

Evolution of the transitional millisecond pulsar PSR J1023+0038 from Aqueye+ and NICER observations

S. Conforti^{1,2,*}, L. Zampieri², M. Fiori², A. Spolon², G. Naletto^{2,3}, and A. Burtovoi^{4,5}

¹ Department of Astronomy, University of Padova, Via Vicolo dell'Osservatorio 3, 35122 Padova, Italy

² INAF – Osservatorio Astronomico di Padova, Via Vicolo dell'Osservatorio 5, 35122 Padova, Italy

³ Department of Physics and Astronomy, University of Padova, Via F. Marzolo 8, I-35131 Padova, Italy

⁴ Università di Firenze – Dip. Fisica e Astronomia, Firenze, Italy

⁵ INAF – Osservatorio Astrofisico di Torino, Pino Torinese, Torino, Italy

Received 28 June 2025 / Accepted 10 February 2026

ABSTRACT

Context. Transitional millisecond pulsars are old, rapidly rotating neutron stars spun up by accretion from a low-mass companion star. These objects can switch between two emission regimes: rotation-powered radio pulsars and accreting X-ray pulsars. The mechanism responsible for these pulsations remains debated, with one prominent model suggesting that optical and X-ray pulsations arise from synchrotron emission produced by a shock resulting from the interaction between the pulsar wind and the accretion disk. This scenario is supported by the minimal phase lag between optical and X-ray pulses in PSR J1023+0038, and by their detection in the high-mode (flaring state) of the system.

Aims. We present a new measurement of the phase lag between optical and X-ray pulse profiles of PSR J1023+0038 and investigate the recent evolution of the binary system (until 2023), monitoring the variation in the time of passage at the ascending node (T_{asc}).

Methods. We performed a timing analysis of the optical observations of PSR J1023+0038 taken with Aqueye+ from 2021 through 2023 and NICER X-ray observations taken in 2023. We used the optical and X-ray data to derive new measurements for the variation in T_{asc} and employed simultaneous Aqueye+ and NICER observations to measure the phase lag between optical and X-ray pulses.

Results. We find the shift in T_{asc} increases by ~ 20 s each year, and in January 2023 we measured a phase lag between optical and X-ray data of 0.067 ± 0.018 , or $112.3 \pm 30.7 \mu\text{s}$.

Conclusions. After 2017, the variation in the time of passage at the ascending node follows a well-defined parabolic increasing trend, suggesting a corresponding increment in the orbital period and orbital separation of the system. This evolution is consistent with a scenario in which the binary system is evolving through nonconservative Roche lobe overflow and the donor is interacting with the pulsar wind, losing mass at a rate much higher than the inferred accretion rate. The measurement of the phase lag between optical and X-ray data confirms the common origin of such pulsations.

Key words. accretion, accretion disks – stars: magnetic field – stars: neutron – pulsars: individual: PSR J1023+0038

1. Introduction

Millisecond pulsars (MSPs) are old and fast-spinning neutron stars, spun up to periods shorter than 30 ms by the accretion of matter and angular momentum from a companion star (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982; Salvo & Sanna 2021). Most are in low-mass binary systems ($< 1 M_{\odot}$), have weak magnetic fields ($\sim 10^8$ – 10^9 G), and are observed as accreting X-ray pulsars or as rotation-powered radio pulsars. Recent works identified MSPs that can switch between these two regimes, called transitional millisecond pulsars (tMPSs). In particular, these sources experience a transition of state on timescales of a few weeks, passing from a rotation-powered regime, where they act like radio pulsars with winds that prevent accretion onto their surface, to a regime where they accrete matter lost by the companion star, emitting a high amount of X-ray luminosity like X-ray binary systems do (Papitto & De Martino 2021). Only three tMPSs are known so far, PSR J1023+0038 (Archibald et al. 2009), PSR J1227–4853 (De Martino et al. 2010), and PSR J1824–2452 (Papitto et al. 2013).

PSR J1023+0038 was initially classified as a cataclysmic variable (Bond et al. 2002), but between 2000 and 2001 observations showed the existence of an accretion disk, which soon disappeared, leaving a radio pulsar (Thorstensen & Armstrong 2005; Archibald et al. 2009). In 2013, the source underwent a new transition in its emission regime, with the disappearance of the radio pulsations, the reappearance of the accretion disk, and the onset of a strong double-peaked H_{α} emission observed in the optical spectrum (Halpern et al. 2013; Patruno et al. 2013; Stappers et al. 2014). PSR J1023+0038 is also the only known tMPS that shows detectable UV (Miraval Zanon et al. 2022; Jaodand et al. 2021) and optical pulsations; the latter were first discovered with SiFAP2 at the Telescopio Nazionale Galileo (Ambrosino et al. 2017) and then confirmed with Aqueye+ at the Copernicus telescope in Asiago (Zampieri et al. 2019) and with the panoramic photometer-polarimeter mounted at BTA in Nizhniy Arkhyz (Karpov et al. 2019). The emission mechanism of these optical pulsations is still under debate. Several models have been proposed to explain it (Campana et al. 2019; Papitto et al. 2019; Veledina et al. 2019, and reference therein). In particular, the shock-driven mini-pulsar nebula scenario (Veledina et al. 2019; Papitto et al. 2019) postulates that optical and X-ray pulsations are produced by synchrotron emission

* Corresponding author: silvia.conforti@phd.unipd.it

caused by shocks that form when the pulsar wind meets the accretion disk. The fact that optical and X-ray pulses show a very short phase lag, between 0 and 0.15, and the fact that both appear only when the source is in the high-mode state, with X-ray pulsations in the high-mode first discovered by Archibald et al. (2015), support this model and a common emission mechanism for the optical and X-ray pulsations (Illiano et al. 2023).

