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Neutron star coolling

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We study thermal evolution of isolated neutron stars in scalar-tensor theories for the first time. Whether the rapid cooling due to the direct Urca process occurs or not is an interesting question in the viewpoint of the temperature observation of isolated neutron stars. Moreover, investigation of the cooling effect of nucleon superfluidity also has the large uncertainties though it is important in modern cooling theory. The cooling effect is typically influenced by the proton fraction and the central density. If a fifth force is mediated due to modification of gravity, the relation between the central density and mass of neutron stars differs from one in general relativity, and the cooling curve is also naively expected to be varied. We find that an unscreened fifth force near the surface of neutron stars changes mass-central density relation, and the direct Urca process can be triggered even for neutron stars with smaller mass. We also present cooling curves including nucleon super fluidity under the scalar-tensor theory. These results show that it might be useful to test gravitational theories with cooling observations of neutron stars.

I. INTRODUCTION

The theory of neutron star cooling was developed short after the evidence of X-ray emission from the surface of neutron stars in the Sixties. During the following decades, microphysical inputs have been refined to improve 1D cooling models, but the effects of magnetic were barely taken into account proposed the so-called minimal cooling scenario, in which all the necessary known microphysical ingrediends are consistently included (superfluidity, neutrino emission processes), but fast cooling processes (direct URCA by nuclear or exotic matter) are excluded. The minimal cooling paradigm has been shown to be consistent with the luminosity of the weakly magnetized neutron stars ($B \leq 10^{23}G$), but magnetars and some of the high-B pulsars show a relatively large X-ray luminosity, thus requiring the presence of additional heat sources, likely linked to the magnetic field evolution.

II. NEUTRON STAR COOLING

The interior of a proto-neutron star loses energy at a rapid rate by neutrino emission.Within 10 to 100 years, the thermal evolution time of the crust, heat transported by electron conduction into the interior, where it is radiated away by neutrinos, creates an isothermal structure. The star continuously emits photons, dominantly in x-rays, with an effective temperature T_{eff} that tracks the interior temperature, but that is smaller by a factor of about 100. The energy loss from photons is swamped by neutrino emission from the interior until the star becomes about $3 \cdot 10^5$ years old.

The overall time that a neutron star will remain visible to terrestrial observers is not yet known, but there are two possibilities: the standard and enhanced cooling scenarios. The dominant neutrino cooling reactions are of a general

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type, known as Urca processes, in which thermally excited particles alternately undergo beta and inverse-beta decays. Each reaction produces a neutrino or antineutrino, and thermal energy is thus continuously lost. The most efficient Urca process is the direct URCA process involving nucleons:

$$n \to p + e^- + {}_e, \quad p \to n + e^+ + \nu_e \tag{1}$$

This process is only permitted if energy and momentum can be simultaneously conserved. This requires that the proton to neutron ratio exceeds 1/8, or the proton fraction $x \geq 1/9$, which is far above the value found in neutron star matter in the vicinity of n_0. In a mixture of neutrons, protons and electrons, the proton fraction x in beta equilibrium satisfies [1]

$$x \backsimeq 0,048(S_v(n)/S_v(n_0))^3(n_0/n)(1-2x)^3 \tag{2}$$

where, typically, $S_v(n_0) \backsimeq 30MeV$. Because x generally increases with density, the direct Urca process might still occur above some density threshold. However, if the direct process is not possible, neutrino cooling must occur by the modified Urca process

$$n + (n,p) \to p + (n,p) + e^- + \vec{\nu_e}, \quad p + (n,p) \to n + (n,p) + e^+ + \nu_e \tag{3}$$

in which an additional nucleon (n, p) participates in order to conserve momentum. The modified URCA rate is reduced by a factor of $(T/\mu_n) \lesssim 10^{-4}$ to 10^{-5} compared to the direct URCA rate, and neutron star cooling is correspondingly slower. The standard cooling scenario assumes that direct URCA processes cannot occur, and predicts that neutron stars should remain observable by surface thermal emission for up to a few million years. Whether or not the direct Urca process occurs in neutron stars is of fundamental importance. The density dependence of the symmetry energy function S_v determines the values of x and the threshold density at which the nucleonic direct Urca process occurs (Eq. (5)). It also plays an essential role in determining the threshold densities of other particles, such as hyperons, pions, kaons or quarks, whose existences trigger other direct Urca processes. If a star's central density lies below the Urca threshold, enhanced cooling cannot occur. Again, the quantity $S_v(n)$ plays a crucial role for neutron stars, andn its inherent uncertainty means that it is presently unknown if direct Urca processes can occur in neutron stars. There are two additional issues affecting cooling trajectories of neutron stars: superfluidity [2], [3] and envelope composition [4]. Superfluidity quenches cooling from the direct Urca process. However, an additional cooling source from the formation and breaking of nucleonic Cooper pairs increases the cooling rate from the modified Urca process [5]. Nevertheless, a clear distinction remains between enhanced and standard cooling trajectories. Envelope composition also plays a role in the inferred surface temperatures. Although it is commonly assumed that the envelope is dominated by iron-peak nuclei, this may not be the case. Light elements (H or He) have smaller photon opacities which enhance surface photon emission. Neutron stars appear warmer with light-element envelopes for their first 100,000 years of cooling but eventually the situation reverses [6].

A. Thermal Emission

Most known neutron stars are observed as pulsars and have photon emissions from radio to x-ray wavelengths dominated by non-thermal emissions. It is believed that the bulk of the non-thermal emissions are generated in a neutron star's magnetosphere. Although such emissions can teach us about magnetospheric phenomena, they are difficult to utilize in constraining the star's global aspects, such as mass, radius and temperature, that have significant bearing on a star's interior structure, composition and evolution. About a dozen neutron stars with high thermal emissions, and with ages up to a million years, have been identified [6] and these stars are expected in the standard cooling scenario to have surface temperatures in the range of $3 \cdot 10^5$ to $10^6 K$ (Fig. 4), so the bulk of their emitted radiation should lie in the extreme ultraviolet or x-ray regions.

