On the Nature of the Central Compact Object in HESS J1731-347 within Hadronic and Kaon-Condensed Frameworks

D. G. Nanopoulos[1,*], P. S. Koliogiannis[2], C. C. Moustakidis[1]

[1] Department of Theoretical Physics, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece

[2] Department of Physics, Faculty of Science, University of Zagreb, Bijenička cesta 32, 10000 Zagreb, Croatia

*dnanopou@physics.auth.gr

D. G. Nanopoulos

Motivation

One of the most important subjects in nuclear physics is the study of the nature of astrophysical compact objects. A quite intriguing scenario when examining the composition of nuclear stellar matter in compact star cores is the presence of exotic constituents such as kaon condensates. In the present conference contribution, we focus our attention on the central compact object (CCO) in the HESS J1731-347 supernova remnant. The CCO's mass and radius have been estimated equal to $M = 0.77^{+0.20}_{-0.17}\, M_{\odot}$ and $\mathrm{R} = 10.4^{+0.86}_{-0.78}$ km (at the 1σ level), while its redshifted surface temperature has been calculated equal to 153^{+4}_{-2} keV at an age of 2-6 kyrs. We attempt to explain not only its mass and radius but also its redshifted surface temperature for the previous time frame via considering two different stellar configurations. The first one dictates a fully hadronic neutron star, while the second one predicts the presence of kaon condensate in the star's core.

Equation of State & Cooling Formalism

We employed two different Equations of State (EOS's), one constructing a purely hadronic neutron star (NS) and the other predicting the existence of a kaon-condensed region in the stellar interior [1-3]. The neutrino emitting processes, which are activated in the purely hadronic regions in both compact star models, are the nucleon-nucleon Bremsstrahlung processes, the Modified Urca processes and the pair breaking and formation (PBF) processes (when superfluidity occurs). The powerful Direct Urca process is oppressed in both previous cases because the triangle condition $p_{Fn} < p_{Fp} + p_{Fe}$ is not satisfied. The kaon condensate of the second stellar configuration develops and induces three additional powerful neutrino emitting processes, whose emission rates are greater than the rates of the aforementioned, activated processes by several orders of magnitude [4]. The emissivities and the specific heat contributions of the nucleons in the both stellar configurations are suppressed by pairing phenomena. More precisely, we consider the neutrons and protons of the core to form $^3P_2$ (neutron triplet) and $^1S_0$ (proton singlet) superfluids, respectively. In Figures 1a and 1b we present the superfluidity models which were implemented, based on the work of Andersson et al. (2005) [5]. We considered two different cases of the heat blanketing envelopes chemical composition. The first one is constructed by heavier, iron-like elements and the second one by lighter, helium-like elements.

Results

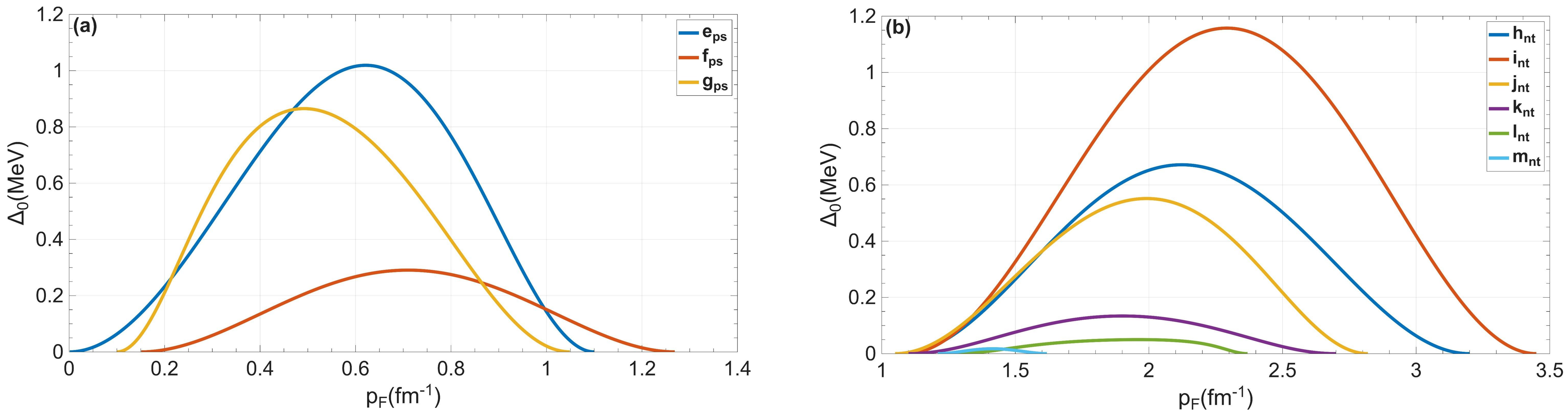

Figure 1. (a) Superfluid energy gaps (in MeV) versus fermi momenta (in fm^{-1}) for the $^1S_0$ pairing models. **(b)** Superfluid energy gaps versus fermi momenta for the $^3P_2$ pairing models.