We studied the evolution of the binary system, monitoring the variation in the time of passage at the ascending node, T_{asc} , and providing a more recent measurement of the phase lag between optical and X-ray pulse profiles. To achieve this, we performed a timing analysis of four Aqueye+ observing runs from 2021 through 2023, as well as of NICER X-ray data from 2023. We derived the timing solution of the source for the 2021 dataset, and we analyzed the evolution of T_{asc} , incorporating results from previous works (Zampieri et al. 2019; Burtovoi et al. 2020; Illiano et al. 2023; Papitto et al. 2019; Ambrosino et al. 2017; Jaodand et al. 2016; Archibald et al. 2009). Finally, we considered a model for the evolution of the Roche lobe radius of the donor as a function of the mass loss rate, to account for the observed long-term behavior of T_{asc} .

In Sect. 2 we present the observations and data reduction for the Aqueye+ and NICER observations. In Sect. 3 we describe the correction for the orbital motion and the results of our timing analysis. We discuss our results in Sect. 4, and a summary follows in Sect. 5.

2. Observations and data reduction

We carried out five observing runs of PSR J1023+0038 with the Aqueye+¹ fast photon counter (Barbieri et al. 2009; Naletto et al. 2013; Zampieri et al. 2015) mounted at the 1.8 m Copernicus telescope (Asiago, Italy) in three different years, January 2021, January-February 2022, and January and December 2023 (see Table A.1). The data were reduced with the QUEST software (v. 1.1.5; Zampieri et al. 2015). The arrival time of each photon was referred to the Solar System barycenter using the TEMPO2 package in TDB units (Edwards et al. 2006; Hobbs et al. 2006), using JPL DE405 ephemerides. The position of PSR J1023+0038 was taken from Deller et al. (2012): $\alpha = 10\text{h } 23\text{m } 47.687198\text{s}$, $\delta = +00^\circ 38' 40.84551''$ at epoch MJD 54995. We modified the barycentered time series, correcting the photon arrival times for the pulsar orbital motion. The orbital parameters are taken from Archibald et al. (2013): the projected semimajor axis $a \sin(i) = 0.343356$ s and the orbital period $P_{\text{orb}} = 0.1980963155$ d. The reference value for the time of passage at the ascending node is MJD 57449.7258 (Ambrosino et al. 2017). Variations in the time of passage at the ascending node are observed in PSR J1023+0038, the origin of which is not understood but clearly indicates variations in the orbital parameters.

Simultaneous NICER X-ray observations were requested for the Aqueye+ runs of January and December 2023. The corresponding log of the observations is reported in Table A.2. For these observations, we applied the standard data processing procedure², using the script `nicer12` – part of HEASoft³ (v.6.34) software – with version 20240206 of the calibration files. The selected energy range for the analysis is 0.5–12 keV. We finally

Table 1. Aqueye+ runs of PSR J1023+0038 carried out between January 2021 and December 2023.

Aqueye+ run	t_0 (MJD)	ΔT_{asc} (s)	T_{asc} (MJD)	P_{spin} (s)
Jan. 2021	59226.0	44.35 ± 0.17	59226.055461	$0.0016879874467 \pm 4.4 \times 10^{-13}$
Jan. 2023	59965.0	81.05 ± 1.23	59964.756622	$0.0016879874472 \pm 9.0 \times 10^{-13}$
Dec. 2023	60290.0	97.33 ± 1.39	60290.030772	$0.0016879874474 \pm 1.1 \times 10^{-12}$

Notes. Aqueye+ runs of PSR J1023+0038, carried out at the 1.82 m Copernicus telescope. The reference epoch (T_{ref}) corresponds to the start time of each run. The ΔT_{asc} are calculated for the value reported in Ambrosino et al. (2017). The spin periods of January and December 2023 are those extrapolated from the long-term timing solution of Burtovoi et al. (2020), at the time of our observations.

barycentered the data with the script `barycorr`. Because of the known light-leak issue affecting NICER from May 2023, the observations from December 2023 presented here are only those in which a signal could be detected.

3. Results

We present a timing analysis of the new Aqueye+ optical and NICER X-ray data for PSR J1023+0038, from 2021 through 2023, and analyze the evolution of the passage at the ascending node, T_{asc} , using observations gathered from 2017 through 2023 and incorporating results from previous works.

3.1. Evolution of the T_{asc}

The time of passage at the ascending node shows significant variations throughout the epochs. In this work, we report the measure of the T_{asc} offset for each Aqueye+ run, from January 2021 to December 2023.

