Neutron stars in $f(R, T)$ gravity using realistic equations of state in the light of massive pulsars and GW170817

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Received September 11, 2020
Revised October 23, 2020
Accepted November 3, 2020
Published December 29, 2020

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https://doi.org/10.1088/1475-7516/2020/12/039
Abstract. In this work we investigate neutron stars (NS) in $f(R, \mathcal{T})$ gravity for the case $R + 2\lambda \mathcal{T}$, $R$ is the Ricci scalar and $\mathcal{T}$ the trace of the energy-momentum tensor. The hydrostatic equilibrium equations are solved considering realistic equations of state (EoS). The NS masses and radii obtained are subject to a joint constrain from massive pulsars and the event GW170817. The parameter $\lambda$ needs to be negative as in previous NS studies, however we found a minimum value for it. The value should be $|\lambda| \lesssim 0.02$ and the reason for so small value in comparison with previous ones obtained with simpler EoS is due to the existence of the NS crust. The pressure in theory of gravity depends on the inverse of the sound velocity $v_s$. Since, $v_s$ is low in the crust, $|\lambda|$ need to be very small. We found that the increment in the star mass is less than 1%, much smaller than previous ones obtained not considering the realistic stellar structure, and the star radius cannot become larger, its changes compared to GR is less than 3.6% in all cases. The finding that using several relativistic and non-relativistic models the variation on the NS mass and radius are almost the same for all the EoS, manifests that our results are insensitive to the high density part of the EoS. It confirms that stellar mass and radii changes depend only on crust, where the EoS is essentially the same for all the models. The NS crust effect implying very small values of $|\lambda|$ does not depend on the theory’s function chosen, since for any other one the hydrostatic equilibrium equation would always have the dependence $1/v_s$. Finally, we highlight that our results indicate that conclusions obtained from NS studies done in modified theories of gravity without using realistic EoS that describe correctly the NS interior can be unreliable.

Keywords: gravity, modified gravity, neutron stars

ArXiv ePrint: 2009.04696
1 Introduction

We have been collecting several possible pieces of evidence that show that General Theory of Relativity (GR) breaks down under some specific regimes. There are also intriguing observational features at galactic and cosmological scales, namely the universe’s dark sector. For example, it is necessary to assume that spiral galaxies are generally filled by invisible or dark matter to account for their rotation curves’ flatness [1, 2]. The structure formation at cosmological scales demands, in the hierarchical scenario, for enormous dark matter haloes [3–6]. Not enough, in length scales larger than clusters of galaxies, the Universe dynamics is dominated by a negative pressure fluid, namely dark energy, which makes the expansion of the universe to accelerate [7, 8].

At the astrophysical level scales, some observational issues are also persistent. Massive pulsars [9, 10] have been observed and can hardly be explained within the GR approach unless one strongly modifies the stellar structure [11–13].

A possible form to account for those observational issues is through extended (modified) gravity theories (EGTs) [14, 15]. The simplest way to extend GR is through $f(R)$ gravity [16, 17], for which $f(R)$ is a general function of the Ricci scalar $R$. Within the metric formalism, such a theory has already shown to be capable of accounting for the acceleration of the universe expansion with no need for dark energy [18–20]. However, the solar system regime seems to rule out most of the $f(R)$ models proposed so far [21–25]. This theory also was applied to neutron stars (NS) [26–29]. Nevertheless, the existence of $f(R)$ gravity singularities could forbid the formation of such objects [30].

Anyhow it is worth to remark that $f(R)$ gravity was also developed in the Palatini formalism [31, 32] and within this context the theory may present optimistic results in the solar system regime, as it was recently shown in [33], and also in what concerns compact stars stability [34, 35].

In the present paper, we shall investigate the hydrostatic equilibrium configurations of stellar objects within EGTs that allow the r.h.s. of Einstein’s field equations to be generalized rather than their l.h.s., as in $f(R)$ gravity.

We will assume the $f(R, T)$ theory as our underlying theory of gravity in the present work. The $T$ stands for the trace of energy-momentum tensor and the $T$-dependence motivation in such a scenario is related to the possibility of imperfect fluids to exist in the universe or to quantum effects [36].
It should also be mentioned that here we work with the metric formalism of the $f(R,T)$ gravity, but this theory has also been developed in the Palatini formalism [37] and some of its applications can be seen in [38, 39].

There are some interesting outcomes obtained from $f(R,T)$ gravity applications. For instance, we quote Reference [40], in which some of us showed that the $f(R,T)$ gravity might increase the maximum masses of white dwarfs, getting in touch with some observational data.

Notably, we are also going to investigate the stellar equilibrium configurations in the present paper, but rather, the equilibrium configurations of neutron stars (NSs). NSs are supernova remnants known for their high density, strong gravitational field, and rapid rotation rate [41, 42]. Their relevance has recently increased in both theoretical and observational aspects. Besides the aforementioned massive pulsars, NSs have been vital sources of detected gravitational waves [43, 44].

The understanding of stellar structure from the modified gravity perspective and the properties of strongly interacting matter at ultra-high densities provide new phenomenological predictions. With recent observations we have a window to constrain parameters coming from both sides.

The hydrostatic equilibrium configurations of NSs in the $f(R,T)$ gravity has been investigated in ref. [45] from a simple barotropic equation of state (EoS) describing matter inside these objects. Here, we intend to be more rigorous than [45] and will consider the stellar structure of neutron stars and apply for the first time in this theory a set of fundamental nuclear matter equations of state based on effective models of nuclear interactions, considering non-relativistic and relativistic cases, and by comparing our results with gravitational-wave observations, particularly concerning to GW170817 event [43], and also with massive pulsars in a joint constrain.

