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### Implications of Kaon Condensation in Dense Nuclear Matter for Recent Light Compact Star Observations

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ARTICLE

# Implications of Kaon Condensation in Dense Nuclear Matter for Recent Light Compact Star Observations

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## Abstract

Recent measurements of the compact star XTE J1814-338, with a mass of  $M = 1.2^{+0.05}_{-0.05} M_{\odot}$  and a radius of  $R = 7^{+0.4}_{-0.4}$  Km alongside those of HESS J1731-347, which has a mass of  $M = 0.77^{+0.20}_{-0.17} M_{\odot}$  and a radius of  $R = 10.4^{+0.86}_{-0.78}$  Km, provide compelling evidence for the potential existence of exotic matter in neutron star cores. These observations offer important insights into the equation of state of dense nuclear matter. In this study, we explore the presence of negatively charged kaons and neutral anti-kaons ( $K^{-}$  and  $\bar{K}^0$ ) within neutron stars (NSs) using a Relativistic Mean Field (RMF) model with first order kaon condensate. To our knowledge, this is the first alternative approach aiming to simultaneously explain the observed properties of both XTE J1814-338 and HESS J1731-347 by invoking kaon condensation in dense matter. Furthermore, we compare our model with recent data from the pulsars PSR J0437-4715 and PSR J1231-1411, and argue that a two-branch scenario, each representing a distinct form of nuclear matter, may be necessary to account for the diverse range of compact astrophysical objects.

**Keywords:** Neutron Stars; Kaon Condensation; Nuclear Matter

## 1. Introduction

It is now well established that NSs are compact objects with central densities that approach or exceed nuclear saturation density. Their bulk properties, such as a maximum mass above  $2 M_{\odot}$  and radii of  $R \simeq 12\text{--}13$  km at the canonical mass of  $1.4 M_{\odot}$ , can be reproduced by nuclear equations of state (EoSs) composed primarily of neutrons, protons, and electrons, even when additional degrees of freedom (e.g., muons, hyperons, or kaons) are included [1, 2]. In this context, kaon condensation in dense matter, first proposed by Kaplan and Nelson [3], has been extensively investigated [4–7]. Because the attractive interaction between  $K^{-}$  mesons and nucleons lowers the kaon energy with increasing density, the  $K^{-}$  energy may eventually fall below the electron chemical potential in  $\beta$ -equilibrated

NS matter, triggering the formation of a  $K^-$  Bose condensate. The kaon–nucleon interaction in vacuum has been modeled by Brown *et al.* [4] using an effective chiral Lagrangian.

The  $K^-N$  interaction is well understood and, unlike the  $K^-p$  channel, is only mildly influenced by resonances. Kaiser *et al.* [6, 7] employed energy-dependent  $K^-N$  amplitudes derived within a coupled-channel framework based on the chiral SU(3) effective Lagrangian, incorporating medium-correlation effects. Their analysis indicates that  $K^-$  condensation sets in at densities exceeding  $4\rho_0$ , where  $\rho_0 = 0.16 \text{ fm}^{-3}$  is the nuclear saturation density. This threshold is comparable to the central density of a  $1.4 M_\odot$  NS, estimated to be roughly  $4\rho_0$  using realistic nuclear-force models [8]. The formation of such a condensate may significantly modify the stellar structure, influencing both the maximum mass and the cooling behavior of massive NSs.

Within the extremely dense core of NSs, the density and pressure can reach quite high values, energetically allowing the formation of kaons in order to balance the Fermi energy and reduce the overall energy density. As the density in NSs increases, electrons become highly degenerate, and beyond a certain threshold, it becomes energetically favorable for  $K^-$  to replace electrons as charge neutralizing agents. This procedure introduces an excess of strangeness, as  $K^-$  contains an anti-strange quark ( $\bar{s}$ ). With further increase in density, the energy conditions favorable the formation of  $\bar{K}^0$  ( $m_{\bar{K}^0}c^2 > m_Kc^2$ ), which, due to their lack of electric charge, introduce additional strangeness without altering the charge neutrality. The presence of  $\bar{K}^0$  leads to further softening of the EoS at high energy density enabling the formation of strangeness-rich compact object.

