Chapter 11
Neutron Star Cooling: I

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11.1 Introduction

This chapter presents a basic, but detailed, introduction to the physical and astrophysical issues involved in the study of the thermal evolution of isolated neutron stars. Results of numerical calculations,\(^1\) for both minimal and enhanced cooling scenarios, are presented and compared with observational data.

The first conjectures about the possible existence of stellar neutron cores by Landau [37] and Baade and Zwicky [6] and the pioneering work of Oppenheimer and Volkoff [48] pointed to very mysterious, exotic, small and dense objects. Forty years after the actual discovery of neutron stars [28] these early thoughts have been fully confirmed: neutron stars are demonstrably very small and dense, they very probably enclose some exotic form(s) of matter, and they are still mysterious.\(^2\)

A theorist view of the interior of a neutron star is depicted in Fig. 11.1: the central region, marked as “?” is the mysterious part and it is the main goal of the study of neutron star cooling, necessarily complemented with the study of many other facets of neutron star phenomenology, to elucidate it. However, any information about this central part which we can glean by observing the surface is conditioned by our understanding and correct modeling of the outer parts of the star. The core, where neutrons and protons form a homogeneous quantum liquid, is distinguished from the crust, where the nucleons cluster and matter is hence inhomogeneous at

\(^1\) A 1D (i.e., assuming spherical symmetry) cooling code, NSCool, with which most calculations presented in this chapter were performed, is available at http://www.astroscu.unam.mx/neutrones/NS-Cooler/.

\(^2\) The existence of pulsars with periods around 1.5 ms implies, by causality, that they have radii smaller than 75 km and, if they are bound by gravity, that their average density is, at least, of the order of \(10^{14}\) g cm\(^{-3}\).
At the microscopic level. This crust–core separation is currently estimated \([44]\) to be located at a density \(\rho_{cc} \approx 1.6 \times 10^{14} \text{ g cm}^{-3}\), i.e., about 60% of nuclear matter density, \(\rho_{\text{nuc}} \approx 2.8 \times 10^{14} \text{ g cm}^{-3}\). \(\rho_{\text{nuc}}\) refers to symmetric nuclear matter, i.e., made of 50% neutrons and 50% protons, at zero pressure and is deduced from the central density of heavy nuclei, while at \(\rho_{cc}\) in a neutron star, pressure is non zero and matter consists of about 95% neutrons with a small 5% proton component.

At the surface of the star we expect a very thin atmosphere composed of hydrogen and in some cases perhaps a mix of heavy elements, or even a condensed magnetic surface \([36]\). This surface is of utmost observational importance because it is where the observable thermal flux \(F(E)\) is emitted. An envelope exists just below the atmosphere where matter is not yet fully degenerate and, with a thickness of a few tens of meters, it acts as a thermal insulator between the hot interior and the surface. The outer 500–1,000 m of the star, its crust, contain nuclei, forming a lattice