

Dense QCD and phenomenology of compact stars

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I discuss three topics in physics of massive (two solar-mass and larger) neutron stars containing deconfined quark matter: (i) the equation of state of deconfined dense quark matter and its color superconducting phases, (ii) the thermal evolution of stars with quark cores, (iii) color-magnetic flux tubes in type-II superconducting quark matter and their dynamics driven by Aharonov-Bohm interactions with unpaired fermions.

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1. Introduction

Compact star phenomenology offers a unique tool to address the outstanding challenges of the modern particle and nuclear physics, in particular the phase structure of dense quantum chromodynamics (QCD). The integral parameters of compact stars depend on their equation of state (hereafter EoS) at high densities. Measurements of pulsar masses in binaries provide the most valuable information on the underlying EoS because these, being deduced from binary system parameters, are model independent within a given theory of gravity [1]. The recent discovery of a compact star with a mass of $1.97 M_{\odot}$, which sets an observationally “clean” lower bound on the maximum mass of a compact star via the measured Shapiro delay [2], spurred an intensive discussion of the phase structure of dense matter in compact stars consistent with this limit [3, 4]. Pulsar radii have been extracted, e.g., from modeling the X-ray binaries under certain reasonable model assumptions, but the uncertainties are large [5]. A recent example is the pulse phase-resolved X-ray spectroscopy of PSR J0437-4715, which sets a lower limit on the radius of a $1.76 M_{\odot}$ solar mass compact star $R > 11$ km within 3σ error (Bogdanov, in Ref. [5]).

Large masses and radii are an evidence for the stiffness of the EoS of dense matter at high densities. Commonly, phase transitions, e.g. the onset of quark matter, softens the EoS close to the transition point, and therefore reduces the maximum achievable mass of a configuration. Thus, if quark matter exists in compact stars, there should be a delicate balance in Nature which allows large enough densities in compact stars to achieve quark deconfinement and stiff enough EoS of strongly interacting matter to support large masses and radii [3]. Indeed, as I review below, one can construct stellar configurations that are dense enough for baryons to deconfine into quarks and are massive enough to be consistent with the maximum mass bound mentioned above. These configurations have also radii large enough to be consistent with the existing bounds [5].

The information gained from measurements of the gross parameters of compact objects, such as the mass, radius or the moment of inertia give us only indirect information on potential phases of matter in their interiors. The studies of rotational, thermal and magnetic evolutions of neutron stars provide complementary information, which is sensitive to the composition of matter. Indeed, modeling cooling neutron stars requires a detailed knowledge of quantities such as the specific heat of components of matter and its neutrino emissivity, which are strongly composition dependent. Thus, the cooling of massive neutron stars needs to be consistent with the ideas of formation of quark matter with stiff equations of state. The studies of cooling of such stars reveals the complexity of the problem (for the recent work see Refs. [6]). Furthermore, the recent observation of the substantial change in the temperature of the neutron star in Cas A poses a challenge for the theory to explain drastic short-term drop in the temperature of this neutron star (for a review see Ref. [7]). Magnetic evolution of a compact star will also depend on the structure of magnetic field in the quark phases, which in turn depends on the dynamics of quantum vorticity in the quark superconductor or superfluid [8, 9]. For example, if the flux-tube dynamics in the type-II superconducting phases of the star occurs on evolutionary time-scales, it will directly affect the magnetic field components of the star that lead to its secular spin-down.

