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Impact of rotation-driven particle repopulation on the thermal evolution of pulsars

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ABSTRACT

Driven by the loss of energy, isolated rotating neutron stars (pulsars) are gradually slowing down to lower frequencies, which increases the tremendous compression of the matter inside of them. This increase in compression changes both the global properties of rotating neutron stars as well as their hadronic core compositions. Both effects may register themselves observationally in the thermal evolution of such stars, as demonstrated in this Letter. The rotation-driven particle process which we consider here is the direct Urca (DU) process, which is known to become operative in neutron stars if the number of protons in the stellar core exceeds a critical limit of around 11% to 15%. We find that neutron stars spinning down from moderately high rotation rates of a few hundred Hertz may be creating just the right conditions where the DU process becomes operative, leading to an observable effect (enhanced cooling) in the temperature evolution of such neutron stars. As it turns out, the rotation-driven DU process could explain the unusual temperature evolution observed for the neutron star in Cas A, provided the mass of this neutron star lies in the range of 1.5 to 1.9 M_{\odot} and its rotational frequency at birth was between 40 (400 Hz) and 70% (800 Hz) of the Kepler (mass shedding) frequency, respectively.

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Numerical cooling simulations of neutron stars allow one to probe the inner structure of these objects, and the properties of ultra-dense matter [1–9]. In the standard treatment, neutron star cooling calculations are carried out for stellar core compositions which are frozen-in, that is, compositions which do not change with time, as it is the case for non-rotating neutron stars. The situation may be very different for isolated rotating neutron stars, which are spinning down due to magnetic braking. Such stars can experience drastic density changes during spin-down, causing the formation of novel states of matter in their cores. Examples of which are the formation of a mixed phase of quarks and hadrons, of pure quark matter, or a condensate made of bosons [10–14]. Another intriguing possibility concerns the rotation-driven changes in the number densities of neutrons, protons and leptons in the cores of rotating neutron stars, which can have important observable consequences for the thermal evolution of such objects, as shown in this Letter.

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Computing the thermal evolution of rotating neutron stars is considerably more complicated than computing the cooling of non-rotating neutron stars. The reasons are several. First, stellar rotation requires solving Einstein's field equations for rotationally deformed fluid distributions [10,11], which renders the problem 2-dimensional. Second, the general relativistic frame dragging effect imposes an additional self-consistency condition on Einstein's field equations. Third, an extra self-consistency condition is encountered when calculating the general relativistic Kepler (mass shedding) frequency of a rotating neutron star. Fourth, the thermal transport equations need to be solved for general relativistic, non-spherical fluids that may experience anisotropic heat transport. Our study accounts for the first three effects. The fourth effect, the anisotropic transport of heat inside neutron stars, is reserved for a separate future study [15].

In this Letter, we consider the cooling behavior of isolated rotating neutron stars. The number of baryons (i.e., the so-called baryon mass) of such stars remains unchanged during spin-down. As known from earlier studies [10,16,17], the spin-down driven gravitational compression can cause substantial changes in the core compositions of such neutron stars. A striking example of this is the direct Urca (DU) process, which describes the direct (no bystander particle necessary) transformation of neutrons to protons,

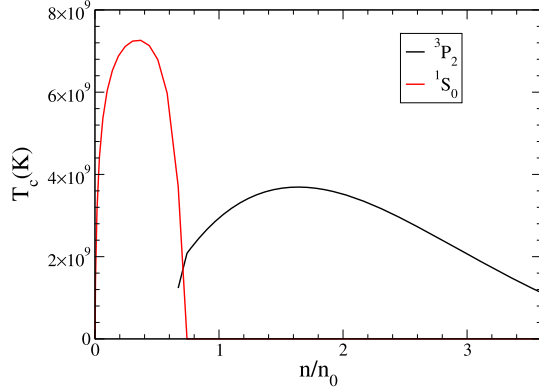


Fig. 1. (Color online.) Critical temperature of superfluid neutrons in 1S_0 and 3P_2 states as a function of baryon number density. (n_0 denotes the density of ordinary nuclear matter.)