Consider the stellar structure, we mean, take in account that neutron stars contain matter at densities from few g/cm$^3$ at their surface to more than $10^{15}$ g/cm$^3$ at the center; due to this change in the stellar density, the composition changes as one moves from the center to the surface, i.e., the EoS changes. According to the current theories, a NS can be subdivided into the atmosphere (where we have a plasma region governed by very intense magnetic/electric fields) and additional four regions: the outer crust, the inner crust, the outer core, and the inner core. So, to describe all these different stellar layers, we need different theories: plasma physics, atomic structure, and nuclear many-body theories in the high density-temperature regime for the outer region (outer and inner crust); for the inner and outer cores, we need many-body theories of high dense strongly interacting systems, for details see §1.3 of the book Neutron Stars 1 by Haensel et al. [46].

Due to all these different regimes/densities, only the outer crust can be described with accuracy (this description can be compared with experimental data of atomic nuclei). The EoS describing the NS interior above nuclear matter density is not yet constrained, being an open question in astrophysics. However, there are some constraints from microscopic physics such as electric neutrality, beta equilibrium, and others to describe the interior of neutron star realistically: causality (the speed of sound, $v_s$, must be less than the speed of light, $c$) and the Le Chateliers’ principles $p \geq 0$ and $dp/d\rho > 0$.

This uncertainty in the description of the NS interior leads to a large variety of EoSs in the literature, and they can be separated in soft and stiff concerning the compressibility of the nuclear matter and their behavior at high densities, i.e., how fast the pressure changes when the energy density changes. They also can be divided by the matter composition: for the outer core, a $npe\mu$ (neutron-proton-electron-muon) plasma; for the inner core, several possibilities.
exist such fermion/boson condensates, hyperons, pion/kaon condensation, or a strange quark star matter at the star core (around 3 km depending on the quark matter model) surrounded by hadronic matter, this last possibility is named as hybrid neutron stars in the literature.

The several methods to calculate the EoS are based on perturbation expansion within the Brueckner-Bethe-Goldstone theory, perturbation expansion within Green’s-function theory, variational method, effective energy-density functionals, and relativistic mean-field (RMF) models [46–50].

Point-coupling (or zero range) models [51, 52] are also used to describe finite nuclei and nuclear matter, as well as nonrelativistic models such as Skyrme [53–55] and Gogny ones [56, 57]. The former is a model in which the nucleon-nucleon potential can be written as a contact interaction, and the latter consists of a density-dependent zero range term along with two finite range ones (Gaussian type) generating a particular momentum dependence in the interaction. By computing only Skyrme and RMF models, it is possible to find more than 500 parametrizations. This large number of possibilities naturally raises the doubt whether all of them can reproduce different nuclear environments simultaneously. In order to start to answer this question, it was studied by some present authors in ref. [58] the capability of 240 Skyrme parametrizations in describing different criteria related to the nuclear matter in the vicinity of nuclear saturation density. It was found that only 16 satisfy all the constraints simultaneously. A complement of this study was performed also in ref. [59] by some of us, in which 263 parametrizations of the RMF model that we are going to use and other ones were tested against an updated set of constraints related to nuclear matter, pure neutron matter (PNM), symmetry energy and its derivatives. They include limits in the density dependence of the pressure in the symmetric nuclear matter (SNM), coming from the experimental data on the motion of ejected matter in the energetic nucleus-nucleus collisions; limits on the incompressibility at saturation density in SNM; limits in the low-density region of the energy per particle in PNM; limits on the symmetry energy at saturation density, obtained from isospin diffusion, neutron skins, pygmy dipole resonances, and other investigations; among other ones. The detailed description of these constraints is found in ref. [59].

The outcome of the analysis performed in ref. [59] is that among the 263 parametrizations of the RMF models studied, only 35 satisfy the updated constraints simultaneously: BKA20,22;24 [60], IU-FSU [61], BSR8–12;15–20 [62], FSU-III-IV [63], FSUGold [64], G2* [65], FSUGold4 [66], ZZ71s2–s6 [67], ZZ71v4–v6 [67], FSUGZ03:06 [68]. These parametrizations also have been studied in the stellar matter regime with and without hyperonic matter included, in the context of general relativity [69]. Some of them can reproduce neutron stars masses around two solar masses. In ref. [70], the stellar matter was further investigated in GR theory, and these 35 parametrizations were used to compute the dimensionless tidal deformability ($\Lambda$). In particular, the interest was to analyze the quantities related to the GW170817 event, in which the LIGO-VIRGO Collaboration established constraints on $\Lambda$, both for the joint constrain from massive pulsars and the gravitational wave event GW170817 $\Lambda_1,\Lambda_2$ of the two companion stars, and for the $\Lambda_{1,4}$ (deformability of the canonical neutron star). Most of the consistent RMF parametrizations also satisfy these limits.

The main motivation of this work is to investigate for the first time neutron stars in the $f(R, T)$ theory of gravity with realistic hadronic EoS and considering realistic stellar models, that we referred before, and also the case of hybrid neutron stars. We would like to stress that we will use the state of the art of hadronic EoS, considering a large set of them that have already been restrained. Furthermore, the neutron star masses and radii obtained with these EoS are subject to a joint constrain from massive pulsars and the gravitational wave
event GW170817. We will look for modifications in the neutron star structure (mass and star radius) in this modified theory of gravity and also compare with previous results obtained with an analytical polytropic EoS [45] by some of us. In order to be rigorous in this investigation, we will consider these different generation methods and potentials for the equations of state and exclude those that no longer satisfy the constraints from massive pulsars and the LIGO-VIRGO binary neutron stars observation. For the $\text{npe}\mu$ nuclear matter we will consider: (i) the SLy, which is an EoS that uses energy density functional; (ii) the APR1–4, FPS, and WFF1–3, obtained from variational-method; (iii) the BBB2, which is a nonrelativistic EoS; ENG and MPA1, which are relativistic, obtained from Brueckner-Hartree-Fock theory; (iv) the BKA20, BSR8, IU-FSU, and Z271s4 which are relativistic mean-field theory EsoS. For the EoS that considers the hybrid matter, we will consider only two parametrizations of ALF, which is a combination of nuclear matter (the crust) and quark matter (the core).

