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Cooling of the neutron star in Cassiopeia A

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We demonstrate that the high-quality cooling data observed for the young neutron star in the supernova remnant Cassiopeia A over the past 10 years—as well as all other reliably known temperature data of neutron stars—can be comfortably explained within the "nuclear medium cooling" scenario. The cooling rates of this scenario account for medium-modified one-pion exchange in dense matter and polarization effects in the pair-breaking formations of superfluid neutrons and protons. Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects. In a few more decades of continued monitoring of Cassiopeia A, the observed data may allow one to put additional constraints on the efficiency of different cooling processes in neutron stars.

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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 330 years, in agreement with the nebula's kinematic age [3]. The distance to the stellar remnant is estimated to be $3.4^{+0.3}_{-0.1}$ kpc [4]. The thermal soft x-ray spectrum of Cas A can be fitted with a nonmagnetized carbon atmosphere model, a surface temperature of 2×10^6 K, and an emitting radius of 8 to 17 km [5]. Analyzing the data from 2000 to 2009, Heinke and Ho [6] reported a rapid decrease of Cas A's surface temperature over this 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 [7,8]. Initial interpretations of Cas A's temperature data were provided very recently by Page *et al.* [9] and Yakovlev and co-workers [10,11].

The interpretation of Page *et al.* [9] is based on the "minimal cooling" paradigm [12], where a minimal number of cooling processes is taken into account. These are photon emission, the MU process, nucleon-nucleon (NN) bremsstrahlung (NB), and the neutron (n) and proton (p) pair-breaking-formation (nPBF and pPBF) processes. The latter are particularly important in the ultradense cores of neutron stars [13–15], where neutrons form Cooper pairs in the $^3P_2$ channel and proton pairing occurs in the $^1S_0$ channel. To calculate the NN interaction entering the emissivities of the MU and NB processes the minimal cooling scenario employs the free one-pion exchange (FOPE) model [16]. As shown in Ref. [9], the Cas A data can be neatly reproduced by assuming a large value for the proton pairing gap throughout the entire stellar core and by fixing the critical temperature for the neutron $^3P_2$ pairing gap at around 0.5×10^9 K. The result is mildly sensitive to the neutron star mass. Surface temperature–age data of other neutron stars, which do not lie on the cooling curve of Cas A, are explained within the minimal cooling scenario mainly by assuming variations in the light-element mass of the envelopes of these stars.

The work of Yakovlev and co-workers [10,11] includes all emission processes which are part of the minimal cooling paradigm and uses also the FOPE to model the NN interaction. As in Ref. [9], it is assumed that the proton gap is large and nonvanishing in the entire stellar core. The latter assumption facilitates a strong suppression of the emissivity of the MU process. 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 (0.7–0.9) $\times 10^9$ K for the neutron pairing gap. 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.

In this Rapid Communication, we present the "nuclear medium cooling scenario" as an alternative model for the successful description of the temperature data of Cas A. Aside from describing the Cas A data extremely well, this model reproduces also all other presently known temperature data of neutron stars, without the need of making any additional assumptions. Before representing the stellar cooling results, we outline the key features of the nuclear medium cooling scenario next.

Nuclear medium cooling. Motivated by the fact that the existing surface temperature–age data of neutron stars seem to be incompatible with a unique cooling evolution, the nuclear medium cooling scenario has been worked out in Refs. [14,17–19]. It provides a microscopic justification for a strong dependence of the main cooling mechanisms on the density (and thus on the neutron star mass). The nuclear medium cooling scenario has been successfully applied to the description of the body of known surface temperature–age data of neutron stars [15,20,21]. The scenario addresses the often disregarded role of medium effects on the MU and NB processes. Furthermore, as is commonly accepted, the neutron and proton superfluidity with density-dependent pairing gaps is causing an exponential suppression of neutrino emissivities of the nucleon processes and of the nucleon specific heat, thereby opening up the new class of nPBF and pPBF processes. We also want to stress that the thermal conductivity is essential for the cooling of young objects such as Cas A. The next paragraph is devoted to a brief discussion of these issues. For more details, we refer to Refs. [18–20].

