Black Hole Mass and Optical Radiation Mechanism of the Tidal Disruption Event AT 2023clx (Postprint)

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Abstract

We present the optical light curves of the tidal disruption event AT 2023clx in the declining phase, observed with Mephisto. Combining our light curve with the ASAS-SN and ATLAS data in the rising phase, and fitting the composite multi-band light curves with MOSFiT, we estimate black hole mass for AT 2023clx is between 105.67 and 105.82M . This event may be caused by either a full disruption of a 0.1 M star, or a partial disruption of a 0.99 M star, depending on the data adopted for the rising phase. Based on those fit results and the non-detection of soft X-ray photons in the first 90 days, we propose that the observed optical radiation is powered by stream-stream collision. We speculate that the soft X-ray photons may gradually emerge in 100–600 days after the optical peak, when the debris is fully circularized into a compact accretion disk.

Full Text

Preamble

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Study on the One-year Accuracy of Pulsar Time-scale
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Abstract

Accurate determination of pulsar timing model parameters is essential for establishing TT(PT), a realization of Terrestrial Time (TT) based on a pulsar timescale (PT). This study investigates how different observational data spans affect the accuracy of these parameters. Using observations of PSR J0437−4715, J1909−3744, J1713+0747, and J1744−1134 from the second data release of the International Pulsar Timing Array (IPTA DR2, Version A), we compare the accuracy of timing model parameters derived from varying data spans. Our results show that for PSR J0437−4715, J1713+0747, and J1909−3744, the amplitude of rotational frequency fluctuations remains within 10^{-15}, 10^{-14}, and 10^{-14} Hz, respectively, when the data spans for parameter determination exceed 13, 14, and 6 years.

Additionally, the one-year accuracy of TT(PT) is crucial for its application in timekeeping. By comparing frequency deviations of TT(PT) relative to TT(BIPM) under both ideal (kr) and actual (kp) conditions across different data spans, we find that when the data span reaches the aforementioned durations, the accuracy of TT(PT) surpasses that of TT(TAI) under ideal conditions, though it remains slightly inferior under actual conditions. This suggests that with improved observational technologies, the accuracy of TT(PT) can be further enhanced.

Key words: (stars:) pulsars: individual (PSRs J1909−3744, J1713+0747, J0437−4715, J1744−1134) -time -methods: data analysis

1. Introduction

Pulsars are rapidly rotating, highly magnetized neutron stars formed from the gravitational collapse of massive stars (Lyne & Graham-Smith 2012). Since the discovery of the first pulsar, PSR B1919+21, pulsar science has gradually developed (Hewish et al. 1968). Shortly thereafter, Reichley et al. (1971) proposed that pulsar signals could serve as clock signals. The discovery of the first millisecond pulsar, PSR B1937+21, significantly advanced the development of pulsar timing applications (Backer et al. 1982). Millisecond pulsars are regarded as nature' s most stable clocks, with some exhibiting fractional stabilities comparable to the best atomic clocks of their era (Taylor 1991). Since then, millisecond pulsar timing has attracted considerable attention from astronomers.

In recent years, the discovery of more millisecond pulsars and advances in observational equipment and technology have prompted numerous researchers to investigate applications of millisecond pulsar timing in pulsar timescales (Rodin 2008; Hobbs et al. 2012, 2020; Zhang et al. 2024).

Pulsar timing applications depend critically on the stability of pulsar rotation, making precise measurement of rotational parameters fundamental to related research. However, due to the vast distances of pulsars from Earth, an accurate pulsar timing model is essential for steering the pulsar timescale (PT) to a reference timescale conforming to the International System of Units (SI), thereby obtaining a realization of Terrestrial Time (TT) based on PT, denoted as TT(PT) (Hobbs et al. 2012; Tong et al. 2017). Hobbs et al. (2006) developed Tempo2, a pulsar timing package based on pulsar timing principles. Using Tempo2 to analyze long-term pulsar timing observations, pulsar timing model parameters can be precisely determined (Edwards et al. 2006). As the number of pulsar timing observations increases, the precision of the pulsar timing model parameters is correspondingly enhanced (Tong et al. 2017).