electrons and anti-electron neutrinos in the cores of neutron stars, according to

$$n \rightarrow p + e^- + \bar{\nu}_e. \quad (1)$$

Reaction (1) can only occur if the proton fraction exceeds between 11% to 15% [18]. The neutrino luminosity associated with this reaction dominates over those of other neutrino emitting processes in the core [3,18]. One may thus speculate that once (1) becomes operative in rotating neutron stars, it could speed up the cooling of such stars substantially, leading to an observational signature in the thermal evolution of such objects. The pairing of neutrons in the 1S_0 singlet and 3P_2 triplet states, which reduces the neutrino emission from neutron stars, would not change this behavior, as will be discussed later in this Letter. Following the approach of [19,20], the critical temperatures assumed for these states are shown in Fig. 1.

Considering the conservation of momentum and the superfluidity suppression, we show in Fig. 2 the intensity of the DU process (defined here as the reduction factor introduced by pairing, i.e. “1” means no reduction, “0” total suppression) in the core of rotating neutron stars for different stellar masses, M , and rotational frequencies, Ω . One sees that, depending on frequency (and thus central density) and temperature (which affects the level at which the DU process is suppressed), the DU process operates at very different intensities. Hence, as a rotating neutron star evolves from a given “initial” state (given frequency, mass, and temperature) in time, the intensity of the DU process at its core can vary substantially. Also shown in Fig. 2 are several evolutionary tracks of neutron stars which spin down because of the emission of magnetic dipole radiation. The intensity of the DU process of stars along these tracks can vary significantly too, depending on the values of the star’s initial parameters, which ought to affect their thermal evolution.

In passing we note that the rotationally driven compositional changes in the cores of rotating neutron stars may also occur, in reverse however, in the cores of neutron stars in binaries, which are spun up by mass accretion. The treatment of such neutron stars is more complicated, however, since both the frequency as well as the star’s mass are changing. In that case the evolutionary tracks shown in Fig. 2 will follow a different path, but the overall modification of the intensity of the DU process may be expected to hold.

The results shown in Fig. 2 are generic for any EoS which predicts a sufficiently large number of protons in the cores of neutron stars so that reaction (1) becomes possible. The EoS used in this Letter is a parametrized version of the Akmal–Pandharipande–Ravenhall (APR) EoS [21,22] (and references therein). For this

parametrization, the binding energy consists of a compression term and a symmetry energy term,

$$BE = E_0 u \frac{u - 2 - \delta}{1 + \delta u} + S_0 u^\gamma (1 - 2x_p)^2, \quad (2)$$

where E_0 is the saturation energy, S_0 the symmetry energy at saturation, $u \equiv n/n_0$ with n the baryon number density and n_0 the baryon number density at saturation, and x_p the proton fraction. The parameters δ and γ can be used to control the nuclear incompressibility and the symmetry energy, respectively. The maximum mass of a neutron star is thus sensitive to changes in δ , and the threshold density for the onset of the DU process is sensitive to changes in γ . Details of the parametrization of the APR EoS have been discussed in [22]. The cooling of neutron stars described by this EoS were first explored in [23]. Very recently, this EoS was used to put constraints on the properties (superfluid gaps) of ultra-dense matter using the temperature data observed for the neutron star in Cas A [8,9,24].

Next, we explore the impact of a varying proton fraction, driven by stellar rotation, on the thermal evolution of isolated rotating neutron stars. In this study we consider the following cooling processes: the direct Urca, the modified Urca, and Bremsstrahlung processes in the stellar core. For the crust, we consider Bremsstrahlung, e^+e^- pair annihilation, and plasmon decay processes. A comprehensive overview of the neutrino emission processes in neutron stars can be found in [10,12,25]. The boundary conditions are determined by the luminosity at the stellar center, $l(0) = 0$, and at the surface $l(R) = L_S$ [26,27]. To establish a connection between the rotational frequency of neutron stars and their respective cooling stages, we model the spin-down rate according to

