Thermal Relaxation of Dark Matter Admixed Neutron Star

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Introduction

- Motivated by the various theoretical studies regarding the efficient capturing of dark matter by neutron stars, we explore the possible indirect effects of captured dark matter on the cooling mechanism of a neutron star.
- We show that the variation in the dark matter momentum vastly modifies the neutrino emissivity through specific neutrino generating processes inside the star.
- The specific heat and the thermal conductivity of a dark matter admixed star have also been investigated to explore the propagation of cooling waves in the interior of the star.
- Further, the metric for internal thermal relaxation epoch has also been calculated with different dark matter momentum and we deduced that increment of dark matter segment amplify the cooling and internal relaxation rates of the star.

E-RMF Model

Lagrangian is defined as

$$
\begin{aligned}
\mathcal{L}_{\mathcal{NM}} \quad = \quad & \sum_{i=p,n} \bar{\psi}_i \Big\{ \gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - \frac{1}{2} g_\rho \vec{\tau}_i \cdot \vec{\rho}^{\,\mu}) - (M - g_\sigma \sigma \\
& - g_\delta \vec{\tau}_i \cdot \vec{\delta}) \Big\} \psi_i + \frac{1}{2} \partial^\mu \sigma \, \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{\zeta_0}{4!} g_\omega^2 (\omega^\mu \omega_\mu)^2 \\
& - g_\sigma \frac{m_\sigma^2}{M} \left(\frac{\kappa_3}{3!} + \frac{\kappa_4}{4!} \frac{g_\sigma}{M} \sigma \right) \sigma^3 + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \\
& + \frac{1}{2} \frac{g_\sigma \sigma}{M} \left(\eta_1 + \frac{\eta_2}{2} \frac{g_\sigma \sigma}{M} \right) m_\omega^2 \omega^\mu \omega_\mu + \frac{1}{2} \eta_\rho \frac{m_\rho^2}{M} g_\sigma \sigma (\vec{\rho}^{\,\mu} \cdot \vec{\rho}_\mu) \\
& + \frac{1}{2} m_\rho^2 \rho^\mu \cdot \rho_\mu - \frac{1}{4} \vec{R}^{\mu\nu} \cdot \vec{R}_{\mu\nu} - \Lambda_\omega g_\omega^2 g_\rho^2 (\omega^\mu \omega_\mu)(\vec{\rho}^{\,\mu} \cdot \vec{\rho}_\mu) \\
& + \bar{\phi}_l \, (i\gamma_\mu \partial^\mu - m_e) \phi_l, \qquad (1)
\end{aligned}
$$

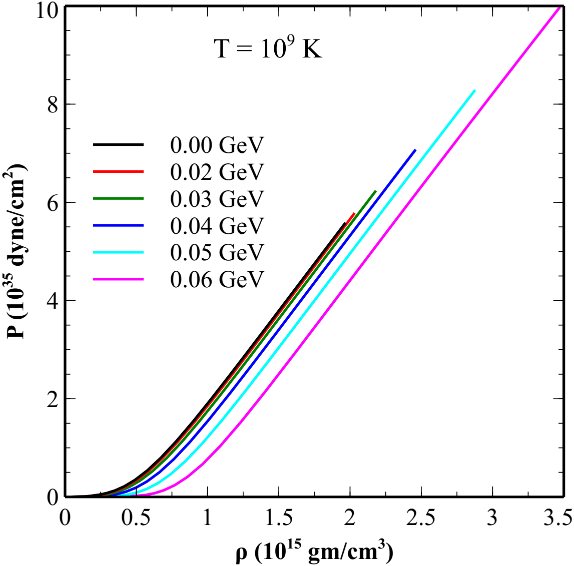
E-RMF Model

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{NM} + \bar{\chi}\left[i\gamma^\mu\partial_\mu - M_\chi + yh\right]\chi + \frac{1}{2}\partial_\mu h\partial^\mu h \\
&-\frac{1}{2}M_h^2 h^2 + \frac{f\,M}{v}\bar{\psi}h\psi,
\end{aligned} \tag{2}
$$

where χ represents the lightest neutralino wave function, which for the present case is assumed as fermionic dark matter candidate, h stands for the Higgs field and, the last term is the nucleon-Higgs coupling.
Charge Neutrality and β equilibrium

$$
\begin{aligned}
\rho_p &= \rho_e + \rho_\mu \\
\mu_n &= \mu_p + \mu_e \\
\mu_e &= \mu_\mu.
\end{aligned} \tag{3}
$$

Equation of State



Mass and Radius

Table 1: The maximum mass (M), radius for maximum mass star (R_M) and canonical star radius ($R_{1.4}$) for different values of dark matter Fermi momentum ($k_f^{\rm DM}$) using IOPB-I parameter set at 10^9 K.