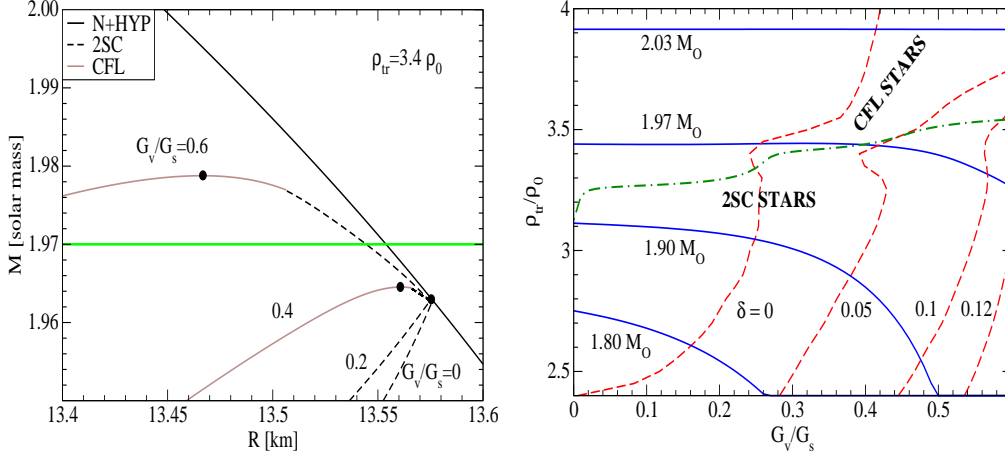


Figure 1: *Left panel.* Mass vs radius for configurations with quark-hadron transition density $\rho_{tr} = 3.4\rho_0$ for four values of vector coupling $G_V/G_S = 0, 0.2, 0.4, 0.6$, where G_S is the scalar coupling. The purely hadronic sequence (i.e. the sequence that includes nucleons and hyperons) is shown by black solid line. The dashed lines and the gray solid lines show the branches where the 2SC and CFL quark phases are present. The filled circles mark the maximum masses of the sequences. The horizontal line shows the mass measurement of Ref. [2]. *Right panel.* Properties of the stars as a function the free parameters G_V and the transition density to quark matter ρ_{tr} in units of saturation density ρ_0 . The solid lines show the maximum mass configurations realized for the pair of parameters G_V and ρ_{tr} . The dashed curves show the amount of CFL matter in the configurations via the ratio $\delta = R_{CFL}/R$, where R_{CFL} is the radius of the CFL core, R is the star radius. The parameter space to the right from $\delta = 0$ line produces CFL stars. The parameter space below the dashed-dotted curve corresponds to stars containing 2SC matter.

2. Two solar-mass compact stars with hyperons and color superconducting quarks

Hybrid stars, i.e. baryonic stars containing quark cores, with two solar masses have attracted a lot of attention in recent years. Cold quark matter should be in one of the possible superconducting phases due to the attractive component in the gluon exchange quark-quark interaction [10]. These two aspects - high masses and color superconductivity - appear to be minimal ingredient of realistic hybrid star modeling. Here I describe briefly a recent work on a model [4], which exemplifies the key features of this class of compact stars.

The nuclear EoS, as is well known, can be constructed starting from a number of principles. In Ref. [4] relativistic mean-field models were employed to model the low density nuclear matter. As is well-known, these models are fitted to the bulk properties of nuclear matter and hypernuclear data to describe the baryonic octet and its interactions [11]. Among the existing parameterization the stiffest EoS is achieved with the NL3 and GM3 parameterizations. The high-density quark matter was described in Ref. [4] by an NJL Lagrangian, which is extended to include the t' Hooft interaction term and the vector interactions with a coupling G_V . The mass-radius relationship for massive stars constructed on the basis of the EoSs described above is shown in the left panel of Fig. 1 together with the mass measurement $M = 1.97 \pm 0.04 M_\odot$ [2]. Masses above the lower bound on the maximum mass are obtained for purely hadronic stars; this feature is prerequisite

for finding similar stars with quark phases. Evidently only for high values of vector coupling G_V one finds stable stars that contain (at the bifurcation from the hadronic sequence) the two-flavor superconducting (2SC) phase, which are followed by stars that additionally contain the color-flavor-locked (CFL) phase (for higher central densities). Thus, we find that the stable branch of the sequence contains stars with quark matter in the 2SC and CFL phases.

The right panel of Fig. 1 shows the changes in the masses and composition of compact stars as the parameters of the model G_V and ρ_{tr} are varied. First, it shows the tracks of constant maximum mass compact stars within the parameter space. The decrease of maximum masses with increasing vector coupling reflects the fact that non-zero vector coupling stiffens the EoS. In other words, to obtain a given maximum mass one can admit a small amount of soft quark matter with vanishing vector coupling by choosing a high transition density; the same result is obtained with a low transition density, but large vector coupling, i.e., a stiffer quark EoS. For low transition densities one finds 2SC matter in stars, which means that weaker vector couplings slightly disfavor 2SC matter. Substantial CFL cores appear in configurations for strong vector coupling and almost independent of the transition density (nearly vertical dashed lines with $\delta \sim 0.1$ in Fig. 1, right panel). Note that for a high transition density there is a direct transition from hypernuclear to the CFL phase. For transition densities below $3.5\rho_0$ a 2SC layer emerges that separates these phases. On the other hand, weak vector couplings and low transition densities produce stars with a 2SC phase only.