For each epoch, we performed an epoch folding search and corrected the barycentered time series for the orbital motion, using the orbital period reported in Jaodand et al. (2016), and varying only the T_{asc} to find the value that gives the highest signal, i.e., the pulsed profile with the highest χ^2 . We used the T_{asc} measured by Ambrosino et al. (2017) as the reference value. Then, for each night, we explored a range of 40 values for the T_{asc} offset (20 in each direction from the expected value), with a time step of 0.5 s. The starting expected value was obtained from the best T_{asc} offset of the previous run, adding approximately 20 s to it. The final offset was determined by fitting the results of the epoch folding search with a Gaussian. The uncertainty on the best ΔT_{asc} was calculated as the square root of the sum of the diagonal terms of the covariance matrix of the fit. The final best values of the T_{asc} are reported in Table 1, along with the final rotational period of the pulsar determined as described in Sect. 3.2. The values of T_{asc} were calculated with a trial pulsar rotational period $P_{\text{init}} = 0.0016879874449$ s.

In Fig. 1 we show the T_{asc} evolution with time using our results and the T_{asc} offsets obtained from previous works (Jaodand et al. 2016; Ambrosino et al. 2017; Papitto et al. 2019; Burtovoi et al. 2020; Illiano et al. 2023). We then performed a fit with a parabola (Illiano et al. 2023):

$$\Delta T_{\text{asc}}(T) = A + BT + \frac{1}{2}CT^2, \quad (1)$$

where T is the time in MJD, and A , B , and C are the free parameters of the fit: $A = (2.46 \pm 0.17) \times 10^4$ s, $B = -0.87 \pm 0.06$ s MJD⁻¹, and $C = (1.5 \pm 0.1) \times 10^{-5}$ s MJD⁻². The

¹ <https://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html>

² https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/

³ <https://heasarc.gsfc.nasa.gov/docs/software/heasoft/>

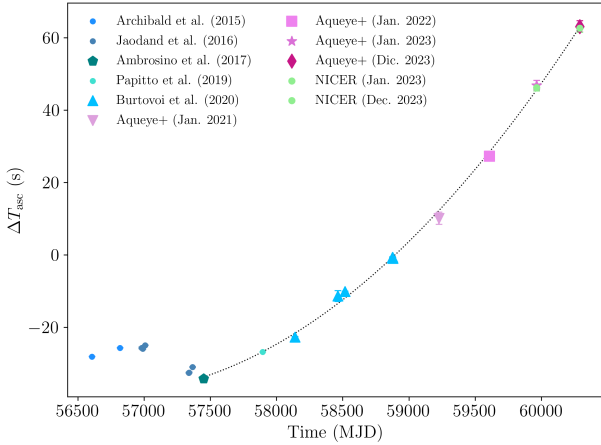


Fig. 1. Variation in the time of passage at the ascending node, T_{asc} , concerning the reference value measured in radio reported in Jaodand et al. (2016). The dotted black line represents the fit of the data with Eq. (1).

parameter C can be expressed in s/s, $C' = (3.52 \pm 0.23) \times 10^{-11}$. It represents the derivative of the orbital period, and it is higher than the value found in Illiano et al. (2023) by a factor of ~ 2 . We fitted only the optical data starting from 2017 (Ambrosino et al. 2017), when the variation in T_{asc} appears to be convincingly consistent with a parabolic trend.

3.2. Folded pulse profiles for the single runs

We report the timing solution for the Aqueye+ data of PSR J1023+0038 for the run of 2021, for which a sufficient number of nights is available to constrain it, and to this purpose, we corrected all the time series for the binary motion using the values of the T_{asc} (see Table 1) found from the previous analyses, and the orbital period and semimajor axis reported in Jaodand et al. (2016, see our Sect. 2). We first folded the light curves of each night using a guess spin period $P_{\text{init}} = 0.0016879874449$ s and referring each folded light curve to a reference time $t_0 = 59226.0$ MJD, i.e., midnight of January 20–21, 2021. The resulting pulsed profiles were fitted with the sum of two harmonically related sinusoids plus a constant (Ambrosino et al. 2017; Zampieri et al. 2019; Burtovoi et al. 2020):

$$f(x) = K\{1 + A_1 \sin(2\pi[x - x_1]) + A_2 \sin(4\pi[x - x_2])\}, \quad (2)$$

where K is a normalization constant, A_1 is the coefficient of the first harmonic, A_2 is the coefficient of the second harmonic, and x_1 and x_2 are the phases of the first and second harmonics, respectively. The measured phases show a drift, $\Psi(t)$, with respect to a uniform rotational spin period, P_{init} (see Zampieri et al. 2014). To correct the spin period, we fitted this phase drift of the second harmonic with the following first-order polynomial:

$$\Psi(t) = \phi_0 + (\nu_0 - \nu_{\text{init}})(t - t_0), \quad (3)$$

where ϕ_0 and ν_0 are the phase and the spin frequency at the reference time t_0 , and $\nu_{\text{init}} = 1/P_{\text{init}}$.

We report in Table 2 the timing solution for the January 2021 run. We show the total pulsed profile of the source in Fig. 2.

The timing analysis for the 2022 Aqueye+ run is reported in Illiano et al. (2023). For the January and December 2023 dataset, the number of nights is not sufficient to perform an analysis similar to that described above; hence, we corrected the data for the

Table 2. Timing solution for PSR J1023+0038 from January 2021 Aqueye+ data.

