Investigating the origin of optical and X-ray pulsations of the transitional millisecond pulsar PSR J1023+0038

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ABSTRACT

Context. PSR J1023+0038 is the first millisecond pulsar that was ever observed as an optical and UV pulsar. So far, it is the only optical transitional millisecond pulsar. The rotation- and accretion-powered emission mechanisms hardly individually explain the observed characteristics of optical pulsations. A synergistic model, combining these standard emission processes, was proposed to explain the origin of the X-ray/UV/optical pulsations.

Aims. We study the phase lag between the pulses in the optical and X-ray bands to gain insight into the physical mechanisms that cause it.

Methods. We performed a detailed timing analysis of simultaneous or quasi-simultaneous observations in the X-ray band, acquired with the XMM-Newton and NICER satellites, and in the optical band, with the fast photometers SiFAP2 (mounted at the 3.6 m Telescopio Nazionale Galileo) and Aqueye+ (mounted at the 1.8 m Copernicus Telescope). We estimated the time lag of the optical pulsations with respect to that in the X-rays by modeling the folded pulse profiles with two harmonic components.

Results. Optical pulses lag the X-ray pulses by ~150 µs in observations acquired with instruments (NICER and Aqueye+) whose absolute timing uncertainty is much smaller than the measured lag. We also show that the phase lag between optical and X-ray pulsations lies in a limited range of values, δφ ∈ (0 – 0.15), which is maintained over timescales of about five years. This indicates that both pulsations originate from the same region, and it supports the hypothesis of a common emission mechanism. Our results are interpreted in the shock-driven mini-pulsar nebula scenario. This scenario suggests that optical and X-ray pulses are produced by synchrotron emission from the shock that formed within a few light cylinder radii away (~100 km) from the pulsar, where its stripped wind encounters the accretion disk inflow.

Key words. (Stars:) pulsars: individual (PSR J1023+0038) – X-rays: binaries – Stars: neutron

1. Introduction

Transitional millisecond pulsars (tMSPs) are rapidly rotating (P ≤ 10 ms), weakly magnetized (≈ $10^8 - 10^9$ G) neutron stars (NSs) that have been observed to swing between distinct states within a few days that are likely powered by different physical mechanisms. These sources are part of binary systems with low-mass ($M \simeq 1 M_\odot$) companion stars. At high-mass accretion rates, an accretion-powered pulsar that is able to channel the inflowing matter toward the NS magnetic poles is observed. When the accretion rate decreases, the pulsar wind sweeps the matter transferred through Roche-lobe overflow away, and a rotation-powered radio pulsar is seen. Variability in the mass inflow rate is the driver of these state changes.

Three confirmed tMSPs are known to date: PSR J1023+0038 (Archibald et al. 2009), XSS J1227-4859 (de Martino et al. 2010; Bassa et al. 2014), and IGR J1824-2452 (Papitto et al. 2013). All of them have also been observed in an intermediate state, called subluminous disk state. The physical mechanism that powers this state still remains to be fully understood. In this state, tMSPs show the presence of an accretion disk and γ-ray emission that is up to ten times more intense than the emission that is observed...
during the rotation-powered state \cite{Papitto_2022} and references therein). This is at variance with low-mass X-ray binaries (LMXBs), which generally do not emit a detectable $\gamma$-ray flux. Another peculiarity of tMSPs is the X-ray luminosity ($L_X \approx 10^{31} - 10^{34}$ erg s$^{-1}$), which is lower than what is usually observed in the outburst phase of accreting millisecond X-ray pulsars (AMXPs) ($L_X \approx 10^{36}$ erg s$^{-1}$), but higher than the luminosity in the rotation-powered state ($L_X < 10^{32}$ erg s$^{-1}$). The X-ray emission is also variable over timescales of a few tens of seconds: different intensity modes (high, low, and flaring modes) have been observed in the X-ray light curves \citep[see, e.g.,][]{DeMartino_2013, Linares_2014, Bogdanov_2015, Archibald_2015, Cohl_2018}. J1023+0038 has been in the subluminous disk state from June 2013 \citep{Patruno_2014, Stappers_2014} until the time of writing (October 2022) and is in high mode for ~80% of the time \citep{Bogdanov_2015, Archibald_2015, Jaodand_2016}. Transitions from high to low mode, and vice versa, occur unpredictably on a timescale of ~10 s. The duration of these modes varies from a few tens of seconds to a few hours \citep{Papitto_2022}.

