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THERMAL EVOLUTION OF NEUTRON STARS AND CONSTRAINTS ON THEIR INTERNAL PROPERTIES

M. Fortin[1], J. L. Zdunik[2], P. Haensel[2] and J. Margueron[3]

Abstract. Neutron stars, the end point of the life of massive stars, are cosmic laboratories for various fields of physics, in particular for nuclear physics of cold and dense matter. The very high densities inside neutron stars can not be reproduced on Earth. Nevertheless, modeling the thermal evolution of both isolated and accreting neutron stars enables to put constraints on the poorly known composition, structure, superfluid and thermal properties of their interior.

Keywords: Neutron stars, cooling, dense matter, equation of state, superfluidity

1 Introduction

Neutron stars are the remnant of the gravitational collapse of $\sim 8-10M_{\odot}$ stars after a supernova event. They have a mass $\sim 1-2M_{\odot}$, a radius ~ 10 km and a magnetic field up to $\sim 10^{15}$ G. They are relativistic objects sustained by the strong interaction. Their extreme properties make them celestial laboratories for general relativity, magnetohydrodynamics, nuclear physics, superfluidity and superconductivity, ...

Their average density $\sim 10^{15}$ g cm^{-3} is unreachable in terrestrial laboratories so neutron stars offer a unique possibility to understand and constraint the properties of cold and dense matter.

2 Structure of a neutron star

Figure 1 schematically shows the structure of a NS. The surface of a neutron star is surrounded by an atmosphere which is a thin layer of plasma at the origin of the electromagnetic radiation. Below the envelope, the outer envelope or outer crust is made of a gas of electrons e and a lattice of ions Z. The neutrons n start to drip out of the nuclei at $\rho_{\rm ND} \simeq 4 \times 10^{11}$ g cm^{-3}. This point defines the boundary between the outer and inner crust. The matter of the latter is composed of electrons, free neutrons that may be superfluid and a lattice of very neutron-rich atomic nuclei. At the core-crust interface, when $\rho \sim 0.5\rho_0$ with $\rho_0 = 2.8 \times 10^{14}$ g cm^{-3} the nuclear saturation density, the nuclei disappear. The inner core consists of neutrons, protons, electrons and probably muons μ and the nucleons are likely to be superfluid. Deeper in the neutron star is the inner core whose composition is still unknown and is the subject of active research. Various theories predict the appearance of hyperons (baryons with a least one strange quark), the formation of condensates of particles such as pions or kaons, or the phase transition to deconfined quark matter.

The composition and the superfluid properties of the matter inside neutron stars are some of the many mysteries of these objects.

3 Thermal evolution of isolated neutron stars

3.1 Thermal history

A neutron star is born hot in a core-collapse supernova explosion, with a temperature $\sim 10^{11}$ K. In about a hundred years, it cools by neutrino emission in the core and by the heat diffusion in the crust. Therefore, the

[1] LUTH, Observatoire de Paris, 5 Place Jules Janssen, F-92195 Meudon, France
[2] N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, PL-00-716 Warszawa, Poland
[3] Institut de Physique Nucléaire, IN2P3-CNRS, and Université Paris-Sud, F-91406 Orsay, France

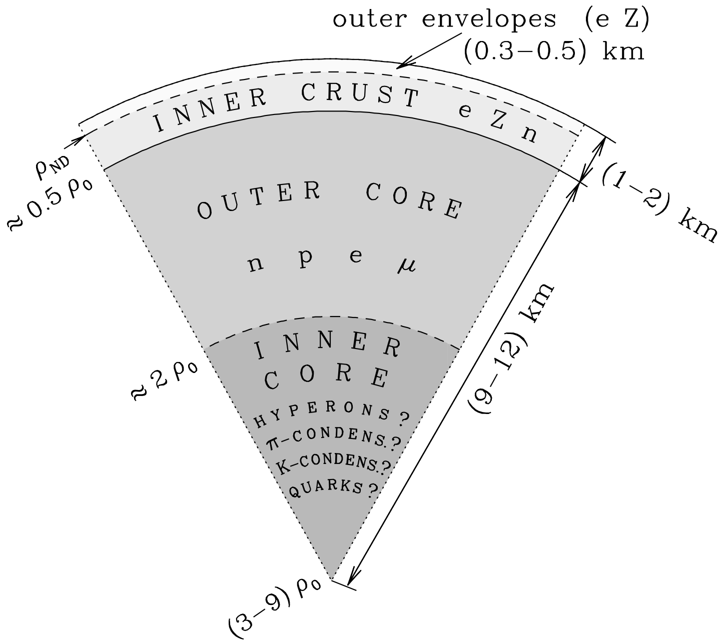

Fig. 1. Structure of a neutron star. From Haensel et al. (2007).

evolution of the surface temperature is connected with the properties and the thermal state of the crust. Later, the temperature inside the core and the crust equilibrates and the cooling of the whole neutron star is driven by the neutrino emission from the core. The thermal state reflects the properties of the core. Finally, after few ten thousand years, the cooling is dominated by the emission of photons at the surface. Therefore, depending on the age of the isolated neutron star whose temperature is determined, one can constraint the physics in different regions of the star.

3.2 Constraining superfluidity with observations

The theoretical modeling of the thermal evolution of an isolated neutron star shows that the cooling depends on the properties of crust, in particular the superfluidity of free neutrons in the inner-crust (Lattimer et al. 1994; Gnedin et al. 2001). Therefore a precise description of the thermal behavior of these neutrons is necessary to simulate the cooling.