Pulsar timing observation is the process of measuring pulsar timing model parameters using TT(BIPM) as the time reference, which is equivalent to establishing a pulsar timescale with TT(BIPM) as the reference. TT(BIPM) is a realization of Terrestrial Time (TT) as defined by the International Astronomical Union (IAU), released annually. Consequently, the one-year accuracy of TT(PT) predicted by these model parameters is crucial for evaluating its feasibility as a time reference.

Accordingly, this paper focuses on the one-year accuracy of TT(PT). To clearly distinguish between different yearly versions of TT(BIPM), we employ the alternative notation TT(BIPMXX), where XX corresponds to the year of the most recent data used (Guinot & Petit 1991). For example, TT(BIPM15) represents the version released in 2015 (Petit 2004). TAI is obtained by the BIPM using the ALGOS algorithm to comprehensively process data from more than 450 high-accuracy atomic clocks worldwide over the past month, released monthly (Panfilo & Arias 2009). TT(TAI) is another realization of TT, defined as TT(TAI) = TAI + 32.184 s. When TT(BIPM) has not been released, TT(TAI) is typically used as the time reference.

Long-term, high-precision pulsar timing observations are fundamental to determining accurate pulsar timing model parameters. Currently, major pulsar timing arrays worldwide include the European Pulsar Timing Array (EPTA; Desvignes et al. 2016), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav; Arzoumanian et al. 2020), the Parkes Pulsar Timing Array (PPTA; Reardon et al. 2021), the Indian Pulsar Timing Array (InPTA; Tarafdar et al. 2022), the MeerKAT Pulsar Timing Array (MPTA; Johnston et al. 2020), the Chinese Pulsar Timing Array (CPTA; Lee 2016), and others. The International Pulsar Timing Array (IPTA), a collaboration of EPTA, NANOGrav, and PPTA, released its second data release (IPTA DR2) in 2019, containing observations of 65 millisecond pulsars (Perera et al. 2019). These timing observations provide the essential foundation for pulsar timing research and gravitational wave detection.

The parameters of different pulsar timing models can be determined using observations with varying spans, but only an appropriate data span yields the most accurate parameters. In this paper, based on IPTA DR2, we select several millisecond pulsars with excellent performance to determine timing model parameters using different observation spans, thereby exploring the optimal data span. Since IPTA DR2 uses TT(BIPM15) as the time reference, this paper also adopts TT(BIPM15). Additionally, we investigate the accuracy of different model parameters and the one-year predictions of TT(PT) based on these parameters.

2. Pulsar Timing Model

Accurate pulsar timing model parameters are fundamental to pulsar timekeeping applications. These parameters primarily include the rotation frequency ( ) of the pulsar, its first derivative (̇), its second derivative (̈), right ascension, declination, proper motion, parallax, binary orbital parameters, and others. We determine these parameters based on pulse arrival times (TOAs) using the least-squares method, which is also the process of constructing a pulsar clock.

During TOA observations, we use the local station atomic clock to record the arrival time, denoted as t_{obs}. To ensure accuracy, t_{obs} must be traced to TT(BIPM) through various time corrections. The arrival of pulsar signals at ground-based telescopes involves numerous physical processes and geometric effects, requiring an accurate timing model to relate the TOA at the Solar System Barycenter (SSB), t_{ssb}, to t_{obs}. This relationship can be expressed as (Edwards et al. 2006):

$$t_{ssb} = t_{obs} + \Delta_A + \Delta_R + \Delta_p + \Delta_D + \Delta_E + \Delta_S$$

where Δ_A denotes atmospheric delays; Δ_R denotes the Roemer delay (the simple vacuum delay between pulse arrival at the observatory and the SSB); Δ_p denotes parallax-induced delays; Δ_D denotes dispersion delays from the interstellar medium; Δ_E denotes the Einstein delay related to relativistic spacetime transformation; and Δ_S denotes the Shapiro delay (excess time delay from pulse passage through curved spacetime). These delay terms can be expressed in detail as (Edwards et al. 2006; Tong et al. 2017):