J1023+0038 is the first millisecond pulsar that was ever observed as an optical pulsar \citep{Ambrosino_2017, Zampieri_2019, Karpov_2019, Burtovoi_2020}. Optical pulses have recently also been observed from the AMXP SX J1808.4-3658 \citep{Ambrosino_2021}, but J1023+0038 so far remains the only tMSP with detectable pulsed emission in the optical band. Optical and X-ray pulsations from J1023+0038 were detected simultaneously in the X-ray high modes, but they disappeared when the source transited in the low modes. This suggests a common emission mechanism \citep{Papitto_2019}. Recently, optical pulses have been observed in the UV band. The UV emission, like the optical emission, undergoes transitions between high and low intensity modes that occur simultaneously with those observed in the X-ray band \citep{Jaodand_2021, Marraval_2022}.

Previous works attempted to determine the physical origin of optical pulsations \citep[see, e.g.,][]{Campana_2019, Papitto_2019, Velledina_2019}. Individually, the standard rotation- and accretion-powered mechanisms hardly explain the observed optical pulsed luminosity \citep{Ambrosino_2017, Papitto_2019}. X-ray pulsations were first interpreted as resulting from the channeling of matter along the magnetic field lines with the subsequent formation of accretion columns at the NS poles \citep{Archibald_2015}. However, the optical luminosity of accretion columns is expected to be much lower than the observed optical pulsed luminosity ($L_{\text{opt}} \approx 10^{31}$ erg s$^{-1}$) \citep{Ambrosino_2017}. Even assuming that optical pulses are generated by electron emission from electrons falling into the accretion columns, the expected luminosity would be about 40 times lower than observed \citep{Ambrosino_2017, Papitto_2019}. Similar energetic arguments can also exclude the reprocessing of accretion-powered X-ray emission at the surface of the companion star and/or in the outermost regions of the disk, as occurs in some X-ray binaries with a strongly magnetized and slowly rotating accreting pulsar \citep{Ambrosino_2017}.

On the other hand, optical emission driven by the rotation of the NS magnetic field would require an efficiency in converting the spin-down power to the pulsed optical emission up to 10$^3$ times higher than the values ($\sim 5 \times 10^{-6} - 2 \times 10^{-9}$) measured for the five isolated rotation-powered pulsars from which optical pulses were detected \citep{Cocke_1969, Mignani_2011, Ambrosino_2017}. Moreover, the fraction of spin-down power converted into X-ray pulses would be much higher than that of almost all rotation-powered pulsars \citep{Papitto_2019}. Consequently, the rotation-powered mechanism by itself cannot be the common origin of X-ray, UV, and optical pulsations from J1023+0038.

These implications led to the proposal of the shock-driven mini pulsar nebula scenario. Optical and X-ray pulsations originate from synchrotron emission in a shock that forms beyond the light cylinder radius, where the stripped pulsar wind meets matter from the inner accretion disk \citep{Papitto_2019, Velledina_2019}. In this region, electrons are accelerated to relativistic speeds and emit synchrotron radiation by interacting with the magnetic field in the shock region. This configuration permits a higher fraction of the spin-down energy to be converted into X-ray pulses compared to the previously discussed cases. Pulsar wind nebulae indeed radiate up to a few percent of the pulsar spin-down power \citep{Kargalsiev_2008, 2010, Vink_2011, Torres_2014}.