Until recently, NSs or compact objects with masses below the canonical value of  $1.4 M_\odot$  remained largely unclassified. Within the past year, the compact object HESS J1731–347 was reported to have a mass of  $M = 0.77^{+0.20}_{-0.17} M_\odot$  and a radius of  $R = 10.4^{+0.86}_{-0.78} \text{ km}$  [9]. In addition, new analyses of XTE J1814–338 [10, 11] suggest a mass of  $M = 1.2^{+0.05}_{-0.05} M_\odot$  and a radius of  $R = 7^{+0.4}_{-0.4} \text{ km}$ . These findings introduce a set of light compact objects that are difficult to interpret within a single physical framework while simultaneously satisfying the maximum-mass constraint for NSs. A further low-mass candidate, PSR J1231–1411 [12], was recently reported with  $M = 1.04^{+0.05}_{-0.03} M_\odot$  and  $R = 12.6^{+0.3}_{-0.3} \text{ km}$ , though the authors caution that convergence issues in the fitting procedure may imply larger uncertainties. The emerging diversity among light compact objects therefore calls for a corresponding diversity in the underlying physical scenarios and internal structures.

Several works have attempted to account for the properties of XTE J1814–338 within hybrid-star frameworks. Pitz and Schaffner-Bielich [13] proposed a bosonic star with a nuclear-matter core, while Yang *et al.* [14] examined a strange star admixed with mirror dark matter. Lopes and Issifu [15] further suggested that the object may instead be a NS containing dark matter. The broader concept of ultra-compact stars had already been explored by Li *et al.* [16], prior to the results of Ref. [9]. Laskos-Patkos and Moustakidis [17] recently demonstrated that agreement with the observed properties of XTE J1814–338 can be obtained by assuming a first-order phase transition with appropriately chosen transition density and energy-density discontinuity. Another viable explanation involves the presence of strangeness as an additional degree of freedom, whose abundance may depend on the star’s formation history. Since strangeness production generally requires high densities and temperatures, compact stars enriched with strangeness are expected to form during the collapse of massive progenitors, where such extreme conditions are naturally realized [18, 19].

Therefore, we employ an EoS capable of describing both the bulk properties of NSs and those of ultra-light compact objects by introducing two distinct branches: (a) a nucleonic branch that satisfies current astrophysical constraints on NSs, and (b) an exotic branch composed of a kaonic mixture that captures the characteristics of ultra-light compact objects [18]. In our previous work [20], we attempted to reproduce the properties of HESS J1731–347 using only a  $K^-$  bosonic condensate. In the present study [21], we extend this approach by incorporating a  $\bar{K}^0$  condensate in addition to the

$K^-$  component.

## 2. The theoretical framework

Within the relativistic mean field (RMF) framework, and employing the extended Dirac–Hartree approximation, the energy density and pressure of neutron matter are expressed as follows [22]:

$$\begin{aligned} \mathcal{E}_N = & \frac{(\hbar c)^3 g_{\omega N}^2}{2(m_\omega c^2)^2} n_N^2 + \frac{(\hbar c)^3 (\frac{g_{\rho N}}{2})^2}{2(m_\rho c^2)^2} \rho_I^2 + \frac{(m_\sigma c^2)^2}{2g_{\sigma N}^2 (\hbar c)^3} (M_N c^2 - M_N^* c^2)^2 + \frac{\kappa}{6g_{\sigma N}^3} (M_N c^2 - M_N^* c^2)^3 \\ & + \frac{\lambda}{24g_{\sigma N}^4} (M_N c^2 - M_N^* c^2)^4 + \sum_{i=n,p} \frac{\gamma}{(2\pi)^3} \int_0^{k_{Fi}} 4\pi k^2 \sqrt{(\hbar ck)^2 + (m_i^* c^2)^2} dk, \end{aligned} \quad (1)$$

$$\begin{aligned} \mathcal{P}_N = & \frac{(\hbar c)^3 g_{\omega N}^2}{2(m_\omega c^2)^2} n_N^2 + \frac{(\hbar c)^3 (\frac{g_{\rho N}}{2})^2}{2(m_\rho c^2)^2} \rho_I^2 - \frac{(m_\sigma c^2)^2}{2g_{\sigma N}^2 (\hbar c)^3} (M_N c^2 - M_N^* c^2)^2 + \frac{\kappa}{6g_{\sigma N}^3} (M_N c^2 - M_N^* c^2)^3 \\ & + \frac{\lambda}{24g_{\sigma N}^4} (M_N c^2 - M_N^* c^2)^4 + \sum_{i=n,p} \frac{1}{3} \frac{\gamma}{(2\pi)^3} \int_0^{k_{Fi}} \frac{4\pi k^2}{\sqrt{(\hbar ck)^2 + (m_i^* c^2)^2}} dk, \end{aligned} \quad (2)$$

