INPC 2025
May 25-30, 2025
DCC, Daejeon, Korea

Contribution ID: **122** Type: **Contributed Oral Presentation**

Vortex Creep Heating in Neutron Star Cooling: New Insights into Thermal Evolution of Heavy Neutron Stars

Friday, 30 May 2025 11:30 (15 minutes)

Neutron stars serve as unique natural laboratories for studying nuclear matter under extreme conditions. The temporal evolution of neutron star luminosity and temperature is intricately linked to various physical properties including the equation of state (EoS) of dense nuclear matter, nucleon superfluidity and superconductivity, envelope composition, and magnetic field, allowing us to indirectly probe these properties through observational data. Recent observations (*e.g.* [1]) have revealed unexpectedly warm temperatures in old neutron stars. The standard cooling scenario, which considers only neutrino emission processes and photon emission during the cooling, predicts much lower temperatures for these old neutron stars, suggesting the presence of additional heating sources. Following previous studies [2] that established vortex creep heating—arising from the friction associated with the creep motion of superfluid vortex lines in the neutron star crust—as a potential heating mechanism, we extend this framework by incorporating both vortex creep heating and Direct Urca processes in our cooling calculations.

In this work, we implement these mechanisms in our computational framework to explore various evolutionary scenarios using the established relationship between heating luminosity and pulsar rotational evolution. We particularly focus on massive neutron stars where Direct Urca processes become active, a regime not previously investigated in conjunction with vortex creep heating. Through detailed numerical calculations, we systematically investigate how the interplay between heating and cooling mechanisms affects the thermal evolution of neutron stars by varying multiple physical parameters: rotational properties (period P, period derivative $\dot{P}$, and initial period P_0), EoS (APR, BSk24), pairing gap models for superfluidity and superconductivity, and envelope compositions. In this talk, we will present new evolutionary pathways for massive neutron stars, suggesting that vortex creep heating can significantly modify the rapid cooling traditionally expected from Direct Urca processes.

[1] V. Abramkin *et al.*, Astrophys. J. **924**, 128 (2022).
[2] M. Fujiwara *et al.*, Journal of Cosmology and Astroparticle Physics (JCAP) **03**, 051 (2024).

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Session Classification: Parallel Session

Track Classification: Nuclear Astrophysics