1. Free versus medium-modified one-pion exchange in dense matter. The insufficiency of the FOPE model for the description of the NN interaction is a known issue [19]. Indeed, calculating the MU emissivity perturbatively one may use both the Born NN interaction amplitude given by the FOPE model and the imaginary part of the pion self-energy. In the latter case one needs to expand the exact pion Green's function $D_\pi(\omega, k) = [\omega^2 - m_\pi^2 - k^2 - \Pi(\omega, k, n)]^{-1}$ to second order using for the polarization function $\Pi(\omega, k, n)$ of the perturbative one-loop diagram, $\Pi_0(\omega, k, n)$. For $k = k_0$, which is the pion momentum at the minimum of the effective pion gap, $\omega^{*2} = -D_\pi^{-1}(\omega = 0, k = k_0)$, the polarization function $\Pi_0(\omega, k = k_0 \simeq p_{\mathrm{F},n}, n)$ yields however a strong NN attraction. Here m_π is the pion mass and $p_{\mathrm{F},n}$ is the neutron Fermi momentum. This attraction is so strong that it would trigger a pion condensation instability already at low baryon densities of $n \sim 0.3\, n_0$ (where $n_0 = 0.16$ fm^{-3} denotes the nuclear saturation density), which is in disagreement with experimental data on atomic nuclei.

The discrepancy is resolved by observing that, together with pion softening [i.e., a decrease of the effective pion gap $\omega^*(n)$ with increasing density, $\omega^{*2}(n_0) \simeq m_\pi^2$], one needs to include the repulsion from the dressed πNN vertices, $\Gamma(n) \simeq [1 + C(n/n_0)^{1/3}]^{-1}$, with $C \simeq 1.6$. A consistent description of the NN interaction in matter should thus use a medium-modified one-pion exchange (MOPE) interaction characterized by the full Green function of the dressed pion, dressed vertices $\Gamma(n)$, and a residual NN interaction, as done in this Rapid Communication. According to Refs. [17,18], the main contribution for $n > n_0$ is given by MOPE whereas the relative contribution of the residual interaction decreases with increasing density. Following the model used in Refs. [20,21], we find that pion condensation may arise only for $n \geqslant n_{cr}^\pi = 3\, n_0$, i.e., for neutron star masses $M \geqslant 1.32 M_\odot$ within a relativistic version of the Akmal, Pandharipande, Ravenhall equation of state [22] which we use. In the calculation of the neutrino emissivity, radiation not only from the nucleon legs but also from intermediate reaction states is now allowed. With such an interaction the ratio of the emissivity of the medium modified Urca (MMU) to the MU process,

$$\frac{\epsilon_\nu[\mathrm{MMU}]}{\epsilon_\nu[\mathrm{MU}]} \sim 3 \left(\frac{n}{n_0}\right)^{10/3} \frac{[\Gamma(n)/\Gamma(n_0)]^6}{[\omega^*(n)/m_\pi]^8}, \qquad (1)$$

strongly increases with density for $n \gtrsim n_0$. 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 unaffected by the proton superconductivity, may yield a relatively large contribution in the region of strong proton pairing. Note that with our choice of values for ω^* and Γ, the ratio of the NN cross sections [19] is $\sigma[\mathrm{MOPE}]/\sigma[\mathrm{FOPE}] < 1$ for $n = n_0$ and increases with increasing density.

2. Pair-breaking formation. The important role of polarization effects in pPBF and nPBF processes was first noted in Ref. [14]. Recently, additional support came from an analysis of the vector current conservation in PBF reactions [23,24]. In these reactions, diagrams with the normal and anomalous Green functions turn out to cancel each other, so that the main contribution to the PBF emissivity comes from processes of the axial current [24]. Another important in-medium effect was recently observed in the calculation of the neutron pairing gap $^3P_2$. By taking into account the polarization effects, it was shown in Ref. [25] that the associated gap $\Delta_{nn}(^3P_2) \lesssim$ keV; i.e., it is dramatically suppressed compared to BCS-based calculations [26]. For completeness, we also mention the possibility of a strong enhancement (more than 1 MeV) of the gap, as argued in Ref. [27]. At first glance, the results of Refs. [25,27] seem to illustrate uncertainties in the value of the $^3P_2$ gap, which would suggest treating $\Delta_{nn}(^3P_2)$ as a free parameter in cooling studies. This, however, is not the case since the solution of the gap equation of Ref. [27] exists only for $\Delta_{nn}(^3P_2) \gtrsim 1$ MeV and disappears for smaller values of the gap. Moreover, they use the approximation $0 < \omega^{*2}(n) \ll m_\pi^2$ so that their new solution may exist only within a narrow range of the critical density for the onset of pion condensation. In realistic treatments, pion condensation appears always as a first-order phase transition [18] with a jump of ω^{*2} from a positive to a negative value. The required small values of the pion gap may therefore not be achieved. Moreover, Grigorian and Voskresensky [21] have verified that the cooling data are hardly described if the gap $\Delta_{nn}(^3P_2)$ were large ($\gtrsim$1 MeV) over a broad density region. We therefore disregard the possibility of a large value of $\Delta_{nn}(^3P_2)$ and adopt a tiny $\Delta_{nn}(^3P_2)$ following [25]. The neutron gap $\Delta_{nn}(^1S_0)$ is taken from [28]. It disappears in the core, for $n \gtrsim 0.7 n_0$. Two different models, labeled I and II, are used for the proton gap $\Delta_{pp}(^1S_0)$ which reaches out to larger densities [20,21]. Model I is from Ref. [29] and model II is from the calculations in Ref. [26]. Neutron star cooling data can be well described within the nuclear medium cooling scenario for both models I and II [20], provided $\Delta_{nn}(^3P_2)$ is strongly suppressed, in agreement with Schwenk and Friman [25].