New calculations of the superfluid properties of the free neutrons in the crust have been performed taking into account the influence of the surrounding nuclei (Fortin et al. 2010). Simulations of the cooling of a neutron star show that the presence of superfluid neutrons in the inner crust fastens the cooling, as compared to normal neutrons, for the first hundred years and that including the effects of the nuclei has a non-trivial influence on the thermal evolution.

Analyzing archival Chandra X-ray Observatory data, Ho & Heinke (2009) show that the compact object in Cassiopeia A supernova remnant is a neutron star with a carbon atmosphere and a surface temperature $T_s \sim 2 \times 10^6$ K. This is the first determination of the composition of the atmosphere of an isolated neutron star. Spectral fits of ~ 10 years of Chandra observations of CasA neutron star with a carbon atmosphere model reveal that the temperature of the neutron star decreases (Heinke & Ho 2010). For the first time, the cooling of an isolated neutron star is directly observed. So far, only the temperature at one instant in time of neutron stars with different ages and different masses were known. Modeling the thermal evolution of CasA neutron star that is ~ 330 years-old, Shternin et al. (2011) and Page et al. (2011) conclude that the protons in the core are superfluid and superconducting. They also put constraints on the superfluid properties of the neutrons in the core and the associated neutrino emissivity. The future monitoring of CasA neutron star offers exciting perspectives.

4 Thermal evolution of quasi-persistent X-ray transients

A subclass of accreting neutron stars, the so-called quasi-persistent X-ray transients (QPXRTs), also enables to constrain the properties of the matter inside neutron stars.

In the active phase, with $L \sim 10^{36-39}$ erg s^{-1}, the neutron star accretes matter from a low-mass companion during years to decades before accretion stops (when $L < 10^{34}$ erg s^{-1}). In the deep crustal heating scenario (Brown et al. 1998), the accreted matter undergoes a series of nuclear reactions (Haensel & Zdunik 2008) while it sinks deeper into the crust under the weight of the newly-accreted material. The reactions produce heat that is at the origin of the thermal relaxation observed just after accretion stops, shown in figure 2.

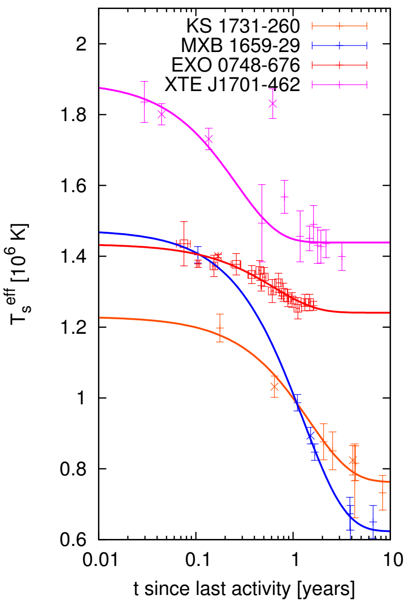

Fig. 2. Thermal relaxation of the four quasi persistent X-ray transients. The temperature as seen by an observer at infinity is plotted versus the time since the source turns to quiescence. The solid lines show the best-fit of the observations by an exponential decay. Observations from Cackett et al. (2010, 2008); Degenaar et al. (2011); Fridriksson et al. (2011).

The modeling of the thermal relaxation after accretion stops depends on the accretion rate, the composition and mass of the neutron star and the microphysical input.

The thermal relaxation of KS 1731 − 260 excludes a very efficient neutrino process, the so-called DURCA process, in the core and is consistent with moderate neutrino emissivity and a crystalline crust with superfluid neutrons (Shternin et al. 2007). The thermal relaxations of KS 1731 − 260 and MXB 1659 − 29 are consistent with the presence of nuclides with different charge numbers at a given density (Brown & Cumming 2009). These two sources have a relaxation time scale τ, after accretion stops, of the order of 500 days (table 1). There are two more QPXRTs whose thermal relaxation has not been successfully modeled yet : EXO 0748 − 676 and XTE J1701 − 462 with much shorter relaxation time scales ($\sim$ 200 and 100 days respectively). These suggest that there exist heat sources at densities lower than the ones that have been considered so far in the models of deep crustal heating. Moreover, XTE J1701 − 462 exhibits in the relaxation stage a sudden increase in temperature that is believed to originate from a sudden spur of accretion.

Source	τ (d)
KS 1731 − 260	540 ± 125
MXB 1659 − 29	465 ± 35
EXO 0748 − 676	230 ± 60
XTE J1701 − 462	95 ± 15

Table 1. Relaxation time scales τ in days of the QPXRTs obtained by a fit of the observations with an exponential decay.

Future work intend to take into account a precise description of the microphysical properties (composition, thermal properties) in the outer part of the neutron star together with an up-to-date model of atmosphere for an accreting neutron star Fortin et al. (2012). The burning of the accreted matter at low density will be taken into account for the first time. Preliminary results show that the thermal relaxation of all four sources can be reproduced by our model. Moreover the thermal evolution of an accreting neutron star in the accreting phase will be calculated. The model can enable to put constraints on the properties of the outer parts of neutron stars and is to be later extended to study the other neutron star transients.

5 Conclusions

The properties of the matter inside neutron stars are poorly-known since the high densities inside them can not be reproduced on Earth. Nevertheless, modeling the thermal evolution of isolated and accreting neutron stars enables to put constraint on the physics of cold and dense matter, in particular on the superfluid properties, the neutrino processes and the composition.

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