In the next section, we will briefly present the resulting hydrostatic equilibrium equation for the underlying $f(R, T)$ gravity theory. In section 3, we will present the piecewise EsoS in the view of the massive NS observed and in section 4, we will present the set of parametrizations used to describe nuclear and stellar matter constructed from the RMF models. Our results are displayed in section 5, where we investigate in detail the neutron star crust effect, followed by a careful and in-depth discussion and conclusion of them in section 6.

## 2 Hydrostatic equilibrium equation in $f(R, T)$ gravity

To work with an EGT that allows the material sector of Einstein’s field equations to be generalized means to have as the starting point an action like [71]

\[ S = \int d^4x \sqrt{-g} \left[ R + f(T) \frac{16\pi}{16\pi} + \mathcal{L} \right], \tag{2.1} \]

where $g$ is the metric determinant, and $f(T)$ is a general function of the trace of the energy-momentum tensor. Throughout this paper, we assume natural units.

Let us take in equation (2.1), as the simplest case, $f(T) = 2\lambda T$, where $\lambda$ is a constant, as done by several authors [72–76], among many others. In this case, the hydrostatic equilibrium equation reads [40, 45]

\[ p' = -\left(\rho + p\right) - \frac{4\pi pr + m}{r^2} - \frac{\lambda(\rho - 3p)r}{8\pi} \left(1 + \frac{\lambda}{2} \left(1 - d\rho dp\right)\right), \tag{2.2} \]

where a prime indicates radial derivative, $m$ is the model-dependent gravitational mass enclosed within a surface of radius $r$, i.e.,

\[ m' = 4\pi \rho r^2 + \frac{\lambda}{2} (3\rho - p)r^2. \tag{2.3} \]

Moreover, when working with the present formalism, we assumed $\mathcal{L} = -p$ in (2.1). It is trivial to check that $\lambda = 0$ retrieves the standard hydrostatic equilibrium equation in GR, the so-called TOV (for Tolman-Oppenheimer-Volkoff) equation [77, 78].

To solve the system of equations, we will employ EsoS from the piecewise-polytrope representation used in [79, 80], and also obtained from relativistic mean-field models [59, 69], focusing on the ultra-dense nuclear matter and in the constraints given by the Laser Interferometer Gravitational-Wave Observatory (LIGO) detections [81, 82].
Boundary conditions. The boundary conditions for $f(R, T)$ are the same as in GR, i.e.,
we have $m(0) = 0$, $p(0) = p_c$, and $\rho(0) = \rho_c$ at the center $(r = 0)$, for which $p_c$ and $\rho_c$ are
the central values of the pressure and energy density inside the star, respectively. The stellar
surface is the point at radial coordinate $r = R$, where the pressure vanishes, $p(R) = 0$.

3 Equations of state in view of the massive neutron stars observed

The piecewise-polytrope representation [79, 80, 83], with few parameters, yields macroscopic
observables for a wide range of EoS. The stellar structure equations map the EoS parameters
into the gravitational mass, radius, and moment of inertia. Piecewise EoS have been exten-
sively used in the context of NSs, and gravitational wave simulations [83–86] and their rep-
resentation can be tested by astronomical data, e.g., X-ray data and gravitational waveform.

In our analyses, we used the EoS from the piecewise-polytrope representation that
yields a maximum mass near $2M_\odot$ considering general relativity. Our primary motivation was
the two massive observed NS pulsars, namely PSR J0348+0432 [9] and PSR J1614-2230 [10],
both with $\sim 2M_\odot$. As the upper limit for the mass, we will consider the extremely massive
millisecond pulsar recently discovered by Cromartie et al. [87], namely J0740+6620, with
$2.14^{+0.20}_{-0.18} M_\odot$ (within 95.4\% credibility interval). The second criterium is that neutron stars
masses and radii obtained by such EoS are within the mass-radius cloud region delimited
by the LIGO-VIRGO observation [81, 82]. Therefore, following these criteria, we obtain NSs
which description is consistent with recent astronomical observations.

Let us also remark that the system PSRJ2215+5135, a millisecond pulsar with a mass
$\sim 2.27 M_\odot$, was also recently observed [88], though the technique used to measure this
source is not as precise as those in reference [87], (the associated errors are enormous). If
these measurements eventually are confirmed with a more precise technique, this pulsar would
be one of the most massive neutron stars ever detected.

Moreover, an important observation, just released by the LIGO-VIRGO collaboration,
reported a coalescence involving a $22.2–24.3 M_\odot$ black hole and a compact object with $2.50–
2.67 M_\odot$, with 90\% credibility [44]. If this black hole companion is an NS, this could be a
breakthrough, since until now no EoS with ordinary matter (i.e., neutrons, protons, electrons)
could explain such a mass in GR context. In this regard, one can check the figure 1 below.

Tentatively, there have been proposed some different models of dense matter for stellar
objects over the last decades, such as hyperon, pions-kaons condensation, quarks-strange
stars, boson stars, among others. These stars, that could be formed by condensations, strange
quarks and bosons stars are still in the theoretical field, and we do not consider them in the
figure 1.

