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Nuclear medium cooling scenario in the era of Cas A cooling data and 2 $M_\odot$ pulsar mass measurements

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Abstract. We show that all reliably known temperature data of neutron stars including those belonging to Cassiopea A can be comfortably explained in our "nuclear medium cooling" scenario of neutron stars. The cooling rates account for medium-modified one-pion exchange in dense matter, polarization effects in the pair-breaking-formation processes operating on superfluid neutrons and protons paired in the $1S_0$ state, and other relevant processes. The emissivity of the pair-breaking-formation process in the $3P_2$ state is a tiny quantity within our scenario. Crucial for a successful description of the Cassiopeia A cooling proves to be the thermal conductivity from both, the electrons and nucleons, being reduced by medium effects. Moreover, we exploit an EoS which stiffens at high densities due to an excluded volume effect and is capable of describing a maximum mass of 2.1 $M_\odot$, thus including the recent measurements of PSR J1614-2230 and PSR J0348+0432.

1. Introduction

The isolated neutron star in Cassiopeia A (Cas A) was discovered in 1999 by the *Chandra* satellite [1]. Its association with the historical supernova SN 1680 [2] gives Cas A an age of 333 years, in agreement with the nebula's kinematic age [3]. The thermal soft X-ray spectrum of Cas A can be fitted with a non-magnetized carbon atmosphere model, a surface temperature of 2×10^6 K, and an emitting radius of 8 to 17 km [4]. Analyzing the data from 2000 to 2009, Heinke & Ho [5] reported a rapid decrease of Cas A's surface temperature over a 10-year period, from 2.12×10^6 to 2.04×10^6 K. Such a rapid drop in temperature conflicts with standard cooling scenarios based on the efficient modified Urca (MU) process [6, 7]. Interpretations of Cas A's temperature data based on hadronic matter cooling scenarios were provided by Page *et al.* [8], Yakovlev *et al.* [9, 10], Blaschke *et al.* [11, 12]. The new analysis of the *Chandra* data performed by Elshamounty *et al.* [13] including a new measured data point allowed to precisely extract the decade temperature decline. The drop in the temperature lies in the range $2 \ldots 5.5\%$, and the most recent results from ACIS-S detector yield a $3 \ldots 4\%$ decline.

The interpretation of Cas A data by Page *et al.* [8] is based on the "minimal cooling" paradigm [14], where a minimal number of cooling processes is taken into account.

The works of Yakovlev *et al.* [9, 10] include all emission processes which are part of the minimal cooling paradigm including the FOPE model for MU reaction rate. They assume that the proton gap is so large that charged current processes are strongly suppressed in the entire stellar core. The value and the density dependence of the $3P_2$ neutron gap are fitted to the Cas A data, leading to a critical temperature of $0.7 \ldots 0.9 \times 10^9$ K for the neutron pairing gap and a neutron star mass $M = 1.65\ M_\odot$. Both groups therefore came to the striking conclusion that the temperature data of Cas A allow one to extract the value of the $3P_2$ neutron pairing gap. Continuing this approach Elshamouty *et al.* [13] arrive at the same conclusion.

The work of Blaschke *et al.* [11, 12] presents the "nuclear medium cooling scenario" as a model for the successful description of all the known temperature data including those of Cas A. This scenario includes efficient medium modified Urca (MMU) and medium nucleon bremstrahlung (MnB, MpB) processes, as motivated by a softening of the virtual pion mode in dense matter [15, 16], a very low (almost zero) value of the $3P_2$ neutron gap, as motivated by the result of Schwenk and Friman [17], and a small thermal conductivity of neutron star matter caused by in-medium effects, as motivated by calculations of the lepton thermal conductivity of Shternin and Yakovlev [18] and evaluations of the effect of pion softening on the nucleon thermal conductivity.

A strong suppression of the thermal conductivity is justified by results of Shternin and Yakovlev [18], who included the in-medium effect of Landau damping of electromagnetic interactions owing to the exchange of transverse plasmons in the partial electron (and muon) contribution to the thermal conductivity. Earlier, this effect has been studied by Heiselberg and Pethick for a degenerate quark plasma [19] and by Jaikumar *et al.* [20] for neutrino bremsstrahlung radiation via electron-electron collisions in neutron star crusts and cores. Now, we incorporate the in-medium modifications of the electron-electron interaction into our scenario, precisely as it has been done in [18]. Moreover, the partial NN thermal conductivity should be suppressed within our scenario owing to the increase of the squared NN interaction matrix element with density caused by the medium modification of the FOPE. Thereby, we additionally suppress the NN thermal conductivity term calculated in [21] by taking into account the softening of the one-pion exchange for this quantity as well as for all processes considered in our scenario.

