Triaxially-deformed Freely-precessing Neutron Stars: Continuous electromagnetic and gravitational radiation

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From Quarks to Cosmos

Introduction

★ A rapidly rotating, asymmetric neutron star (NS) in the Milky Way undergoes free precession, making it a potential source for multimessenger observation. The free precession could manifest in (i) the spectra of continuous gravitational waves (GWs), and (ii) the timing behavior and pulse-profile of radio and/or X-ray pulsars.

★ We extend previous work and investigate in great detail the free precession of a triaxially deformed NS with analytical and numerical approaches. In particular, its associated continuous GWs and pulse signals are derived. Explicit examples are illustrated for the continuous GWs, as well as timing residuals in both time and frequency domains.

Methods

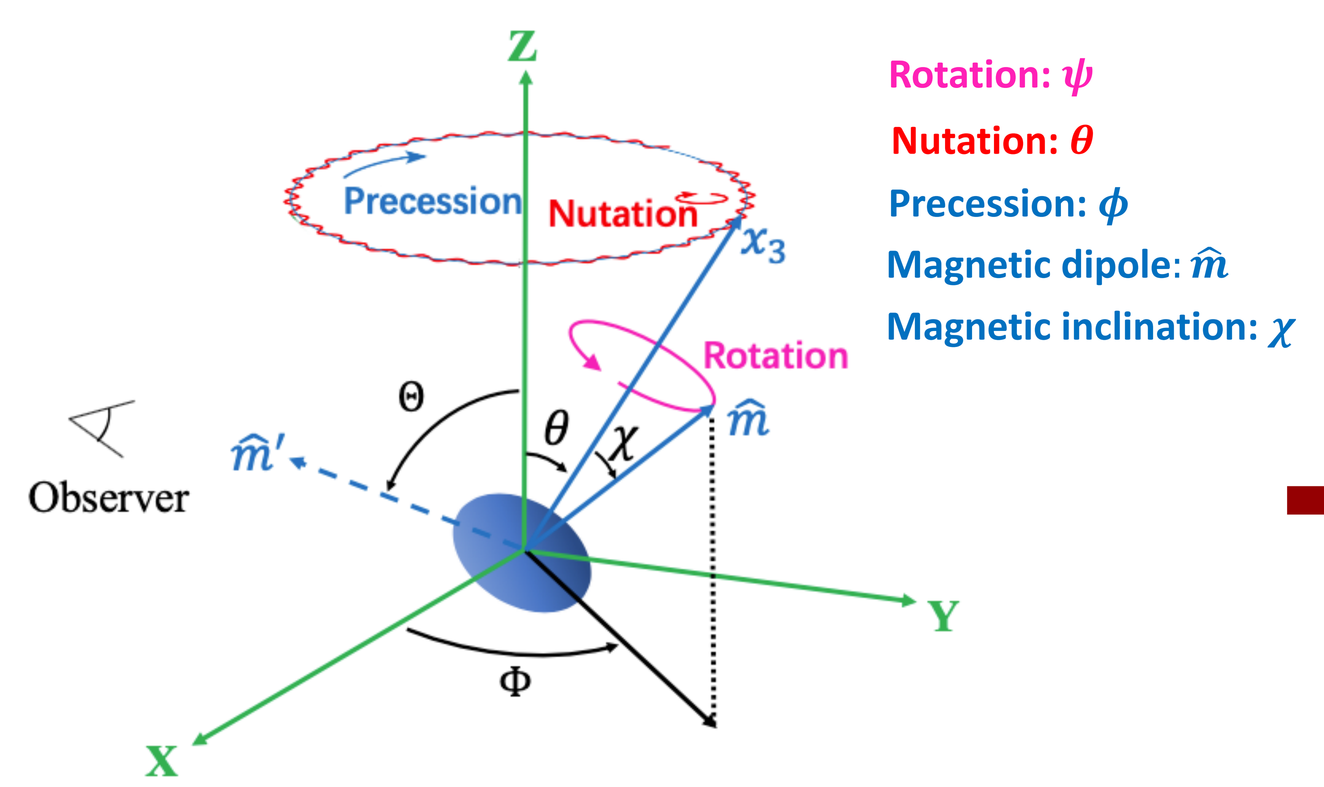


Figure 1. Configuration and kinematics of freely-precessing triaxially-deformed NS.