$k_f^{\rm DM}$ (GeV)	Max. Mass (M) ($M_\odot$)	R_M (km)	$R_{1.4}$ (km)
0.00	2.130	11.987	13.497
0.02	2.099	11.774	13.190
0.03	2.031	11.296	12.504
0.04	1.918	10.494	11.380
0.05	1.770	9.655	10.414
0.06	1.604	8.688	9.250

Thermal Evolution

Energy Balance and Transport Equations (Thorne 1977)

$$\frac{\partial}{\partial r}(Le^{2\phi(r)}) = -\frac{4\pi r^2 e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}}\left(C_V \frac{\partial T}{\partial t} - e^{\phi(r)}(Q_\nu + Q_h)\right), \quad (4)$$

$$\frac{\partial}{\partial r}(Te^{\phi(r)}) = -\frac{L}{\kappa\, 4\pi r^2} \frac{e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}}, \quad (5)$$

where t and ϕ are the time coordinate and Schwarzschild gravitational potential respectively.

$C_V \longrightarrow$ specific heat.

$Q_\nu \longrightarrow$ neutrino emissivity.

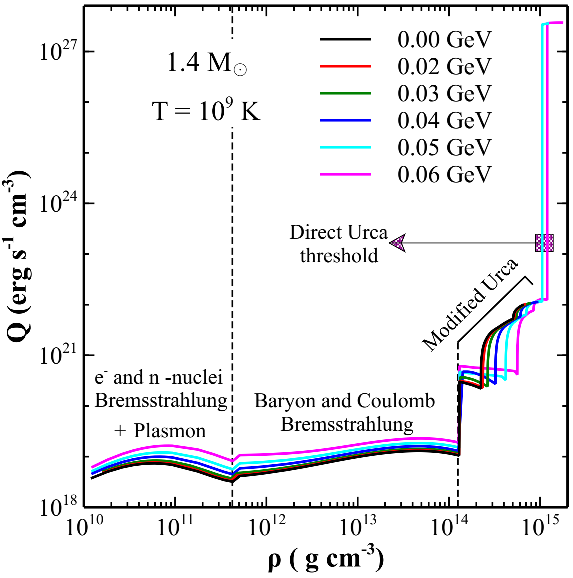
$Q_h \longrightarrow$ heat produced per unit volume due to several factors (for instance, dissipation of rotational energy, magnetic dissipation etc.) (ignored in the present calculations)

$\kappa \longrightarrow$ thermal conductivity.

$L \longrightarrow$ total luminosity (neutrino and radiation part).

Neutrino Emitting Processes

- **Plasmon decay** $[\gamma \longrightarrow \nu\bar{\nu}]$.
- **Pair annihilation** $[e^- e^+ \longrightarrow \nu\bar{\nu}]$.
- e^-**-nucleus Bremsstrahlung** $[\, e\,\{A, Z\} \longrightarrow e\,\{A, Z\}\,\nu\bar{\nu}\,]$; **neutron-nucleus Bremsstrahlung** $[\, n\,\{A, Z\} \longrightarrow n\,\{A, Z\}\,\nu\bar{\nu}\,]$.
- **Bremsstrahlung**: **Neutron-neutron** $[nn \longrightarrow nn\,\nu\bar{\nu}]$; **proton-proton** $[pp \longrightarrow pp\,\nu\bar{\nu}]$; **neutron-proton** $[np \longrightarrow np\,\nu\bar{\nu}]$; **Coulomb** $[\, ep \longrightarrow ep\,\nu\bar{\nu},\ \mu p \longrightarrow \mu p\,\nu\bar{\nu},\ ee \longrightarrow ee\,\nu\bar{\nu},\ \mu\mu \longrightarrow \mu\mu\,\nu\bar{\nu},\ e\mu \longrightarrow e\mu\,\nu\bar{\nu}\,]$.
- **Direct Urca processes** $[\, n \longrightarrow pe^-\bar{\nu},\ pe^- \longrightarrow n\nu,\ n \longrightarrow p\mu\bar{\nu},\ p\mu \longrightarrow n\nu\,]$ $[\boldsymbol{k_{F_n} \leq k_{F_p} + k_{F_e}}]$.
- **Modified Urca processes:** (Neutron branch) $[\, nn \longrightarrow npe^-\bar{\nu},\ nn \longrightarrow np\mu\bar{\nu},\ npe^- \longrightarrow nn\nu,\ np\mu \longrightarrow nn\nu\,]$; (Proton branch) $[\, pn \longrightarrow ppe^-\bar{\nu},\ pn \longrightarrow pp\mu\bar{\nu},\ ppe^- \longrightarrow pn\nu,\ pp\mu \longrightarrow pn\nu\,]$ $[\boldsymbol{k_{F_n} < 3k_{Fp} + k_{F_e}}]$