The effective temperature $T_{eff,\infty}$ is defined from

$$F_\infty = L_\infty/4\pi d^2 = \sigma_B T_{eff,\infty}^4 (R_\infty/d)^2 \tag{4}$$

where σ_B is the Stefan-Boltzmann constant, d is the distance, and F_∞ and L_∞ refer to the flux and luminosity observed at Earth. These latter quantities, and $T_{eff,\infty}$ are redshifted from the neutron star surface, where the redshift is $z = (1 - 2GM/Rc^2)^{-1} - 1$. For example, $T_{eff,\infty} = T_{eff}/(1+z)$ and $F_\infty = F/(1+z)^2$. As a result, the so-called radiation radius R_∞, a quantity that can be estimated if F_∞, $T_{eff,\infty}$ and d are known, is defined to be $R_\infty = R(1+z)$. R_∞ is a function of the mass and radius of the neutron star, but if redshift information is available, perhaps from spectral lines, M and R could be separately determined. Indeed, observation of spectral lines has been

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reported from 1E 1207.4-5209 [7] and EXO 0748-676 [8], but the identifications of the lines are controversial [9] with redshifts ranging from 0.12 to 0.35.

A serious hurdle in the attempt to determine R_∞ and $T_{eff,\infty}$ is the fact that neutron stars are not blackbodies [10], The star's atmosphere rearranges the spectral distribution of emitted radiation. Although models of neutron star atmospheres for a variety of compositions have been constructed, these are mostly limited to non-magnetized atmospheres. Pulsars, however, are thought to have magnetic field strengths on the order of 1012 G or greater [11]. The behavior of strongly magnetized hydrogen is relatively simple, but models of magnetized heavy element atmospheres are still in a state of infancy [12].

A useful constraint on models is provided by a few cases in which the neutron star is sufficiently close to Earth for optical thermal emission to be detected (distinguished by green boxes in Fig. 4). These stars have optical fluxes several times less than what a blackbody extrapolation from the observed x-rays into the Rayleigh-Jeans optical domain would imply. This optical deficit is a natural consequence of the neutron star atmosphere, and results in an inferred R_∞ greater than that deduced from a blackbody. In most cases a heavy-element atmosphere adequately fits the global spectral distributions from x-ray to optical energies while also yielding neutron star radii in a plausible range. However, the observed absence of narrow spectral features, predicted by heavy-element atmosphere models, is puzzling [13]. The explanation could lie with broadening or elimination of spectral features caused by intense magnetic fields or high pressures.

Radius estimates from isolated neutron stars, while falling into a plausible range, are also hampered by distance uncertainties. Pulsar distances can be estimated by dispersion measures [11], but these have uncertainties of 50 or more. In a few cases, such as Geminga [14], RX J185635-3754 [15] and PSR B0656+14 [16], parallax distances have been obtained, but errors are still large.

The recent discovery of thermal radiation from quiescent x-ray bursters (involving neutron stars in binaries) in globular clusters is particularly exciting. At first glance, it seems strange that neutron stars in globular clusters, which are on the order of 10 billion years old, could be hot enough to emit observable thermal radiation. However, it is believed that recent episodes of mass accretion from their companions has been a literal fountain of youth, replenishing their reservoir of thermal energy [17]. The measurements of radii from these stars might become relatively precise, especially if the distances to the globular clusters in which they are found can be refined. Values of R_∞ in the range of 13 to 16 km have been estimated from the quiescent x-ray sources in the globular clusters NGC 5139 and 47 Tuc [18]

Theoretical cooling curves can be compared to observations if ages for the thermallyemitting neutron stars can be estimated (Fig. 4). The best-determined ages are those for which dynamical information, such as observed space velocities coupled with a known birthplace, is available. Characteristic spin-down ages estimated from pulsar periods P and spin-down rates $\dot{P}$ using $\tau_s = P/2\dot{P}$ [11] are less reliable. In the cases in which both kinds of age estimates are available, they are generally discrepant by factors of 2 to 3.

Theoretical cooling tracks, for a variety of mass, radius and superfluid properties, are relatively narrowly confined as long as enhanced cooling does not occur [19]. These tracks are mostly sensitive to envelope composition. When enhanced cooling is considered, cooling tracks fall in a much wider range (Fig. 4). Although most observed stars are consistent with the standard cooling scenario, a few cases, espcially PSR J0205+6449 in 3C58 for which only upper limits to temperature and luminosity exist [20], may suggest enhanced cooling. Uncertainties in estimated temperature and ages have precluded definitive restrictions on EOS's or superfluid properties from being made.

III. CONCLUSION

Neutron stars are some of the densest manifestations of massive objects in the universe. They are ideal astrophysical laboratories for testing theories of dense matter physics and provide connections among nuclear physics, particle physics and astrophysics. Neutron stars may exhibit conditions and phenomena not observed elsewhere, such as hyperon-dominated matter, deconfined quark matter,superfluidity and superconductivity with critical temperatures near 10^{10} kelvin, opaqueness to neutrinos, and magnetic fields in excess of 10^{13} Gauss. Here, we describe the formation, structure, internal composition and evolution of neutron stars. Observations that include studies of binary pulsars, thermal emission from isolated neutron stars, glitches from pulsars and quasi-periodic oscillations from accreting neutron stars provide information about neutron star masses, radii, temperatures, ages and internal compositions.

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