3. Thermal evolution of massive stars

Having developed the models of massive compact stars, we are in a position to study their cooling, using as an input a particle composition, that is consistent with the underlying EoS. Such program was carried out with the sequences of massive compact stars constructed in Refs. [12]. These sequences of stable stars permit a transition from hadronic to quark matter in massive stars ($M > 1.85M_\odot$) with the maximal mass of the sequence $\sim 2M_\odot$. Hess and Sedrakian, in Ref. [6], assumed quark matter of light u and d quarks in beta equilibrium with electrons. The pairing among the u and d quarks occurs in two channels: the red-green quarks are paired in a condensate with a gap of order of the electron chemical potential; the blue quarks are paired with a gap of order of keV, which is thus comparable to the core temperature during the neutrino-cooling epoch [13]. For the red-green condensate, a parameterization of neutrino emissivity was chosen in terms of the gaplessness parameter $\zeta = \Delta/\delta\mu$, where Δ is the pairing gap in the red-green channel, $\delta\mu$ is the shift in the chemical potentials of the u and d quarks (Jaikumar et al, in Ref. [6]). The magnitude of the gap in the spectrum of blue quarks was treated as a free parameter.

The stellar models were evolved in time, with the input described above, to obtain the temperature evolution of the isothermal interior. The interior of a star becomes isothermal for timescales $t \geq 100$ yr, which are required to dissolve temperature gradients by thermal conduction. Unless the initial temperature of the core is chosen too low, the cooling tracks exit the non-isothermal phase and settle at a temperature predicted by the balance of the dominant neutrino emission and the specific heat of the core *at the exit temperature*. The low-density envelope maintains substantial temperature gradients throughout the entire evolution; the temperature drops by about 2 orders of magnitude within this envelope. The input parameters in the evolution code are the neutrino and photon luminosities, the specific heat of the core, and the heating processes. The resulting

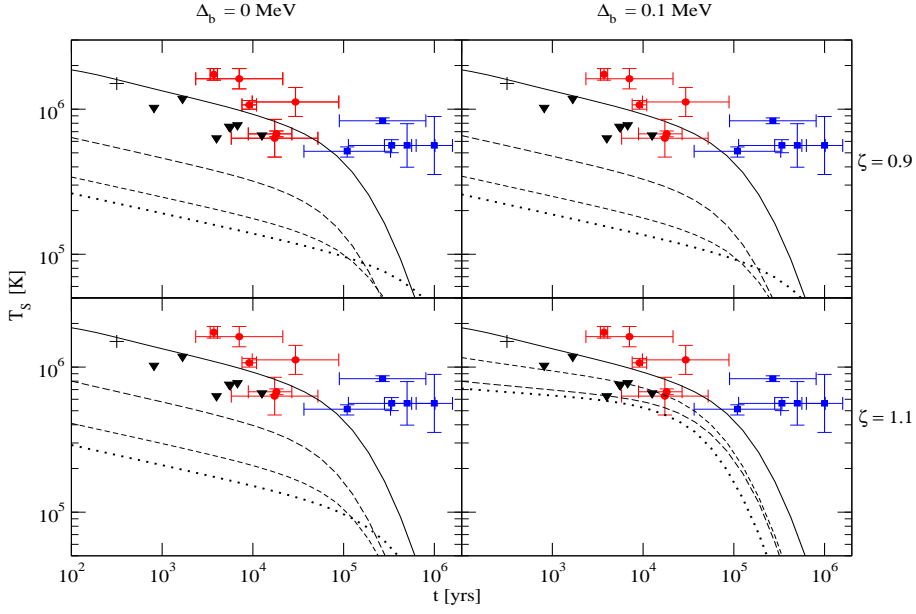


Figure 2: Time evolution of the surface temperature of four models with central densities 5.1 (solid line), 10.8 (long-dashed line), 11.8 (short-dashed line), 21.0 (dotted line) given in units of $10^{14} \text{ g cm}^{-3}$. For the observational data see Hess and Sedrakian in Ref. [6]. The upper two panels correspond to cooling when the red-green condensate has $\zeta = 0.9$, i.e., is not fully gapped; the lower panels correspond to $\zeta = 1.1$, i.e., the red-green condensate is fully gapped. The left two panels correspond to evolution with negligible blue-quark pairing ($\Delta_b = 0$); the right two panels show the evolution for large blue pairing $\Delta_b = 0.1 \text{ MeV}$.