To compare the effects on the hydrostatic equilibrium equations, we choose a set of EoS
considering the pure nuclear matter and one EoS for hybrid matter, i.e., with deconfined
quarks. They are labeled according to their name in the literature. For pure nuclear matter,
we have non-relativistic equations of state: APR [89], which considers variational-method
(VM) with modern nuclear potentials such as Argone and Urbana potentials; BBB [90],
which is obtained in the framework of the Brueckner-Hartree-Fock (BHF) approximation of
the Brueckner-Bethe-Goldstone (BBG) theory, with realistic two-three particle potentials;
the FPS EoS [91], being a modern version of the EoS by Friedman and Pandharipande [92]
(FP) it is an EoS which uses the Skyrme model with an energy density functional (EDF) that
considers a nucleon-nucleon interaction by the Urbana potential and phenomenological three-
nucleons interaction; the Skyrme type SLy EoS [93], which uses a phenomenological EDF with
Figure 1. Mass-radius relation in GR for several EoS considering nucleons. The blue and orange regions are the constraints for mass-radius form the GW170817 event \cite{81}. In continuous red line we have the minimum mass of the compact object detected by the event GW190414 from the LIGO-VIRGO collaborations \cite{44}.

effective Lyon nuclear interaction of two potentials, it is similar to the APR one; the WFF EoS \cite{94} derived from the variational many-body theory with two-body Urbana potential and a three-body phenomenological potential (this EoS is also an improvement on the FP one). Concerning relativistic EoS we consider: ENG \cite{95}, a relativistic Dirac-Brueckner-Hartree-Fock (DBHF) approach, with modern meson-exchange potential models, and the MPA \cite{96}, an extended relativistic BHF approach for nuclear matter with the exchange of $\pi$ and $\rho$-mesons. These last two EoS consider the dependence upon neutron-proton asymmetry. For EoS containing a hybrid matter of nucleons and quarks, we consider the ALF EoS \cite{97}. In this case, the EoS is the combination of nuclear matter (the crust) and quark matter (the core). The crust is described by the APR EoS and the core by a phenomenological parametrization of neutral quarks and an MIT bag model.

From these EoS, we give special attention to a set of parametrizations: WFF1, APR4, SLy, and MPA1, which are constrained by the gravitational wave event GW170817 \cite{81, 82}. In Most et al. \cite{98}, further constraints were obtained using the GW170817 event. For a pure hadronic NS with a mass of 1.4 $M_\odot$, the radii were constrained to be 12.00 $\pm$ $R_{1.4}$/km $\pm$ 13.45 with 2$\sigma$ confidence, most likely $R_{1.4} = 12.39$ km. Other works of different groups used such an event to constrain other EoS as well \cite{99}. For details, see figure 51 in ref. \cite{100}. All the EoS described above are obtained from meson-exchange nuclear potential, and not phenomenological parametrized relativistic mean field hadronic models that we will present in the next section.
Furthermore, constraints from the electromagnetic counterparts of gravitational wave events are now becoming available [101, 102]. These studies have the potential to constrain the NS matter tightly.

4 Relativistic mean-field models

We also study neutron stars in \( f(\mathcal{R}, T) \) gravity through a widely known class of parametrizations used to describe nuclear and stellar matter, namely, those constructed from the so-called relativistic mean-field models that we already discussed in the Introduction. Connecting with the last section concerning the general description of many-nucleon systems (MNS), there are at least two well-established treatments. One of them is based on a microscopic approach in which a suitable parametrization of the two-nucleon potential is essential to ensure the reproduction of some observables, for instance, those related to the deuteron such as its binding energy and scattering data [47–49]. A way of constructing MNS from the knowledge of the nucleon-nucleon interaction is from using some methods, such as the Brueckner-Hartree-Fock one [47–50] as we pointed out in the last section. An alternative to these microscopic calculations is the use of phenomenological hadronic models based on the mean-field approximation. From this specific point of view, the thermodynamic equations of state of the models are obtained (pressure, energy density, chemical potentials, and others) and the free constants of each used parametrization are fitted in order to reproduce data from MNS such as those from finite nuclei or infinite nuclear matter (isotropic system with an infinite number of nucleons with no spatial boundaries and no Coulomb interaction). Here, we focus on the latter description and analyze some parametrizations of the finite range relativistic mean-field (RMF) model given by the following Lagrangian density [59, 103],

\[
\mathcal{L} = \overline{\psi}(i\gamma^\mu \partial_\mu - M)\psi + g_\sigma \overline{\psi} \sigma \psi - g_\omega \overline{\psi} \gamma^\mu \omega_\mu \psi - \frac{g_{\rho}}{2} \overline{\psi} \gamma^\mu \rho_\mu \tau_3 \psi + \frac{1}{2} (\partial^\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2) - \frac{A}{3} \sigma^3 - \frac{B}{4} \sigma^4 - \frac{1}{4} F_{\mu\nu}^{\sigma} F^{\mu\nu}_{\sigma\rho} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + C \left( g_2^2 \omega_\mu \omega^\mu \right)^2 - \frac{1}{4} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu \\
+ g_\sigma g_\omega \omega_\mu \omega^\mu \left( \alpha_1 + \frac{1}{2} \alpha_1' g_\sigma \sigma \right) + g_\sigma g_\rho \rho_\mu \tilde{\rho}_\mu \left( \alpha_2 + \frac{1}{2} \alpha_2' g_\sigma \sigma \right) + \frac{1}{2} \alpha_3' g_\sigma g_\omega \omega_\mu \omega^\mu \tilde{\rho}_\mu \tilde{\rho}^\mu, \tag{4.1}
\]