$$\Delta_R = (\hat{n} \cdot r)/c$$
$$\Delta_p = - (\hat{n} \cdot r)^2/(2R_0 c)$$
$$\Delta_E = {t_0}^{t{obs}} [U_{} (t') + v_{}^2(t')/2 + \Phi(t_0) - \Phi(t')]\, dt'$$
$$\Delta_S = - {k=1}^{l} (2GM_k/c^3) \ln|r_k + \hat{n} \cdot r_k| + (1 + \gamma)GM_{} /c^3 \ln|(r_e + \hat{n} \cdot r_e + 2GM_{} /c^2)/R_{} |$$

where c is the speed of light, $\hat{n}$ is the unit vector to the pulsar in the Barycentric Celestial Reference System (BCRS), r is the telescope position vector at the observation moment, v is the pulsar velocity vector relative to the SSB, Δt =

t - t_0 with t_0 as a reference epoch, R_0 is the pulsar distance to the SSB at t_0, U_ is the gravitational potential at the geocenter from all solar system bodies except Earth, v_ is the geocenter velocity relative to the SSB, PN = 1.097 $\times$ 10^{-16} and W_0 = 6.969290134 $\times$ $10^{-10}c^2$ apply corrections for higher-order relativistic terms, s is the vector from geocenter to observatory, G is Newton' s gravitational constant, M_k is the mass of the kth solar system object, r_k is the telescope position vector relative to the kth object, l is the number of major solar system objects used in Shapiro delay calculation, r_e is the telescope-Sun distance, M_ is solar mass, is the Sun-pulsar-telescope angle, f_{SSB} is the observing frequency transformed to the barycentric frame, and DM_e is the dispersion measure from the interplanetary medium.

After converting t_{obs} to t_{ssb}, we obtain the observed rotation phase f(t_{ssb}) and the theoretically predicted rotation phase N(t_{ssb}) based on the pulsar phase model:

f(t_{ssb}) = f_0 + (t_{ssb} - t_0) + (1/2)$\dot{}$(t_{ssb} - $t_0)^2$ + (1/6)$\ddot{}$(t_{ssb} - $t_0)^3$

where f_0 is the phase at t_0, is the rotation frequency, and $\dot{}$ and $\ddot{}$ are its first and second derivatives. N(t_{ssb}) is always the nearest integer to f(t_{ssb}). The differences between these phases constitute the timing residuals:

R_i = f_i - N(t_{ssb},i)

where f_i is the measured ith pulse phase and R_i is the ith timing residual. In this paper, we trace t_{obs} to TT(BIPM15) during time corrections. Without any fitting operation, R_i is called the pre-fit timing residual. To obtain accurate parameters, we perform a least-squares fit to the pre-fit residuals using:

^{2} = Σ_i (R_i/σ_i)^2

where σ_i represents the uncertainty in R_i. We minimize ^{2} using the least-squares method to obtain new model parameters. This fitting process repeats until residuals level off within computational precision, yielding accurate timing model parameters and post-fit residuals.

Theoretically, once determined, pulsar timing model parameters remain valid over long periods. However, parameters obtained using different data spans differ. To identify the optimal data span for parameter determination, we discuss the impact of varying data spans on model parameters.

3. Accuracy Analysis of Pulsar Timing Model Parameters

To obtain accurate pulsar timing model parameters, we determine these parameters using different data spans and analyze their accuracy. When differences between parameter sets become minimal, the parameters are considered to have leveled off. For simplicity, this paper analyzes only the accuracy of rotation parameters (, $\dot{}$) determined with different data spans and the accuracy of pre-fit timing residuals predicted by these parameters.

3.1. Methods for Determining Pulsar Timing Model Parameters

Selecting appropriate pulsar timing observations is crucial for determining accurate model parameters. Based on IPTA DR2 observations, we selected PSR J1909−3744, J0437−4715, J1713+0747, and J1744−1134, which exhibit high timing precision (Verbiest et al. 2016; Perera et al. 2019). Their information is summarized in Table 1, and their post-fit timing residuals are shown in Figure 1. The parameters requiring fitting include rotation frequency, its first derivative, right ascension, declination, proper motion, parallax, dispersion, and others. Additionally, since PSR J1909−3744, J0437−4715, and J1713+0747 are binary systems, binary parameters must also be fitted, including orbital period, its derivative, projected semimajor axis, longitude of periastron, periastron advance rate, orbital eccentricity, companion mass, and others.