➢**Assumptions:**

1. the moments I_i $(i = 1,2,3)$ are constant
2. the NS undergoes free precession

➢**Time evolution of the configuration:**

1. Analytical solution with elliptic functions
2. Numerical approach using quaternions

➢**Parameterized description of precessing NS:**

$$\epsilon \equiv \frac{I_3 - I_1}{I_3} \qquad \delta \equiv \frac{I_2 - I_1}{I_3 - I_2} \qquad \gamma \equiv \tan\theta_{\min}$$

Oblateness | **Nonaxisymmetry** | **Wobble**

➢**Modulated timing signals of pulsar:**

$$\Delta\Phi = F(\psi, \theta, \phi)$$

Phase residual = Function of NS configuration

➢**Modulated pulse profile:**

$$W = G(\Theta), \qquad \Theta = H(\psi, \theta, \phi, \chi, \iota)$$

Pulse width = Function of configuration, emission cone, line of sight

➢**Quadrupole radiation of GW:**

$$h_{ij}^{\mathrm{TT}} = \frac{2G}{c^4 r}\frac{\mathrm{d}^2 I_{ij}}{\mathrm{d}t^2} = -\frac{2G}{rc^4}\mathcal{R}_{ik}\mathcal{R}_{jl}A_{kl}$$

Result 1: timing residual

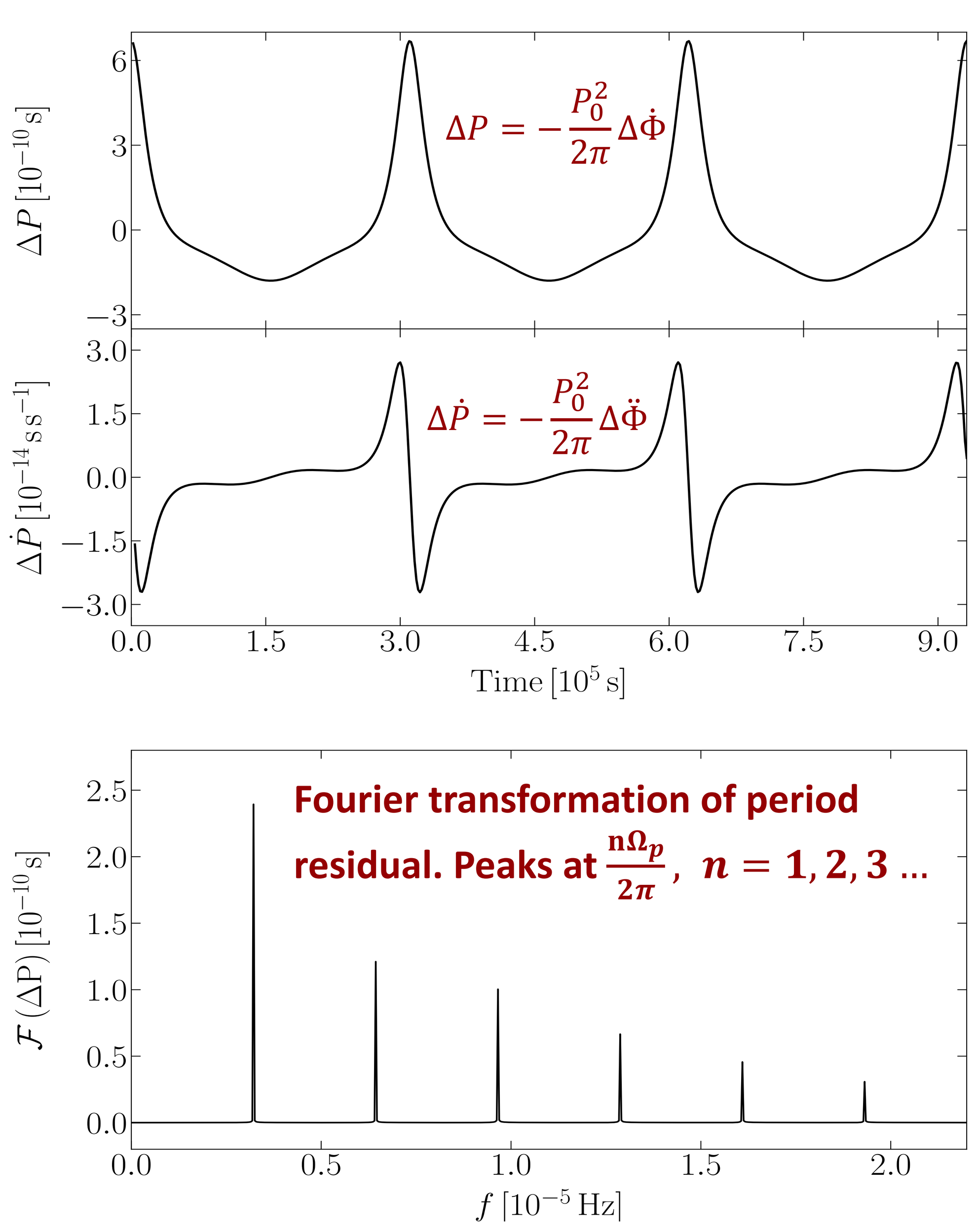


Figure 2. Timing residuals for a large wobble angel case. Ω_p **is the free precession angular frequency.**

★ To the second order expansion of ϵ, δ, and γ (small wobble case), the period residual is

$$\Delta P \approx \frac{P_0^2}{2\pi}\Omega_p\gamma(\delta+1)\cot\chi\cos(\Omega_p t) + \frac{P_0^2}{4\pi}\Omega_p\gamma^2\left(1+2\cot^2\chi\right)\cos(2\Omega_p t)$$