Aqueye+ Timing solutions	
January 2021	
t_0	59226 MJD
ϕ_0	0.799 ± 0.035
ν_0	$592.42146709 \pm 1.7 \times 10^{-7}$ Hz
P_0	$0.0016879874473 \pm 5 \times 10^{-13}$ s

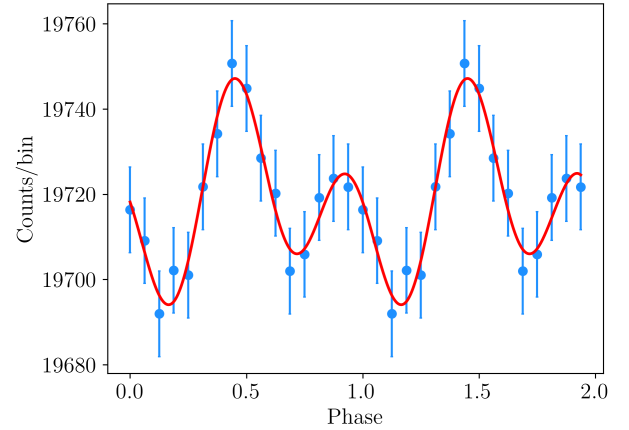


Fig. 2. Optical pulse profile of PSR J1023+0038 obtained with Aqueye+ from January 12 to 16, 2021. The red line is the fit with Eq. (2).

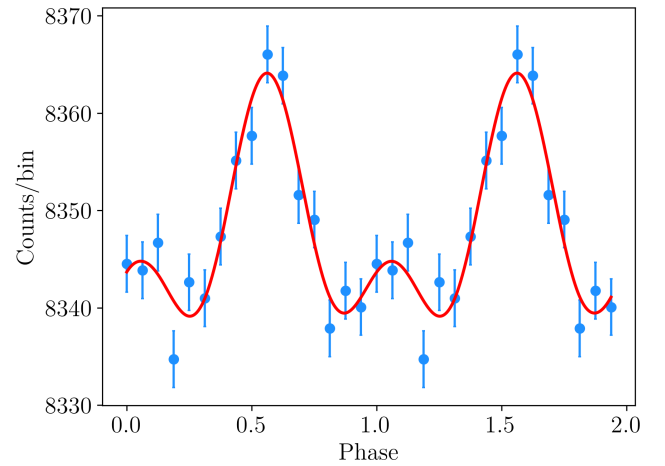


Fig. 3. Optical pulse profile of PSR J1023+0038 obtained with Aqueye+ from December 12 and 15, 2023. The red line is the fit with Eq. (2).

binary motion and folded them with the rotational period extrapolated from the accurate timing solution in Burtovoi et al. (2020, values are reported in our Table 1), which differs from the spin period of 2018 by only 4.4×10^{-13} s. We performed the fit with Eq. (2) and show the final folded profile in Figs. 3 and 4.

3.3. Time delay between optical and X-ray data

We measured the delay between the time of arrival of the X-ray and optical pulses using the Aqueye+ and NICER data of

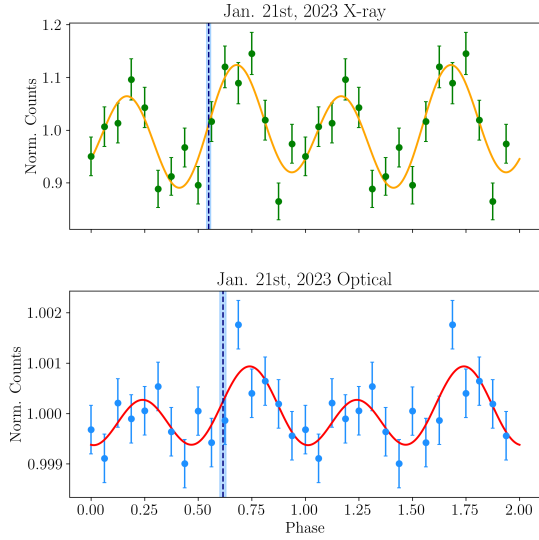


Fig. 4. Pulse profiles of PSR J1023+0038 from January 21, 2023, in the optical (Aqueye+, bottom panel, blue dots) and X-ray (NICER, top panel, green dots) energy bands. Both profiles are fitted with the same model (yellow and red lines; see Eq. 2), folded with the same spin period (see Table 1) and with the same $t_0 = 59965.0$ MJD. The dashed navy lines in both panels represent the phase of the second harmonic (x_2), used to measure the phase lag, and the light blue shaded bands indicate the corresponding uncertainties.

January 2023 (Tables A.1 and A.2). We used the simultaneous NICER observation of January 21 to perform an epoch folding search to find the value of the T_{asc} offset (using only acquisitions when the source was in the high mode for 70–80% of the time). We found an offset of 80.25 ± 0.89 s (computed taking the T_{asc} from Ambrosino et al. 2017 as the reference value). The offset is compatible within the uncertainties with that found from the optical data (Table 1). We corrected both the X-ray and optical datasets for binary motion (considering only the optical observations within the X-ray high-mode window) with the T_{asc} offset of the X-ray data (80.25 s), the signals of which have a higher root mean square pulse amplitude. We also performed an epoch folding search using all the NICER observations reported in Table A.2 to find the T_{asc} offset for January and December 2023; we obtained 80.43 ± 0.92 s and 96.86 ± 1.13 s, respectively, which are consistent with the optical data (see Fig. 1).