where  $\mathcal{E}_N$  is the energy density,  $\mathcal{P}_N$  is the pressure,  $g_{\sigma N}$ ,  $g_{\omega N}$  and  $g_{\rho N}$  are the couplings of the scalar boson, vector boson, and iso-vector  $\rho$ -meson to nucleons, respectively,  $m_\sigma$ ,  $m_\omega$  and  $m_\rho$  are the rest masses of scalar and vector bosons, and  $\rho$ -meson, respectively, the term  $\rho_I$  involves the difference between the proton and neutron densities (important for finite nuclei),  $\kappa$  and  $\lambda$  are the couplings of the cubic and quartic self-interaction of the scalar boson,  $M_N$  and  $M_N^*$  are the rest mass and the effective mass of the nucleon,  $n_N$  is the nucleonic density,  $k_F$  is the Fermi momentum of nucleons at zero temperature and  $\gamma$  is the degeneracy, with value  $\gamma = 4$  for symmetric nuclear matter and  $\gamma = 2$  for neutron matter.

The kaon condensate is incorporated following the first-order kaon condensate (FOKC) model of Glendenning and Schaffner-Bielich [23, 24]. It specifically considers  $K^-$  particles that can play a role analogous to that of electrons in neutron-star matter. The kaon potential was fixed by the saturation density value  $\rho_0$  of symmetric nuclear matter [25, 26]:

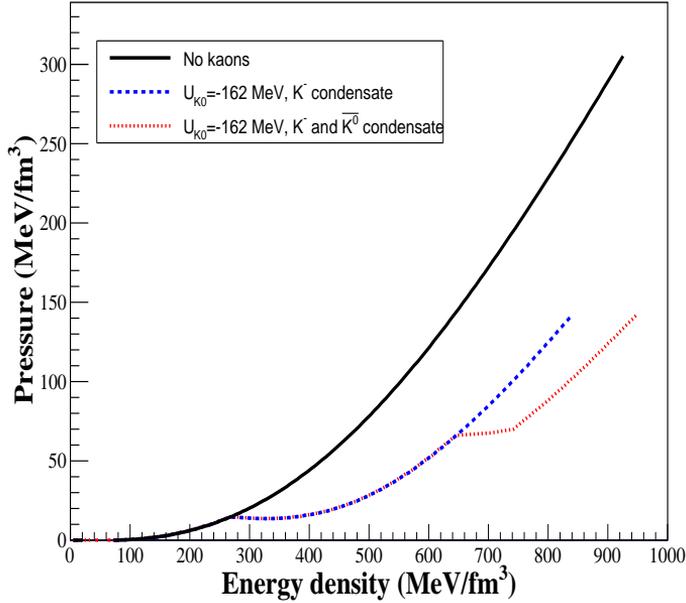
$$U_K(\rho_0) = -g_{\sigma K} \frac{(M_N - M_N^*(\rho_0))c^2}{g_{\sigma N}} - (\hbar c)^3 g_{\omega K} g_{\omega N} \frac{\rho_0}{m_\omega^2 c^4}, \quad (3)$$

where  $g_{\sigma K}$  and  $g_{\omega K}$  are couplings of  $\sigma$  and  $\omega$  mesons to  $K^-$ . The  $K^-$  chemical potential at a given baryonic density was evaluated as:

$$\begin{aligned} \mu_{K^-}(\rho, x_p) = & m_K c^2 - g_{\sigma K} \frac{(M_N - M_N^*(\rho_N, x_p))c^2}{g_{\sigma N}} \\ & - (\hbar c)^3 g_{\omega K} g_{\omega N} \frac{\rho_N}{m_\omega^2 c^4} - (\hbar c)^3 g_{\rho K} g_{\rho N} \frac{\rho_N}{m_\rho^2 c^4} (1 - 2x_p), \end{aligned} \quad (4)$$

where  $g_{\rho K}$  is a coupling of  $\rho$  meson to  $K^-$  and  $x_p$  is the proton fraction. The formula for the chemical potential of  $\bar{K}^0$  is similar to the one of  $K^-$ , where the only difference is the opposite sign of the last term. The effective mass  $M_N^*(\rho, x_p)$  is approximated by parabolic dependence on  $x_p$  between values for symmetric nuclear matter and pure neutron matter. The value of  $\mu_{K^-}(\rho, x_p)$  is then used to calculate the conditions for the chemical equilibrium of the system:

$$\mu_n - \mu_p = \mu_e = \mu_K, \quad \rho_p = \rho_e + \rho_K, \quad (5)$$



**Figure 1.** Equation of state for no kaons (black solid line) and for the kaonic potential  $U_{K0} = -162$  MeV using  $K^-$  (blue dashed line) and both the  $K^-$  and  $\bar{K}^0$  condensates (red dotted line).