Result 2: pulse-width modulation

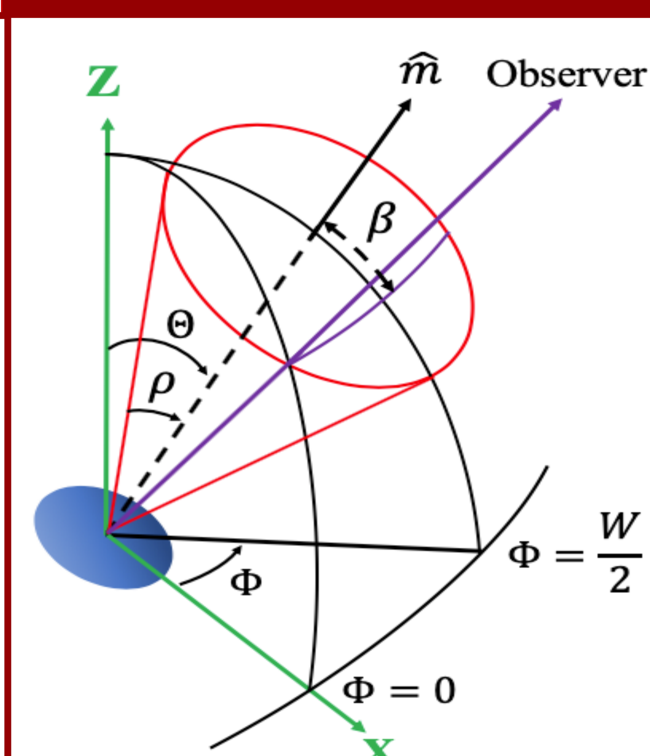


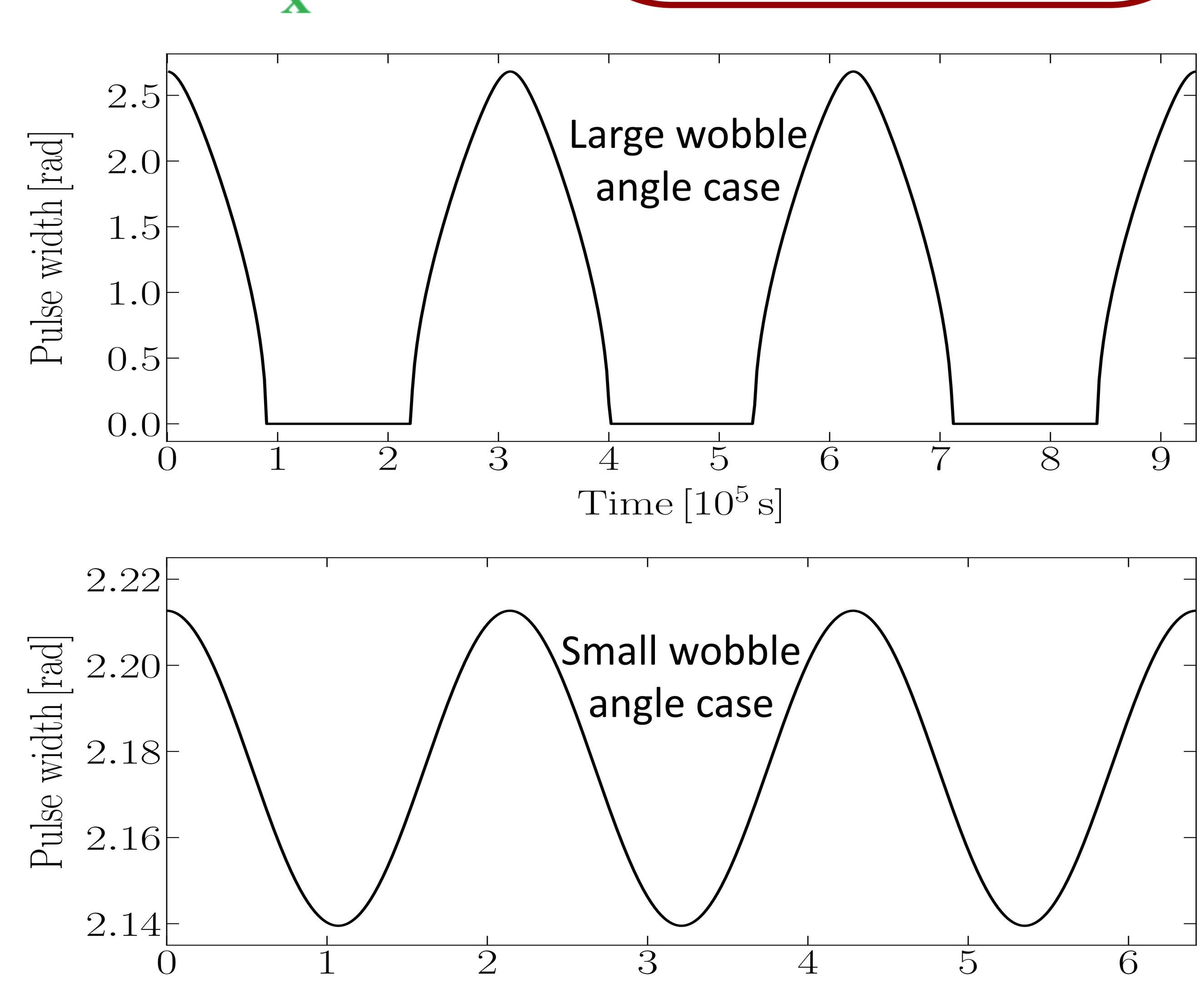
Figure 3.

Left: Emission geometry

1. Electromagnetic radiation is confined in a emission cone with angular radius ρ
2. Different cuts through the cone correspond to different pulse widths

