The effect of late-time heating in hybrid millisecond pulsars

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Abstract:

We study the thermal evolution of compact stars within the realistic hybrid equation of state that incorporates hadronic matter and quark-gluon plasma in the core of the star. By performing 1D numerical simulations of the thermal evolution of compact stars, it is shown that for rapidly rotating millisecond pulsars matter can deviate from the chemical equilibrium causing an appearance of a new heating source, dubbed the rotochemical heating. Moreover, these simulations accounted for a different atmosphere composition, as well as pairing between nucleons and quarks. The obtained results reveal a noticeable effect of the rotochemical heating in quark matter on the cooling of old millisecond pulsars that could be used to probe the existence of deconfined quarks.

I. Neutron star cooling

Neutron star (NS) releases heat via photon and neutrino emission.

- Photon emission occurs via Stefan-Boltzmann law on the surface

$$L_\gamma^\infty = \sigma_B T_s^{\infty,4} 4\pi R^{\infty,2}$$

- Neutrino emission occurs throughout the NS's volume mostly via weak interaction.

$$L_\nu^\infty = \int_0^R Q_\nu(r) e^{2\Phi(r)} 4\pi r^2 e^{\Lambda(r)} dr$$

Here $Q_\nu(r)$ represents the total reaction rates. The most relevant ones are

- Hadron/Quark direct URCA (beta decay)
- Hadron/Quark modified URCA (beta decay with spectating baryon)
- Hadron/Quark bremsstrahlung
- Cooper pair breaking and formation

They are further modified by presence of critical phenomena (superfluidity, superconductivity), which affects (mostly reduces) the neutrino emission.

- These quantities form the basis for classical cooling theory, which, in its equilibrium formulation, follows

Time evolution of red-shifted temperature

$$C_v \frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty$$

C_v - total heat capacity of the NS
L_ν^∞ - neutrino red-shifted luminosity
L_γ^∞ - photon red-shifted luminosity.

II. Equation of state

For our purposes, we use a hybrid (hadron+quark) EoS with realistic interactions

- DD2 – relativistic mean field model for hadrons [1]
- Relativistic Density Functional (RDF) – chirally symmetric Lagrangian model for quarks[2], which reproduces chiral dynamics and mimics deconfinement via self-energy growth.
- These are glued via Maxwell construction

III. Rotochemical heating

- Classical cooling theory (Fig. 1) has been successful at describing X-ray data (Table 1 from [3])
- Old millisecond pulsars (MSPs) observations suggest (Fig. 2) an emergence of extra heating term, which can be explained by *rotochemical heating* effect
  - MSPs are rapidly rotating objects with slow spindown. For usual MSP, initial period of 1 ms and spindown of 10^{-20} are typical.
  - Rotational rate decreases -> star contracts -> local perturbation of the chemical equilibrium -> accumulates over time, affects star properties upon reaching spindown timescale. **This scale is only reasonably low (~1 Myr) for MSPs.**
  - The effect manifests itself, as a heating source in the thermal balance equation