$$\dot{\Omega} = -K\Omega^n, \quad (3)$$

where Ω denotes the neutron star spin frequency, and K and n are constants [11]. The constant K can be parametrized as (for $n = 3$) $K = 1.55 \times 10^{-17} \times R_{10}^4 B_{12}^2 / (M/M_\odot)$ s, where B_{12} is the surface magnetic field in units of 10^{12} G, R_{10} the radius in units of 10 km, and α the inclination angle of B (note that the moment of inertia was approximated by $2MR^2/5$). Using the frequencies and time derivatives of observed pulsars available at the ATNF pulsar data base [28], we find that $10^{-21} \leq K \leq 10^{-11}$ (in the same units as above, i.e., s) for a braking index $n = 3$. The latter value corresponds to neutron stars which spin-down due to the emission of magnetic dipole radiation, as considered in this Letter. By integrating Eq. (3) one obtains the frequency as a function of time. With the aid of Eq. (3), we can now trace the thermal evolution of isolated, spinning-down neutron stars.

The results are shown in Figs. 3 and 4. It is evident from Fig. 3 that the temperature drops dramatically when the DU process (1) becomes operative during spin-down. The characteristic time scale of the thermal coupling between the core and the crust of non-rotating stars is $\tau_C = (\Delta R/1 \text{ km})^2 (1 - 5.04 \times 10^{-2} (M/M_\odot)/R_{10})^{-3/2} t_1$, where ΔR is the crust thickness, and t_1 is a constant with dimension of time, that depends on the microscopic properties of the star, and whose value is ~ 30 years [29]. For a traditional neutron star $\tau_C = 50\text{--}150$ years [29], and in this work we set $\tau_C = 100$ years. In the case of spinning-down neutron stars considered here, we must also consider the relaxation time of the spin-evolution, which we define as the time it takes for the star to spin down to half of its original frequency. This time scale is given by $\tau_S = 3/(2K\Omega_0^2)$, where Ω_0 denotes the birth frequency of the object. The parameter

$$\beta \equiv \frac{\tau_S}{\tau_C} = \frac{M/M_\odot (1 - 5.04 \times 10^{-2} (M/M_\odot)/R_{10})^{3/2}}{1.03 \times 10^{-17} R_{10}^4 B_{12}^2 \sin^2 \alpha \Delta R_{\text{km}}^2 \Omega_0^2 t_1} \quad (4)$$