We first determine model parameters using four-year observations through the following procedure: (1) Using the reference epoch (PEPOCH) 55000 provided by IPTA DR2, we employ Tempo2 to fit pulsar timing model parameters with four-year observational data until convergence, then output parameters such as and ˙ along with their uncertainties (_{err} and ˙ *{err}). (2) We fix the four-year data span but shift it in one-year steps, as shown in Figure 2, repeating step (1). For example, for J0437−4715 with its 18.6-year observational span, the data can be divided into 15 overlapping four-year intervals, yielding 15 parameter sets. (3) Following 3σ guidelines, we eliminate parameters with large errors from these 15 sets, then compute the average of the remaining parameters (denoted as ¯ and ¯˙) to obtain mean parameters for a four-year data span, with corresponding errors* (¯{err} and ¯˙_{err}) derived from error propagation theory. (4) We increase the data span in one-year increments and repeat steps (1)-(3) to obtain average parameters for different data spans.

3.2. Accuracy Analysis

The results are presented in Figure 3. Figures 3(a) and 3(b) show pulsar timing model parameters for the four pulsars (with initial parameters from Table 1 subtracted) across different data spans, while Figures 3(c) and 3(d) show corresponding measurement errors. To more accurately analyze parameter variations, Table 2 presents differences in timing model parameters between adjacent data spans for each pulsar. Specifically, to understand differences between five-year and four-year data spans, the "Adjacent data span" column in Table 2 would show 5-4, with similar representations for other span differences.

3.2.1. PSR J0437−4715 For J0437−4715, Figures 3(a), 3(b), and Table 2 show that differences in between adjacent data spans level off within 10^{-15} Hz when the data span reaches 13 years or more, while differences in ˙ level off within 10^{-23} s^{-2}. This indicates that J0437−4715 timing model parameters are sufficiently accurate when the determination data span exceeds 13 years. Among the four pulsars, J0437−4715 exhibits minimal parameter variation (Figures 3(a) and 3(b)), attributed to its high timing precision and low timing noise.

Spectral analysis of timing residual sequences can estimate noise levels. In astronomy, the power spectral density (PSD) of time series is typically dominated by red noise exhibiting power-law behavior. The red noise power-law model is defined as (Coles et al. 2011):

$S(f) = A^2/(1 + (f/f\_c)^2)\hat{}(q/2)$

where A is red noise intensity, f_c is corner frequency, and q is spectral exponent. To analyze red noise levels, we performed PSD analysis on post-fit timing residuals, shown in Figure 4. Figure 4(a) shows J0437−4715' s red noise PSD with corresponding A, f_c, and q. Compared to J1744−1134 and J1713+0747, J0437−4715 has lower red noise intensity, resulting in minimal parameter variation. Figures 3(c) and 3(d) show that within 8-year data spans, J0437−4715's parameter measurement errors are significantly smaller than those of J1744−1134 and J1713+0747, determined by TOA measurement accuracy. As data span increases, measurement errors gradually decrease and level off, indicating that additional observations greatly reduce measurement errors.

3.2.2. PSR J1713+0747 For J1713+0747, Figures 3(a) and 3(b) show significant parameter variation within 6-year data spans, related to its timing noise. Figure 4(b) shows J1713+0747' s red noise intensity exceeds that of J0437−4715, directly causing larger parameter variations. Figures 3(a), 3(b), and Table 2 demonstrate that when the data span exceeds 14 years, differences in between adjacent spans level off within 10^{-14} Hz, and differences in ˙ level off within 10^{-22} s^{-2}. This indicates J1713+0747 timing model parameters are sufficiently accurate when the determination span exceeds 14 years. Figures 3(c) and 3(d) show J1713+0747 exhibits larger measurement errors within 8-year spans, suggesting relatively poor early TOA measurement accuracy. However, with accumulated observations and improved equipment and techniques, its parameter measurement errors approach those of J0437−4715.