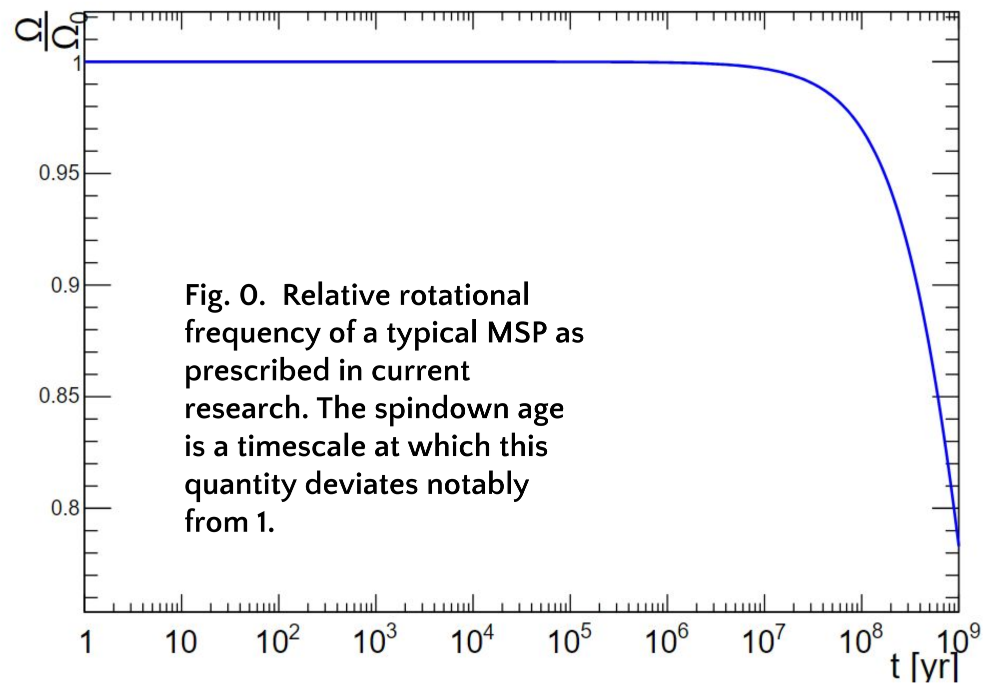

Fig. 0. Relative rotational frequency of a typical MSP as prescribed in current research. The spindown age is a timescale at which this quantity deviates notably from 1.

$$\eta_e(t) \approx -Z_{npe} I_{\Omega,e} \left(\Omega(t)^2 - \Omega_0^2\right) \approx Z_{npe} I_{\Omega,e} \Omega_0^2 \cdot \frac{2}{n-1}\frac{t}{t_{sd}}$$

Following 1st thermodynamics law,

$$T^\infty dS \equiv C_v dT^\infty = -(L_\nu^\infty + L_\gamma^\infty)dt - \sum_i \mu_i^\infty \dot{N}_i dt. \tag{1}$$

Under usual considerations, the term related to chemical heating vanishes in a closed system. However, if a detailed balance is not met, there is an associated energy release

$$L_H^\infty = -\sum_i \delta\mu_i^\infty \dot{N}_i, \tag{2}$$

where $\delta X \equiv X - X^{eq}$ denotes the quantity's acquired value due to departure from equilibrium.

