Dark Matter Admixed Neutron Stars

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Abstract

Dark matter-neutron interactions, controlled by the coupling (g^2), can heat neutron stars through resonant conversions. We find that large g^2 values lead to excess heating, producing temperatures inconsistent with observed neutron stars. This allows us to rule out parts of dark matter parameter space based on thermal constraints.

Dark Matter Induced Heating

The model assumes a weak coupling between neutrons and dark baryons, enabling resonant conversions in neutron stars when their energies align. These conversions release energy, heating the star. The equation shown gives the depletion heating rate per unit volume.

$$H_{dep} = \frac{g^2}{4\pi^3}\iint dE_n dE_\chi(\mu_n - E_n)[kinematics]$$

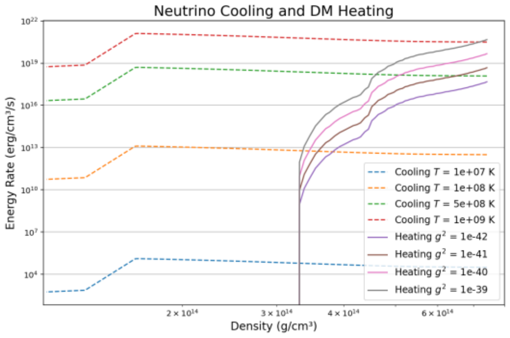

Figure 1. Dark Matter-Induced Heating and Neutrino Cooling as a Function of Density

TOV Equations for Stellar Structure

Neutron star structure was computed by solving the TOV equations using a 4th-order Runge-Kutta method with the TFSU Garnet equation of state, which a yields stiff equation of state and radii of 12–14 km. Outputs include mass, radius, and density profiles used in thermal modeling. The model supports up to 2.07 M⊙.

$$\frac{dP}{dr} = -\frac{G(\rho+Pc^{-2})(M+4\pi r^3 Pc^{-2})}{r(r-2GMc^{-2})}$$

$$\frac{dM}{dr} = 4\pi r^2\rho$$

Computing the Cooling Curve

The heat diffusion equation was solved using the Crank–Nicolson method in baryon number shells. The model includes neutrino cooling, dark matter heating, thermal conductivity, and specific heat, showing temperature evolution over time inside the star.

$$\frac{c_V}{n_b}\frac{\partial(e^{\frac{\nu}{2}}T)}{\partial t} = \frac{\partial}{\partial N_b}\left((4\pi r^2)^2 n_b \kappa e^{\frac{\nu}{2}}\frac{\partial}{\partial N_b}\left(e^{\frac{\nu}{2}}T\right)\right) + \frac{e^{\frac{\nu}{2}}}{n_b}(H-Q)$$

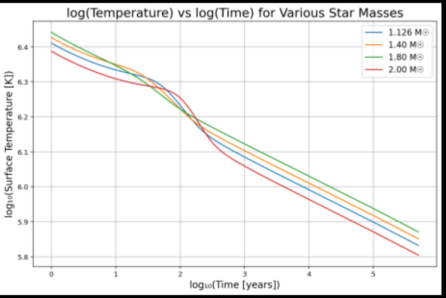

Figure 2. Cooling Curve Without Dark Matter Contributions

Equilibrium Temperature

An alternate cooling curve was computed by finding the temperature where neutrino cooling equals dark matter heating. Due to the large magnitude of dark matter heating, solving the full evolution equation directly caused numerical instability. Instead, we solved for equilibrium temperatures at various timepoints, where volume-integrated heating and cooling balance. This is supported by Figure 3 which shows dark matter heating dominates across wide conditions. This method captures energy balance without requiring full time evolution.

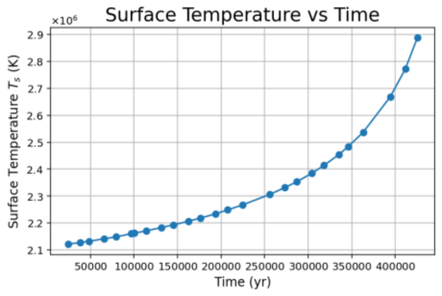

Figure 3. Temperature at Which Neutrino Cooling Equals Dark Matter Induced Heating for a 1.4 M ⊙ Star Where $g^2 = 10^{-40}$

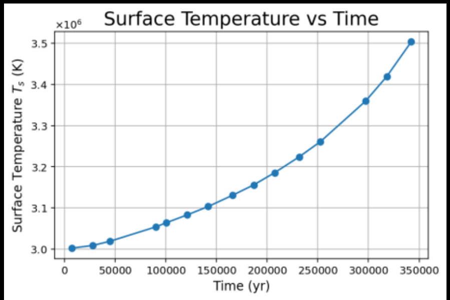

Figure 4. Temperature at Which Neutrino Cooling Equals Dark Matter Induced Heating for a 1.4 M ⊙ Star Where $g^2 = 10^{-38}$

Discussion

Our results show that dark matter-induced heating can significantly impact neutron star temperatures. For large values of the coupling constant g^2, the heating exceeds neutrino cooling, leading to equilibrium temperatures too high to match observations of old neutron stars as seen in Figure 2.

This allows us to rule out portions of parameter space where g^2 is too large, as these models predict surface temperatures inconsistent with known cooling behavior. Our method offers a new way to constrain dark matter models based on thermal effects in neutron stars, complementing direct detection efforts.

Acknowledgments

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References

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