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Constraining a possible time-variation of the gravitational constant through "gravitochemical heating" of neutron stars

A. Reisenegger[1,*], P. Jofré[2], and R. Fernández[3,4]

[1] Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile, e-mail: `areisene@astro.puc.cl`
[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, Garching, Germany
[3] Department of Astronomy and Astrophysics, University of Toronto, ON M5S 3H4, Toronto, Canada
[4] Present Address: Institute for Advanced Study, Princeton, NJ 08540, USA

Abstract. A hypothetical time-variation of the gravitational constant G would make neutron stars expand or contract, so the matter in their interiors would depart from beta equilibrium. This induces non-equilibrium weak reactions, which release energy that is invested partly in neutrino emission and partly in internal heating. Eventually, the star arrives at a stationary state in which the temperature remains nearly constant, as the forcing through the change of G is balanced by the ongoing reactions. Using the surface temperature of the nearest millisecond pulsar (PSR J0437−4715) inferred from ultraviolet observations and results from theoretical modelling of the thermal evolution, we estimate two upper limits for this variation: (1) $|\dot{G}/G| < 2 \times 10^{-10}$ yr^{-1}, if the fast, "direct Urca" reactions are allowed, and (2) $|\dot{G}/G| < 4 \times 10^{-12}$ yr^{-1}, considering only the slower, "modified Urca" reactions. The latter is among the most restrictive upper limits obtained by other methods.

Key words. Stars: Neutron, Dense matter, Gravitation, Relativity, Pulsars: general, Pulsars: individual (PSR J0437−4715), Ultraviolet: stars

1. Introduction

A number of theorists have proposed that the so-called "fundamental constants" of Nature may vary with cosmological time, ever since Dirac suggested that the gravitational force may be weakening (Dirac 1937). Several experiments aimed at constraining the time variation of G have been conducted, and their results can be grouped by the time scales they probe (see Reisenegger et al. 2007 for a list with references): (1) *Human lifetime* ($\sim$ 10 yr) experiments rely on real-time monitoring of distances within the Solar System, white-dwarf oscillation periods, and pulse arrival times of isolated and binary pulsars, (2) *long time* ($\sim 10^{9-10}$ yr) measurements use stellar astrophysics and paleontology, and (3) *cosmological* ($\gtrsim 10^{10}$ yr) experiments use the Big Bang nucleosynthesis and Cosmic Microwave Background anisotropies to compare the value of G in the early Universe to the present value. Generically, they set constraints on $|\dot{G}/G|$ down

Send offprint requests to: A. Reisenegger

to $\sim 10^{-12}$ yr^{-1}, although the comparison between different timescales depends on the assumed form of the function $G(t)$.

Here, we review our previously introduced method for setting constraints on $\dot{G}$ (Jofré et al. 2006), to our knowledge the only one so far to probe timescales $\sim 10^{7-9}$ yr, intermediate between the *human* and *long* timescales mentioned above. It relies on the change in the internal structure of a neutron star induced by a change in G, which, together with the slow response timescale of weak interactions, result in internal heating and an increase in the observed surface temperature.

Neutron stars have mean densities exceeding nuclear saturation density, $\rho_{\rm nuc} \sim 3 \times 10^{14}$ g cm^{-3}. In their outer layers, they are composed of heavy atomic nuclei and free electrons, giving way to free neutrons, free protons, muons, and potentially more exotic particles as the density increases inward. A short time after their formation, their internal temperatures drop orders of magnitude below the Fermi energies of free particles ($\sim 10 - 100$ MeV), and so their structure is well approximated by zero-temperature models.

Nonetheless, weak interactions still play an important role, as characteristic temperatures 10^{6-8} K yield non-negligible neutrino emission. Given that the equation of state of matter above nuclear density still remains poorly known, researchers construct models to calculate the evolution of the thermal content of neutron stars and compare their predictions with X-ray observations, in order to set constraints on the models for dense matter (e.g., Yakovlev & Pethick 2004). In these thermal evolution models, the structure of the star is calculated assuming an equation of state, and the evolution of the internal temperature is obtained by considering losses due to different neutrino emission processes from the stellar interior, as well as thermal electromagnetic radiation from the surface.

We have previously explored *rotochemical heating*, the effect of the progressive loss of rotational support of millisecond pulsars has on their internal structure, which leads to weak interaction processes (beta decays) and net heating (Reisenegger 1995, 1997; Fernández & Reisenegger 2005). A time variation of the gravitational constant has an analogous effect: it compresses the star and therefore also causes heating (*gravitochemical heating*, Jofré et al. 2006). In what follows, we discuss how this process constrains $\dot{G}$.

2. Method

Neutron star matter is composed of degenerate fermions of various kinds: neutrons (n), protons (p), leptons (l), and possibly other, more exotic particles. Neutrons are stabilized by the presence of other, stable fermions that block (through the Pauli exclusion principle) most of the final states of the beta decay reaction $n \rightarrow p + l + \bar{\nu}$, making it much slower than in vacuum. The large chemical potentials μ_i ($\approx$ Fermi energies) for all particle species i also make inverse beta decays, $p + l \rightarrow n + \nu$, possible. The neutrinos (ν) and antineutrinos ($\bar{\nu}$) leave the star without further interactions, contributing to its cooling. The two reactions mentioned tend to drive the matter into a chemical equilibrium state, defined by $\eta_{npl} \equiv \mu_n - \mu_p - \mu_l = 0$. Depending on the relative abundance of protons, the reactions mentioned above (called *direct Urca processes*) may not be able to conserve momentum, in which case an additional nucleon must participate in the reactions (yielding the *modified Urca processes*, e. g., Yakovlev et al. 2001), with strongly reduced rates.