evolution tracks are shown in Fig. 2, where we display the dependence of the (redshifted) surface temperature on time. Each panel of Fig. 2 contains cooling tracks for the same set of four models with increasing central density. The cooling tracks for the purely hadronic model (solid lines) are the same in all four panels. The panels differ in the values of micro-physics parameters (for further explanations see the caption of Fig. 2). It can be seen that (i) the neutrino-cooling is slow for hadronic stars and becomes increasingly fast with an increase of the size of the quark core, in those scenarios where there are unpaired quarks or gapless excitations in the superconducting quark phase. The temperature scatter of the cooling curves in the neutrino cooling era is significant and can explain the observed variations in the surface temperature data of same age neutron stars. (ii) If quarks of all colors have gapped Fermi surfaces, the neutrino cooling shuts off early, below the pairing temperature of blue quarks; in this case, the temperature spread of the cooling curves is not as significant as in the fast cooling scenarios. (iii) As the stars evolve into the photon cooling stage the temperature distribution is inverted, i.e., those stars that were cooler in the neutrino-cooling era are hotter during the photon cooling stage.

Our preliminary studies show that the rapid cooling of Cas A can be understood as an evidence of a phase transition from perfect 2SC phase to a crystalline color superconducting state. We assume the Fulde-Ferrell type superconductivity as discussed in Refs. [14]; (for more complex order parameters see Ref. [15] and references therein). The phase transition is characterized by its temperature T^* and the timescale τ^* needed to complete such a phase transition. While *equilibrium*

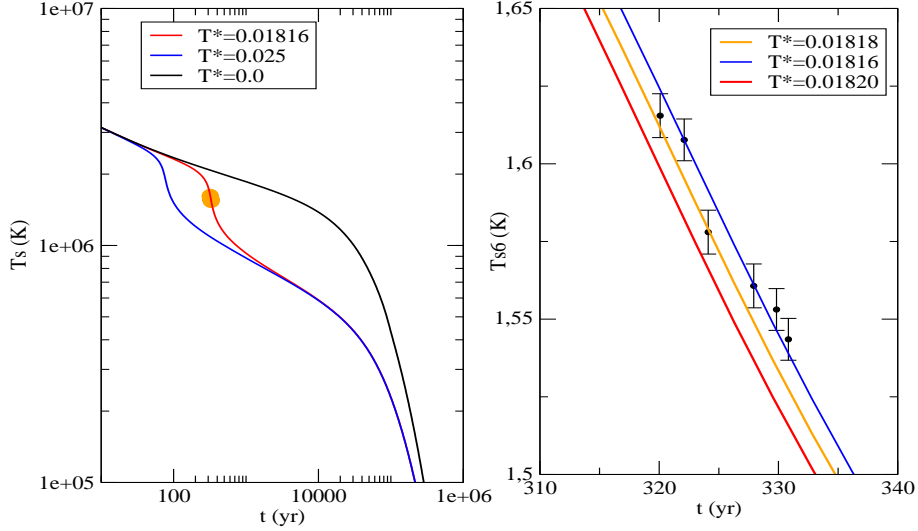


Figure 3: *Left panel.* Dependence of the surface temperature on time for the values of the transition temperature T^* (in MeV) indicated in the plot and for fixed τ^* . The underlying model is the $1.91 M_{\odot}$ compact star model from Ref. [12]. *Right panel.* Dependence of the surface temperature (in units of 10^6 K) on time for the same model. The points with error bars show the Cas A data, the solid lines are fits to these data by variation of T^* .

model calculations provide a value for $T^* \sim 10$ MeV in a particular (NJL Lagrangian based) model, the physically realizable value of T^* may depend on dynamical factors and nucleation history of the quark phase. Because of the density dependence of the critical temperature T^* in the stellar interiors, this phase transition will not occur globally in the quark core, but gradually within some shells. Therefore, the values of T^* and τ^* will be determined by the local conditions in the shells, the transition being a gradual propagation of phase-separation fronts rather than a coherent instantaneous transition. In our study we treat the transition temperature T^* as the key free parameter to fit the cooling model to the Cas A data. These fits are not sensitive to the precise value of time τ^* characterizing the duration of the transition.