Then, we folded the light curves of the simultaneous observations using the same t_0 (59965.0 MJD) and the spin period extrapolated from the Burtovoi et al. (2020) long-term timing solution reported in Table 1. We then fitted both profiles with Eq. (2) and measured the related drift of the second harmonic, whose power spectral density is higher than that of the first harmonic. The optical pulses are found to be delayed with respect to the X-ray ones by 112.3 ± 30.7 μs , which corresponds to a phase lag of 0.067 ± 0.018 . In Fig. 4 we show the X-ray and optical pulse profiles for January 21, 2023.

4. Discussion

4.1. Evolution of T_{asc}

In Sect. 3.1 we present the variation in the time of passage at the ascending node from 2021 through 2023. We report our results in Fig. 1, alongside those obtained in previous works. We fitted the ΔT_{asc} evolution with a second-order polynomial (see Eq. (1)), which is consistent with the observed trend of the data, in

particular if we consider the ΔT_{asc} values after the observations performed by Ambrosino et al. (2017). In the past, the variation in the T_{asc} was consistent with an irregular evolutionary scenario for the binary system; this scenario is further supported by its initial oscillating behavior after the onset of the accreting phase. Recent results, however, seem to support a different scenario, in which the increase in the T_{asc} could be driven by a rise in the orbital period and, thus, an increase in the separation between the companion star and the neutron star. In this section we discuss a possible general evolutionary scenario consistent with our recent results and the characteristics of this binary system.

Assuming accretion through Roche lobe overflow (Verbunt 1993; Frank et al. 2002), the exchange of mass leads to a variation in the distance between the two stars, due to the conservation of angular momentum, which translates into variations in the orbital period. Let us consider the general equation of the total angular momentum of the system, J , and its time derivative, \dot{J} , assuming a circular orbit:

$$J = M_1 M_2 \sqrt{\frac{Ga}{M_1 + M_2}} M_{\odot}^{3/2}, \quad (4)$$

where G is the gravitational constant, a is the orbital separation, and M_1 and M_2 are the masses of the neutron star and the donor star, respectively. The time derivative of Eq. (4) is

$$2 \frac{\dot{J}}{J} = \frac{\dot{a}}{a} + 2 \left(\frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} \right) - \frac{\dot{M}_1 + \dot{M}_2}{M_1 + M_2}, \quad (5)$$

and the total mass and mass ratio of the system are defined as

$$M = M_1 + M_2, \quad q = \frac{M_2}{M_1}. \quad (6)$$

We used the equation that approximates the evolution of the Roche lobe radius of the donor star, R_{2L} , for $0.1 \leq q \leq 0.8$, which is given by (Frank et al. 2002)

$$\frac{\dot{R}_{2L}}{R_{2L}} = \frac{\dot{a}}{a} + \frac{\dot{M}_2}{3M_2} - \frac{1}{3} \frac{\dot{M}}{M}. \quad (7)$$

The accretion luminosity in X-rays is $L_X = 7 \times 10^{33}$ erg s $^{-1}$ in the high-mode state, and $L_X = 3 \times 10^{33}$ erg s $^{-1}$ in the low-mode state (Messa et al. 2024). Neglecting emission from the neutron star surface, we estimated the mass accretion rate of the source as

$$L_{\text{acc}} = \xi \frac{GM\dot{M}_{\text{acc}}}{R_{\star}}, \quad (8)$$

where G is the gravitational constant, M the mass of the neutron star, \dot{M}_{acc} the mass accretion rate, R_{\star} the radius of the neutron star, and ξ the accretion efficiency, which depends on the inner radius, R_{in} , of the accretion disk ($\xi = R_{\star}/R_{\text{in}}$). In the case of PSR J1023+0038, in the high-mode state, material channeled along the magnetic field lines is likely not accreted onto the neutron star (as it would otherwise quench the pulsar wind) but rather expelled in a jet (Baglio et al. 2023). In the Papitto et al. (2019) model, the inner radius of the disk, in the high-mode state, is beyond the light cylinder radius, at ≈ 80 ; however, when the source is in the low-mode state, the disk recedes up to a distance of ≈ 1600 km, and most of the X-ray emission is produced by the compact jet along the pulsar rotational axis. Assuming $R \approx 80$ km, and considering the X-ray accretion luminosity in the high mode, we obtain

$$\dot{M}_{\text{acc}} = 4.22 \times 10^{14} \left(\frac{M}{M_{\odot}} \right)^{-1} \text{ g} \cdot \text{s}^{-1}. \quad (9)$$

For a conservative mass transfer, the value of the mass accretion rate is between $\dot{M}_2 = -1.1 \times 10^{19} \text{ g s}^{-1}$ (if $q = 0.1$) and $\dot{M}_2 = -2.5 \times 10^{18} \text{ g s}^{-1}$ (if $q = 0.8$; see Frank et al. 2002). These values, being at least four orders of magnitude higher than the value obtained from the observed X-ray luminosity, demonstrate the inconsistency of a conservative accretion scenario.