As the nuclear matter equation of state (EoS), in [11] we used the Heiselberg-Hjorth-Jensen (HHJ) EoS [22] (with a fitting parameter $\delta = 0.2$) that fits the microscopic Akmal-Pandharipande-Ravenhall (APR) $A18 + \delta v + UIX^*$ EoS [23] for symmetric nuclear matter up to $4n_0$, where $n_0 = 0.16$ fm^{-3} is the nuclear saturation density. This yields an acceptable (although not perfect) fit of the APR EoS of neutron star matter for those densities. The maximum neutron star mass calculated with the HHJ($\delta = 0.2$) EoS, $M_{\rm max} = 1.94\ M_\odot$, proves to be smaller than the one calculated with the original APR EoS, $M_{\rm max} \simeq 2.2\ M_\odot$. However, the latter EoS becomes acausal for $n > 0.86$ fm^{-3}, whereas all HHJ($\delta \geq 0.13$) EoS respect causality at all densities. Recent measurements of two massive neutron stars, with $M_{1614} = 1.97 \pm 0.04\ M_\odot$ for PSR J1614-2230 [24] and $M_{0348} = 2.01 \pm 0.04\ M_\odot$ for PSR J0348-0432 [25], motivate us to use a stiffer EoS than that of HHJ($\delta = 0.2$) at large densities. In the present work we follow [12] where the EoS was modified in order to fulfill the new observational constraints on masses of neutron stars. To that end we incorporate excluded volume corrections in the HHJ($\delta = 0.2$) EoS such that it would remain unchanged for $n \lesssim 4n_0$ but would become stiffer for higher densities.

2. Nuclear medium cooling scenario

The nuclear medium cooling scenario worked out in Refs. [26, 27, 16, 28, 29] has been successfully applied to the description of the body of known surface temperature–age data of neutron stars [30, 31, 32, 33, 11].

We exploit the Fermi liquid approach, where the short-range interaction is treated with the help of phenomenological Landau-Migdal parameters, whereas long-range collective modes are explicitly presented. The most important effect comes from the mode with the pion quantum numbers treated explicitly, as it is a soft mode ($m_\pi \ll m_N$, with m_π (m_N) being the pion (nucleon) mass). The key effect is the softening of the pion mode with increasing density [15, 16]. Only with the inclusion of this softening effect the phase transition to a pion condensation state in dense nucleon matter may appear. Thus it is quite inconsistent to use FOPE model for description of NN-interaction and simultaneously include processes going on pion condensation.

This approach exploits a strong dependence of the main cooling mechanisms on the density and thus on the neutron star mass.

The insufficiency of the FOPE model for the description of the NN-interaction is a known issue. Actually, using the FOPE for the NN interaction amplitude, and simultaneously considering pion propagation as free, violates unitarity. Indeed, calculating the MU emissivity perturbatively one may use both the Born NN interaction amplitude given by the FOPE and the optical theorem, considering the imaginary part of the pion self-energy [26, 27, 28].

In the latter case, at low densities one needs to expand the exact pion Green's function to second order using for the polarization function $\Pi(\omega, k, n)$. The effective pion gap defined as $\omega^{*2} = -D_\pi^{-1}(\omega = 0, k = k_0)$. The polarization function $\Pi_0(\omega, k = k_0 \simeq p_{\mathrm{F},n}, n)$ yields a strong P-wave attraction. This attraction proves to be so strong that it would trigger a pion condensation instability already at low baryon densities of $n \sim 0.3\, n_0$, which is in disagreement with experimental data on atomic nuclei at the nuclear saturation density n_0. Note that the perturbative calculation contains no one free parameter. The paradox is resolved by observing that together with pion softening (i.e., a decrease of the effective pion gap $\omega^*(n)$ with increasing density for $n > n_{cr}^{(1)}$, $\omega^{*2}(n_{cr}^{(1)}) = m_\pi^2$) one needs to include a short-range repulsion arising from the dressed πNN vertices, $\Gamma(n) \simeq [1 + C(n/n_0)^{1/3}]^{-1}$ with $C \simeq 1.6$. This evaluation exploits an estimated value of the Fermi-liquid spin-spin Landau-Migdal parameter g and the Lindhard function taken in the limit of low transferred energy $\omega \ll p_{\mathrm{F},n}$. A consistent description of the NN interaction in matter should thus use a medium modified one-pion exchange (MOPE) interaction characterized by the fully dressed pion Green function, dressed vertices $\Gamma(n)$, and a residual NN interaction. We stress that dressing the pion mode is similar to the ordinary dressing of the photon mode in a plasma.

However, according to evaluations in [26, 16], the main contribution for $n > n_0$ is given by MOPE, whereas the relative contribution of the residual interaction diminishes with increasing density owing to polarization effects. Thus, in our simplified treatment the main dependence on the short-range interaction enters MOPE via the phenomenological vertex suppression factor $\Gamma(n)$.