3.2.3. PSR J1744−1134 For J1744−1134, Figures 3(a) and 3(b) show the largest parameter variations, failing to converge even with increasing data spans. This results from J1744−1134 having the worst timing residual accuracy and fewest TOAs (Table 1). Figure 4(c) shows J1744−1134 has the highest red noise intensity among the four pulsars. Figures 3(c) and 3(d) confirm its parameter measurement errors are largest, indicating the worst TOA measurement accuracy. Although parameter measurement errors tend to level off when the determination span exceeds 16 years, they remain larger than the other three pulsars, indicating that increased observations alone are insufficient to significantly reduce errors; further TOA measurement accuracy improvements are necessary.

3.2.4. PSR J1909−3744 Table 1 shows J1909−3744 has the shortest observational span, which may not meet minimum convergence requirements. However, due to its largest number of TOAs and highest timing accuracy, we discuss its parameters. Figures 3(a) and 3(b) show minimal parameter variation for J1909−3744. Table 2 indicates that when the data span exceeds 6 years, differences in between adjacent spans level off within 10^{-14} Hz, and differences in ˙ level off within 10^{-21} s^{-2}. This demonstrates J1909−3744 parameters are sufficiently accurate when the determination span exceeds 6 years, attributable to its highest timing accuracy, largest TOA count, and lowest red noise intensity. Figure 4(d) shows J1909−3744 has the lowest red noise intensity among the four pulsars. Figures 3(c) and 3(d) indicate its parameter measurement errors are relatively small and level off with increasing observations, demonstrating high TOA measurement accuracy. In summary, J1909−3744' s high timing accuracy, large TOA count, low red noise intensity, and high measurement precision make it an excellent millisecond pulsar, with its primary limitation being the relatively short observational span. Nevertheless, as observations accumulate, its timing model parameter precision is expected to improve, establishing it as a prime candidate for future pulsar-based timekeeping studies.

4. Accuracy Analysis of TT(PT) on a One-year Timescale

Sufficient accuracy is a prerequisite for TT(PT) to serve as a timescale. Therefore, after determining accurate pulsar timing model parameters, we discuss the one-year accuracy of TT(PT) predicted by these parameters.

4.1. Accuracy Calculations

Once model parameters are determined, pre-fit timing residuals can be predicted using Equation (8). The absolute value of the slope of these residuals, denoted kp, reflects the frequency deviation of TT(PT) relative to TT(BIPM15). This deviation arises from pulsar rotational characteristics, timing model parameter inaccuracies, timing noise, fitting errors, and other factors. Smaller frequency deviation indicates higher TT(PT) accuracy. Additionally, the relative frequency deviation (kr), derived from determined over two adjacent data spans, also reflects TT(PT) frequency deviation relative to TT(BIPM15). The data spans for parameter determination are shown in the blue portion of Figure 5. The kr between adjacent determination spans can be expressed as:

kr = | _{n,m+1} - _{n,m}| / _{n,m}

where _{n,m} is the rotational frequency in the mth parameter set determined over an n-year span. We use the subsequent one-year interval (red portion in Figure 5) to examine pulsar clock predictions based on pre-fit timing residuals. The parameter determination method follows Section 3.1.1, with the prediction interval being the adjacent one-year period following the determination span, as shown in Figure 5' s red portion. kp_{nm} is the slope of one-year pre-fit residuals predicted by the mth parameter set determined over n years. kr depends on two values from adjacent spans and reflects the optimal TT(PT) level under ideal conditions, while kp reflects actual TT(PT) accuracy.

4.2. Accuracy Analysis

To evaluate kp and kr accuracy, we selected TT(TAI) as an alternative time reference. We calculate TT(TAI)' s relative frequency deviation relative to TT(BIPM15) over the same interval as the pre-fit residuals, denoted ktai, then conduct detailed comparative analysis of kp, kr, and ktai across different intervals.

