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INTERNAL HEATING AND THERMAL EMISSION FROM OLD NEUTRON STARS: CONSTRAINTS ON DENSE-MATTER AND GRAVITATIONAL PHYSICS

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RESUMEN

La composición de equilibrio de la materia en estrellas de neutrones se alcanza mediante interacciones débiles (decaimiento beta directos e inversos), las cuales proceden lentamente. Si se perturba la densidad de un elemento de materia, éste se relajará al nuevo estado de equilibrio químico mediante reacciones que ocurren fuera del equilibrio y por lo tanto producen entropía. Ésta es parcialmente liberada mediante la emisión de neutrinos, mientras una fracción similar calienta la materia y es eventualmente radiada como fotones térmicos. Examinamos dos posibles causas de tales perturbaciones de densidad: 1) la reducción progresiva de la fuerza centrífuga al reducirse la velocidad de rotación de estas estrellas (en particular pulsares de milisegundos), que lleva a *calentamiento rotoquímico*, y 2) una hipotética variación temporal de la constante de gravitación G, predicha por algunas teorías de la gravedad y modelos cosmológicos actuales (*calentamiento gravitoquímico*). Si sólo interacciones lentas pueden ocurrir en la estrella (reacciones Urca modificadas, con o sin apareamiento de Cooper), el calentamiento rotoquímico puede dar cuenta de la emisión ultravioleta observada del pulsar de milisegundos más cercano, PSR J0437−4715, la cual también provee una cota a $|dG/dt|$ del mismo orden que las mejores dadas en la literatura.

ABSTRACT

The equilibrium composition of neutron star matter is achieved through weak interactions (direct and inverse beta decays), which proceed on relatively long time scales. If the density of a matter element is perturbed, it will relax to the new chemical equilibrium through non-equilibrium reactions, which produce entropy that is partly released through neutrino emission, while a similar fraction heats the matter and is eventually radiated as thermal photons. We examined two possible causes of such density perturbations: 1) the reduction in centrifugal force caused by spin-down (particularly in millisecond pulsars), leading to *rotochemical heating*, and 2) a hypothetical time-variation of the gravitational constant G, as predicted by some theories of gravity and current cosmological models (*gravitochemical heating*). If only slow weak interactions are allowed in the neutron star (modified Urca reactions, with or without Cooper pairing), rotochemical heating can account for the observed ultraviolet emission from the closest millisecond pulsar, PSR J0437−4715, which also provides a constraint on $|dG/dt|$ of the same order as the best available in the literature.

Key Words: **DENSE MATTER — PULSARS: GENERAL — RELATIVITY — STARS: NEUTRON — STARS: ROTATION**

Neutron star matter is composed of degenerate fermions of various kinds: neutrons (n), protons (p), electrons (e), probably muons (μ) and possibly other, more exotic particles. (We refer to electrons and muons collectively as leptons, l.) 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 $\eta_{npl} \equiv \mu_n - \mu_p - \mu_l = 0$.

If a matter element is in some 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), and partly used to heat the matter. The

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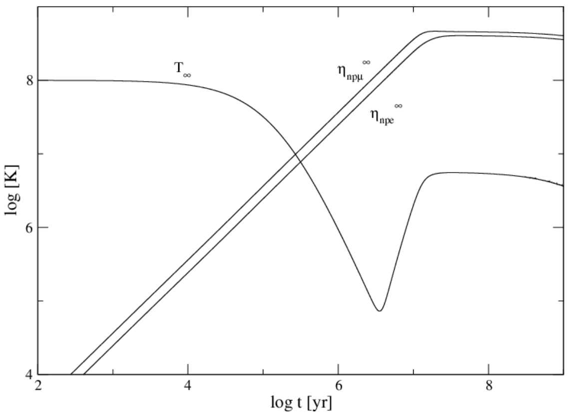

Fig. 1. (taken from FR05) Evolution of the internal temperature and chemical imbalances for a $1.4 M_{\odot}$ star calculated with the A18 + $\delta\upsilon$ + UIX* EOS (Akmal et al. 1998), with initial temperature $T_{\infty} = 10^8$ K, null initial chemical imbalances, and magnetic dipole spin-down with field strength $B = 10^8$ G and initial period $P_0 = 1$ ms.

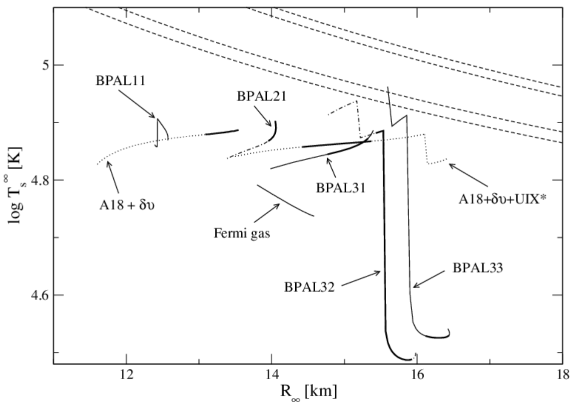

Fig. 2. (taken from FR05) Quasi-steady effective temperatures $T_{s,eq}^{\infty}$ for different EOSs and stellar masses, for the spin parameters of PSR J0437-4715. Dashed lines are 68% and 90% confidence contours of the blackbody fit to the emission from this pulsar (Kargaltsev et al. 2004). Bold lines indicate, for each EOS, the mass range allowed by the constraint of van Straten et al. (2001), $M_{PSR} = 1.58 \pm 0.18 M_{\odot}$.

heat is eventually lost as thermal (ultraviolet) photons emitted from the stellar surface.

We have considered two forcing mechanisms that can perturb the chemical equilibrium in neutron stars, causing possibly observable radiation:

1) *Rotochemical heating* (Reisenegger 1995, 1997; Fernández & Reisenegger 2005, hereafter FR05; Reisenegger et al. 2006): Many neutron stars are observed as pulsars, whose regular pulses indicate a very stable rotation rate that slowly decreases with time at a precisely measurable rate. Thus, the centrifugal force decreases progressively, and the neutron star matter is compressed, increasing the chemical potentials μ_i by different amounts (due to different particle masses, concentrations, and interactions), causing finite values for η_{npe} and $\eta_{np\mu}$. An imbalance between the reaction rates tries to keep up with the changing equilibrium, releasing energy that heats the star.

2) *Gravitochemical heating:* A number of theorists have suggested that perhaps the so-called "fundamental constants" of Nature vary with cosmological time. Many experiments have been performed to constrain such changes, in particular those of Newton's gravitational constant, G. A change in the latter would also cause progressive, structural changes in a neutron star, like those considered in the previous paragraph, with identical consequences, whose magnitude depends on that of the time derivative $\dot{G}$.

Figure 1 shows the typical evolution of a millisecond pulsar subject to rotochemical heating. It first cools down from its high birth temperature, while the chemical potential imbalances η_{npl} slowly increase due to the decreasing rotation rate. Eventually, these are so high that the increased reaction rates can keep up with the ongoing contraction, leaving the chemical imbalance at a constant level, at which also the energy released by reactions and that emitted from the surface compensate, keeping the temperature at a constant and, in principle, predictable value. For the nearest millisecond pulsar, Figure 2 compares such predictions (for various equations of state [EOSs] and neutron star masses) to the temperature inferred from an HST observation. Similar results can be obtained for gravitochemical heating with various assumed values of $\dot{G}$, constraining the latter through the same observation (Jofré et al., paper in preparation).

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