The density dependence of the effective pion gap ω^* that we use for $n > n_{cr}^{(1)}$, taken to be 0.8 n_0, is demonstrated in Fig. 1 of [31]). Following the model used here and in [31, 32] within the HHJ($\delta = 0.2$) EoS, the pion condensation arises for neutron star masses $M \geq 1.32\ M_\odot$ (corresponding to the choice $n \geq n_{cr}^{\pi} = 3\, n_0$). To avoid misunderstanding we stress that, although to construct the curves $\omega^*(n)$ we used available experimental information and well established general principles [16], the quantitative density dependence of $\omega^*(n)$ remains essentially model dependent due to a lacking knowledge of the NN interaction in neutron star matter at large densities. Thus we hope that our successful description of the neutron star cooling may be helpful to correctly choose the parameterization of the interaction.

The direct Urca (DU) process, $n \to pe\bar{\nu}$, is too efficient for a description of the full set of

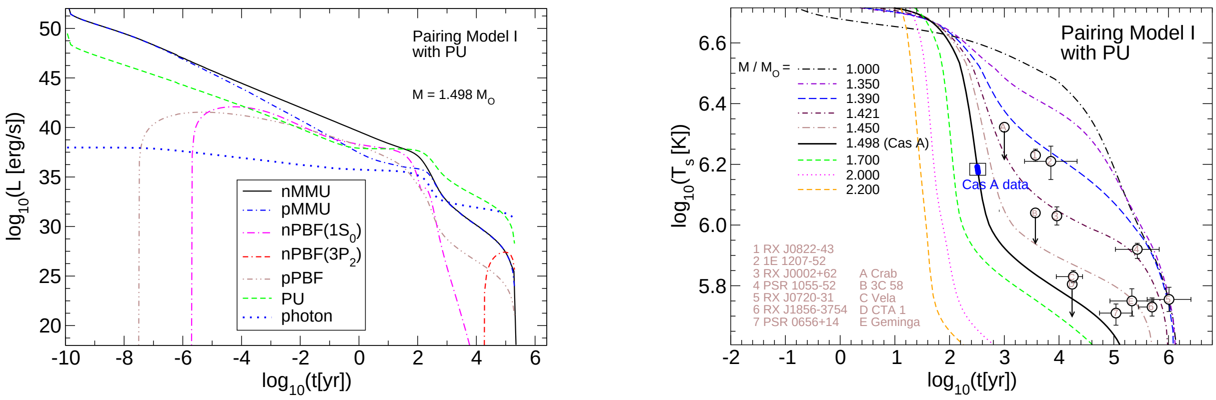

Figure 1. (Color online) Left panel: Individual contributions of the cooling processes, nMMU and pMMU, $1S_0$ pPBF and nPBF, $3P_2$ nPBF, PU, and surface photon emission, to the total stellar luminosity for the neutron star of mass 1.498 $M_\odot$ shown in the right panel of this figure. Modeling with PU exploits curves 1a+2 for the pion excitations, and 3 determining the pion condensate amplitude in Fig. 1 from [12], pairing gaps from model I. Right panel: Cooling of neutron stars in the nuclear medium cooling scenario, with different masses within model I for pairing and with PU, cf. also Fig. 17 of [31] and Fig. 1 of [11]. Data from Refs. [14, 9]. New data for Cas A from [13].

neutron star cooling data. Moreover, the DU process occurs only for high proton fractions, $x_p = n_p/n > 0.11 \ldots 0.14$. This process is practically excluded because of the choice of EoS. We adopted the HHJ($\delta = 0.2$) EoS for the description of the nucleon contribution. The energy density of nucleons is parameterized as follows

$$E_N = un_0 \left[m_N + e_{\rm B} u \frac{2 + \delta - u}{1 + \delta u} + a_{\rm sym} u^{0.6} (1 - 2x_p)^2 \right] , \tag{1}$$

where $u = n/n_0$, $e_{\rm B} \simeq -15.8$ MeV is the nuclear binding energy per nucleon, $a_{\rm sym} \simeq 32$ MeV is the symmetry energy coefficient and we chose $\delta = 0.2$. With these values of parameters one gets the best fit of APR (A18+δv+UIX*) EoS for symmetric nuclear matter up to $n \sim 4\, n_0$.

