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Relativistic Correction of Neutrino Emission in Neutron Stars[†] [⋆]

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Abstract By the relativistic mean field theory and relevant weak-interactional cooling theory, the relativistic cooling properties in the conventional and hyperonic neutron star matter are studied. Also a comparison between the relativistic and non-relativistic results after taking consideration of the gravity correction is performed. The results show that the relativistic effect of neutrino emission reduces the neutrino emissivity, luminosity, and the cooling rate of stellar objects, in comparison with the non-relativistic case. In the neutron star matter without hyperon, the amplitude of the cooling rate reduction caused by the relativistic effect is maximal after taking the gravity correction into consideration, it attains 56% for a $2\,M_{\odot}$ neutron star composed of conventional neutron star matter, and in the hyperonic matter the amplitude of reduction is minimal, about 38%.

Key words stars: neutron, stars: relativistic effect, stars: gravity correction, stars: hyperon

1. INTRODUCTION

The mass of a neutron star is about 1-2 solar mass[1,2], the radius is 10-20 km, such a highly compact material environment provides an ideal and natural laboratory for studying the properties of compact matter, neutrino radiation, compact star evolution, and so on. In the recent several decades, because of the technical development of temperature detections of neutron stars, the studies on the structure and cooling properties of neutron stars become the hot spots in the fields of astrophysics and nuclear physics.

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The temperature reduction of a neutron star from an extremely high temperature of 10^{11} K in the time of birth to the lower temperature of 10^8 is realized mainly by emitting neutrinos, and among the neutrino emission mechanisms, the one with the highest cooling efficiency is the direct Urca process of nucleons (briefly called the dUrca process in the following), there are secondly the direct Urca processes of hyperons, negative K-mesons, quarks, etc.[3,4]. In the neutrino emission process of the neutron star interior, the neutrino emissivity is a key important physical parameter, it gives the energy carried away by the neutrino emission in the unit time and unit volume. At present, there are mainly two formulae of neutrino emissivity, which are commonly used by scholars: the formula derived by Lattimer et al.[5] in 1991 with no account of the relativistic effect, and the formula proposed by Leison et al.[6] in 2001 with the relativistic effect taken into consideration. Obviously, the result obtained from the later one is more believable, because that in the common case, the critical density for producing the dUrca process is about $2\rho_0$ (ρ_0 is the saturated nuclear density), under such a high density, the velocities of particles participated in the dUrca process must be very high, the relativistic effect should be taken into consideration. However, most of the previous discussions on the neutrino emission adopted the formula without the relativistic effect, if making recalculations the amount of work will be quite large. Hence, to give quantitatively the relativity corrections for the cooling properties of the neutron stars with the different masses and different material compositions will be helpful for the extended and accurate applications of the previously obtained scientific results, this is of realistic significance.

The recent observational data indicate that the mass of neutron stars is slightly greater than what people thought. For example, the mass of the millisecond pulsar PSR J1614-2230 is precisely measured to be $(1.97\pm0.04)\,M_\odot$ ($M_\odot$ is the solar mass), the radius is 11–15 km[7], and the mass of the pulsar PSR J0348+0432 observed in 2013 is even larger[8], it is $(2.01\pm0.04)\,M_\odot$. Such a large mass has a certain difference from the canonical mass $1.4\,m_\odot$ of neutron stars predicted by theories, the scholars suggested that this is mainly caused by two reasons: one is that the equation of state (EoS) of the neutron star matter should be even harder, but the previous theoretical results are on the softer side; the second is that in the theoretical calculations some factors, which must be taken into consideration, may be neglected, for example the gravity correction[9−11], the effect of strong magnetic field[12], the effect of electric field[13], and so on, in which the gravity correction has being gradually accepted by scholars. Gravity is the force known most early by human beings, but up to now it has not yet been studied thoroughly, some phenomena still cannot be explained by the gravitation theory[14−16]. And the experiments and theories in recent years indicate as well that under the high-density environments as like neutron stars, when we study a physical problem at an extremely small scale, the gravity may deviate the Newtonian inverse square proportion law[17,18]. The studies made by Chen L. W. et al. indicate that the gravity correction can harden the EoS, and make a significant influence on the structure of neutron

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