The fact that the pulsar in PSR J1023+0038 is active implies that a powerful pulsar wind hits the donor surface, contributing to slowly evaporate the companion, as observed in other “red-back binary systems”. We can then consider a nonconservative case in which the accretion rate onto the neutron star is negligible and the mass loss is dominated by the donor, $\dot{M}_1 \approx \dot{M}_{\text{acc}} \ll -\dot{M}_2$, and $\dot{M} \approx \dot{M}_2$. Then, Eq. (5) assumes the following form:

$$2 \frac{\dot{J}}{J} = \frac{\dot{a}}{a} + 2 \left(\frac{\dot{M}_2}{M_1} \right) - \frac{\dot{M}_2}{M_1 + M_2}. \quad (10)$$

Taking the time derivative of Kepler’s third law, under the same assumptions, we obtain

$$\frac{\dot{a}}{a} = \frac{1}{3} \frac{\dot{M}_2}{M_2} \frac{M_2}{M} + \frac{2}{3} \frac{\dot{P}}{P}, \quad (11)$$

where P is the orbital period. Since we do not know exactly how the companion star evolves as it interacts with the pulsar wind, we considered a general case in which the radius of the donor evolves as

$$\frac{\dot{R}_2}{R_2} = \alpha \frac{\dot{M}_2}{M_2}. \quad (12)$$

When $\alpha = 1$, this relation represents the evolution of a low-mass donor that is losing mass in a quasi-steady state. Assuming that the system is in (or close to) Roche lobe overflow, and hence $R_2 \approx R_{2L}$, we substituted this expression into Eq. (7) and then combined it with Eq. (11). The resulting relation is

$$\frac{\dot{P}}{P} = \frac{3}{2} \beta \frac{\dot{M}_2}{M_2}, \quad \text{where} \quad \beta = \left(\alpha - \frac{1}{3} \right). \quad (13)$$

As mentioned above, the case $\alpha = 1$ represents the evolution of a low-mass donor in a quasi-steady state. This is not a plausible scenario since $\beta = -2/3$ and $\dot{P}/P = \dot{M}_2/M_2 < 0$, which is at variance with the observed increase in the orbital period. The same conclusion holds in general for $\alpha > 1/3$, while for $\alpha < 1/3$, $\dot{P}/P \propto -\dot{M}_2/M_2 > 0$, which is consistent with the observations. We note that the case $\alpha = 0$ ($\beta = 1/3$) would represent the evolution of a system with a constant donor and Roche lobe radius. In these conditions, the mass-loss rate of the donor would be $-\dot{M}_2/M_2 = (1/2)(\dot{P}/P) = 8.2 \times 10^{18} \text{ g s}^{-1}$, higher by four orders of magnitude than the mass accretion rate. As we do not know the physics of the interaction between the pulsar wind and the donor, different values of α would be possible – implying different evolutions for the donor and different values for the mass-loss rate – but they must be on the same order of magnitude as the previous estimate for $|\alpha| \approx 1$. At this pace, the donor would be completely consumed in $\sim 8 \text{ Myr}$. Thus, a scenario with a binary system evolving through nonconservative Roche lobe overflow, similar to the one presented above, appears to be consistent with the observed steady parabolic increase in the orbital period with time.

4.2. Time delay between optical and X-rays

We analyzed NICER and Aqueye+ data from January 2023 to perform new measurements of the time shift between the optical and X-ray pulses of PSR J1023+0034. We managed to measure the shift simultaneously between optical and X-rays only

for the January 2023 data (January 21) because for the December 2023 dataset, the duration of the simultaneous X-ray observation (December 15) was too short. The time lag between optical and X-ray pulses is 0.036 ± 0.016 , which corresponds to $60.7 \pm 27.7 \mu\text{s}$. This result is consistent with that of Illiano et al. (2023), who report that, from the second harmonic of the pulsed profiles, the time lag between optical and X-ray pulses lies in the range (0–250) μs . This, along with the fact that the optical and X-ray pulses have similar morphologies, confirms that they are produced in the same region and with the same emission mechanism, as proposed by Papitto et al. (2019) and Veledina et al. (2019, see the references therein). They present a possible scenario to explain such a simultaneous emission, the so-called striped wind model. In this scenario, the source is in the disk state but still able to emit a relativistic wind. In a region a few light cylinder radii from the star, the pulsar wind interacts with the accretion disk, producing two shocked symmetric regions; this is where synchrotron radiation is produced and pulsed emission in the X-ray and optical bands originates. They also estimated the synchrotron timescale for optical photons, obtaining a value compatible with the lag observed between optical and X-ray photons.

