Unified description of dense matter in neutron stars and magnetars

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Abstract. We have recently developed a set of equations of state based on the nuclear energy density functional theory providing a unified description of the different regions constituting the interior of neutron stars and magnetars. The nuclear functionals, which were constructed from generalized Skyrme effective nucleon-nucleon interactions, yield not only an excellent fit to essentially all experimental atomic mass data but were also constrained to reproduce the neutron-matter equation of state as obtained from realistic many-body calculations.

Keywords. stars: neutron, dense matter, equation of state, gravitation, magnetic fields, stars: interiors

1. Introduction

With a mass of the order of that of our Sun compressed inside a radius of about 10 km only, neutron stars (NS) are among the most compact objects in the universe (see e.g. Haensel *et al.* 2007). Their central density can exceed several times the density encountered in the heaviest atomic nuclei. NS are also the most strongly magnetized objects. Surface magnetic fields of order $10^{14} - 10^{15}$ G have been estimated in soft gamma-ray repeaters and anomalous X-ray pulsars assuming that their spin-down is due to magnetic dipole radiation (see e.g. McGill SGR/AXP online catalog). In addition, circumstantial evidence of surface magnetic fields greater than 10^{15} G have been reported from spectroscopic studies (see e.g. Strohmayer & Ibrahim 2000, Gavriil *et al.* 2002, Woods *et al.* 2005). The internal magnetic field of a NS could be even stronger than its surface field, as found in the Sun (see e.g. Solanki *et al.* 2006). In particular, according to the magnetar model of Thompson & Duncan (1993), magnetic fields up to $\sim 10^{17}$ G could be generated via dynamo effects in hot newly-born NS.

The outer crust of a cold non-accreting NS is primarily composed of pressure ionized iron atoms arranged in a regular crystal lattice and embedded in a highly degenerate electron gas. With increasing density, nuclei become more and more neutron-rich due to electron captures. Eventually, at a density $\sim 4 \times 10^{11}$ g/cm³, some neutrons start to drip out of nuclei, thus defining the boundary between the outer crust and the inner crust. At densities above $\sim 10^{14}$ g/cm³, the crust dissolves into a uniform plasma of nucleons and leptons. The composition of the core remains very uncertain.

We have determined the internal structure a cold non-accreting NS endowed with a strong magnetic field using a unified treatment of dense matter based on the nuclear energy-density functional (EDF) theory.

2. Brussels-Montreal equations of state

The EDF theory provides a self-consistent description of various nuclear systems, from finite nuclei to homogeneous nuclear matter. It is therefore well suited for studying the interior of a NS. The Brussels-Montreal EDF BSk19, BSk20 and BSk21 were derived from generalized Skyrme effective nucleon-nucleon interactions which fit essentially all measured masses of atomic nuclei (calculated using the Hartree-Fock-Bogoliubov method) with an rms deviation as low as 0.58 MeV. In addition, these EDF were constrained to reproduce three different representative neutron-matter equations of states (EoSs) obtained from microscopic calculations using realistic two- and three- body forces and reflecting the current lack of knowledge of dense neutron matter (see Goriely *et al.* 2010).

We used these EDF to calculate consistently the properties of all regions of the interior of a non-accreting NS, from its surface down to the center, under the assumption of cold catalyzed matter (see Pearson *et al.* 2011, Pearson *et al.* 2012). The core was assumed to be made of nucleons and leptons only. The resulting unified EoSs are consistent with the radius constraints of Steiner *et al.* (2010) inferred from observations of X-ray bursters and low-mass X-ray binaries (Fantina *et al.* 2011). However, only the EoSs based on the BSk20 and BSk21 EDF are stiff enough at high densities to support NS as massive as PSR J1614$-$2230 (see Chamel *et al.* 2011).

3. Internal structure of magnetars

The internal composition of a magnetar can be substantially different from that of an ordinary NS, especially in the outermost layers. We have therefore recalculated the EoS of the outer crust of a NS taking into account the presence of the magnetic field using the BSk21 EDF (see Chamel *et al.* 2012). In a strong magnetic field, the electron motion perpendicular to the field is quantized into Landau levels and this can change the sequence of equilibrium nuclides. We have found that the deviations become particularly significant for $B \sim 10^{16}$ G. Moreover, strong magnetic fields tend to prevent neutrons from dripping out of nuclei thus increasing the pressure at which the neutron drip transition occurs. The effects of the magnetic field on nuclei, which we have neglected, could also have an impact on the crust for $B \gtrsim 10^{17}$ G (Peña Arteaga *et al.* 2011).

Strong magnetic fields can change the EoS in the surface regions where only a few Landau levels are filled. However, with increasing density the effects of B become less and less important as more and more levels are populated and the EoS matches smoothly with that obtained for $B = 0$. For $B \sim 10^{15}$ G, only the EoS in the outer crust is affected. Therefore the global structure of a magnetar would be almost undistinguishable from that of an ordinary NS.

4. Conclusions

We have developed a series of EoSs of cold catalyzed matter based on the EDF theory and describing consistently all regions of a cold non-accreting NS (Chamel *et al.* 2011). These EoSs have been recently extended to magnetars by taking into account the effects of the strong magnetic field in the outer crust (Chamel *et al.* 2012). We have found that the outer crust of a magnetar could have a substantially different composition (hence also different properties) compared to that of an ordinary NS.

Table 1. Sequence of equilibrium nuclides with increasing depth in the outer crust of a cold non-accreting magnetar endowed with a magnetic field $B = 10^{17}$ G. For comparison, the results obtained for $B = 0$ are also indicated.

$B = 10^{17}$ G	$B = 0$
^{56}Fe	^{56}Fe
^{62}Ni	^{62}Ni
-	^{58}Fe
-	^{64}Ni
-	^{66}Ni
^{88}Sr	-
^{86}Kr	^{86}Kr
^{84}Se	^{84}Se
^{82}Ge	^{82}Ge
^{132}Sn	-
^{130}Cd	-
^{128}Pd	-
^{126}Ru	-
-	^{80}Zn
-	^{79}Cu
-	^{78}Ni
-	^{80}Ni
^{124}Mo	^{124}Mo
^{122}Zr	^{122}Zr
^{121}Y	^{121}Y
^{120}Sr	^{120}Sr
^{122}Sr	^{122}Sr
^{124}Sr	^{124}Sr

Acknowledgements

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