Cooling of Neutron Stars with Color Superconducting Quark Cores

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We show that within a recently developed nonlocal chiral quark model the critical density for a phase transition to color superconducting quark matter under neutron star conditions can be low enough for these phases to occur in compact star configurations with masses below 1.3 $M_\odot$. We study the cooling of these objects in isolation for different values of the gravitational mass and argue that, if the quark matter phase would allow unpaired quarks, the corresponding hybrid stars would cool too fast. The comparison with observational data puts tight constraints on possible color superconducting quark matter phases. Possible candidates with diquark gaps of the order of 10 keV - 1 MeV such as the "2SC+X" and the color spin locking (CSL) phase are presented.

1. Introduction

The cooling of compact stars is a complex problem which requires knowledge of the physics of strongly interacting matter and its coupling to leptonic degrees of freedom in a wide domain of temperatures, isospin asymmetries and densities from the solid-state like crust to the core of the star, where at supersaturation densities a transition to quark matter with a variety of possible superconducting phases is expected to occur. We are witnessing a new era of compact star physics now when observational data reach a level of accuracy which allows to discriminate between theoretical models. One example is the recent mass measurement in a neutron star - white dwarf binary system where for the pulsar PSR 0751+1807 a mass of 2.1 $\pm$ 0.2 $M_\odot$ has been reported [1]. If such a mass value for a compact star would be settled within the limits given by the presently reported 1 σ level, this would rule out all hybrid star models with a quark matter core known up to now. Another example is the upper limit for the surface temperature of the pulsar PSR J0205+64 in the supernova remnant 3C58 [2] which is significantly below the *normal* cooling behavior, given the young age for this object associated with the historical supernova from AD 1181. This implies a sensible dependence of the cooling processes on one of the characteristic parameters unknown for that compact star, such as the mass, see Fig. 1. For more observational constraints on neutron star properties, see [8] and Refs. therein. It has been demonstrated recently in Ref. [3], that a satisfactory description of

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cooling data and structure of compact stars can be given within a hadronic model without quark matter (*nuclear medium cooling* (NMC) scenario [4,5]), where medium effects are taken into account consistently. This approach could also satisfy the independent Log N - Log S test of a population synthesis model [6] and the brightness constraint [7]. One particular result of the NMC approach was the formulation of a direct Urca (DU) constraint on the equation of state (EoS) under compact star conditions: If a nuclear EoS allows the DU process to occur in typical compact star configurations with masses below ~ 1.5 $M_\odot$, then this EoS has to be abandoned since otherwise a satisfactory description of cooling data cannot be obtained. For details, see also [9,10]. The DU constraint holds in essence also for stars with quark matter phases where, however, the pairing of all quark species with appropriate pairing gaps can result in an acceptable cooling phenomenology [11–14]. In the present contribution we discuss the constraints on superconducting quark matter phases from the cooling phenomenology of stable hybrid stars when chiral quark matter models are used.

2. Compact star cooling constraints on superconducting quark matter phases

The state-of-the-art calculations for a three-flavor quark matter phase diagram within a chiral (NJL) quark model of quark matter and selfconsistently determined quark masses are described in Refs. [15–17]. ¿From these results follows that for the discussion of late cooling stages when the temperature is well below the opacity temperature $T_{\rm opac} \sim 1$ MeV for neutrino untrapping four phases are relevant: the normal quark matter (NQ), the two-flavor superconducting matter (2SC), a mixed phase of both (NQ-2SC) and the color-flavor-locking phase (CFL). The detailed structure of the phase diagram in these models still depends on the strength parameter G_D of the diquark coupling (and of the formfactor of the momentum space regularization, see [18]). For all values of G_D no stable hybrid stars with a CFL phase could be found yet, see [19], and Refs. therein. We are left with the discussion of 2SC and NQ phases (the discussion of the NQ-2SC mixed phase brings no new aspects and will be omitted for brevity).

