Warm Dense Matter and Cooling of Supernovae Remnants

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Introduction

- One of the most prominent energetic events of the universe is manifested by the core-collapse supernovae explosion of the giant stars having mass in the range of 8 - 40 times of the mass of sun.
- The energy emerged during this explosion is carried off by the photons and the neutrinos, which are billion trillion trillion in numbers and hauled the most of the energy released.
- In this exploring era of every tiny and massive object through modern science, neutron stars still hold the mystery in itself and are poorly known objects.
- In the present work, we studied in detail the effects of temperature on the properties (incompressibility, symmetry energy etc.) of symmetric nuclear matter and the correlations among them using the most familiar **NL3, IU-FSU** and recently developed **G3** parameter sets.
- We also explore the dependence of cooling mechanism of a hot dense matter through direct **URCA** process on the EoS and the variation in mass-radius profile of a proto-neutron star with temperature.

Temperature Dependent RMF Model

The expression for the energy density of a warm nuclear system using relativistic mean-field formalism can be naively derived as

$$E = \sum_{\alpha=p,n} \frac{2}{(2\pi)^3}\int_0^{k_\alpha} d^3k\, \mathcal{E}^*_\alpha(k)\left[f_\alpha(\mu^*_\alpha,T)+\bar{f}_\alpha(\mu^*_\alpha,T)\right] + n\, g_\omega\, \omega + m_\sigma^2\sigma^2\left(\frac{1}{2}+\frac{\kappa_3}{3!}\frac{g_\sigma\sigma}{M} + \frac{\kappa_4}{4!}\frac{g_\sigma^2\sigma^2}{M^2}\right) - \frac{1}{2}m_\omega^2\,\omega^2\left(1+\eta_1\frac{g_\sigma\sigma}{M}+\frac{\eta_2}{2}\frac{g_\sigma^2\sigma^2}{M^2}\right) - \frac{1}{4!}\zeta_0\, g_\omega^2\,\omega^4 + \frac{1}{2}n_3\, g_\rho\, \rho - \frac{1}{2}\left(1+\frac{\eta_\rho g_\sigma\sigma}{M}\right)m_\rho^2\,\rho^2 - \Lambda_\omega\, g_\rho^2\, g_\omega^2\,\rho^2\,\omega^2 + \frac{1}{2}m_\delta^2\,\delta^2, \quad (1)$$

where $f_\alpha(\mu^*_\alpha,T)$ and $\bar{f}_\alpha(\mu^*_\alpha,T)$ are the thermal distribution function of the nucleons and the anti-nucleons; and μ^*_α is the effective chemical potential of the nucleons.
The formula for neutrino emissivity (Q) through direct **URCA** process is given by

$$Q = \frac{457\pi}{10080}G_F^2\, C^2\, T^6\,\Theta(k_e+k_p-k_n)\Big\{(C_A^2-C_V^2)\,M_p^*\,M_n^*\,\mathcal{E}_e + \frac{1}{2}(C_V^2+C_A^2)\Big[4\,\mathcal{E}_n\,\mathcal{E}_p\,\mathcal{E}_e - (\mathcal{E}_n - \mathcal{E}_p)\left((\mathcal{E}_n+\mathcal{E}_p)^2-k_e^2\right)\Big] + C_V C_M\frac{\sqrt{M_p^* M_n^*}}{M}\left[2\,(\mathcal{E}_n-\mathcal{E}_p)\,k_e^2 - \left(3\,(\mathcal{E}_n-\mathcal{E}_p)^2-k_e^2\right)\mathcal{E}_e\right] + C_A\left(C_V+2\frac{\sqrt{M_p^* M_n^*}}{M}C_M\right)(\mathcal{E}_n+\mathcal{E}_p)\left(k_e^2-(\mathcal{E}_n+\mathcal{E}_p)^2\right) + C_M^2\frac{1}{4M^2}\Big[8M^{*2}\,(\mathcal{E}_n-\mathcal{E}_p)\left(k_e^2-(\mathcal{E}_n-\mathcal{E}_p)\,\mathcal{E}_e\right) + \left(k_e^2-(\mathcal{E}_n-\mathcal{E}_p)^2\right)(2\mathcal{E}_n^2+2\mathcal{E}_p^2-k_e^2)\,\mathcal{E}_e - \left(k_e^2-(\mathcal{E}_n-\mathcal{E}_p)^2\right)(\mathcal{E}_n+\mathcal{E}_p)\,(2\mathcal{E}_n-2\mathcal{E}_p-\mathcal{E}_e)\Big]\Big\}$$

