pulsars, in contrast to younger NSs, exhibit much higher surface temperatures than the values predicted by these three heating mechanisms. Furthermore, by restricting the dark matter heating parameters to the current values that were fitted and/or measured for the local dark matter density, masses and neutron star radii, the models studied here also do not reproduce the upper limits of the temperatures from the surface of Black Widows or the actual temperatures of other ancient pulsars. We conclude that if the upper limits for Black Widows are close to real temperatures, dark heating will not represent a convincing explanation of these results, indicating that rotochemical mechanisms may be favored.

Keywords: Internal heating mechanism; dark matter; neutron stars.

PACS numbers:

1. Introduction

In the recent decades, the study of compact stars has achieved extraordinary progress as a result of the launching of several technically advanced observational facilities spanning the radio, optical, UV and X-ray regimes, and pushing the limits of our understanding of stellar timing, spectra and imaging. These technological advances and the consequent advances in our knowledge about compact objects have consolidated our understanding of the role of neutron stars and pulsars as unique laboratories for probing matter under extreme conditions of density, gravity, and high-intensity magnetic fields, physical conditions not available in any terrestrial facility.

The death of a massive star in a supernova explosion and the ejection of the stellar envelope results in a neutron star or a black hole, depending on the progenitor mass and other poorly known details.[1,2] There may be additional evolution channels not yet fully understood (see ref.[3]). Once the compact star achieves "maturity" (a very short time indeed), the surface of a neutron star is composed by a thin atmosphere of hydrogen and helium atoms and possibly of heavier ashes that resulted from the supernova process, resting on a solid crust of heavier atoms. Below this layer, the gravitational pressure is so intense that almost all protons combine with electrons, striped from atomic nuclei, to generate neutrons. In the most internal regions, speculations about its composition have not yet been given a definitive answer: whether neutrons are the dominant particles in an environment composed of protons, neutrons and electrons, or if the extreme gravitational pressure compresses the matter inducing the appearance of more exotic particles like hyperons, the decomposition of protons and neutrons into up, down and strange quarks in almost equal proportions, either existing at high pressure or possibly absolutely stable (strange matter), or even a Bose-Einstein condensate, a state of matter in which all subatomic particles behave as a single quantum mechanical entity.

After decades of speculation, and thanks to a newly launched instrument, the International Space Station Neutron Star Interior Composition Explorer (NICER),[4] that enables rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft $(0.2 - 12\,keV)$ X-ray band with unprecedented sensitivity, expectations are growing of probing the interior structure and the origin of dynamic internal phenomena, as well as the composition and global properties of these compact objects. The capabilities the NICER device brings to the investigation of these compact objects are unique: simultaneous fast timing and spectroscopy, with low background and high throughput, also providing more broadly continuity in X-ray timing astrophysics.

Before the advent of NICER, the masses and sizes of neutron stars, essential quantities for discerning different theoretical models of composition, structure and the equation of state (EoS) of these compact objects, were estimated by observing binary star systems using Kepler's laws and light-curve/spectral modeling.[5] The determination of masses and radii by the latter method results in considerable uncertainties in the properties of these objects, and only a few cases (mainly Double Neutron Star systems) could be measured with accuracy. NICER already produced quite precise measurements including radii, allowing an indirect exploration of the exotic states of matter within neutron stars and helping to improve our knowledge about these compact stars. In short, NICER measurements, combined with other multi-messenger observations, can offer significant observational evidence for the quest of the EoS of dense stars and narrow down its microscopic composition.

In the family of binary neutron stars and pulsars, there is a particular group which has received increasing attention in recent years. These are called Black Widow (BW) spiders, a type of system consisting of a millisecond pulsar, in close orbits with a smaller companion star, which is actually being ablated by the pulsar wind. The group of BWs raised a renewed theoretical interest in the study of these systems.[6–20] Among the characteristics and properties that differentiate Black Widow pulsars, there are hints of high surface temperature (upper limits for now, see below).[21] The standard models of neutron star cooling predict surface temperatures of $T_s < 10^5$ K for stars ages $\tau > 10^{5-6}$ years.[22–24] The confirmed ultraviolet thermal emissions detected from millisecond "conventional" pulsars younger than 10^7 years may imply that BWs do not cool much, in spite of their very old age[6,9] if their surface temperature remains around $T_s \sim 10^5$ K.[25,26] It appears that Black Widows could feature surface temperatures ranging from one to three orders of magnitude higher[21] than expected, a trend that requires a consistent approach to determine whether the mechanisms responsible for such a phenomenon can explain the measured values, a task that has motivated our present work.

Guided by these observations, in this article we compare the predictions of heating and cooling mechanisms affecting young, mature and Black Widow pulsars to expand our knowledge about these objects under extreme physical conditions.

2. Dark Matter in galactic halos and neutron stars

The fundamental nature of dark matter (DM), one of the most fascinating and intricate mysteries of the cosmos, is still unknown. The first evidence for the existence of DM comes from studies involving the movement of galaxy clusters. Zwicky[27] found in the 30's that the amount and distribution of luminous matter of the galaxies