The influence of superfluid core cooling in the braking index of Pulsars.

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Abstract: Pulsars are stars from which electromagnetic radiation is observed to pulsate in well-defined time intervals as the star rotates and the emission of electromagnetic signal is located in a place different from the rotation center. The frequencies of the pulses decay with time, quantified by the braking index (n). In the canonical model n = 3, in general, for all pulsars, but observational data shows that n is lower than 3. In this work a new model is presented, based on a modification of the canonical one incorporating the influence of neutron and proton density that appear in the superfluid core and, as the star cools down, the density of the superfluid core increases making the star to shrink with time and temperature, making the inertia moment to decrease. The difference of this model from the canonical one is that the star moment of inertia decreases with time (what would accelerate the rotation of the star) what makes the star to not slow down as fast as it should without this process.

1. Introduction
The Graviton Group is a research Brazilian group dedicated to the study of Gravitational Waves, Neutron Stars is a candidate source of Gravitational Waves, that is the reason the group is devoted in the study of Pulsars. The detection of gravitational waves came after a long road of experiments planned in 2010 [1], in 2016 finally the detection was made [2,3]. A very strong evidence of the existence of Gravitational Waves appeared in the PSR B1913+16 (also known as PSR J1915+1606, PSR 1913+16, and the Hulse–Taylor binary named after its discoverers) is a pulsar (a radiating neutron star) binary system. PSR 1913+16 was the first binary pulsar to be discovered and its orbital period is decreasing with time due the emission of gravitational waves [4]. The first attempts to gravitational wave detection starts in the early sixties [5] with the resonant mass gravitational wave detection [6,7,8,9].

The Brazilian efforts towards the detection of gravitational waves are centered on the Schenberg detector. In the Schenberg detector six sensors are connected to the surface of the sphere, arranged according to the distribution of Merkowitz and Johnson [10,11]. These transducers are located as if they were in the center of 6 pentagons connected in a surface corresponding to half dodecahedron. Each transducer amplifies the motion occurring on the region of the sphere in which it is connected. The already amplified movement excites the membrane of one resonant cavity. In this resonant cavity microwaves are pumped, which generate the electronic signal that will return taking all the information of the OG's. Intensity and direction of the OGs can be obtained from the analysis of the output signal of these 6 transducers [12,13,14].

To reach the resonant cavities, first the microwaves are conducted from the outside of the dewar (thermo flask where every antenna system is contained) by cabling to microstrip antennas. These antennas, located in front of the parametric transducers, conduct the microwaves into the resonant cavity and another set of antennas pick up the returned signal. The Brazilian efforts on the field can be summarized in [15-26]. Much of this work is made using Finite Element Modelling (FEM) [27,28].
2. The neutron stars
Pulsars are astrophysical objects normally modeled as neutron stars originated from the collapse of a progenitor star [29]. In a model, which we will refer as the canonical one, pulsars are described by spherical rotating magnetized dipoles, usually with the magnetic axis misaligned relatively to the rotation axis. This misalignment would be responsible for the observation of radiation emitted in well-defined time intervals in a certain direction, which is the typical observational characteristic of this kind of star.

Observation shows that the rotation frequency of pulsars is slowly decaying with time, implying a gradual decrease of the angular velocity, according to the canonical model [30]. Such decay can be quantified by a dimensionless parameter known as the braking index, $n$. The canonical model predicts that this index has only one value for all pulsars, equal to 3. However, observational data shows that actual braking indices are different from 3, indicating that the canonical model requires some corrections [31, 32].

3. The modified URCA process
Murca process can work with a slight modification at lower densities from the Durca process. The modified Urca process can cool the star

\[
\begin{align*}
    n+N &\rightarrow p+N+l+\nu_l, \\
    p+N+l &\rightarrow n+N+\nu_l
\end{align*}
\]

where $N$ is a nucleon - a proton or a neutron, $l$ is a lepton and $\nu_l$ is the neutrino or antineutrino of the lepton. This process can work at much lower densities, but produces 7 orders of magnitude more emissivity than the Urca process. As a result, it's the dominant process in the superfluid core.

4. The neutron star density increases as the temperature decreases
As the neutrino emission takes place, the neutron star superfluid core cools down and its density increases. This can be seen on Figure 1 [33]. If there is only this process happening, the rotation of the star should increase to keep the angular momentum constant, but there is other process happening, the one described as the canonical, then the star braking index should be less than 3.

5. The cooling down of the superfluid core
The superfluid core cools down in complex ways, but in a period 100 to 100 thousand years it cools down in a very specific way as can be seen on Figure 2, see reference [34].

![Figure 1: Temperature versus baryon density for neutron star matter assuming local and global charge neutrality. Source [33].](image-url)
Figure 2: The region circulate on the curve shown as $T^\infty$ is the period where the star cool down, the approximated expression for the superfluid core temperature from time equal to 100 to 100,000 years is also shown. Source [34].

6 The neutron potential

The neutron potential in the core of the neutron star can be approximated to the neutron potential in a nucleous [35], this potential can be seen on Figure 3. This potential is a non-relativistic one, as the neutron star core is relativistic, this potential is used only as an approximation. In the same figure, there is a line tangential to the curve at the temperature of 1 Billion Kelvin, what means a thermic energy of approximately 0.1 MeV, the slope of this line is 0.001 fm/MeV. What will happen to the curve if the temperature drops to 0.1 billion Kelvin? The curve will shift to the left proportional to the slope of the curve at 0.1 MeV. Then the neutron will move closer to the other neutron by 0.0001 fm. As the distance is close to one fm, the neutron will move closer to the other neutron by a factor of $10^{-4}$. As the diameter of the neutron star is approximately 10 km, the neutron star will shrink by one meter in diameter.

Figure 3: Neutron potential plotted against the distance from another neutron.
7 Conclusions
In the scenario presented the density of the superfluid core of the neutron star increases with time. The results presented here corroborates that the neutron star shrinks as it cools down, this makes the star to decelerate slower and, then, makes the braking index lower than 3. Nevertheless the result is too small to make a difference, as this decreasing in size happens during a very long time. This also justify the use of a non relativistic potential because the difference in the braking index is very small, it won’t justify the use of a much more complex potential to reach the same conclusion.

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