4.2.1. PSR J0437−4715 For J0437−4715' s 18.6-year observational span, we divided it into 15 parameter determination spans and 14 pre-fit residual prediction intervals, yielding 14 comparative cases. We selected representative spans of 4, 8, 13, and 15 years, shown in Figure 6. As Section 3 indicates, J0437−4715 parameters vary significantly within 6 years and level off after 13 years. Figure 6 shows that when the determination span is less than 6 years, kr and kp are relatively close. However, as span increases, their difference gradually becomes significant, particularly beyond 13 years. This occurs because kp is always affected by timing noise and other uncertainties, while kr is minimally affected once parameters level off, approaching ideal conditions. Therefore, when the determination span is less than 6 years, both kp and kr are influenced by timing noise, showing minimal differences. After parameters are accurately determined, kp remains affected by timing noise while kr becomes nearly ideal, creating significant differences.

Notably, with an 8-year determination span, kr and kp show similar trends in the first eight parameter sets but diverge significantly afterward. This reflects continuous TOA measurement accuracy improvements from advances in observational technology and telescope equipment, making later-observation-based parameters more accurate than early-observation-based ones. As the determination span increases, kp decreases, indicating improved TT(PT) accuracy. To more intuitively analyze kp, kr, and ktai variations across different determination spans, we remove outliers using 3σ guidelines and calculate remaining data averages, shown in Figure 7(a) and Table 3. Results indicate that when the determination span is less than 5 years, kr accuracy is inferior to ktai. When the span exceeds 5 years, kr accuracy rapidly improves, stabilizing after 13 years and surpassing ktai. This demonstrates the critical importance of long-term observations for accurate parameter determination. While kp accuracy remains inferior to ktai, it improves with increasing span. When the span exceeds 13 years, one-year pre-fit residual prediction accuracy is slightly lower than TT(TAI). Considering pulsars' long-term stability, we speculate that pre-fit residual accuracy on timescales longer than one year could be comparable to TT(TAI). kr represents the optimal achievable TT(PT) level under ideal conditions. With continuous observation accumulation and technological advances, TT(PT) accuracy is expected to increasingly approach this ideal state.

4.2.2. PSR J1713+0747 For J1713+0747' s 22.5-year observational span, we divided it into 20 determination spans and 19 prediction intervals, yielding

19 comparative cases. We selected spans of 4, 10, 14, and 18 years, shown in Figure 8. Section 3 shows J1713+0747 parameters vary significantly within 6 years and level off after 14 years. Figure 8 reveals kp and kr variation trends similar to J0437−4715: as determination span increases, the difference between kr and kp grows and parameter accuracy improves. Figures 8(a)-8(d) illustrate the gradual increase in kp-kr differences. As with J0437−4715, newer-observation-based parameters are more accurate than older-observation-based ones due to measurement accuracy improvements. After removing outliers using 3σ guidelines, we calculate kp, kr, and ktai averages, shown in Figure 7(b) and Table 4. Results show that when the determination span is less than 10 years, kr accuracy is inferior to ktai, but gradually surpasses ktai when the span exceeds 10 years. This further substantiates the importance of long-term observations. kp accuracy improves slightly with increasing span but remains inferior to ktai. Compared to J0437−4715, J1713+0747 shows slower kr accuracy improvement and inferior kp accuracy due to higher red noise intensity and worse TOA measurement accuracy. Similar to J0437−4715, after parameters level off, kr accuracy surpasses ktai while kp remains inferior, implying potential for further TT(PT) accuracy improvements with observational technology advances.

4.2.3. PSR J1744−1134 For J1744−1134’ s 19.9-year observational span, we divided it into 16 determination spans and 15 prediction intervals, yielding 15 comparative cases. We selected spans of 4, 8, 13, and 17 years, shown in Figure 9. Figure 9 shows a significant kr-kp difference only when the span reaches 17 years, demonstrating that J1744−1134 parameters do not level off until exceeding 17 years, related to its worst timing accuracy, highest red noise intensity, and sparsest observations. Across spans, we remove outliers using 3σ guidelines and calculate averages, shown in Figure 7(c) and Table 5. Figure 7(c) shows kr decreasing and accuracy increasing with span. When the span exceeds 13 years, kr accuracy surpasses ktai, though remaining worst among the four pulsars. kp accuracy also improves with span, being inferior to ktai within 15 years but surpassing ktai beyond 15 years. Notably, kp accuracy exceeds kr when the determination span exceeds 15 years—an anomalous result likely attributable to randomness and fitting errors caused by J1744−1134’ s worst measurement precision and highest red noise intensity.