For the 2SC phase stable hybrid star configurations with masses even below 1.3 $M_\odot$ have been obtained when a Gaussian formfactor regularization has been used. This phase has one unpaired color of quarks (say blue) for which the very effective quark DU process works and leads to a too fast cooling of the hybrid star in disagreement with the data [14]. We have suggested to assume a weak pairing channel which could lead to a small residual pairing of the hitherto unpaired blue quarks. We call the resulting gap Δ_X and show that for a density dependent ansatz

$$\Delta_X(\mu) = \Delta_c \ \exp[-\alpha(\mu - \mu_c)/\mu_c] \ , \qquad (1)$$

with μ being the quark chemical potential, $\mu_c = 330$ MeV, $\alpha = 10$ and $\Delta_c = 1.0$ MeV an acceptable cooling phenomenology can be obtained [14], see Fig. 1. The physical origin of the X-gap remains to be identified. It could occur, e.g., due to quantum fluctuations of color neutral quark sextett complexes [20]. Such calculations have not yet been performed with the relativistic chiral quark models.

For sufficiently small G_D, the 2SC pairing may be inhibited at all. In this case, due to the absence of this competing spin-0 phase with large gaps, one may invoke a spin-1 pairing channel in order to avoid the DU problem. In particular the color-spin-locking (CSL) phase [21] may be in accordance with cooling phenomenology as all quark species are paired and the smallest gap channel may have a behavior similar to Eq. (1), see [22]. A consistent cooling calculation for this phase, however, requires the evaluation of neutrino emissivities and transport coefficients which is still to be performed.

Gapless superconducting phases can occur when the diquark coupling parameter is small so that the pairing gap is of the order of the asymmetry in the chemical potentials of the quark species to be paired. Interesting implications for the cooling of gapless CFL quark matter have been conjectured due to the particular behavior of the specific heat and neutrino emissivities [23]. We find for reasonable values of G_D, however, that these phases do occur only at too high temperatures to be relevant for late cooling, if a stable hybrid configuration with these phases could be achieved at all.

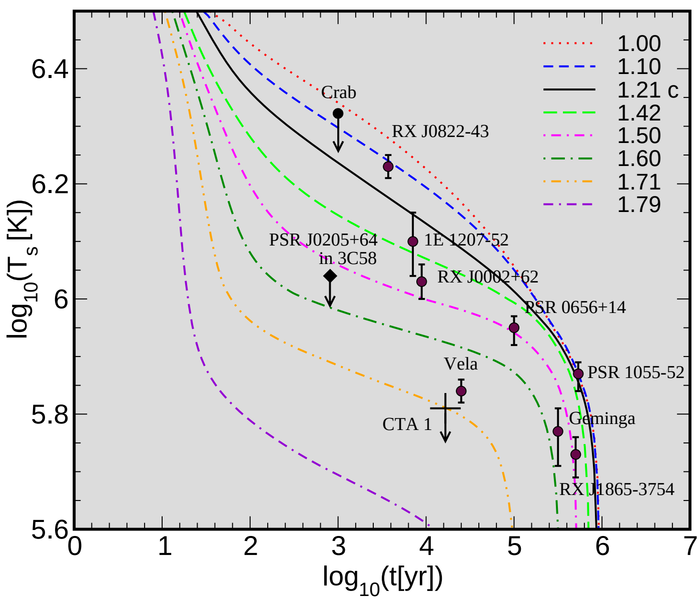

Figure 1. Cooling curves for hybrid star configurations with Gaussian quark matter core in the 2SC+X phase with density-dependent X-gap. The labels correspond to the gravitational masses of the configurations in units of the solar mass where 'c' denotes the critical one for the occurence of a quark matter core.

3. Conclusions

We have discussed that for modern phase diagrams for color superconducting three-flavor quark matter obtained within chiral quark models with selfconsistently determined quark masses out of the variety of possible phases remain the 2SC+X and the CSL phases when the following conditions are applied:

- hybrid star stability against gravitational collapse,
- compact star neutrality and β equilibrium constraints,
- DU constraint for hadronic and quark matter.

However, the physical origin of the X-gap has not yet been clarified and a consistent cooling calculation of a hybrid star with CSL quark matter has still to be performed. Gapless phases are unlikely to occur at low enough temperatures to be relevant for simulations of the late cooling of compact stars.

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