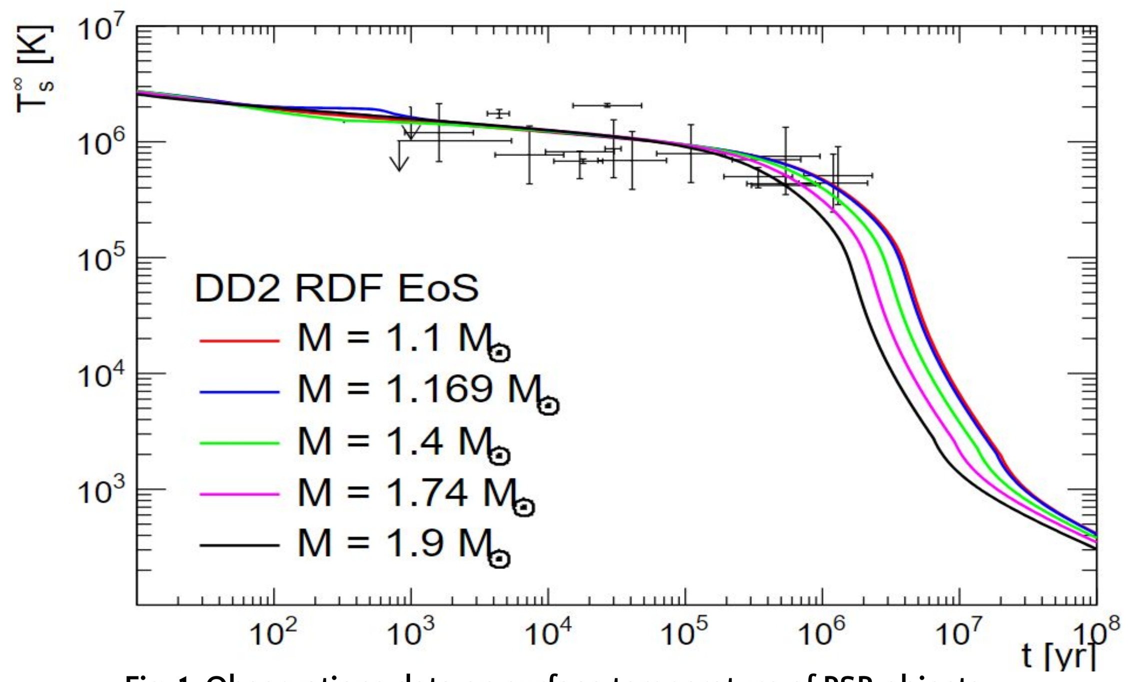

Fig. 1. Observations data on surface temperature of PSR objects superimposed with the classical cooling simulation of strongly interacting matter, prescribed by DD2-RDF EoS with quarks suppressed by 2SC superconducting gap. Cooling is only governed by photons and neutrino.

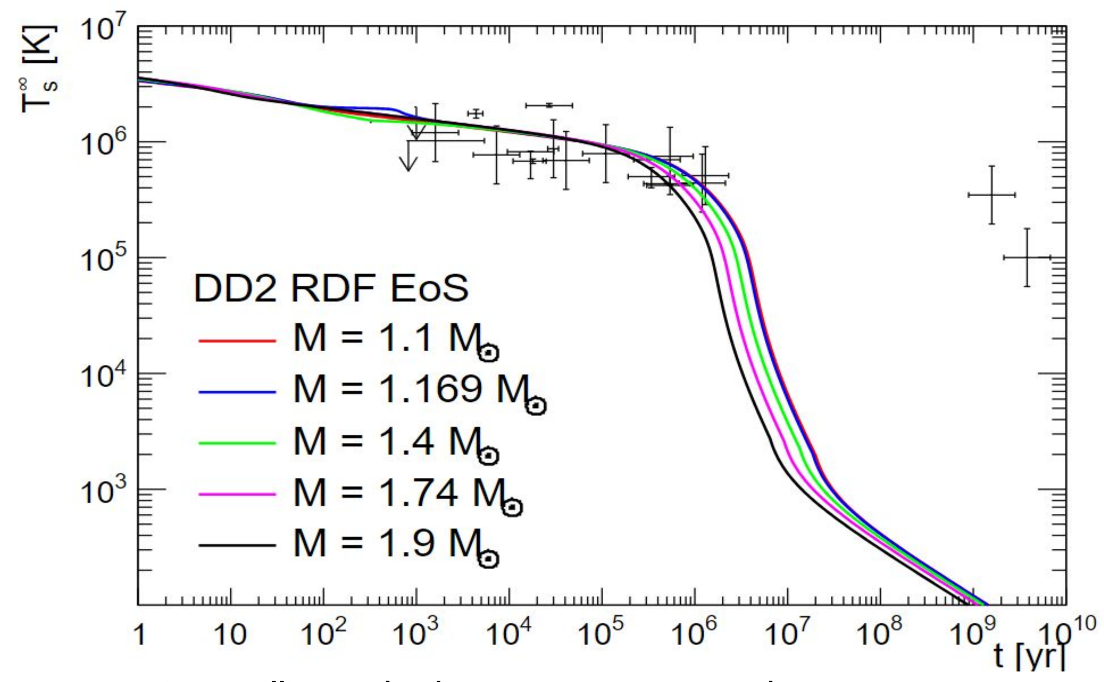

Fig. 2. Millisecond pulsars PSR J0437-4715 and PSR J2124-3358 are included (exp. data on the right), demonstrating disagreement with classic cooling theory.