which also provides the electron and kaon densities. When the kaons chemical potential drops to zero,  $\bar{K}^0$  particles also produced in dense nuclear matter. Finally, the energy density for kaons can be expressed as:

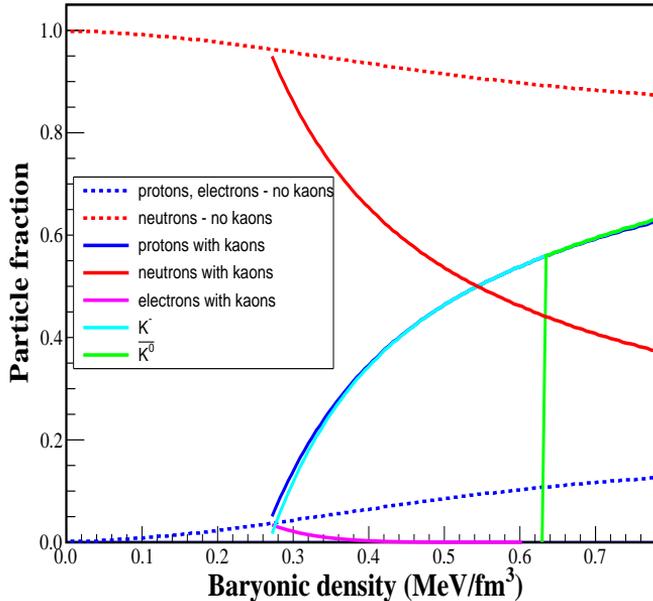
$$\epsilon_K = \mu_K \rho_K. \quad (6)$$

Consistent with Refs. [23, 24], both kaon condensates are assumed not to contribute to the pressure.

### 3. Results and Discussion

In the present work we extend the previous investigation of Ref. [20] by introducing a  $\bar{K}^0$  condensate at higher densities than the emerge of  $K^-$ , in order to soften the EoS and simultaneously describe the properties of the XTE J1814-388 and HESS J1731-347 light compact objects. This implies that the mass–radius ( $M$ – $R$ ) relation of compact objects may exhibit a *kaonic* branch, deviating from the standard nucleonic NS sequence. Specifically, we employ the RMF model [22] with a parameter set calibrated for nucleonic matter, reproducing current constraints on the maximum NS mass and the radius at canonical mass  $1.4 M_\odot$ . As in our previous work [20], the  $K^-$  condensate implemented according to Glendenning and Schafner-Bielich [23, 24], and further extended by the introduction of  $\bar{K}^0$  condensate. Specifically, the  $\bar{K}^0$  condensate can emerge when its chemical potential ( $\omega_{\bar{K}^0} = \omega_{K^-} + 2 g_{\rho K} R_{03}$ ) reaches zero [23, 24]. It is worth noting that, as the considered kaons form an isospin doublet, the model predicts equal densities for both condensates. Using the above parametrization, we computed the bulk properties of compact stars for various kaon potential values, assuming  $\beta$ -equilibrium as in Eq. (5).

Fig. 1 displays the dependence of the pressure on the energy density, where the onset of  $K^-$  softens the EoS. Additionally, the onset of  $\bar{K}^0$  condensate further softens the EoS at energy densities above  $600 \text{ MeV/fm}^3$ , corresponding to baryonic densities above  $0.6 \text{ fm}^{-3}$ , where both kaonic condensates already make a significant part of total mass density.