Below: Pulse-width modulation

1. Large wobble angle: may lose the emission during precession
2. Small wobble angle: modulation is much weaker



Result 3: GW waveform

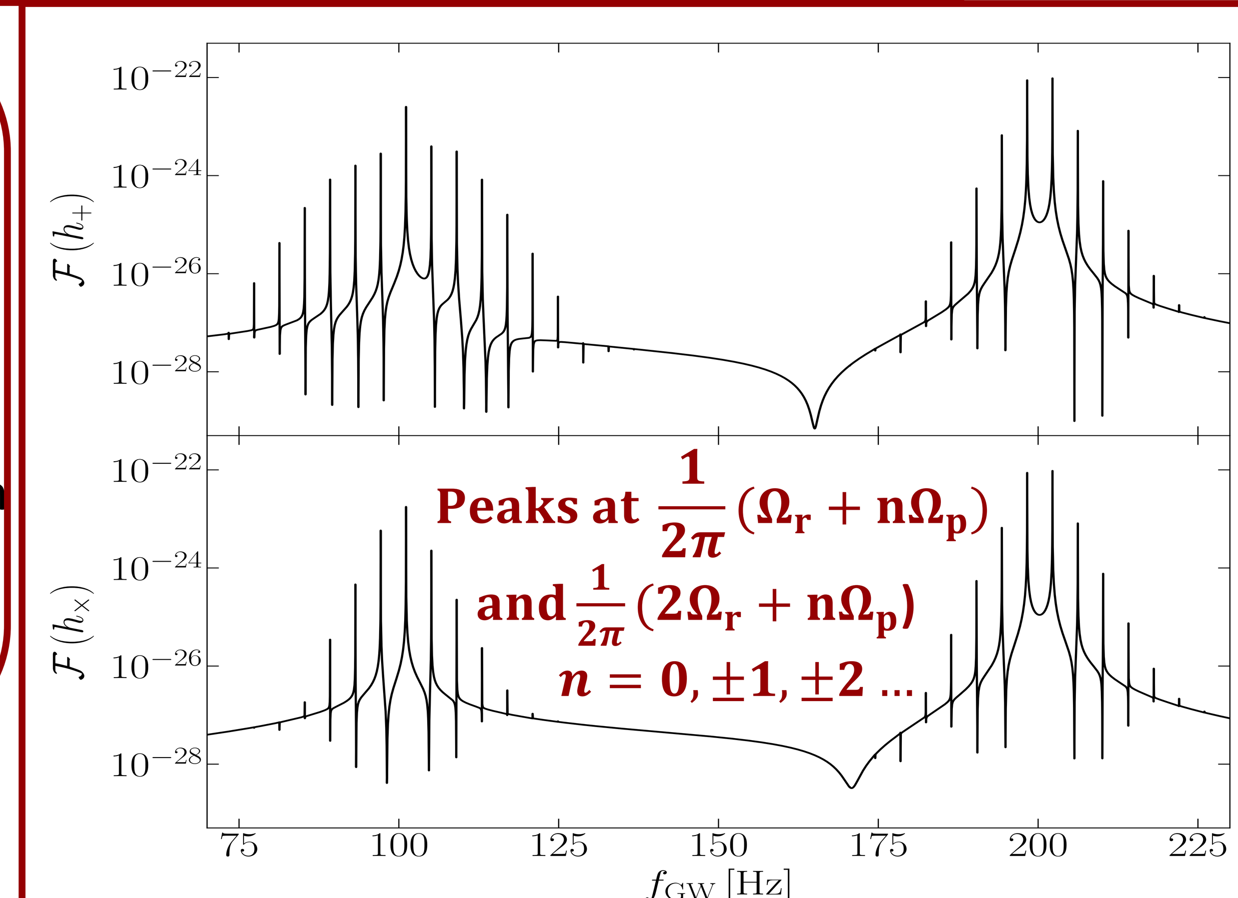


Figure 4. The Fourier amplitudes of h_+ and $h_\times$. The parameters ϵ, δ, and γ have been exaggerated for illustration. Physical parameter can be easily implemented. Ω_r **is the rotation angular frequency.**

★ To the second order expansion of ϵ, δ, and γ (small wobble angle case), the peaks of GW angular frequencies are at

first order lines

$\Omega_r + \Omega_p$ and $2\Omega_r$

second order lines

$2(\Omega_r + \Omega_p)$, $\Omega_r - \Omega_p$, $\Omega_r - 3\Omega_p$, and $2(\Omega_r - \Omega_p)$

Conclusion

1. Radio/X-ray signals and continuous GWs of freely-precessing NSs will provide valuable information about the wobble angle, the nonaxisymmetry, and the oblateness of the source.
2. The next-generation GW detectors may detect the continuous GWs from precessing NSs and constrain the equation of state of NSs.

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