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Probing regularity of the time-ticks from neutron star laboratories with high-precision timing of GMRT-discovered millisecond pulsars

S. Sahoo[(1)], B. Bhattacharyya [(1)]
(1) National Center for Radio Astrophysics, Pune, India, 411007, e-mail: ssahoo@ncra.tifr.res.in; bhaswati@ncra.tifr.res.in

In the realm of astrophysics, pulsars are highly magnetized, rotating neutron stars emitting beams of electromagnetic radiation that, when swept by line-of-sight these beams, look like a pulse of radiation, hence the name 'pulsar'. Millisecond pulsars (MSPs) are a class of pulsars with very short periods of less than 30 milliseconds. MSPs are known for their precise and stable periods, which can be comparable to stability of atomic clocks, and have the potential to detect gravitational waves, making them an essential component of pulsar timing arrays (PTAs). MSPs are also used for laboratories in space for testing general relativity, studying the interstellar medium, understanding neutron star physics, aiding galactic navigation, analyzing binary systems, and to study the behavior of matter in extreme conditions. Pulsar timing involves measurement of the time of arrivals (ToAs) and timing residuals (precise intervals between pulses from a pulsar) over an extended period of time to disentangle the phenomena that affecting them like rotation, motion, and the influence of gravitational forces, with applications in detecting gravitational waves. The Giant Metrewave Radio Telescope (GMRT), a highly sensitive instrument spanning a broad radio frequency range from 120 to 1460 MHz, has proven its capability in precise low-frequency timing measurements. We have extended the timing analysis of isolated MSP J0248+4230, discovered by GMRT with a spin period of 2.6 milliseconds [1]. The timing baselines for J0248+4230 have been extended from 5 years (2013-2017, with legacy GMRT) to 11 years using phased array observations from uGMRT. This comprehensive study achieved precision in ToAs measurements with a reduced root-mean-square (rms) deviation of approximately 13.658 microseconds, resulting in more accurate estimations of model parameters such as spin period value of 2.60083478563372 milliseconds. This means we can measure the spin period very precisely, to within 10^{-14} milliseconds, and the change in the period very accurately, to within 10^{-26} seconds per second. This level of precision shows that the period will only change by 5 nanoseconds (5 billionths of a second) over 10,000 years, establishing this as a precise clock. The extended timing baselines with uGMRT datasets led to the first-time detection of proper motion ($\mu\_T = 1.35 \pm 0.35$ milli-arcsecond per year) with a transverse velocity ($V\_T = 15.3 \pm 4.4$ km/s) for this MSP. The improved rms of timing residual of 6.328 microseconds is achieved using only the coherent de-dispersed mode which is comparable to the rms of timing residuals for MSPs included in the European PTA (EPTA) [2]. We plan to further extend this timing study beyond 11 years to enhance the precision of timing measurements, achieving more accurate pulsar parameter values, which may facilitate the addition of J0248+4230 to the pulsar list of PTA. Finally, our work demonstrates that, with the aid of precise pulsar timing, the GMRT discovered pulsars can act like a precise clock and can hold great promise to probe fundamental physics.

[1] B. Bhattacharyya *et al.*, “Discovery and Timing of Three Millisecond Pulsars in Radio and Gamma-Rays with the Giant Metrewave Radio Telescope and Fermi Large Area Telescope,” *Astrophysical journal/͂The œAstrophysical journal*, vol. 910, no. 2, pp. 160–160, Apr. 2021, doi: https://doi.org/10.3847/1538-4357/abe4d5.

[2] B. Perera *et al.*, “The International Pulsar Timing Array: second data release,” vol. 490, no. 4, pp. 4666–4687, Oct. 2019, doi: https://doi.org/10.1093/mnras/stz2857.