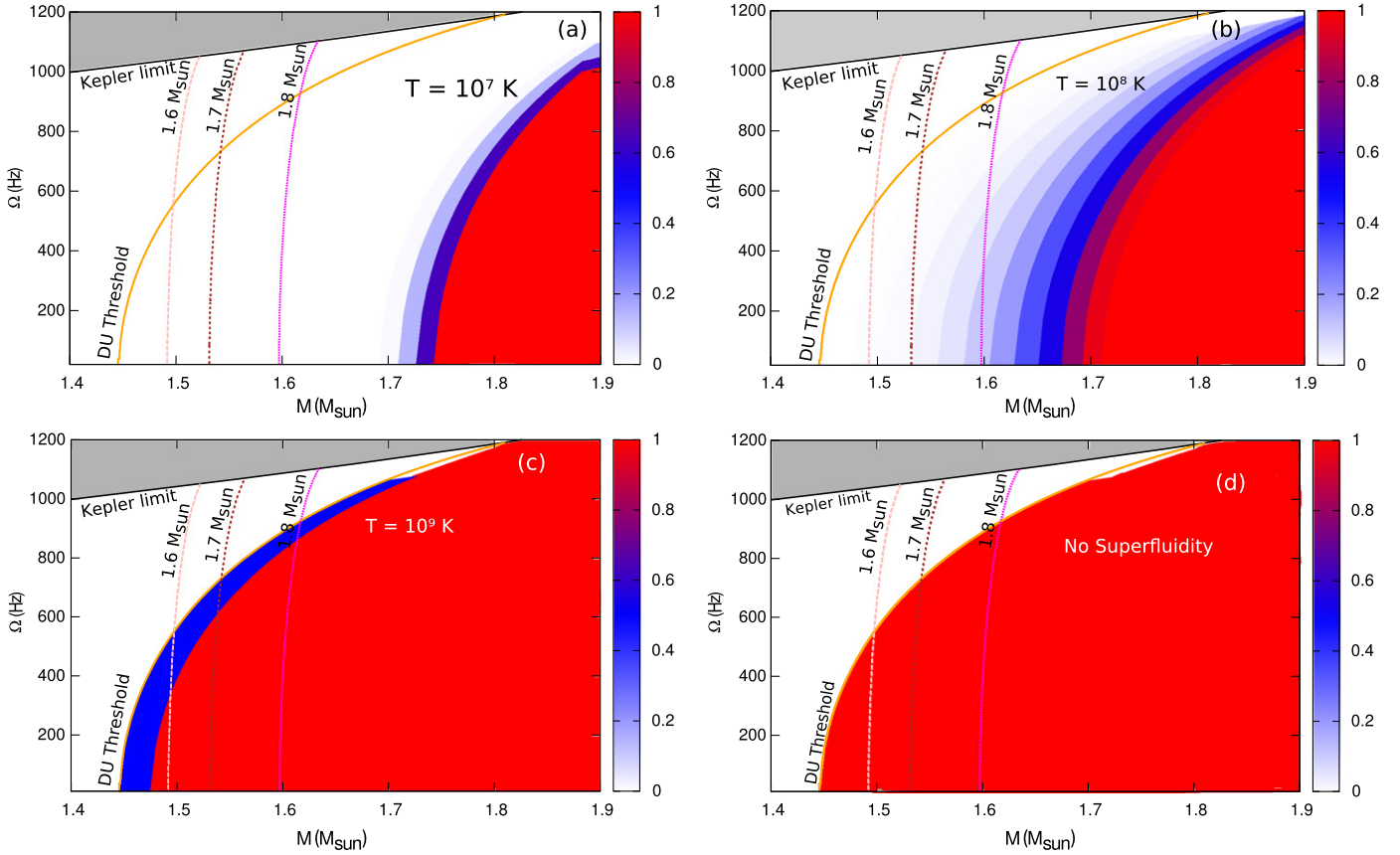


Fig. 2. (Color online.) Intensity of the direct Urca (DU) process in rotating (frequency Ω) neutron stars, for different stellar temperatures, T . M denotes the gravitational mass. The intensity ranges from 0 (plain white areas) to 100% (red). No stars are allowed above the curve labeled Kepler limit because of stellar mass shedding. The vertical curves show evolutionary tracks of isolated rotating neutron stars, whose baryon mass (M_0) during spin-down remains constant. One sees that for several stars evolving along these tracks the DU process (i.e., reaction (1)) becomes possible at lower rotation rates. The color coding indicates the intensity of the DU process.

can then be used to determine the impact of the spin-down compression on the cooling of the star. Evidently this analysis is only valid for objects that are born in the white regions of the figures shown in Fig. 2, and thus may cross-over into the DU region (red in the web version shaded areas) during their evolution. For the EoS studied here, this is limited to objects whose non-rotating gravitational masses are $\gtrsim 1.5M_\odot$. The following cases emerge: I. If $\beta < 1$, the star spins down to low frequencies ($\Omega \rightarrow 0$) before the core and crust are thermally coupled. This causes the cooling of the star to be similar to the cooling of a spherically symmetric star of same mass. II. If $\beta \sim 1$, the star is still rotating at relatively high frequencies ($\sim \Omega_0/2$) when the core and crust become thermally coupled. The thicker crust of such a star allows the core and crust to couple more quickly, effectively speeding up the cooling. III. If $\beta > 1$, the star keeps rotating at high frequencies for a long time, which delays the onset of the DU process (1). We note that, as was the case for $\beta \sim 1$, the star also becomes isothermal at an earlier time. However the late onset of the DU process decouples the core and crust one more time, which yields to a second thermal coupling, characterized by a sharp drop in temperature at a later time. IV. If $\beta \rightarrow \infty$, the spin-down relaxation time is much greater than the time scale of the core-crust thermal coupling. This means that during most of the cooling period, the object will remain in the high frequency domain, and the onset of the DU process may never be achieved, leading to a slow stellar cooling. The different scenarios I–IV are graphically illustrated in Fig. 3. The curves underline the important role of β for the classification of the cooling behavior of spinning-down neutron star. If superfluidity effects were considered, one should expect that the temperature reductions for $\beta \sim 1$