3. Heat conductivity. The heat conductivity, κ, of superfluid neutron star matter is another key ingredient crucial for the cooling of young neutron stars, such as Cas A. It is given by $\kappa = \sum_i \kappa_i$, where κ_i are the partial contributions to κ. In Refs. [20,29] the electron and nucleon heat conductivities computed according to Ref. [30] were used. More recent studies [31] showed that the total thermal conductivity is actually reduced by an order of magnitude (see Fig. 2 in the second paper of Ref. [31]). Moreover, as we argued in Ref. [20], pion softening effects may additionally suppress the neutron contribution κ_n to the thermal conductivity. Indeed, $\kappa_n \propto 1/\sigma[\mathrm{MOPE}] \propto [\omega^*(n)]^4/\Gamma^4(n)$ is decreasing with increasing density for $n > n_0$; an effect which is not included in Ref. [31].

The impact of a low thermal conductivity on the thermal evolution of neutron stars accomplished by introducing a factor

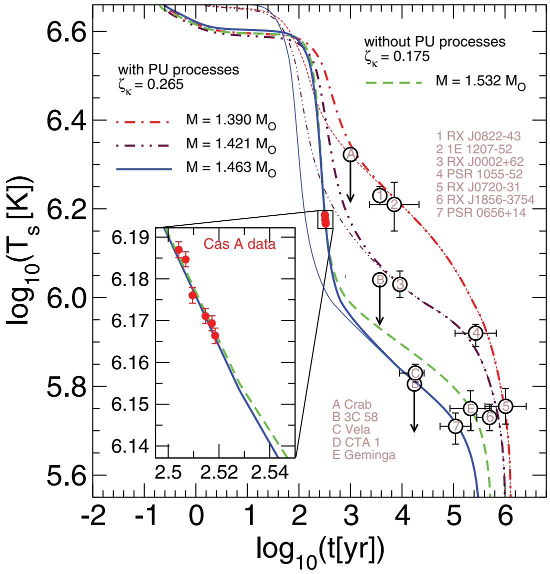

FIG. 1. (Color online) Cooling of neutron stars with nuclear medium effects, with and without pion condensation (PU) (see also Fig. 17 of Ref. [20]). The data are from Refs. [10,12].

$\zeta_\kappa = 0.3$ was demonstrated in Fig. 17 of Ref. [20]. The net effect is a delay of the temperature decline of young (∼300 years) neutron stars. This idea of a possible strong suppression of the thermal conductivity, as supported by [31], proves essential for the explanation of the rapid cooling of Cas A in this Rapid Communication.

The Neutron Star in Cas A. The ingredients of the nuclear medium cooling scenario discussed above lead to the neutron star cooling curves in Fig. 17 of Ref. [20], where model I for the proton gap has been used and the role of the heat conductivity on the hot early stages of hadronic neutron star cooling was elucidated. In Fig. 1 we redraw those cooling curves, allowing for a minor readjustment of the heat conductivity parameter. The bold curves are for a heat conductivity suppressed by a factor of $\zeta_\kappa = 0.265$, while the thin lines are for the unsuppressed heat conductivity of Ref. [30]. One sees that for a suppression factor of $\zeta_\kappa = 0.265$ and a stellar mass of $M = 1.463 M_\odot$ (blue bold solid line) we are able to fit the temperature data for Cas A perfectly, as can be seen from the magnified 10-year epoch for which high-precision cooling data exist. This star is our best-fit model. By lowering the neutron star mass to $M = 1.390 M_\odot$ (red dash-dotted line), the whole set of available cooling data is covered. By assuming the absence of a pion condensate in the core of a neutron star, the Cas A cooling data can still be reproduced by reducing ζ_κ from 0.265 to 0.175 and readjusting the neutron star mass to a somewhat higher value of $1.532 M_\odot$ (see Fig. 1). The proton gap of model II is significantly smaller than that of model I. Nevertheless, the Cas A data can still be nicely fitted for $\zeta_\kappa \leqslant 0.015$ and neutron star masses $M \geqslant 1.73 M_\odot$.