in which the Dirac spinor \( \psi \) is the nucleon field, where \( \sigma \), \( \omega^\mu \), and \( \tilde{\rho}_\mu \) represent the scalar, vector and isovector fields related to the mesons \( \sigma \), \( \omega \), and \( \rho \), respectively. \( F_{\mu\nu}^{\sigma} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu \) and \( \tilde{B}_{\mu\nu} = \partial_\nu \tilde{\rho}_\mu - \partial_\mu \tilde{\rho}_\nu \) give the antisymmetric tensors \( F_{\mu\nu}^{\sigma} \) and \( \tilde{B}_{\mu\nu} \). The nucleon mass is \( M \), and the mesons masses are \( m_\sigma \), \( m_\omega \), and \( m_\rho \) (\( g_\sigma \), \( g_\omega \), \( g_\rho \), \( A \), \( B \), \( C \), \( \alpha_1 \), \( \alpha_1' \), \( \alpha_2 \), \( \alpha_2' \) and \( \alpha_3' \) are the coupling constants). Through the use of the Euler-Lagrange equations, it is possible to obtain the filed equations of the model. Furthermore, the implementation of the mean-field approximation [104, 105] in these equations allows the determination of the energy-momentum tensor. This quantity determines the energy density \( \rho \) and pressure \( p \) of the model. All the remaining thermodynamics can be found from \( p \) and \( \rho \). For detailed calculations, we address the reader to references [59, 103].

Here we choose BKA20, BSR8, IU-FSU, and Z271s4 as representative parametrizations of the “families” BKA, BSR, FSU, and Z271, in order to investigate their predictions on the mass-radius diagram when submitted to the \( f(\mathcal{R}, T) \) gravity theory. We present our findings in section 5.
5 Results

In figure 2, we present the mass-radius relation for all parametrizations of the APR equation of state; this EoS considers modern nuclear potentials and frequently appears in the literature. One of its parametrizations, the APR4, was constrained within the LIGO-VIRGO [81, 82] observational area, highlighted as the blue and orange cloud regions in the figures. The top orange region corresponds to the heavier and the bottom blue region to the lighter NS detected.

We generated mass-radius curves for all sets of parametrizations, and for five different values of \( \lambda \), being \( \lambda = 0 \) the curves for general relativity and \( \lambda = -0.06, -0.04, -0.02 \) and \(-0.01\) the curves for the \( f(R, T) \) gravity. We also plotted a continuous blue line representing the 2.0 \( M_\odot \) pulsar, a magenta dot-dashed line representing the 2.14 \( M_\odot \) pulsar, and a yellow dotted line representing the 2.27 \( M_\odot \) pulsar. They represent the most massive pulsars observed up to now.

On the upper side of figure 2 it is possible to see the first two parametrizations, APR1 figure 2a, and APR2 figure 2b. If one considers GR, i.e., \( \lambda = 0 \), the curves give a radius of less than 10 km for stars with more than 0.6 solar mass; this makes stars with \( M > 1.4 \ M_\odot \) out of cloud region by the GW170817 event. Considering the contributions from the \( f(R, T) \) gravity, it is possible to see an increase in the radius in both cases, and the curves are brought inside to the cloud region. In figure 2a, the curves between \( \lambda = -0.04 \) and \(-0.02\) present values of mass-radius better ranged within the observational region constrained by the LIGO-VIRGO collaboration. In the case of figure 2b, values between \(-0.02\) and \(-0.01\) are the better ones. We can observe that for the APR1 and APR2 EoS, contributions from the \( f(R, T) \) gravity can put the curves within the LIGO-VIRGO constrains for the radius; however, it is not possible to reach two solar mass with these two parametrizations.

On the lower side of figure 2, we have the APR3 2c and APR4 2d parametrizations. In the case of GR, it is possible to see that the curves are inside the LIGO-VIRGO region. For APR3 we can see that a 2.27 \( M_\odot \) pulsar could be explained by this parametrization, although there is substantial uncertainty in the mass of this one. The two parametrizations could reach the massive NS with 2.14 \( M_\odot \) and satisfying the mass-radius region of the LIGO-VIRGO observation simultaneously. In both figures, one can see that the \( \lambda \)’s minimum value is around \(-0.02\); otherwise, the mass-radius starts to stay out of the cloud region. The LIGO-VIRGO teams well studied the APR4 parametrization. The mass-radius and tidal parameters are the most promising parametrization of this EoS. However, according to Radice et al. [102], the APR4, as well as the FPS (that we will see ahead) are tentatively excluded by the electromagnetic (EM) counterpart of the multi-messenger observation.

In figure 3, we present two EoSs: the BBB2, which is a parametrization of the BBB EoS and the FPS one. The BBB2 in a non-relativistic EoS in the framework of BBG, it is for medium-stiff EoS with crust thickness about 0.8 km [46]. We show the BBB2 EoS in figure 3a, being the theory for GR (\( \lambda = 0 \)) inside the LIGO-VIRGO cloud region. However, it does not achieve two solar masses. The \( f(R, T) \) gravity theory increases a small fraction of the mass, but it is not enough to reach significant values; the radius, on the other hand, has a significant increment: the minimum value of its parameters is around \( \lambda = -0.04 \). In figure 3b, we show the mass-radius for the FPS equation of state, and, as the previous one, it is inside the LIGO-VIRGO cloud region for GR and does not reach the two solar mass. The minimum value of the \( f(R, T) \) parameter is about the same also, \(-0.04\). These two EoS can be excluded in our case since they predict masses smaller than 2 \( M_\odot \) under GR or \( f(R, T) \) gravity.
Figure 2. Mass-radius relation: on the upper left side, the mass-radius relation for the APR1 equation of state. On the upper right side, the mass-radius relation for the APR2 equation of state. On the lower left side, the mass-radius relation for the APR3 equation of state. On the lower right side, the mass-radius relation for the APR4 equation of state. It was considered five values of $\lambda$ in the mass-radius for each EoS, going from $\lambda = -0.06$ to $0.0$, for $\lambda = 0$, the theory retrieves general relativity. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at $2.0 \, M_\odot$, the magenta dot-dashed line at $2.14 \, M_\odot$ and the yellow dot line at $2.27 \, M_\odot$ represent the most massive pulsars observed up to now. The pulsar with $2.14 \, M_\odot$ has a 95.4% credibility level.

