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Gravitational waves from r-mode instability in pulsars

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Introduction

The Rossby mode (r-mode) instability in neutron star (NS) as a steady gravitational wave (GW) source is explored. The time evolution and the intensity of the emitted GWs in terms of the strain tensor amplitude are estimated with the approximation of slow rotation using equation of state (EoS) obtained from Brussels-Montreal BSk24 Skyrme effective interaction [1]. Our choice of the EoS is dictated by the fact that this EoS leads to maximum NS masses $\sim 2.28 M_\odot$ in accordance with recent observations. The NS core has been considered to be β-equilibrated nuclear matter composed of neutrons, protons, electrons and muons, which is surrounded by a solid crust. Calculations have been made for the critical frequencies, the evolution of frequencies and frequency change rates with time as well as the fiducial viscous and gravitational timescales, across a broad range of NS masses.

Non-radial perturbations in NSs

The instability in the r-mode oscillation grows because of gravitational wave emission which is opposed by the viscosity. The amplitude of r-modes evolves with time as $\exp[i\omega t - t/\tau]$ where ω is the angular frequency of the perturbation and the imaginary part of the frequency $1/\tau$ is given by

$$\frac{1}{\tau(\Omega,T)} = \frac{1}{\tau_{GR}(\Omega,T)} + \frac{1}{\tau_{BV}(\Omega,T)} + \frac{1}{\tau^{ee}_{SV}(\Omega,T)} + \frac{1}{\tau^{nn}_{SV}(\Omega,T)} + \frac{1}{\tau^{ee}_{VE}(\Omega,T)} + \frac{1}{\tau^{nn}_{VE}(\Omega,T)} \quad (1)$$

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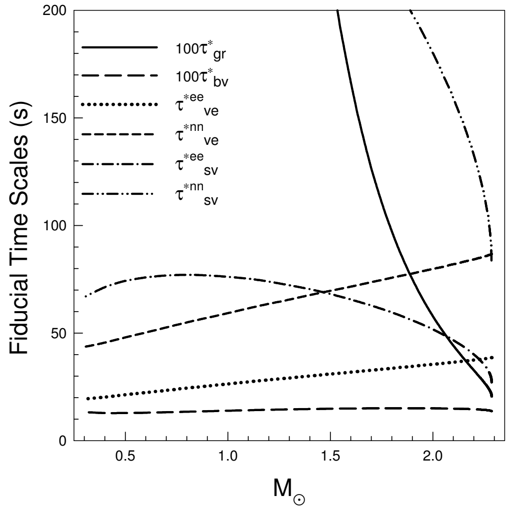

FIG. 1: Variation of fiducial timescales with gravitational mass of NS.

with Ω being the angular velocity of the star. Here τ_{GR}, τ_{BV}, τ_{SV} and τ_{VE} are, respectively, the contributions from gravitational radiation, bulk and shear viscous time scales in the fluid core and viscous dissipation in the crust–core boundary layer [2]. Superscripts ee and nn represent leptonic and baryonic contributions.

Gravitational waves from NSs

The angular momentum gets transferred as a NS accretes mass from its companion causing increase in its rate of rotation. Ultimately it surpasses Ω_c, its critical value. The NS begins to emit GW at this epoch due to the perturbation of r-mode. The GW emission fuels this perturbation due to r-mode because of CFS mechanism, resulting in an increase in the amplitude α_r until it saturates. The NS spins down to the region of stability by emitting GWs which take away the energy and the angular momentum with it. In the present calculations the emitted GW intensity radiated

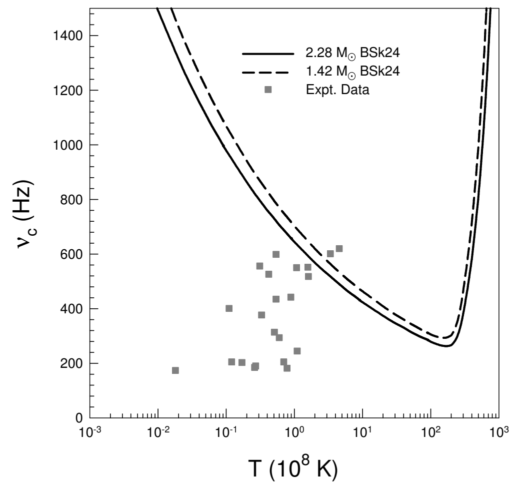

FIG. 2: Critical frequency with respect to temperature for different NS masses. The square dots represent recent observational data.

by NSs has been estimated and compared with the observational data of LIGO-Virgo collaboration [3]. The GW intensity is given in terms of strain tensor amplitude h_0 which is related to the r-mode amplitude α_r:

$$h_0 = \sqrt{8\pi/5} G c^{-5} r^{-1} \alpha_r \omega^3 M R^3 \widetilde{J}, \qquad (2)$$

where M and R are, respectively, the mass and radius of NS, the r-mode angular frequency $\omega = -\Omega\,(l-1)\,(l+2)\,/(l+1)$, $\widetilde{J} = \int_0^R \varrho(r) r^6 dr/(MR^4)$ and $\varrho(r)$ is mass density.

Calculations and results

The fiducial timescales versus the gravitational masses of NSs have been plotted in Fig. 1 for the BSk24 EoS. While the timescale for gravitational radiation falls off rapidly, it is observed that the timescales for viscous damping increase almost linearly with increasing mass. The critical frequency versus temperature plots are shown in Fig. 2 along with the observed data of Low Mass X-ray Binaries and Millisecond Radio Pulsars. This implies that most of the observed NSs lie in the stable region of the r-mode oscillations. The plots of strain tensor amplitude h_0 as a function of distance of $2.28 M_\odot$ NS mass for two spin frequencies of 200 Hz and 700 Hz are shown in Fig. 3.

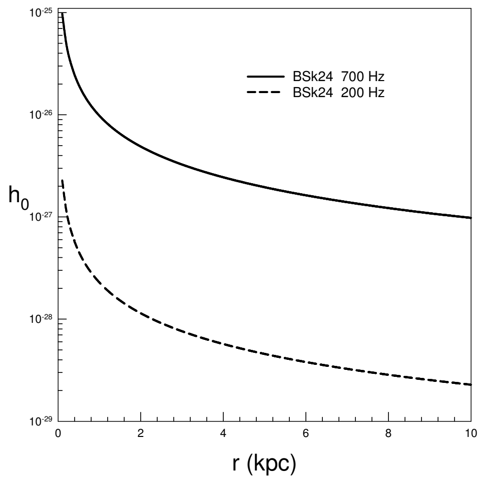

FIG. 3: Strain tensor amplitude h_0 as a function of distance for two different rotational frequencies of $2.28 M_\odot$ NS.

Summary and conclusions

We explore the instability due to the r-mode oscillations for slowly rotating NSs. The fiducial gravitational radiation timescale and the timescales for shear viscosity drag have been calculated in the framework of Skyrme-BSk24 interaction for a wide range of NS masses. Using the present EoS, it is seen that while the viscous damping timescales increase more or less linearly with increasing NS mass, the GW emission timescales decrease rapidly and the core temperatures and spin frequencies of the observed pulsars mostly lie below the region of the r-mode instability. This fact implies that for the NSs spinning faster than their corresponding critical frequencies have unstable r-modes leading to the emission of GWs.

Acknowledgments

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References

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