5. Summary

We have studied the evolution of the PSR J1023+0038 binary system, monitoring the long-term variation in the time of passage at the ascending node, T_{asc} , and providing new measurements of the phase lag between the optical and X-ray pulse profiles. We performed a timing analysis of three runs of Aqueye+ optical data from 2021 through 2023, as well as NICER X-ray data from 2023. We derived the timing solution of the source for January 2021, and we analyzed the evolution of the T_{asc} , including also results from previous works. We measured the shift between optical and X-ray pulses using simultaneous Aqueye+ optical data and NICER X-ray data from January 2023. The phase lag measured is 0.036 ± 0.016 , in agreement with Illiano et al. (2023) and extending the baseline of these measurements by one year. This result further confirms the common origin and emission mechanism of X-ray and optical pulses. Concerning the evolution of the T_{asc} , starting from 2017, it follows a parabolic increasing trend, which translates into an increase in the orbital period and orbital separation of the system. A scenario of a binary system evolving through nonconservative Roche lobe overflow in which the donor is interacting with the pulsar wind, losing mass at a rate much higher than the inferred accretion rate, appears to be consistent with the observed steady increase in the orbital period of the system. The large majority of the mass stripped from the donor was likely shocked by the pulsar wind itself and ejected from the system after crossing the Roche lobe. Further optical and X-ray timing observations of PSR J1023+0038 are needed to continue to monitor the evolution of the parameters of the binary system and to determine the long-term rotational history of the pulsar.

Acknowledgements. SC is supported by the INAF Doctorate program. SC and LZ acknowledge financial support from the INAF Research Grant “Uncovering the optical beat of the fastest magnetized neutron stars (FANS)”. Based on observations collected at the Copernico 1.82m telescope (Asiago Mount Ekar, Italy), INAF – Osservatorio Astronomico di Padova. This work has made use of data products and software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC), a service of the Astrophysics Science Division at NASA/GSFC and the High Energy Astrophysics Division of the Smithsonian Astrophysical Observatory. We would like to express our thanks to Alessandro Papitto, Giulia Illiano, and Arianna Miraval Zanon for the very

interesting discussions on the content of this article, in particular Alessandro Papitto for his support in training S.C. on pulsar timing techniques.

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Appendix A: Observations

Table A.1. Aqueye+ observations of PSR J1023+0038 from January 2021 to December 2023.

Observation ID	Start Time (UTC)	Start Time (MJD)	Duration (s)
Aqueye+ Optical Data			
QEYE_20210112-022231	Jan. 12, 2021 01:29:24.778	59226.062092	1798.663
QEYE_20210112-030013	02:07:05.713	59226.088260	1798.633
QEYE_20210112-033504	02:41:56.956	59226.112464	1799.053
QEYE_20210112-041003	03:16:57.119	59226.136772	1799.441
QEYE_20210112-044613	03:53:07.535	59226.161892	1799.062
QEYE_20210112-052324	04:30:18.917	59226.187718	1799.048
QEYE_20210112-055805	05:05:00.102	59226.211806	898.946
QEYE_20210113-023449	Jan. 13, 2021 01:41:48.080	59227.070695	1798.449
QEYE_20210113-030825	02:15:24.161	59227.094029	1798.656
QEYE_20210113-034203	02:49:02.057	59227.117384	1799.250
QEYE_20210113-041733	03:24:32.436	59227.142042	1799.179
QEYE_20210113-045130	03:58:29.992	59227.165624	1799.019
QEYE_20210113-052515	04:32:15.278	59227.189065	1798.947
QEYE_20210113-055900	05:06:00.408	59227.212504	898.935
QEYE_20210114-023019	Jan. 14, 2021 01:37:24.769	59228.067647	1798.919
QEYE_20210114-030423	02:11:28.018	59228.091296	1798.919
QEYE_20210114-034050	02:47:55.149	59228.116610	1799.128
QEYE_20210114-041437	03:21:42.531	59228.140075	1799.448
QEYE_20210114-044832	03:55:37.890	59228.163632	1799.323
QEYE_20210114-052236	04:29:42.140	59228.187293	1798.765
QEYE_20210114-055632	05:03:38.144	59228.210858	898.920
QEYE_20210116-031012	Jan. 16, 2021 02:17:29.737	59230.095483	1799.314
QEYE_20210116-034531	02:52:48.148	59230.120001	1799.044
QEYE_20210116-042150	03:29:08.508	59230.145237	1798.887
QEYE_20210116-045712	04:04:30.720	59230.169799	1799.143
QEYE_20210116-053219	04:39:36.737	59230.194175	1798.975
QEYE_20220129-014645	Jan. 29, 2022 00:55:06.246	59608.038267	1799.43
QEYE_20220129-021723	01:25:43.430	59608.059530	1799.43
QEYE_20220129-024810	01:56:30.724	59608.080911	1799.43
QEYE_20220129-032714	02:35:35.497	59608.108050	1799.05
QEYE_20220129-035755	03:06:17.308	59608.129367	1799.43
QEYE_20220129-042915	03:37:37.355	59608.151127	1799.43
QEYE_20220129-050002	04:08:23.269	59608.172491	1799.43
QEYE_20220130-010757	Jan. 30, 2022 00:16:21.299	59609.011358	1799.43
QEYE_20220130-014125	00:49:50.371	59609.034611	1799.43
QEYE_20220130-021621	01:24:45.800	59609.058863	1799.26
QEYE_20220130-024724	01:55:49.132	59609.080430	1799.24
QEYE_20220130-032433	02:32:58.415	59609.106232	1799.3
QEYE_20220130-035525	03:03:51.420	59609.127678	1799.43
QEYE_20220130-042708	03:35:33.409	59609.149692	1799.43
QEYE_20220130-231911	22:27:39.820	59609.935877	1799.21
QEYE_20220130-235112	22:59:40.488	59609.958108	1799.43
QEYE_20220131-005611	Jan. 31, 2022 00:04:40.260	59610.003244	1799.43
QEYE_20220131-013048	00:39:16.346	59610.027273	1799.43
QEYE_20220131-020246	01:11:14.682	59610.049475	1799.34
QEYE_20220131-023337	01:42:05.895	59610.070902	1799.43
QEYE_20220202-010515	Feb. 2, 2022 00:13:50.934	59612.009617	1799.37
QEYE_20220202-014053	00:49:29.535	59612.034370	1799.05
QEYE_20220203-005757	Feb. 3, 2022 00:06:37.468	59613.004600	1799.43
QEYE_20220203-012943	00:38:23.091	59613.026656	1799.07
QEYE_20220203-020723	01:16:04.096	59613.052825	1799.43
QEYE_20220203-023800	01:46:40.636	59613.074081	1799.12
QEYE_20220203-031435	02:23:15.591	59613.099486	1799.26
QEYE_20220203-034549	02:54:29.691	59613.121177	1799.07
QEYE_20230121-012433	Jan. 21, 2023 00:32:14.118	59965.022386	1799.1
QEYE_20230121-015546	01:03:27.477	59965.044068	1799.04
QEYE_20230121-023109	01:38:50.496	59965.068640	1799.41
QEYE_20230121-033656	02:44:38.231	59965.114331	1799.09
QEYE_20231212-014334	Dec. 12, 2023 00:46:27.276	60290.032260	1798.773
QEYE_20231212-021736	01:20:29.214	60290.055893	3599.222
QEYE_20231212-032349	02:26:43.528	60290.101893	1799.328
QEYE_20231212-035751	03:00:45.943	60290.125532	3599.406
QEYE_20231212-050313	04:06:08.712	60290.170934	1798.973
QEYE_20231212-053409	04:37:04.884	60290.192417	1798.899
QEYE_20231215-015007	Dec. 15, 2023 00:53:26.054	60293.037107	1799.301
QEYE_20231215-022539	01:28:57.344	60293.061775	607.544
QEYE_20231215-031850	02:22:09.147	60293.098717	1798.976
QEYE_20231215-035152	02:55:12.259	60293.121696	1799.171
QEYE_20231215-042249	03:26:08.911	60293.143159	1798.632
QEYE_20231215-045716	04:00:36.745	60293.167092	1799.169

