Інститут ядерних досліджень
Національної академії наук України
Щорічна конференція
2025

Ідентифікатор подання: **105**
Тип: **Секційна доповідь**

Macroscopic approach to rotating neutron stars

четвер, 29 травня 2025 р. 12:55 (20 хвилин)

Macroscopic approach to rotating neutron stars

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In this report we present the macroscopic model for a neutron star (NS), as a perfect liquid drop in equilibrium, in line of Tolman–Oppenheimer–Volkoff (TOV) equations derivations [1], for slow azimuthal rotation frequency ω around the symmetry axis. Within the Friedman–Ipser–Stergioulas [2] formalism for the Kerr metric in Boyer–Lindquist coordinates in the external region [3] and the Hogan metric inside of the star [4] we apply the effective-surface approximation [5] assuming a small crust thicknes a with respect to the radius R NS, $a/R \ll 1$. The surface gradient terms are taken into account in the energy density $E(\rho)$ for the macroscopic equation of state (EoS) within the Extended Thomas Fermi (ETF) approach but with a strong gravitational field. The angular momentum I and the moment of inertia (MI), $=dI/d\omega$, are macroscopically calculated in the adiabatic approach. The adiabatic MI can be expressed as $=\ _{av}/(1+G_{t\varphi})$, where $_{av}$ is the statistically averaged MI, and $G_{t\varphi}$ is a correlation term due to the time–azimuthal coupling,

$$_{av} = \int dV E\left(\rho\right) e^{-\nu} r^2 \sin^2\theta \ , \ G_{t\varphi} = \frac{1}{M} \int dV E\left(\rho\right) e^{-\nu} \tau \sin^2\theta \ .\#\left(1\right)$$

Here, the Schwarzschild metric length element modified by a small rotation frequency $\approx I/M \approx \omega\ /M$, asymtotically far from the NS, is given by ($c = G = 1$):

$$ds^2 = -e^{\nu} dt^2 + 2\tau\ \sin^2\theta\ dt d\varphi + e^{\lambda} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta\ d\varphi^2, \#\left(2\right)$$

where ν and λ are its well-known parameters, $\tau = 1 - \left(\sqrt{1 - r^2/R_S^2} - 3\sqrt{1 - R^2/R_S^2}\right)^2/4$, $R_S = \sqrt{3/(8\pi E_0)}$ is the Schwarzschild radius [3], R is the NS radius, and E_0 is an internal value of the NS energy density.
 (Fig.1 and Fig.2 can be seen in the attachment)

Fig. 1 shows the moment of inertia Θ as a function of the radius R. As seen from Fig. 1, the correlation term $G_{t\varphi}$ [see Eq. (1)] in a strong gravitational NS field leads to a significant shift of the Schwarzschild R_S to the Kerr R_K asymptote. The moment of inertia contributions Θ_{av} and $G_{t\varphi}$ are the sums of the volume and surface components in terms of the ETF energy density $E(\rho)$, $\Theta_i = \Theta_{iV} + \Theta_{iS}$ ($i = av, t\varphi$), and $E = E_S + E_V$ is the total NS ETF energy. The subscript V denotes the NS volume V, and S represents the NS surface (proportional to the surface tension coefficient) terms. The leptodermic and incompressibility parameters are given by a small a/R and a large $\kappa = 10$ for strong gravitation, respectively.

We also verify the adiabatic condition, $(1/2)\Theta\omega^2 \ll E$, for applications to several NS rotation periods, $P \gg P_0 = 2\pi\sqrt{\Theta/(2E)}$, where E is the total ETF energy, and P_0 is the asymptotic boundary period limit; see Fig. 2. For a range of well-known pulsars with spin periods between about 5 and 3000 ms, the adiabatic approach is applicable to the description of these rotating NS systems, in good agreement with their observational data. The internal densities used in these calculations are typically two to three times larger than that of nuclear matter. For all these calculations, the NS radii R are on the order of 10 km, and masses are 1.2–2.1 $M_\odot$ in NS stable equilibrium.

Fig. 2. Periods P (in units of ms) as functions of R/R_S, where R_S is the Schwarzschild radius. Black (blue) circles and red (green) squares represent the minimal and maximal values of R/R_S for the first and second sets of experimental data for the J0030+0451 (J0740+6620) neutron star, respectively. Solid black (dotted magenta) and dashed red lines are the characteristic periods P_0 with (volume evaluations) and without accounting for the $t - \varphi$ correlations. Other parameters are the same as in Fig. 1.

With increasing incompressibility κ, the boundary periods P_0 become greater. To improve accuracy, we should account for non-adiabatic effects, especially for the J0740+6620 star with larger mass. As a perspective, one can apply our analytical macroscopic approach for calculations of NS rotation frequency corrections to the TOV equations.

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Тип засідання: Теоретична ядерна фізика

Класифікація за напрямком: Теоретична ядерна фізика