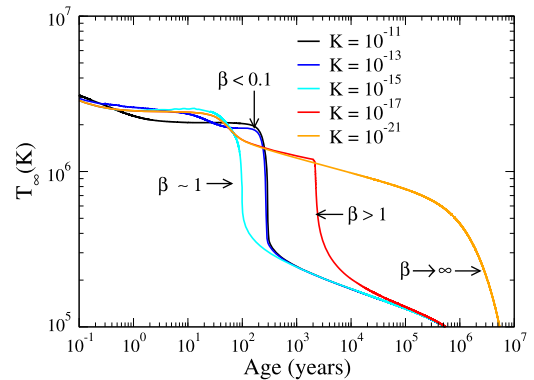


Fig. 3. (Color online.) Neutron star temperature at infinity as a function of stellar age, for a sample neutron star with baryon mass of $1.5M_\odot$. (The gravitational mass at zero rotation is $1.4M_\odot$.) Depending on the value of K , four distinctly different cooling epochs emerge, which are discussed in the text.

and $\beta > 1$ are less pronounced. The actual magnitude of the reduction will depend on the microscopic pairing model used.

We conclude this Letter with a discussion of the temperature data observed for the neutron star in Cas A over a 10 year period [30]. The rapid cooling of this neutron star has been explained recently through the presence of superfluidity in dense matter [8, 9]. Our study indicates that the temperature evolution of this neutron star could also be explained by the late onset of the DU process, if one assumes that the neutron star was created with an initial rotational frequency somewhere between 40 and 70% of

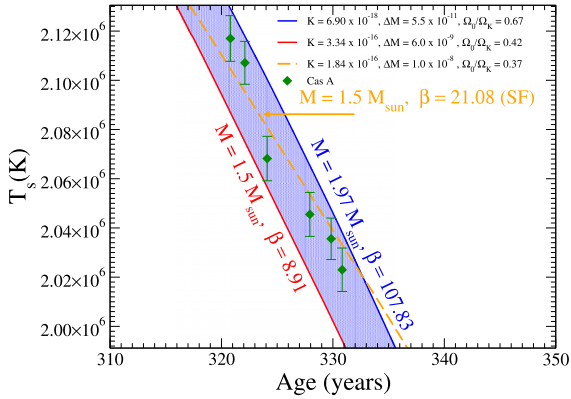


Fig. 4. (Color online.) Cooling simulations reproducing the temperatures observed for the neutron star in Cas A over a ten-year period. K is defined in the text, ΔM denotes the mass (in unit of the mass of the neutron star) of the accreted envelope, and Ω_0/Ω_K denotes the star's birth frequency relative to the Kepler frequency. Superfluidity and Pair-Breaking Formation of nucleons is taken into account in the curve labeled SF.

its mass shedding frequency (see Fig. 4), depending on the unknown mass of this neutron star. Masses between 1.2 and $2.1 M_\odot$ (99% confidence) have been established for this neutron star [9]. The simulations shown in Fig. 4 have thus been performed for two sample masses, 1.5 and $1.9 M_\odot$. The mass of the accreted envelope, due to the fallback of matter after the supernova explosion [27], is assumed to be $\Delta M/M = 5.5 \times 10^{-11}$ and 6.0×10^{-9} , in accordance with [31]. Our calculations predict a birth frequency (Ω_0) for the $1.5 M_\odot$ star of 42% ($\Omega_0 = 400$ Hz) of the Kepler frequency if the star is made of non-superfluid matter. This figure drops down to 37% if neutron superfluidity in the 1S_0 and 3P_2 channels and Pair-Breaking Formation [8] is included. It is an open issue whether proton superconductivity takes place in the core of a neutron star. If it does, it may affect the thermal evolution of the object [8], depending on the magnitude and density dependence of the superfluid gap and its critical temperature. In the case that proton superconductivity extends to very high densities, and has a high critical temperature, it might suppress the impact of the DU process on the thermal evolution of a neutron star.