IV. Results and discussion

- Fig. 3 concludes the simulation, reproducing the old MSPs data, for paired and non-paired quark matter
  - Yet, paired version allows for larger mass selection and demonstrate significant distinction between hadron and hybrid modes.
- **Preliminarily, with more old MSP cooling data there may be statistically significant distinction.**

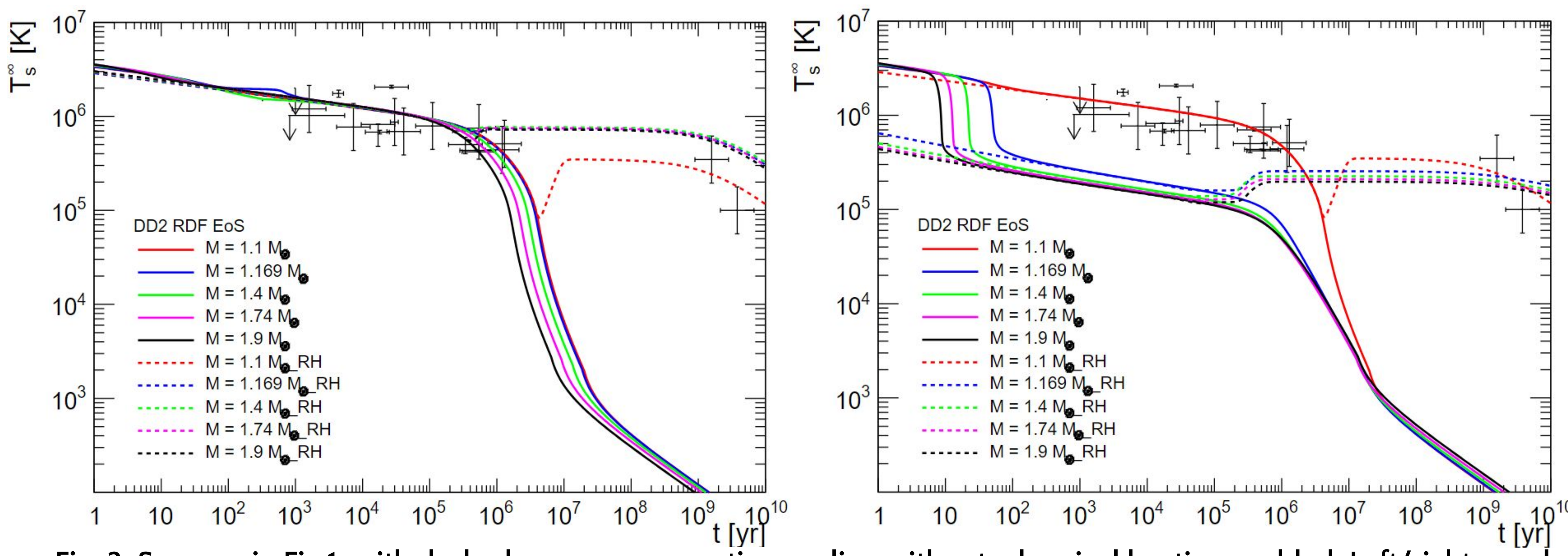

Fig. 3. Same as in Fig.1, with dashed curves representing cooling with rotochemical heating enabled. Left/right panel : quark superconductivity enabled/disabled (2SC phase, [2]).

V. Summary

- **We simulate for the first time the rotochemical heating for npeμuds matter under realistic hybrid EoS and compare it against old MSPs.**
- Late-time heating can serve a complimentary future probe of deconfinement in compact objects
- Rotochemical heating effect is relatively sensible to the emergence of QGP degrees of freedom

VI. References

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