In figure 4, we present the mass-radius relationship for the WFF EoS and its set of parametrizations. On the upper side, we have two parametrizations, WFF1 4a and WFF2 4b, on the left and right sides, respectively. Both sets reach more than two solar masses and are inside the cloud region considering GR; the lower limit of the $f(R, T)$ parameter is around $-0.04$ for both cases. In figure 4a, the maximum mass is near $2.14 \, M_\odot$. We can see that the $f(R, T)$ increases a bit the maximum mass. However, one can go to higher values of $\lambda$ in modulus. The LIGO-VIRGO collaborations’ paper constrained the parametrization WFF1. Using tidal deformability through GW and EM measurements, Coughlin et al. [101] have disfavored WFF1 compared with other EoSs. In figure 4b, we show the WFF2 EoS, and, as
in the previous case, it is possible to reach 2.14 $M_\odot$. This parametrization allows an increase in the mass and radius compared to WFF1. In figure 4c, we present the WFF3 parametrization, which has an intermediate stiffness. As we can see, the gravitational mass of this parametrization does not reach more than two solar mass, either in GR or $f(R, T)$ gravity.

In figure 5, we have two equations of state, the SLy on the left side, figure 5a, and the ENG on the right side, figure 5b. The SLy is a well-studied EoS either in modified theories (with analytical representation in $f(R)$, for example) or General Relativity. It is a Skyrme type EoS with an effective nuclear interaction and was considered in the LIGO-VIRGO work. As one can see, the SLy can reach two solar masses and is inside the mass-radius cloud region from LIGO-VIRGO observation. However, it cannot achieve 2.14 $M_\odot$. This EoS is often used to describe the star’s inner crust, while the BPS [106] EoS describes the outer crust. In GR, the crustal EoSs have little importance to the global parameters of neutron stars [46].

The SLy describes the core and inner crust in a unified manner. If we consider the $f(R, T)$ gravity, the minimum value for the $\lambda$ parameter is around $-0.02$, similar to APR3–4. On the right side of figure 5, we have the ENG equation of state, figure 5b; it is an EoS that reaches 2.14 $M_\odot$ and is inside the cloud region if one considers general relativity. This EoS was studied in an entirely realistic hydrodynamic simulation [86], considering spin and other parameters in the context of GW170817, and this context of binary star merger if it could lead to the formation of a supra massive NS [85]. Using neural networks, Fujimoto et al. [107] showed that ENG and other many-body models, are favoured. Considering the $f(R, T)$ gravity, this EoS has similar behaviour with the APR3–4 and SLy, i.e., the lower value of $\lambda$ is $-0.02$ for the mass-radius to stay inside the cloud region observed. The $f(R, T)$ gravity increases the mass, however not enough to reach a 2.27 $M_\odot$, for example.
Figure 4. Mass-radius relation: upper on the left side the mass-radius relation for the WFF1 equation of state. Upper on the right side the mass-radius relation for the WFF2 equation of state. Lower the mass-radius relation for the WFF3 equation of state. It was considered five values of \( \lambda \) in the mass-radius for each EoS, going from \( \lambda = -0.06 \) to 0.0, for \( \lambda = 0 \), the theory retrieves general relativity. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at 2.0 \( M_\odot \), the magenta dot-dashed line at 2.14 \( M_\odot \) and the yellow dot line at 2.27 \( M_\odot \) represent the most massive pulsars observed up to now. The pulsar with 2.14 \( M_\odot \) has a 95.4% credibility level.

In figure 6, we show the MPA1 equation of state. This EoS was also studied in the LIGO-VIRGO work, along with SLy, WFF1–2, ENG, and APR3–4. The MPA1 EoS can reach the two solar mass limit if we consider only general relativity. Given the stiffness of this EoS, it is possible to reach mass around the 2.5 value; however according to Ma et al. [85], the absence of a supra massive NS signature in the event GW170817/AT2017gfo could rule out the MPA1 or even the APR3. The lower boundary for the \( \lambda \) parameter is around -0.02 as the other stiff EoS.

The last EoS studied from the piecewise representation is the ALF, in figure 7, which leads to the possibility of hybrid stars. We have chosen two sets of parametrizations, the ALF2 in figure 7a and ALF4 in figure 7b. Other highlighted EoS is the H1–7, which includes
Figure 5. Mass-radius relation: on the left side the mass-radius relation for the SLy equation of state. On the right side the mass-radius relation for the ENG equation of state. It was considered five values of $\lambda$ in the mass-radius for each EoS, going from $\lambda = -0.06$ to 0.0, for $\lambda = 0$, the theory retrieves general relativity. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at $2.0 \, M\odot$, the magenta dot-dashed line at $2.14 \, M\odot$ and the yellow dot line at $2.27 \, M\odot$ represent the most massive pulsars observed up to now. The pulsar with $2.14 \, M\odot$ has a 95.4% credibility level.

Figure 6. Mass-radius relation for the MPA1 equation of state. It was considered five values of $\lambda$ in the mass-radius for each EoS, going from $\lambda = -0.06$ to 0.0, for $\lambda = 0$, the theory retrieves general relativity. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at $2.0 \, M\odot$, the magenta dot-dashed line at $2.14 \, M\odot$ and the yellow dot line at $2.27 \, M\odot$ represent the most massive pulsars observed up to now. The pulsar with $2.14 \, M\odot$ has a 95.4% credibility level.

hyperons; one of its parametrizations was constrained in the LIGO-VIRGO paper, being out of the cloud region. The H4 was also constrained by the tidal parameter in a joint constrain from multimessenger observation [102], being ruled out by the LIGO-VIRGO paper.
Considering the ALF2, we see that this parametrization is inside the cloud region and could admit the \( \lambda \) around \(-0.01\) in the case of \( f(R, T) \); however, it cannot reach \( 2.14 \, M_\odot \). In the case of the ALF4 parametrization, the allowed radii for \( f(R, T) \) are broader than the previous case, and the \( \lambda \) parameter could reach values less than \(-0.02\). However, the maximum mass does not reach \( 2 \, M_\odot \) in any case.