We note that on the basis of theoretical calculations of the mapping between initial and final neutron star spins, likely spin-down mechanisms, and observational constraints from pulsars and supernova energetics, it has been argued [32] that the initial precollapse central iron core periods inside of massive stars, which give birth to neutron stars and pulsars, are on average greater than ~ 50 seconds. The associated neutron stars would then be born with rotation periods greater than around 10 ms [32]. This figure agrees with the birth periods established in [33]. If the central iron core periods should be smaller by a factor of 5, the birth periods of neutron stars would drop down to a millisecond. In our work, initial birth periods of 2.5 ms (400 Hz) and 1.25 ms (800 Hz) are required to fit the thermal data of the neutron star in Cas A. Such rotational periods are on the small end of probabilities, but given the many poorly understood issues (estimated iron core spin rates, angular momentum profiles, progenitor mass, general relativistic effects), which complicate the study of stellar evolution with rotation, the birth periods considered in our study are in the realms of possibility.

A further aspect concerns the energy loss during spin-down for the assumed birth frequencies. For our model scenario, we find that $\dot{E} = I\Omega\dot{\Omega} \sim 10^{39}$ erg/s. This figure would imply that the neutron star in Cas A ought to emit a pulsar wind, which, however, has not been observed. If the pulsar wind should not exist, the birth frequencies of the neutron star in Cas A may have been somewhat

smaller than the values assumed in this Letter for neutron stars made of non-superfluid matter. Interestingly, the inclusion of superfluidity among neutrons and Pair-Breaking Formation reduces the region in the star where the DU process takes place, shifting the onset of the DU process toward lower rotational frequencies (see curve labeled “SF” in Fig. 4).

The results shown in Fig. 4 were obtained by assuming value of K in the range of $\sim 10^{-16}$ and $\sim 10^{-18}$. The value of K is connected to the magnetic field through $K \propto R_{10}^4 B_{12}^2 / (M/M_\odot)$. It is known from observations that the upper limit for the magnetic field of the neutron star in Cas A is 2×10^{11} G, which would imply $K \sim 10^{-18}$ (assuming a stellar mass of $M = 2.0 M_\odot$ and a radius of $R = 15$ km), in agreement with one of the parameter combinations considered in Fig. 4 (blue curve in the web version).

We also note that given the different nature of the processes employed to explain the temperature drop (late onset of the DU process in our case, and pair breaking/formation in references [8, 9]), continuous observation of the neutron star in Cas A may decide which model is favorable. A continuous analysis of the slope of the temperature ($s = d \log_{10} T_s / d \log_{10} t$) might allow one to do that. While the slope found by us ($s = -1.5$) should remain at this value while the surface temperature drops drastically, in the model described in [8], it should go to the asymptotic value found by the authors ($s = -1/12$), before the surface temperature changes drastically.

Our results show that rotation-driven repopulation processes can be of very great importance for the thermal evolution of spinning-down neutron stars. The reason for this is two-fold: first, the geometry of the object is modified as they spin down, which changes the stellar surface gravity and therefore the stellar surface temperature [27]. Second, the spin-down renders neutron stars gradually more dense, which changes the stellar core compositions. We also discovered that the ratio of the spin-down relaxation time to the core-crust coupling time, β , emerges as a most valuable parameter that serves to classify the cooling behavior of rotating pulsars. Furthermore, the methodology discussed in this Letter can be generalized to more elaborated scenarios like accreting (X-ray) neutron stars, and possibly objects undergoing more rapid braking mechanisms like r-modes. Evidently, in such cases, re-heating processes are important, although they do not invalidate the conclusions drawn by us in this Letter, i.e. that particle repopulation plays an important role for the thermal evolution of neutron stars.

In summary, the key point put forth in this letter is that the particle composition in the core of an isolated rotating neutron star changes due to the spin-down compression of the star caused by magnetic braking. This compression is a robust physical phenomenon, experienced by any isolated rotating neutron star. This scenario is applied to the neutron star in Cas A. We show that the remarkable temperature drop of this neutron star can be explained by the onset of the rotation-driven direct Urca process. We also show that continuous observation of the thermal evolution of this neutron star over the next ten to twenty years will allow us to determine whether our explanation of the fast cooling of this neutron star is correct, or whether other physical processes (as suggested in [8,9]) are responsible for the star's dramatic temperature drop.

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