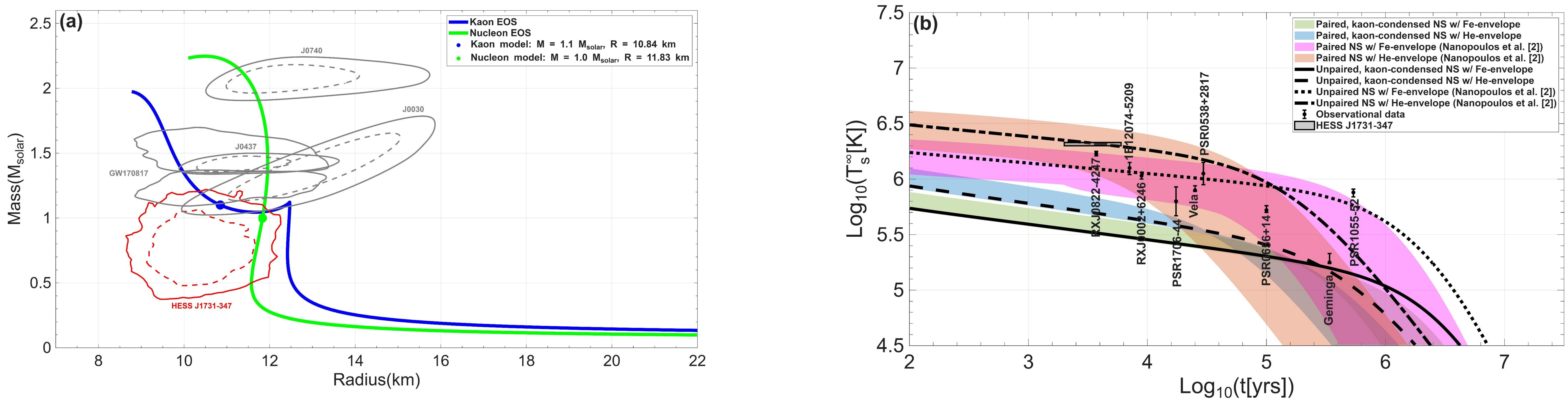

Figure 2. (a) Mass–radius curves for each of the constructed EOS's. The solid contours correspond to the 2σ confidence, while the dashed contours to the 1σ confidence. **(b)** Evolution of the redshifted surface temperature with respect to time for both models. The pink and orange regions correspond to the superfluid, hadronic NS and the blue and green regions to the kaon condensed NS. The dot-dashed and dotted lines correspond to the non superfluid, hadronic NS, while the solid and dashed curves to the non superfluid, kaon condensed NS.

Conclusions

(I) Kaon condensed NS's are unable to predict the redshifted surface temperature of the HESS J1731-347 at the specific time frame for both cases of the envelope's composition. The activation of the strong neutrino emitting processes lead to a rapid cooling scenario.

(II) The fully hadronic, paired NS with an envelope constructed by lighter elements is able to reconcile with the thermal evolution constraints of the CCO. The same stellar configuration, when considering an envelope composed by iron like elements, deviates from the redshifted surface temperature of the specific compact object.

(III) The hadronic, unpaired NS with an helium-like envelope is able to reach agreement with the CCO's observational constraints, which is not possible when considering an iron-like envelope. The absence of a strong neutrino emitting process like the Direct Urca process leads to a standard cooling scenario, which helps the prediction of higher redshifted surface temperatures.

Acknowledgements

This work is supported by the Croatian Science Foundation under the project Relativistic Nuclear Many-Body Theory in the Multimessenger Observation Era (HRZZ-IP-2022-10-7773) and by the European Union – NextGenerationEU through the National Recovery and Resilience Plan 2021-2026 -- Institutional grant of University of Zagreb Faculty of Science (Nuclear Astrophysics).

References

[1] Lattimer, J.M. Constraints on Nuclear Symmetry Energy Parameters. *Particles* **2023**, *6*, 30-56.

[2] Nanopoulos, D.G.; Laskos-Patkos, P.; Moustakidis, C.C. On the Cooling of Compact Stars in Light of the HESS J1731-347 Remnant. *Universe* **2026**, *12*, 18.

[3] Veselský, M.; Koliogiannis, P.S.; Petousis, V.; Leja, J.; Moustakidis, C.C. How the HESS J1731-347 object could be explained using K-condensation. *Phys. Lett. B* **2025**, *860*, 139185.

[4] Kubis, S.; Kutschera, M. Kaon condensates, nuclear symmetry energy and cooling of neutron stars. *Nucl. Phys. A* **2003**, *720*, 189–206.

[5] Andersson, N.; Comer, G.L.; Glampedakis, K. How viscous is a superfluid neutron star core? *Nucl. Phys. A* **2005**, *763*, 212-229.