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Precession and free core nutation of neutron stars

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In 1992 Wolszczan and Frail discovered a planetary system around the pulsar PSR 1257+12 [1]. The system is the most interesting and лrich by number of planets (A, B, C and D). It is located in the Virgo constellation at the distance of 300 pc. Two of them, B and C, move in the resonance 3:2. At the present time the question is under discussion whether there exist other planetary systems around three pulsars: PSR 0329+54 (1 planet), PSR B1620–26 (1 planet) and PSR 1828–11 (3 planets — A, B, C). The orbital periods $P_A = 0.68$ yr, $P_B = 1.35$ yr, $P_C = 2.71$ yr show that the extrasolar planets around PSR 1828-11 follow the same 1:2:4 harmonic relationship as those of Jovian satellites. In 2000 Stairs, Lyne and Shemar [2] reported the discovery of the long–term, highly periodic and correlated variations pulse shape and the rate of slow–down of pulsar PSR B1828–11 with the period variations of approximately 1000, 500 and 250 days. There is also strong indication of the presence of a further harmonically–related periodicity of approximately 167 days in both shape and rotation. There are three potential explanations of the arrival time from pulsar related with the interior of the neutron star, planetary bodies and free precession. The radial velocity of a star is obtained by measuring the magnitude of the Doppler effect in its spectrum. The stars showing small amplitudinal variation of radial velocity have been interpreted as systems having planetary companions. Assuming that the pulsar has the mass of $1.35 M_\odot$, the Keplerian orbital radii identified with the three harmonically related sinusoids are 0.9, 1.4 and 2.1 AU while the masses are $3.1 M_\oplus \sin i$, $10.2 M_\oplus \sin i$, $4.6 M_\oplus \sin i$, where i is the orbital inclination. Second explanation: the periods of Tkachenko oscillations of the neutron superfluid vortex array, which carries much of the angular momentum of the neutron star, depends on the size of the star and the square root of the pulse period. For Crab pulsar (PSR 0531+21) Tkachenko oscillations are expected to amount to 4 months; for the PSR B1828–11 the period of the Tkachenko oscillations are 13 months [2]. Unfortunately, the theory of the Tkachenko oscillations does not easily explain the existence of multiple harmonics in the PSR B1828–11 timing residuals. Third case: the most likely possibility is the free precession of the pulsar with a rigid neutron star. It will occur if the star is deformed so that the spin axis is not aligned to its angular momentum vector. The time scale for precession depends on the degree of deformation of the pulsar. To produce a periodicity of 1000 days, the deformation of a rigid-body neutron star would amount to approximately 5×10^{-9}. This value is comparable with or smaller than that expected for a spining neutron star [2]. Another family of neutron stars, the anomalous X–ray pulsars, are known to display "wobbles" in their slowdown rates.

It is known that rotation of the terrestrial planets having rigid mantle and elliptical liquid core is characterized by Free Core Nutation (FCN). Any celestial body whose rotation axis does not coincide with the main inertia axis is characterized by Chandler Wobble (CW). These phenomena of FCN and CW are manifested as periodical oscillations of the rotation axis of the pulsar in inertial reference system. For rotating pulsar we deal with the case of modulation of pulses emitted around the direction of the magnetic axis of a pulsar whose symmetry axis is misaligned with the angular velocity vector. Two modes in a polar oscillation are obtained when a free rotation of the two–layer pulsar was studied:

$$P_{CW} = \frac{P_{pulsar}}{2\sqrt{\alpha\beta}} \frac{A_{core}}{A} \qquad P_{FCN} = \frac{P_{pulsar}}{\sqrt{\alpha\beta}} \frac{A_{core}}{A} \left(\frac{A_{core}}{C_{core} - A_{core}} \right) \qquad (1)$$

Correctly extending the theory of core–mantle differential rotation of the planets to neutron star [3] we have obtained the period of CW and free nutation of liquid part of the N–star. It was made in the frame of the Hamiltonian approach for description of rotation of two–layer deformable pulsar having rigid crust and liquid mantle. Two modes of free pulsar libration are obtained in the case of polar motion from the Hamilton's equations: a Chandler–like wobble with a period P_{CW} and a FCN with a period P_{FCN}:

PSR B1828–11: $P_{FCN} \approx 250$ days for $a - c = 5m$, $a_{core} - c_{core} = 5.6m$;
PSR 1257+12: $P_{FCN} \approx 67$ days for $a - c = 1m$, $a_{core} - c_{core} = 1.1m$;
PSR 0531+21: $P_{FCN} \approx 120$ days for $a - c = 1m$, $a_{core} - c_{core} = 3.2m$.

References

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2. Stairs I. H., Lyne A. G., Shemar S. L. Nature, 2000, **406**, 484–486.

3. Petrova N., Gusev A. Cel. Mech. & Dyn. Astron., 2001, **80,** 215.