4.2.4. PSR J1909−3744 For J1909−3744’ s 10.8-year observational span, we divided it into 7 determination spans and 6 prediction intervals, yielding 6 comparative cases. We selected spans of 4, 5, 6, and 8 years, shown in Figure 10. Section 3 indicates J1909−3744 parameters show minimal overall variation, leveling off after 6 years. Figure 10 shows kr-kp differences become distinct at 5-year spans, attributable to high timing accuracy and low noise intensity enabling accurate parameters from short spans. Moreover, newer-observation-based parameters consistently exceed older-observation-based parameters in accuracy. Across spans, we remove outliers using 3σ guidelines and calculate averages, shown in Figure 7(d) and Table 6. Figure 7(d) and Table 6 show J1909−3744’ s kr decreasing and accuracy improving with span, always surpassing ktai. kp accuracy improves slightly with span but remains slightly inferior to ktai. Compared to J0437−4715 and J1713+0747, J1909−3744' s kp accuracy shows substantial improvement due to its excellent properties: high timing accuracy and low timing noise. Despite its shorter observational span, J1909−3744' s high accuracy makes it a primary object for pulsar timescale studies. As observations accumulate, TT(PT) accuracy is expected to improve further.

5. Conclusions

We studied how different data spans for determining pulsar timing model parameters affect their accuracy and discussed the accuracy of TT(PT) established by these parameters. From IPTA DR2, we selected four high-precision pulsars—J0437−4715, J1713+0747, J1744−1134, and J1909−3744—as our study objects. We determined timing model parameters using an initial four-year data span, then divided the total span into different intervals to obtain multiple parameter sets, calculating averages of and ˙. We increased the data span in one-year increments, similarly computing and ˙ averages. Timing model parameters are considered sufficiently accurate when and ˙ averages level off across different spans.

Results indicated that for PSR J0437−4715, when the data span exceeds 13 years, fluctuations remain within 10^{-15} Hz and ˙ fluctuations within 10^{-23} s^{-2}. For PSR J1713+0747, when the span exceeds 14 years, and ˙ fluctuations remain within 10^{-14} Hz and 10^{-22} s^{-2}, respectively. For PSR J1909−3744, when the span exceeds 6 years, fluctuations remain within 10^{-14} Hz and ˙ fluctuations within 10^{-21} s^{-2}. For J1744−1134, and ˙ did not level off across spans due to its poorer properties.

After exploring data span effects on parameters, we discussed one-year TT(PT) accuracy established by these parameters. Following the same procedure with an initial four-year span, we obtained multiple parameter sets, then calculated TT(PT) accuracy in actual cases (kp) and ideal cases (kr). Increasing the span in one-year increments, we calculated kp and kr for different parameters. To assess one-year accuracy, we compared results with TT(TAI).

Results showed that one-year TT(PT) accuracy depends on pulsar properties including timing precision, noise intensity, and TOA count. Among the four pulsars, J1909−3744's excellent properties yielded the highest TT(PT) accuracy, while J1744−1134' s poor properties yielded the lowest accuracy and exhibited anomalous kp > kr behavior beyond 16-year spans, indicating it is unsuitable for single TT(PT) studies. For J0437−4715, J1713+0747, and J1909−3744, once parameters leveled off, kr consistently surpassed ktai while kp remained inferior to ktai. This suggests that under ideal conditions, one-year TT(PT) accuracy exceeds TT(TAI), though currently actual-case accuracy is lower. However, with continuous observation accumulation and precision improvements, actual-case accuracy is expected to approach ideal-case accuracy, providing a theoretical basis for using TT(PT) as a time standard.

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Note: Figure translations are in progress. See original paper for figures.