Fig. 3, left panel, shows the cooling evolution of the $M = 1.91 M_{\odot}$ model of a compact star for several values of T^* and fixed τ^* . It is seen that for a specific value of T^* the cooling curves pass through the location of Cas A in the log T -log t plain. The right panel of Fig. 3 shows the observationally covered evolution of Cas A for the same value of τ^* and several (fine-tuned) values of T^* . It is seen that the data can be accurately fitted by fine-tuning a single parameter T^* . In each case the critical temperature of pairing for the blue quarks is assumed to satisfy the condition $T_{cb} \gg T^*$, which implies that blue quarks have no effect on the dynamics of the transition process. The numerical value $T_{cb} = 0.1$ MeV was used in the simulations.

4. Color-magnetic flux tubes

We turn now to the response of dense quark matter to a magnetic field. Our discussion will be focused on the formation and dynamics of color-magnetic flux tubes in the two-flavor color su-

perconducting (2SC) phase. Type-II superconductivity leads to formation of flux tubes if the cost of inserting a flux tube, which has always a positive self-energy (flux-tension) in a superconductor is compensated by the interaction energy of the flux tube with external magnetic field intensity. The critical intensity (lower critical field) H_{c1} for the formation of Abrikosov flux tubes containing color-magnetic flux is large, of order 10^{17} G. However, when the quark matter cools into the 2SC phase, the process of domain formation and amalgamation is likely to leave some of the flux trapped in the form of flux tubes [9]. These flux-tubes may be topologically unstable, however their formation and decay timescales in an externally imposed field are unknown.

The 2SC phase contains three species of gapless fermions: two quarks (“blue up” and “blue down”) and the electron. These are expected to dominate its transport properties. Light ungapped fermions will be scattered from color-magnetic flux tubes due to the Aharonov-Bohm (hereafter AB) effect [16]. The scattering of electrons and blue quarks of the flux tubes in the 2SC cores of compact stars contributes to the transport coefficients of matter and acts as a dissipative force on the flux tubes. The relaxation time for incident light fermion on a flux tube is given by [9] $\tau_f^{-1} = (n_v/p_F) \sin^2(\pi\tilde{\beta})$, where n_v is the flux density, p_F is the fermion momentum and β is the dimensionless AB parameter computed in Ref. [9]. It is easy to understand this result. It is of the standard form for classical gases $\tau^{-1} = cn\sigma$, where $c = 1$ is the speed of the particles, $n = n_v$ is the density of scattering centers, and $\sigma \propto \sin^2(\pi\tilde{\beta})/p_F$ is the cross section for AB scattering. One of the blue quarks, the blue down quark, has no AB interaction with the flux tubes ($\tilde{\beta} = 0$). The other two light fermions, the electron and blue up quark, have identical AB factors although their Fermi momenta are different.

Because the ambient magnetic field in a neutron star is below the lower critical field required to force color-magnetic flux tubes into 2SC quark matter, the trapped flux tubes will feel a boundary force pulling them outwards. This force will be balanced by the drag force (“mutual friction”) on the moving flux tube due to its AB interaction with the thermal population of gapless quarks and electrons, and also by the Magnus-Lorentz force. An estimate of the timescale for the expulsion of color-magnetic flux tubes from a 2SC core on the basis of balance of forces acting on the vortex shows that it is of order 10^{10} years [9]. Therefore, it is safe to assume that the magnetic field will be trapped in the 2SC core over evolutionary timescales in the absence of other external forces.

5. Final remarks

Much remains to be done. First, our understanding of the EoS of dense quark matter and its phases needs further exploration. The strangeness degrees of freedom including hypernuclear matter and three-flavor quark matter should be further explored building, e.g., upon the work of Ref. [4]. The equilibrium and stability of massive compact objects, constructed from these EoSs, should be studied including rapid rotations and oscillations. Second, we need a better understanding of the weak interaction rates in quark and (hyper)nuclear matter, which are required input in cooling simulations of compact stars. Third, the transport coefficients of dense color superconducting quark matter, such as the thermal conductivity, are input for modelling an array of phenomena, which include thermal evolution, magnetic evolution, and oscillation modes.

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