On the Cooling of the Neutron Star in Cassiopeia A

D. Blaschke,1,2 H. Grigorian,3 D. N. Voskresensky,4,5 and F. Weber6

1 Institute for Theoretical Physics, University of Wroclaw, 50-204 Wroclaw, Poland
2 Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia
3 Department of Theoretical Physics, Yerevan State University, 375025 Yerevan, Armenia
4 National Research Nuclear University (MEPhI), 115409 Moscow, Russia
5 EttreNe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
6 Department of Physics, San Diego State University, San Diego, California 92182, USA

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.

The thermal soft X-ray spectrum of Cas A can be fitted to the neutron pairing gap throughout the entire stellar core and by fixing the critical temperature for the neutron pairing gap at around $0.5 \times 10^9$ 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 et al. includes all emission processes which are part of the minimal cooling paradigm and uses also the FOPE to model the NN interaction. As in [9], it is assumed that the proton gap is large and non-vanishing 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 Letter, 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 NSs, 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 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\cite{13,22,21}. The scenario addresses the often disregarded role of medium effects on the MU and NB processes. Furthermore, as it 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, and opens 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 essentials for the cooling of young objects such as Cas A. For more details, we refer to\cite{18–20}.

1. Free versus medium-modified one-pion-exchange in dense matter: The insufficiency of the FOPE model for these issues. For more details, we refer to\cite{18–20}.

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as supported by [31], proves essential for the explanation of the rapid cooling of Cas A in this letter.

The Neutron Star in Cas A.— The ingredients of the nuclear medium cooling scenario discussed above lead to 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 ζκ = 0.265, while the thin lines are for the unsuppressed heat conductivity of [30]. One sees that for a suppression factor of ζκ = 0.265 and a stellar mass of M = 1.463 M⊙ (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. Lowering the neutron star mass to M = 1.390 M⊙ (red dash-dotted line) the whole set of available cooling data is covered. 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 ζκ from 0.265 to 0.220 and readjusting the neutron star mass to a somewhat higher value of 1.506 M⊙, 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 ζκ ≤ 0.015 and neutron star masses M ≥ 1.73 M⊙.

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⊙ neutron star (ζκ = 0.265) for stellar ages from 10−8 to 103 years. One sees that the heat conductivity is important during the first t ≤ 300 years and would thus affect the cooling history of Cas A.

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⊙ and ζκ = 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 rather similar shapes as the nMMU and pMMU curves. Note that PU processes affect the NS cooling primarily at later times.

Summary and Conclusion.— We have shown in this Letter 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 [20], in this scenario the rapid cooling of very young objects like
FIG. 3: (Color online) Individual contributions of the cooling processes \text{nMMU} and \text{pMMU}, \text{LS}_0 \text{pPBF} and \text{nPBF}, \text{3P}_2 \text{nPBF}, \text{PU}, and surface photon emission to the total stellar luminosity for the neutron star shown in Fig. 2.

Cas A is due to the efficient MMU and MnB processes, a very low (almost zero) value of the $^3P_2$ neutron gap, a large proton gap and a small thermal conductivity of neutron star matter.

Our explanation of the Cas A cooling constitutes an alternative to that of \cite{11, 19}, which is based on a strong PBF process due to $^3P_2$ superfluidity in neutron star interiors. We support, however, the conclusion of these authors that a large value of the proton gap is preferable, albeit not necessarily in the entire neutron star core. The results presented in Fig. \ref{fig:3} predict that the rapid cooling observed for Cas A will continue for a few more decades until it slows down when the temperature domain around log$_{10}T_s[K] = 6$ is reached. Already in about ten years from now of continued monitoring, the high accuracy of the data for Cas A’s surface temperature will allow one to distinguish at the 2 $\sigma$ level between models with and without additional fast cooling processes (pion condensation in our case).

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. A recent study of this kind \cite{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 which have not yet been identified.

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