1.4 M⊙
T = 10^9 K
0.00 GeV
0.02 GeV
0.03 GeV
0.04 GeV
0.05 GeV
0.06 GeV
Direct Urca threshold
Modified Urca
e- and n -nuclei Bremsstrahlung + Plasmon
Baryon and Coulomb Bremsstrahlung
Q (erg s-1 cm-3)
ρ (g cm-3)

Heat Capacity and Thermal Conductivity

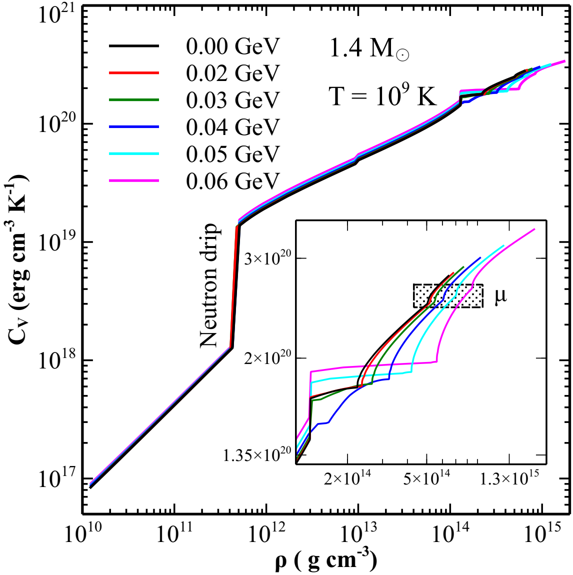
For temperature of the interest in the present case $T << \mu_i$ and in the absence of superfluidity, the specific heat of each constituent particle can be stated as,

$$C_V = \sum_i \frac{M_i^* \, n_i}{k_{F_i}^2} \pi^2 \, k_B^2 \, T. \qquad (6)$$

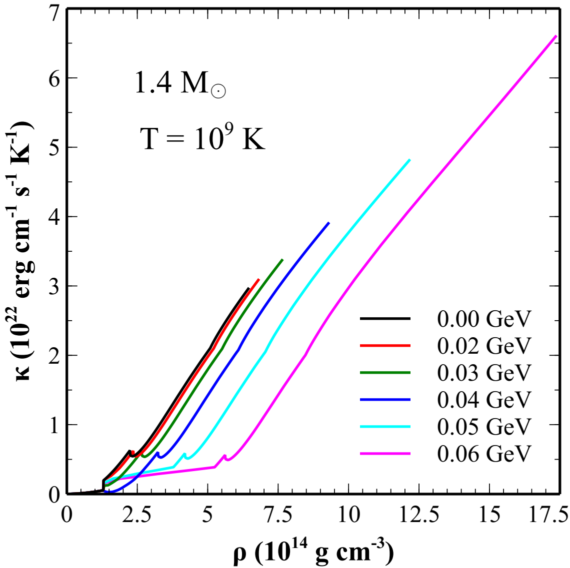
The analytical expression for the thermal conductivity of each type of particle (i) is analogous to the equation,

$$\kappa_i = \frac{\pi^2 \, k_B^2 \, n_i \, T \, \tau_i}{3 \, m_i^*}, \quad i = n, p, e^- \,\&\, \mu \qquad (7)$$

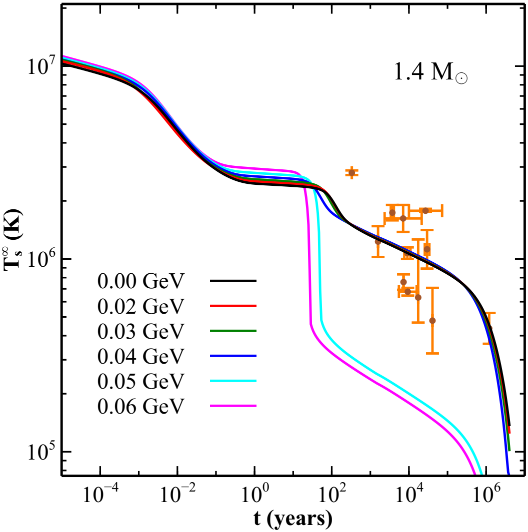
where τ_i is the effective relaxation time of each constituent and calculated separately for the crust and core sections of the star .