If G changes, so does the hydrostatic equilibrium structure of cold neutron stars, and all matter elements in their interior are compressed or expanded, and in this way driven away from chemical equilibrium ($\eta_{npl} \neq 0$). Free energy is stored, which is released by an excess rate of one reaction over the other. This energy is partly lost to neutrinos and antineutrinos (undetectable at present), the remainder heats the stellar interior. The heat is eventually lost as thermal (typically ultraviolet) photons emitted from the stellar surface.

The thermal evolution of the star is calculated by solving a system of ordinary differential equations of the form

$$\dot{T} = \frac{1}{C(T)} \left[L_H(T, \eta_{npl}) - L_\nu(T, \eta_{npl}) \right.$$

$$- L_\gamma(T)\Big] \qquad (1)$$

$$\dot{\eta}_{npl} = A(T, \eta_{npl}) + B\dot{G}, \qquad (2)$$

where T is the internal temperature, C the heat capacity of the star, L_H, L_ν, and L_γ the heating, neutrino cooling, and photon cooling luminosities, respectively, A represents the change in the particle abundances due to reactions, and B a constant coefficient that depends only on the structure of the star. See Jofré et al. (2006) and Fernández & Reisenegger (2005) for more details.

3. Results

The typical result of integrating equations (1) and (2) is as follows (details for the analogous, rotochemical heating case are given in Fernández & Reisenegger 2005 and Reisenegger et al. 2007). The star first cools down (within $\lesssim 10^7$ yr) from its high birth temperature, while the chemical potential imbalances η_{npl} slowly increase due to the gravitational forcing term in equation (2). After $\sim 10^{7-9}$ yr, depending on $|\dot{G}|$, the imbalances are so high that they increase the reaction rates to the point where they keep up with the forcing, stabilizing the chemical imbalance. At this point, the energy released by reactions and that emitted from the surface also compensate in equation (1), keeping the temperature at a constant value $\sim 10^5$ K, whose precise value can be predicted if $|\dot{G}|$ and the neutron star model (mass and equation of state) are given.

In order to constrain $\dot{G}$, we therefore need sensitive ultraviolet observations of known neutron stars older than 10^7 yr. Such an observation only exists for the nearest millisecond pulsar, PSR J0437−4715, for which an HST observation detected what appears to be the ultraviolet Rayleigh-Jeans tail of a blackbody at $\sim 10^5$ K (Kargaltsev et al. 2004). Figures 1 and 2 compare theoretical predictions for various equations of state and a range of neutron star masses to the error contours obtained from this observation. The upper limit on $|\dot{G}/G| = 2 \times 10^{-10}$ yr^{-1} (Fig. 1) is obtained by requiring that all stationary temperature curves lie above the observational constraints. Restricting the models to only modified Urca reactions yields

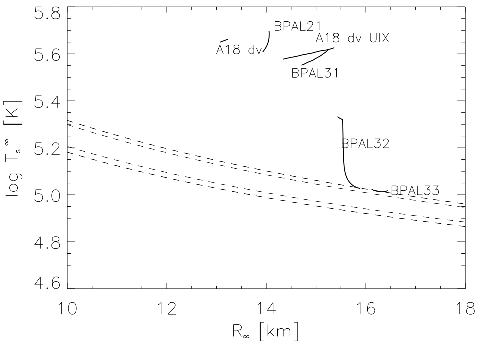

Fig. 1. Comparison of the gravitochemical heating predictions to observations of PSR J0437-4715. The solid lines are the predicted stationary surface temperatures as functions of stellar radius, for different equations of state (A18 from Akmal et al. 1998 and BPAL from Prakash et al. 1988), constrained to the observationally allowed mass range for this pulsar van Straten et al. (2001). Dashed lines correspond to the 68% and 90% confidence contours of the blackbody fit of Kargaltsev et al. (2004) for the ultraviolet emission from this object. The value of $|\dot{G}/G| = 2 \times 10^{-10}$ yr^{-1} is chosen so that all stationary temperature curves lie above the observational constraints. (BPAL32 and BPAL33 allow direct Urca reactions in the observed mass range of J0437.)

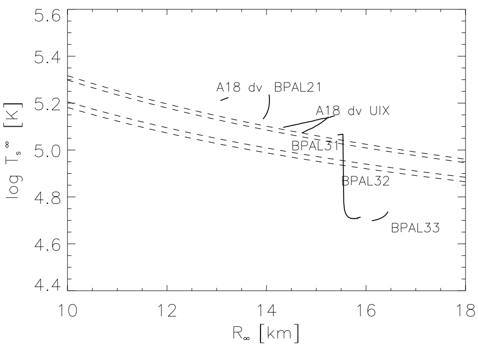

Fig. 2. Same as Figure 1, but now the value of $|\dot{G}/G| = 4 \times 10^{-12}$ yr^{-1} is chosen so that only the stationary temperature curves with modified Urca reactions are above the observational constraints.

a more restrictive constraint, $|\dot{G}/G| = 4\times10^{-12}$ yr^{-1} (Fig. 2).

4. Discussion

Gravitochemical heating sets constraints on the time variation of the gravitational constant, using the fact that a non-zero change would generate internal heating in neutron stars, which for nearby cases can be detected with existing telescopes. These constraints are the only ones on timescales 10^{7-9} yr. If it could be assured that the observed neutron stars cannot have direct Urca reactions, these constraints would be of the same order as the best ones available on other time scales. This is not the case at the moment, but could become so as neutron star interiors become better understood from other studies. In particular, observed temperatures of other old neutron stars (such as millisecond pulsars) will provide useful information.

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