Cooling of Neutron Stars with Superconducting Quark Matter Cores

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Interiors of compact stars are considered as systems where high-density phases of strongly interacting matter do occur in nature. Consequences of different phase transition scenarios for the cooling of compact stars have been reviewed recently, see e.g. [1], in comparison with X-ray data.

A completely new situation might arise if scenarios suggested color superconductivity (CS), see [2, 3], with large diquark pairing gaps ($\Delta_q \sim 50 \div 100$ MeV) in quark matter are applicable to neutron star interiors. Various phases are possible. The two-flavor (2SC) or the three-flavor (3SC) superconducting phases allow for unpaired quarks of one color, whereas in the color-flavor locking (CFL) phase all the quarks are paired. CS may, in principle, also manifest itself in heavy ion reactions in strangelets and for $T > T_c$ via correlation effects.

Estimates of the cooling evolution have been performed [4] for a self-bound isothermal quark core neutron star (QCNS) which has a crust but no hadron shell, and for a quark star (QS) which has neither crust nor hadron shell. It has been shown there that in the case of the 2SC (3SC) phase of QCNS the cooling is governed by the quark direct Urca process (QDU) and the consequences for the cooling curves are similar to the scenario of enhanced cooling of the hadronic neutron stars. For the CFL case it has been shown that the cooling might still be much faster, inspite of opposite naive expectations, since the drop in the specific heat of CS quark matter dominates over the reduction of the neutrino emissivity. As has been pointed out in [4], it should be however an additional delay of the cooling at an early stage due to the heat transport disregarded there. Ref. [5] estimated the cooling of hybrid neutron stars (HNS), which have a crust, a wide hadronic shell and CS core, disregarding heat transport effects.

We have developed a more detailed scenario for the thermal evolution of HNS and QCNS which includes the heat transport in both the quark and the hadronic matter [6]. A detailed comparison of the cooling evolution (lg T_s vs. lg t) of HNS for different values of quark and hadron gaps is given in Fig. 1. We have found that the curves for $\Delta_q > 1$ MeV are very close to each other demonstrating typical large gap behaviour. As representative example we take $\Delta_q = 50$ MeV. The behaviour of the cooling curve for $t \lesssim 50 \div 100$ yr is determined by the heat transport within the CS core. The subsequent time evolution is governed by the processes in the hadronic shell and by a delayed transport within the quark core with a dramatically suppressed neutrino emissivity from the CS region. In order to demonstrate this feature we have also performed a calculation with the nucleon gaps ($\Delta_i(n)$, $i = n, p$) being artificially suppressed by a factor 0.2. The curves labelled "MMU" are calculated with the rates of modified Urca processes, with inclusion of appropriate medium modifications in the NN interaction [7].

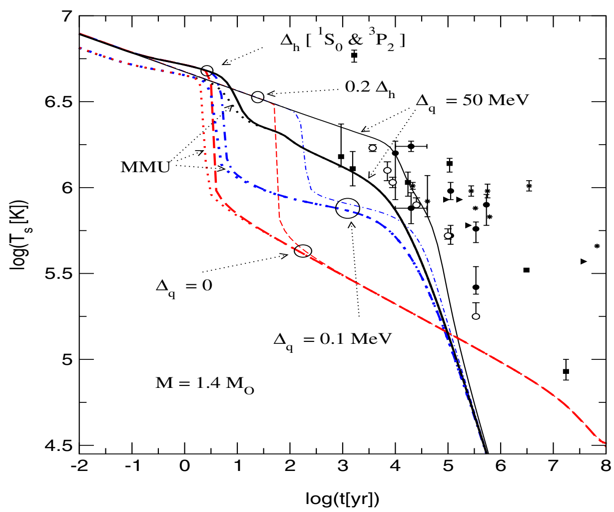

Figure 1: Evolution of the surface temperature T_s of HNS with $M = 1.4 M_\odot$ for $T_s \propto T_m^{2/3}$, where T_m is the mantle temperature, see [6] for details.

Summarizing, we have found for the CFL phase with large quark gap, which was expected to exhibit the most prominent manifestations of CS in HNS and QCNS, an essential delay of the cooling during the first $50 \div 300$ yr due to a dramatic suppression of the heat conductivity in the CS region. It seems, however, rather difficult to explain the majority of the presently known data both in the cases of the HNS and QCNS, whereas in the case of pure hadronic stars the available data are much better fitted within the same model for the hadronic matter we used here. For 2SC (3SC) phases we expect analogous behaviour to that demonstrated by $\Delta_q = 0$ since QDU processes on unpaired quarks are then allowed. We do not exclude that new observations may lead to lower surface temperatures for some supernova remnants and will be better consistent with the model which also needs further improvements. On the other hand, if future observations will show very large temperatures for young compact stars they could be interpreted as a manifestation of large gap CS in their interiors.

References

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