In figure 8, we present the study of the \( f(R, T) \) hydrostatic equilibrium for the relativistic mean-field models. We have chosen four EoS from RMF models, which are representative parametrizations of the set BKA, BSR, FSU, and Z271. These EoS are well suitable in the context of tidal deformability in the GW170817 event. In figure 8a, we have the parametrization BKA20; in figure 8b, we have the parametrization BSR8; in 8c the parametrization IU-FSU; and in 8d, the last one, the Z271S4. As we can see, these parametrizations almost do not reach two solar masses if we consider GR only, being the worst case for Z271S4, which is under \( 1.8 \, M_\odot \). The BKA20 is out of the LIGO-VIRGO region delimited by the gravitational wave detection. If one considers the contributions coming from \( f(R, T) \) gravity, mass-radius values get even worsen, i.e., there are no values in this model for the \( \lambda \) parameter. For the BSR8, the GR case is within a less dense cloud region, and there are no values for the \( \lambda \) also. The IU-FSU is in a more dense region, and it is possible to have a minimum value for \( \lambda \) around \(-0.01\); however, neither GR nor \( f(R, T) \) can reach two solar masses. These EoS in the case of GR and \( f(R, T) \) theories of gravity do not predict a maximum mass upper to \( 2 \, M_\odot \). Besides, if we consider these RMF hadronic models in \( f(R, T) \) theory of gravity, the NS radii are out of the mass-radius region of LIGO-VIRGO observation except for the IU-FSU where the magnitude of \( \lambda \) needs to be very small, less than 0.01.

The crust. As can we observe from figure 2 to 8, there is no significant enhancement in the mass of the compact star if we consider the \( f(R, T) \) theory with realistic equations of
state: the maximum increment was less than 1%. These new results are different from our
previous one [45], where we considered an EoS described by a polytrope, with $\Gamma = 5/3$ and
an EoS (using the MIT bag model) for strange stars. By increasing the absolute value of the
$\lambda$ parameter, we saw a significant increment in the mass of those stars. In another work [40],
we considered the Chandrasekhar EoS [108, 109] for a white dwarf, and we observed an
increment of up to 5% in the white dwarf mass. The limit of 5% was related to the limit of
$\lambda$, which must be around $-4 \times 10^{-4}$. For values below that, the mass tends to a plateau, and
the radius would increase indefinitely.

As we could observer for white dwarfs, the main contribution from the $f(R, T)$ model
was regarding the stars’ radius, i.e., there is an increment in the radius for a decrease in the
central density; we found the same result in this work considering realistic EsoS.

The physical reason for the difference relies on the presence of a crust, or more funda-
mentally due to the low sound speed. When we model the stellar structure, the models
should consider the stellar core and a crust, i.e., as one moves from the core to the surface, the density diminishes, and for a very low density, the EoS changes. The crust is generally described by two layers, an inner and an outer crust. Atomic structure combined with the nuclear theory is needed for the inner surface layer \[46\], while the outer layer requires atomic structure combined with plasma physics in high density/temperature regimes. For hadronic and hybrid stars, in general, it is used the Baym-Pethick-Sutherland (BPS) \[106\] in this low-density regime.

Here, we considered two cases to describe the NS; the first one was a star composed of a core and an inner crust only; the inner layer should have 1–2 km and a maximum density of \(\sim 0.5\rho_0\), where \(\rho_0\) is the nuclear saturation density. In the inner core, we used the SLy EoS (this EoS, and in few cases the FPS one, are generally used do describe the inner crust, for details see the ref. \[46\]). In the second case, we considered a core, an inner, and an outer crust. A polytropic form describes the inner crust as \(p = A + B\rho^{4/3}\), where \(A\) and \(B\) are constants determined in the matching with the core and with the outer layer. The BPS EoS describes the outer layer; for details, see the ref. \[110\].

If we consider only the core (figure 9), i.e., a bare star, one can have an increment in the mass, as in the case of the NS and quark star, described by a simple polytropic and an MIT bag model respectively \[45\], where the speed of sound is not reduced drastically near the surface of the star. As we can see in figure 9, one can have large absolute values of \(\lambda\) compared to the one where we have to consider a crust.

In fact, in the results just presented, we found that using several relativistic and non-relativistic models the small increment on the neutron star mass and the variation in the stellar radius are almost the same for all the EoS, which manifests that our results are very insensitive to the EoS high density part of the star core in \(f(R, T)\) gravity, in some sense an unexpected result. It confirms that stellar structure changes in this alternative gravity theory depend almost only on the star crust, where the EoS is essentially the same for all the models.

6 Discussion and conclusion

In this paper, we obtained the mass-radius relationship within the \(f(R, T)\) gravity for different sets of EoS with different parametrizations. It is the first time that the hydrostatic equilibrium equations are solved using realistic EoS and having taken into account a joint constraint from massive pulsar and the gravitational wave event GW170817 (LIGO-VIRGO event) in the scope of \(f(R, T)\) for the case \(f(R, T) = R + 2\lambda T\). We took the stellar mass of \(2 \, M_\odot\) as a benchmark and the radius from the LIGO observation as a threshold for the allowed EoS and the values of the lambda parameter in the hydrostatic equilibrium equations. The EoS used are from a wide range of softest/stiffness, which can be constrained by gravitational and electromagnetic events simultaneously. Some of them are based on experimental nuclear physics, making use of many-body computations and other kinds of state-of-the-art calculations.