0.00 GeV
0.02 GeV
0.03 GeV
0.04 GeV
0.05 GeV
0.06 GeV
1.4 M☉
T = 10^9 K
Neutron drip
μ
C_V (erg cm^-3 K^-1)
ρ (g cm^-3)
10^17
10^18
10^19
10^20
10^21
10^10
10^11
10^12
10^13
10^14
10^15
3×10^20
2×10^20
1.35×10^20
2×10^14
5×10^14
1.3×10^15

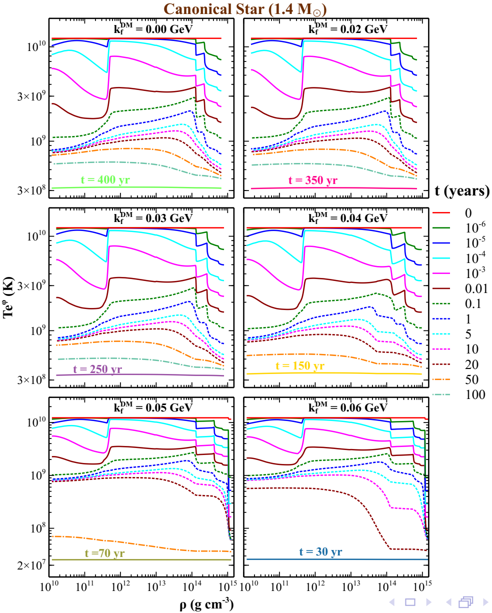
Thermal Conductivity



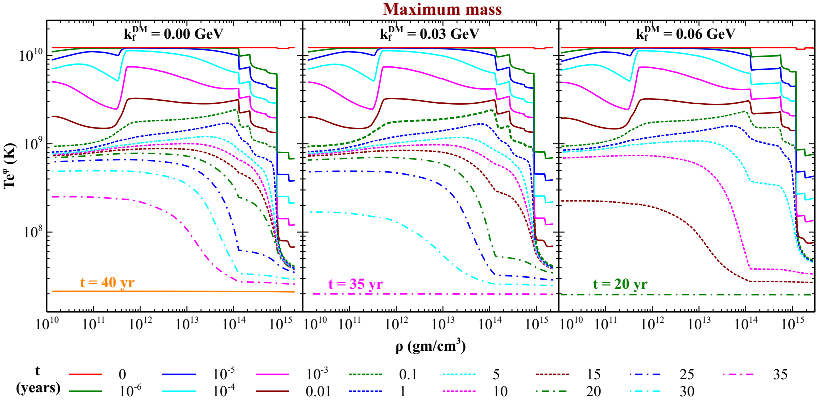
Surface Temperature



Redshifted internal temperature



Redshifted internal temperature



Conclusions

- We observe that if the theoretically considered availability of dark matter segment in a canonical star is such that $k_f^{DM} > 0.04 GeV$, then the compositional structure of the star enables the direct Urca reactions in the core.
- The specific heat of the crustal segment of the star appears to be independent of the dark matter inclusion while for the core part it is reduced to some extent with increase in the dark matter momentum.
- The thermal conductivity curve reflects the same nature as that of EOS for the canonical star. The core of a dark matter concentrated canonical star is highly dense and much more conductive than a normal star (without dark matter).
- The presence of an enhanced neutrino cooling mechanism sends cooling wave from the stellar core to the crust which causes a sudden drop in the surface temperature and mainly responsible for the fast cooling mechanism of the star. The internal thermal relaxation time period of the star is very sensitive to the percentage of dark matter adopted.

References

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- *Systematic study for the surface properties of neutron stars.* Ankit Kumar, H. C Das, J. A. Pattnaik, S. K. Patra . Physical Review C **105**, 045804 (2022).
- *Pasta properties of the neutron star within effective relativistic mean-field model.* Vishal Parmar, H. C. Das, Ankit Kumar, Ankit Kumar, M. K. Sharma, S. K. Patra. Physical Review D (Accepted), (2022), arXiv:2203.16827.
- *Crustal properties of a neutron star within an effective relativistic mean-field model.* Vishal Parmar, H. C. Das, Ankit Kumar, M. K. Sharma, S. K. Patra. Physical Review D **105**, 043017 (2022).

Thank You