Results

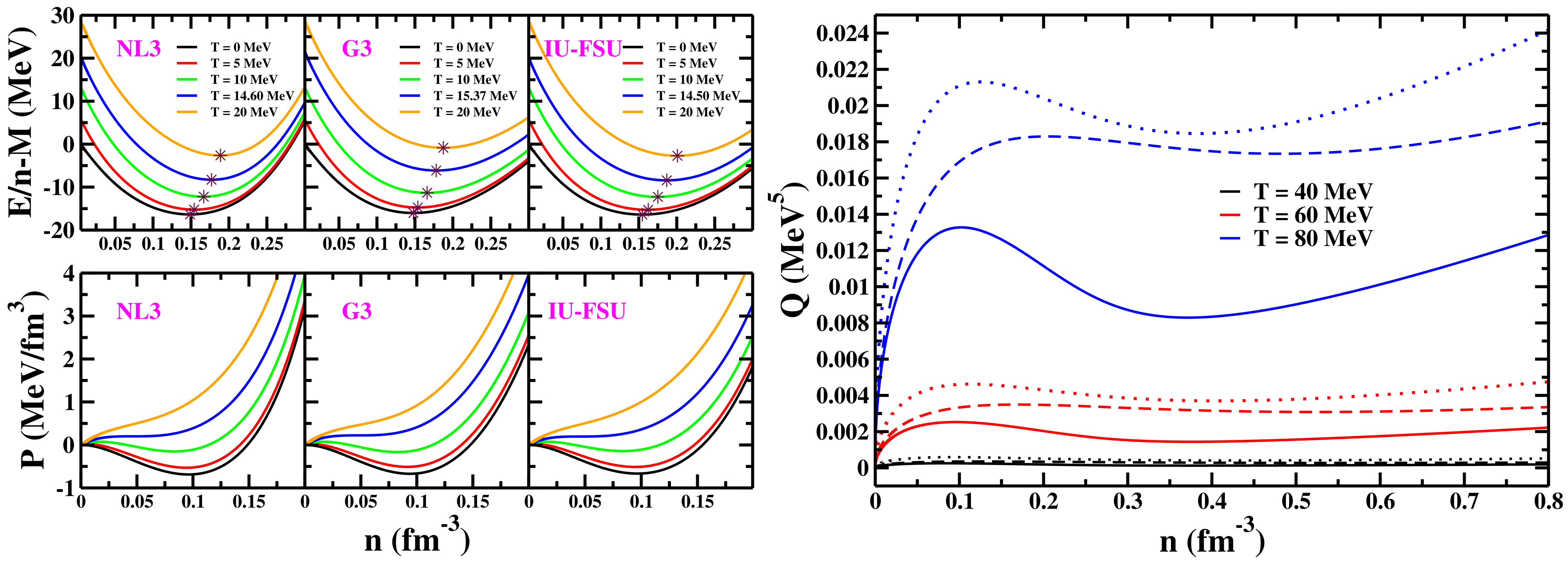

Figure 1: Binding energy and pressure as a function of nucleon density for symmetric nuclear matter at different temperatures (left); Neutrino emissivity at different temperatures as a function of nucleon density for NL3 (solid line), G3 (dashed line) and IU-FSU (dotted line) parameter sets (right).