Our work shows that the main contribution from this \(f(R, T)\) model is an increase in the stars’ radius, i.e., we can have grander stars with smaller central density, as we have already shown in our previous works \[40, 45\] for neutron stars (considering simplest EoS) and white dwarfs. In these previous works, for the case of the NS (a polytrope with \((\Gamma = 5/3)\) and quark star (an MIT bag model with \(a = 0.28\) and \(B = 60\) MeV/fm\(^3\)), it was found that the maximum mass increases with the increment of the absolute value of \(\lambda\), the same behaviour we observed in WDs using the Chandrasekhar EoS \[108, 109\], where we found a very slight
Figure 9. Mass-radius relation for bare stars: on the left side the mass-radius relation for the BKA20 equation of state. On the right side the mass-radius relation for the BSR8 equation of state. It was considered four values of \( \lambda \) in the mass-radius for each EoS, going from \( \lambda = -1.2 \) to 0.0, for \( \lambda = 0 \), the theory retrieves general relativity. Here we considered the stellar structure only composed of a core, i.e., the star do not have a crust. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at \( 2.0 \, M_\odot \), the magenta dot-dashed line at \( 2.14 \, M_\odot \) and the yellow dot line at \( 2.27 \, M_\odot \) represent the most massive pulsars observed up to now. The pulsar with \( 2.14 \, M_\odot \) has a 95.4\% credibility level.

Looking for the physical reason for the difference between these new results and the previous ones, we found that the neutron star crust is responsible for this discrepancy. When we considered the crust, the maximum mass increase is minimal; this is due the term \( [1 + \lambda/(8\pi + 2\lambda)(1 - dp/dp)] \) in (2.2), where \((1 - dp/dp) = (1 - 1/v_s^2)\) considering the EoS sound speed definition.\(^1\) In the causal limit, theory’s contribution is zero, while \( v_s^2 \to 0 \) the term goes to \( -\infty \). With the crust, the speed of sound is drastically reduced in the outer layers and it is not possible to have a significant enhancement in the mass. This will be valid for any equilibrium equation involving the sound speed, likewise for the works described in §2.3.11 of the ref. [111] where the majority have considered bare stars.

The speed of sound determines the parameter \( \lambda \) in (2.2) i.e., the softest/stiffness of the EoS, so the allowed values are \(-4\pi < \lambda \leq 0 \) for \( 0 < v_s \leq 1 \); whereas for \( 0 < \lambda \) or \( \lambda < -4\pi \) the condition \( \lambda/(3\lambda+8\pi) < v_s \) must be satisfied. In the case of a MIT bag model, where the sound speed is constant and satisfies the last condition, it is possible to have positive values of \( \lambda \).

Thus, because of the NS stellar structure considered here, which has a crust with a very soft EoS and, it is not possible to have big absolute values for the \( \lambda \) parameter. Since this parameter is responsible for the strength of the new contributions coming from the theory and the corresponding masses and radii of NSs in \( f(R, T) \), we can conclude that this alternative gravity cannot improve GR results in order to raise the two solar mass threshold.

Our results show that only the following EoS are suitable within the \( f(R, T) = R + \lambda T \) model: APR3–4, WFF1–2, ENG, and MPA1. From these EoS and the joint constrains from the massive pulsar and the GW170817 event, we could deduce that the minimum allowed value for the \( \lambda \) parameter would be around \(-0.02 \) for neutron stars, and this would increase

\[ dp/dp = 1/v_s^2(\rho) \geq 1/c^2. \]

\(^1\)
the maximum mass less than 1% for these stars. Moreover, since $\lambda$ needs to be so small, not only the star mass is almost unchanged but also the star radius cannot become very large as in previous studies, and its increase compared to general relativity results is limited to be around 2.5–3.6% in all the cases considered. The conclusion concerning the crust NS effect implying very small values of $\lambda$ does not depend on the form we have used to the $f(T)$, since for any other function of the trace of the energy-momentum tensor we could have chosen we would always have the inverse sound speed dependence $d\rho/dp$ in the relativistic hydrostatic equilibrium for the neutron star, see eq. (3) in ref. [112].

Let us stress that with the purpose of checking the possibility of attaining higher maximum masses for NSs, the present analysis may be extended to incorporate $R^2$ correction terms in gravitation, what was done, for instance, in [113–115]. Note that this incorporation could be a possibility to alleviate the $f(R)$ gravity shortcomings mentioned in the Introduction.

Finally, we would like to emphasize that our results indicate that conclusions obtained from compact stars studies done in alternative theories of gravity without using realistic EoS to describe correctly the neutron star interior can be unreliable.

Acknowledgments

RL has been supported by U.S. Department of Energy (DOE) under grant DE-FG02-08ER41533, the LANL Collaborative Research Program by Texas A&M System National Laboratory Office and Los Alamos National Laboratory, CAPES/PDSE/88881.134089/2016-01 and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) process 141157/2015-1. PHRSM would like to thank CAPES for financial support. MGBA acknowledges CNPq Project 150999/2018-6 for financial support. The authors acknowledge the FAPESP Thematic Project 2013/26258-4. This work is also a part of the project INCT-FNA Proc. No. 464898/2014-5. OL and MD thank the support from CNPq, under Grants No. 310242/2017-7 (OL), No. 406958/2018-1 (OL), and No. 433369/2018-3 (MD), and from FAPESP under the thematic Project No. 2017/05660-0. WP thank the support from CNPq, under grants No. 438562/2018-6 and No. 313236/2018-6 and CAPES under the grant 88881.309870/2018-01. M.M. acknowledges also Capes and CNPq for the financial support. We thank both the Referee and Scientific Editor for valuable help in optimizing the presentation of our paper as well as for the detailed and constructive discussions.

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