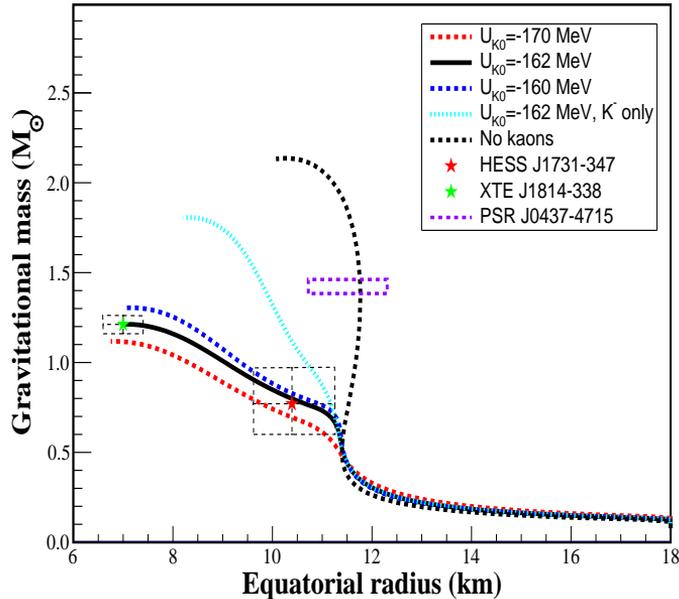
**Figure 2.** Particle fractions versus baryonic density (in  $\text{MeV}/\text{fm}^3$ ) for the RMF EoS with kaon potential  $U_{K0} = -162$  MeV.

This behavior is also depicted in Fig. 2, where the particle fractions are illustrated as functions of the baryonic density. With the appearance of the  $K^-$  onset on the  $\beta$ -equilibrium, the net  $K^-$  field reduces the population of electrons and subsequently replacing them. Furthermore, when the conditions are favorable for the formation of  $K^0$ , additional strangeness is introduced in dense matter without altering the charge neutrality as the fraction of  $K^0$  tracks the fraction of  $K^-$  due to isospin symmetry.

Figure 3 shows the gravitational mass–radius ( $M$ – $R$ ) relation for different kaon potential values. The nucleonic branch satisfies both the astrophysical constraints on the maximum mass and the observed properties of PSR J0437–4715. [27]. It should be noted that the nucleonic branch in Fig. 3 does not reproduce the radius of the light compact object PSR J1231–1411 [12] within the reported uncertainty ( $R = 12.3$ – $12.9$  km,  $M = 1.03$ – $1.09 M_\odot$ ). However, this uncertainty may be underestimated due to convergence issues in the analysis and discrepancies with other observed objects.

In any case, a moderate adjustment of the hadronic component of the EoS can reproduce the reported properties while maintaining the overall physical picture. Upon the onset of kaons, the EoS softens appropriately, thereby reproducing the bulk properties of the light compact object XTE J1814–338. It is also noteworthy, that for  $U_{K0} = -162$  MeV, the EoS is able to reproduce both the XTE J1814–338 and HESS J1731–347 light compact objects, under the same theoretical framework. For completeness, the  $K^-$  branch is also presented. Remarkably, the value  $U_{K0} = -162$  MeV is compatible with the value  $U_{K0} = -180 \pm 20$  MeV, obtained in the study of kaonic atoms [28]. The presence of kaon condensates in light compact objects offers a simple mechanism to account for their properties, without invoking more exotic scenarios such as hybrid stars, first-order phase transitions in nuclear matter, or dark-matter admixtures. The recent observations of PSR J1231–1411 and XTE J1814–338, which have similar masses but a substantial radius difference ( $\sim 3.5$  km), highlight that a purely nucleonic EoS cannot simultaneously describe both objects, emphasizing the potential importance of kaon condensation.

The main conclusion of this work is that a purely hadronic EoS cannot account for two compact objects with similar masses but markedly different radii. Explaining both simultaneously requires



**Figure 3.** Mass–radius ( $M$ – $R$ ) diagram for various kaon potentials, including the case without kaons. For the kaonic potential  $U_{K^0} = -162$  MeV (both  $K^-$  and  $\bar{K}^0$  condensation) the dependence crosses directly across the central regions for the reported HESS J1731-347 (red star)[9] and the XTE J1814-338 (green star)[10], compact objects. The case considering only  $K^-$  condensation is also depicted.

two distinct branches, each associated with a different nuclear-matter composition. The possibility of such dual branches in NSs is not a new concept. This was first discussed by Haensel, Bejger, and Zdunik [18], who aimed to examine the Bethe and Brown model prediction of  $M_{NS}^{max} = 1.5 M_{\odot}$  [29, 30], with the  $2.1 M_{\odot}$  NS reported by Nice et al. [31] by introducing the two branches of NSs in order to reconcile a  $2 M_{\odot}$  pulsar and the SN 1987A. In the same spirit, Brown, Lee, and Rho [19] later presented an extensive study on kaon condensation and its astrophysical implications.

In this context, we propose that the onset of kaon condensation at high densities modifies the EoS, potentially explaining compact objects with relatively low masses yet small radii.

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