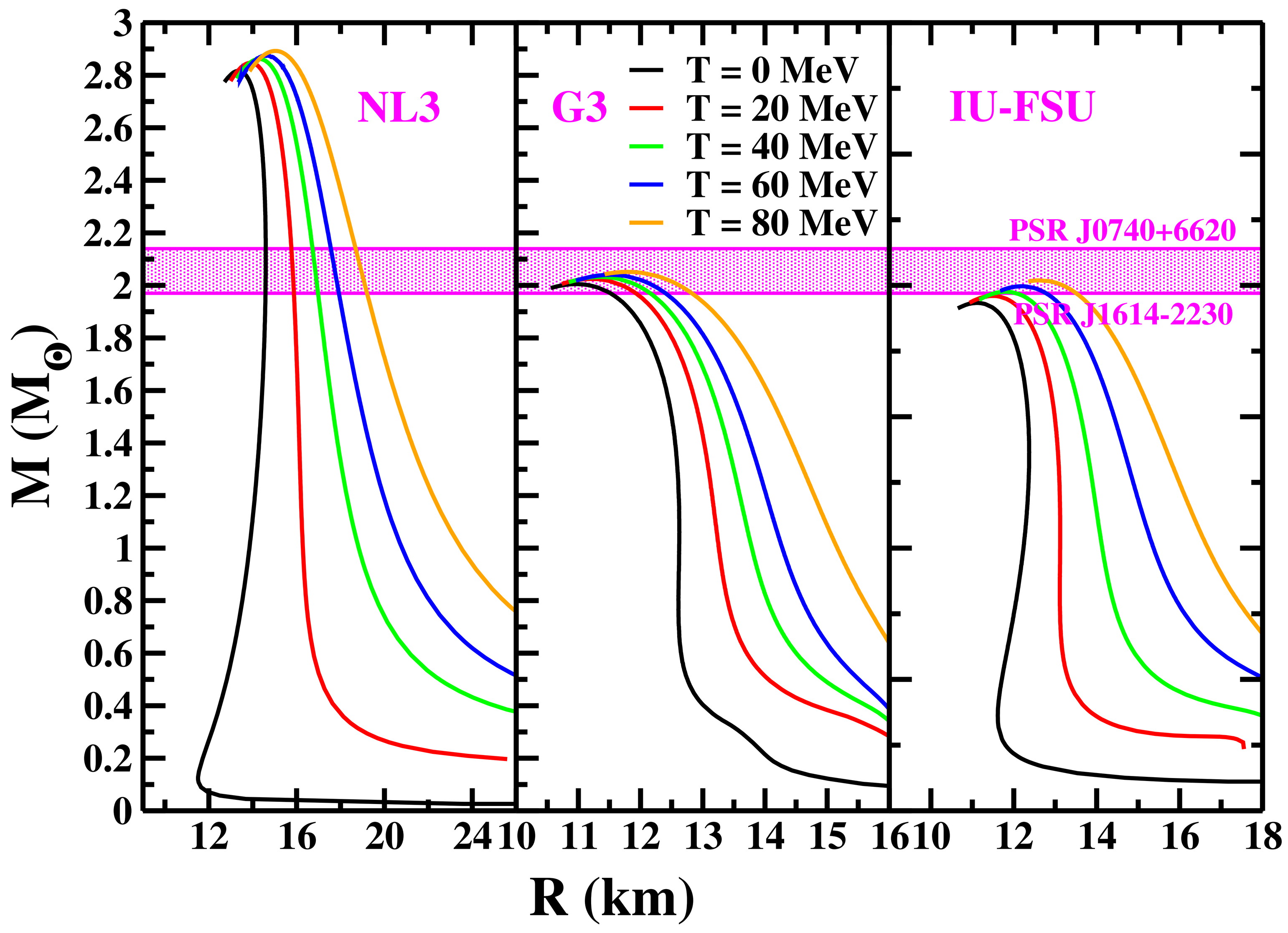

Figure 2: Mass-Radius profile of a proto-neutron star at different temperatures for NL3 (left panel), G3 (middle panel) and IU-FSU (right panel) parameter sets.

Conclusion

1. We observed a decrement in the binding energy and saturation density of the symmetric nuclear matter with temperature, which indicates that the system becomes more loosely bound at higher temperature.
2. The adaptation of pressure with temperature is utterly important in determining the critical parameters of liquid-gas phase transition, specially the critical temperature, T_C. We found the value of T_C as 14.60, 15.37 and 14.50 MeV for NL3, G3 and IU-FSU parameters respectively.
3. The magnitude of the neutrino emissivity (Q) is considerably affected by the nature (stiff or soft) of the EoS. We also concluded that direct **URCA** process is mainly responsible only for the initial cooling of the newly born star.
4. The mass and radius of the neutron star goes on decreasing with decrease in temperature. The NL3 parameter set predicts higher mass and larger radius in comparison to G3 parameter set.

References

[1] L.B. Leinson and A. Pérez. Relativistic direct urca processes in cooling neutron stars. *Physics Letters B*, 518(1):15 – 22, 2001.

[2] J. M. Lattimer and M. Prakash. The physics of neutron stars. *Science*, 304(5670):536–542, 2004.

[3] Ankit Kumar, H. C. Das, S. K. Biswal, Bharat Kumar, and S. K. Patra. Warm dense matter and cooling of supernovae remnants. *The European Physical Journal C*, 80(8), Aug 2020.