Table A.2. NICER X-ray observations of PSR J1023+0038 from January 20 to December 30, 2023.

Observation ID	Start Time (UTC)	Start Time (MJD)	End Time (MJD)	Duration ^a (s)
NICER X-ray Data				
5034060101	Jan. 20, 2023 19:23:29	59964.808752	59964.948583	2846
5034060102	Jan. 21, 2023 00:01:53	59965.001308	59965.981259	4221
5034060103	Jan. 22, 2023 00:48:20	59966.033565	59966.964547	8649
5034060104	Jan. 23, 2023 21:50:22	59967.002062	59967.932244	8964
5034060105	Jan. 24, 2023 19:35:20	59968.042594	59968.835403	10077
5034060106	Jan. 25, 2023 21:42:19	59969.010523	59969.918461	14733
5034060107	Jan. 26, 2023 00:48:06	59970.034180	59970.174872	3830
6034060104	Dec. 14, 2023 21:55:49	60292.913764	60292.916848	265
6034060105	Dec. 15, 2023 02:36:24	60293.108613	60293.110349	149
6034060106	Dec. 16, 2023 03:21:36	60294.140002	60294.141540	132
6034060107	Dec. 17, 2023 22:39:34	60295.944145	60295.948157	345
6034060108	Dec. 18, 2023 00:12:55.053	60296.008984	60296.989498	3439
6034060109	Dec. 19, 2023 00:58:24.468	60297.040592	60297.957787	3280
6034060110	Dec. 20, 2023 00:13:00.322	60298.009053	60298.990252	5636
6034060111	Dec. 21, 2023 00:59:08.636	60299.041079	60299.958039	2561
6034060112	Dec. 22, 2023 00:14:41.391	60300.010210	60300.990190	6354
6034060113	Dec. 23, 2023 04:05:16.602	60301.170349	60301.952179	2152
6034060114	Dec. 24, 2023 00:15:41.227	60302.010905	60302.991047	2434
6034060115	Dec. 25, 2023 00:59:56.287	60303.041634	60303.959167	3667
6034060116	Dec. 26, 2023 00:13:45.797	60304.009574	60304.217321	4892
6034060117	Dec. 27, 2023 22:39:24.615	60305.944065	60305.959518	1334
6034060118	Dec. 28, 2023 00:12:15.104	60306.008567	60306.991997	2098
6034060120	Dec. 30, 2023 00:33:11.253	60308.023057	60308.992345	3242

Notes. ^aDuration of the effective observing time after applying the standard filtering. Owing to the light-leak problem affecting NICER in December 2023, the time that was discarded on average is quite significant ($\sim 20\%$).