To demonstrate the impact of the heat conductivity on the cooling process we present in Fig. 2 the temperature profiles for the $1.463 M_\odot$ neutron star ($\zeta_\kappa = 0.265$) for stellar ages from 10^{-8} to 10^3 years. One sees that the heat conductivity is important during the first $t \lesssim 300$ years and would thus affect the cooling history of Cas A.

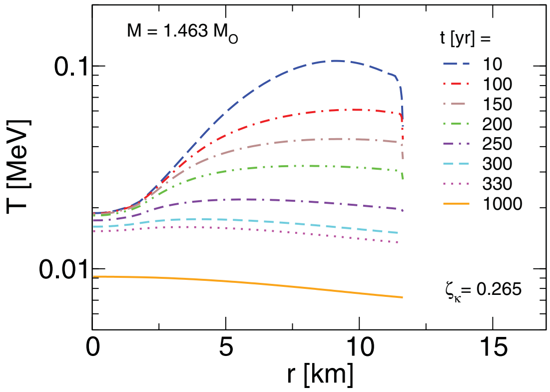

FIG. 2. (Color online) Snapshots of temperature profiles for the Cas A cooling curve (blue bold solid line) of Fig. 1.

In Fig. 3 we show the individual contributions of the cooling processes of our scenario to the total neutron star luminosity for the neutron star, $M = 1.463 M_\odot$ and $\zeta_\kappa = 0.265$, which best reproduces the cooling of Cas A in Fig. 1. We see that the nMMU is the most efficient process in our scenario, while all PBF processes are less important. The MnB and MpB luminosities dominate over those of PBF. They are not shown in Fig. 3 since they have shapes rather similar to those of the nMMU and pMMU curves. Note that PU processes affect the neutron star cooling primarily at later times.

Summary and Conclusion. We have shown that the nuclear medium cooling scenario allows one to nicely explain the observed rapid cooling of the neutron star in Cas A. As demonstrated already in Ref. [20], in this scenario the rapid cooling of very young objects like Cas A is due to the efficient MMU and MnB processes, a very low (almost zero) value of the $^3P_2$ neutron gap, and a small thermal conductivity of neutron star matter.

Our explanation of the Cas A cooling constitutes an alternative to that of Refs. [9,11], which is based on a strong

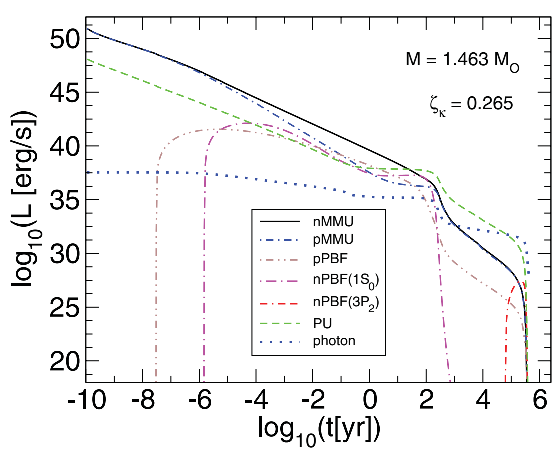

FIG. 3. (Color online) Individual contributions of the cooling processes nMMU and pMMU, $^1S_0$ pPBF and nPBF, $^3P_2$ nPBF, PU, and surface photon emission to the total stellar luminosity for the neutron star shown in Fig. 2.

PBF process due to $^3P_2$ superfluidity in neutron star interiors. We support, however, the conclusion of these authors about the sensitivity of the result to the value of the proton gap. In our scenario this sensitivity appears due to the strong dependence of the MMU emissivity on the proton gap existing up to $n \lesssim (3\text{–}4)n_0$ in the neutron star core where the MMU process is most efficient. The results presented in Fig. 1 for model I of p pairing predict that the rapid cooling observed for Cas A will continue until it slows down when the temperature domain around $\log_{10} T_s[\text{K}] = 6$ is reached. Through continued monitoring for a few more decades, the high accuracy of the data for Cas A's surface temperature may allow one to put constraints on the efficiency of the MMU processes that we use in our scenario, distinguishing at the 2σ level between models with and without additional fast cooling.

To discriminate between alternative cooling scenarios, further tests may be considered, such as the comparison of log N-log S distributions from population synthesis with the observed one for isolated neutron stars. The authors of Ref. [32] favored model II for the proton gaps. Thus it may well be that actual values of the thermal conductivity are smaller than assumed in Fig. 1 or that there are other important aspects of the cooling of Cas A.

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