In the calculation of the neutrino emissivity of two-nucleon processes, e.g., $nn \to npe\bar{\nu}$, not only radiation from the nucleon legs but also from intermediate reaction states is allowed. For $n \gtrsim n_0$, the latter processes prove to be more efficient than the ordinary MU process from the legs. With such an interaction the ratio of the emissivity of the medium modified Urca (MMU) to the MU process, see [31, 32, 11],

$$\frac{\epsilon_\nu[\mathrm{MMU}]}{\epsilon_\nu[\mathrm{MU}]} \sim 3 \left(\frac{n}{n_0} \right)^{10/3} \frac{[\Gamma(n)/\Gamma(n_0)]^6}{[\omega^*(n)/m_\pi]^8} , \tag{2}$$

strongly increases with density for $n \gtrsim n_0$. For $n < n_{cr}^{(1)}$ we use ϵ_ν[MU] as in the minimal cooling scenario. Although an increase of the ratio of emissivities of the medium modified nucleon (neutron) bremsstrahlung process (MnB) to the unmodified bremsstrahlung (nB) is less pronounced, the MnB process, being not affected by the proton superconductivity, may yield a relatively large contribution in the region of a strong proton pairing. Note that being computed with values ω^* and Γ, which we use, the ratio of the MOPE NN cross section to that of the FOPE [28] proves to be $\sigma[\mathrm{MOPE}]/\sigma[\mathrm{FOPE}] \sim 1/3 \ldots 1/2$ for $n = n_0$ but it increases with increasing density. The subsequent increase of the cross section with density is due to the dominance of the softening of the pion mode owing to πNN and $\pi N\Delta^*(1236)$ P-wave attraction compared to the

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suppression of vertices owing to repulsive NN correlations [16, 28]. Thus the known suppression of the in-medium NN cross section at $n \lesssim n_0$ compared to that given by the FOPE [34, 35] does not conflict with a strong enhancement of the MMU emissivity with increasing density. Estimated strong density dependence of the in-medium neutrino-processes motivated authors of [26] to suggest that difference in surface temperatures of neutron stars is explained by different masses of the objects (that time only upper limits on surface temperatures were put). At the end, we should stress that in order to explain the cooling of both slowly and rapidly cooling stars one requires neutrino emissivities that differ by a factor $> 10^3$. Therefore, an uncertainty of the order of one in the emissivity of the processes does not affect the general cooling picture. In Fig.1 we show the time profiles of the individual contributions of the cooling processes. The simulation shows that the most active process in our scenario is the MMU.

3. Cooling of the young neutron star in CasA

The ingredients of the nuclear medium cooling scenario discussed above lead to neutron star cooling curves in Fig. 17 of Ref. [31], where model I for the proton gap has been adopted and the role of the thermal conductivity on the hot early stages of hadronic neutron star cooling was elucidated (see curves for $\kappa = 0.3$ in [31]). In Fig. 1 of [11] we redrew those cooling curves permitting readjustment of the thermal conductivity parameter. This allowed us to describe all cooling data including those for Cas A, known at that time.

4. Conclusions

We have shown in this paper that the nuclear medium cooling scenario allows one to nicely explain the observed rapid cooling of the neutron star in Cas A, as well as all other existing neutron star cooling data. As demonstrated already in [31] and then in [11], in our scenario the rapid cooling of very young objects like Cas A is mainly due to the efficient MMU processes, a very low (almost zero) value of the $3P_2$ neutron gap and a small thermal conductivity of neutron star matter. In the present work we do not use any artificial suppression parameter to demonstrate the effect of a small thermal conductivity caused by in-medium effects on Cas A cooling, but we *use the same values for the lepton thermal conductivity* as in Ref. [18]. The required smallness of thermal conductivity is provided by taking into account the collective effect of Landau damping.

We stress that, contrary to the minimal cooling models, within the nuclear medium cooling scenario we are trying to consistently include the most important collective effects in all relevant processes – the pion softening effect in the NN interaction amplitude [16], collective effects in the pair-breaking-formation processes [36], collective effects in the pairing gaps, the screening effect in the lepton contribution to the thermal conductivity [19] and a decrease of the nucleon contribution owing to the mentioned pion softening, etc. And we did not introduce any significant changes in our scenario developed in 2004 in [31], except for including the suppression of the thermal conductivity, now performed as in [18]. Thus in difference with other scenarios, explanation of the Cas A data straightly follows the predictions of our previous work [31].

Alternative explanations include the suggestion [37] that Cas A is a rapidly rotating star and during its spin-down the efficient DU process is switched on when the redistribution of matter leads to an increase of the central density beyond the DU threshold. Ref. [38] suggests that Cas A is a hybrid star. However, note that except our scenario other works aiming at a description of Cas A do not demonstrate their capability to obtain in the framework of the same assumptions an overall agreement with other available neutron star cooling data.

Further tests may be considered, such as a comparison of log N-log S distributions from population synthesis with the observed one for isolated neutron stars [39]. Also a continuation of the measurements of Cas A and new measurements of neutron star temperatures are welcome to discriminate between alternative cooling scenarios.

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