of second order.

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