Analyses of simultaneous observations performed in May 2017 with XM-M-Newton and the fast optical photometer SiFAP2, mounted at the INAF Telescopio Nazionale Galileo (TNG), found that optical pulses lag the X-ray pulses by ~200 $\mu$s \citep{Papitto_2019}. The proposed model interprets this time lag in terms of the different timescales that synchrotron X-ray and optical photons take to be emitted. However, the above measurement was affected by the absolute timing accuracy of SiFAP2 ($\sim 60 \mu$s; \citealt{Papitto_2019}) and by that of XM-M-Newton/EPIC. In a Calibration Technical Note of May 2022\footnote{https://xmmweb.esac.esa.int/docs/documents/CAL-TN-0226.pdf}, the uncertainties on arrival times acquired through XM-M-Newton/EPIC were reviewed and reached a value of 100 $\mu$s for the timing mode, which is more than twice that calculated by \cite{Martin-Carrillo_2012} of 48 $\mu$s and considered by \citealt{Papitto_2019} to estimate the significance of the optical/X-ray pulse phase lag they measured. The absolute timing accuracy of these instruments makes the systematic error associated with time lag estimated in \cite{Papitto_2019} compatible with the measure itself. This highlights the importance of presenting an in-depth study of the relation between optical and X-ray pulsations that also analyzes simultaneous observations acquired only with NICER and the fast optical photometer Aqueye+, mounted at the Copernicus Telescope in Asiago. The NICER absolute timing accuracy is estimated to be $< 300$ ns\footnote{https://heasarc.gsfc.nasa.gov/docs/nicer/mission_guide/}, while that of Aqueye+ is $< 0.5$ ns \citep{Zampieri_2015}. We report here a detailed timing analysis performed on optical/X-ray simultaneous or quasi-simultaneous observations to elucidate the physical mechanisms that cause the observed pulsations. Our data were acquired with the XM-M-Newton and NICER X-ray satellites and with the fast optical photometers SiFAP2 and Aqueye+ over a time ranging from May 2017 to the beginning of February 2022.

Section \ref{sect:obs} is dedicated to the description of the observations and the data processing techniques. In Sect. \ref{sect:phap} we perform the phase analysis of simultaneous or quasi-simultaneous observations in the optical and the X-ray bands. By modeling the pulse profiles as the sum of two harmonic components, we study the time lags between the pulsations in the two different observational bands. We discuss our results in Sect. \ref{sect:disc} and constrain the synergistic model proposed to explain the emission mechanisms of optical and X-ray pulsation from J1023+0038. Last, in Sect.
we summarize our main results and outline future prospects.

2. Observations

Table lists the observations analyzed in this paper. They were selected with the aim of studying (quasi-)simultaneous observations of J1023+0038 in the optical and X-ray bands in a time interval of about five years. In the following, we detail the analysis of the different data sets.

2.1. X-ray observations

2.1.1. NICER

We present the analysis of NICER observations of J1023+0038 that were simultaneously or quasi-simultaneously performed with optical observations from January 2019 to February 2022. The events were reduced and processed using HEASoft with optical observations from January 2019 to February 2022 that were simultaneously or quasi-simultaneously performed with optical observations from January 2019 to February 2022. The events were reduced and processed using HEASoft version 6.28 and NICERDAS version 7a. We corrected the photon arrival times to the Solar System Barycenter (SSB) using the JPL ephemerides DE405. We adopted the source coordinates R.A. (J2000)=10:23:47.687198(2) and DEC. (J2000)=+40:38:40.84551(4) (Deller et al. 2012). We use these coordinates throughout the rest of the work. We estimated the background contributions to our data with the tool nibackgen3C50 (Remillard et al. 2022).

Generally, it was sufficient to analyze the individual observations listed in Table to derive an orbital solution (Table), except in the case of the June 2019 data set, for which the close-by observation of 2019 June 13 (Obs. ID: 2531010401) had to be used as well.

2.1.2. XMM-Newton/EPIC

The XMM-Newton observations were performed on 2017 May 23 and 24 (presented in Papitto et al. 2019), and on 2018 December 11 and 15 (Table). The data were reduced using the Science Analysis Software (SAS) v.16.1.0. In each observation, the EPIC-pn was operating with a time resolution of 29.5 μs (timing mode) and a thin optical blocking filter. The photon arrival times observed by XMM-Newton were reported to the SSB, using the JPL ephemerides DE405 and the barycen tool from HEASoft. We defined source and background regions with coordinates RAWX=27–47 and RAWX=3–5, respectively, and retained good events characterized by a single or a double pattern.

2.2. Optical observations

2.2.1. TNG/SiFAP2

We analyzed the optical observations reported in Table acquired with the SiFAP2 fast optical photometer (Meddi et al. 2012) Ambrosino et al. 2016, 2017 mounted at the TNG. The arrival times of each photon were referred to the SSB through the TEMPO2 package (Hobbs et al. 2006), using the JPL ephemerides DE405.

In the January 2019 data set, the statistics was too poor to obtain precise measurements of the epoch of passage at the ascending node, , and of the spin period, (Table). In this part of the analysis, we merged that observation with SiFAP2 observations carried out on 2019 February 1, with a total exposure of ~ 10 ks.

The SiFAP2 quartz clock is characterized by drifts with respect to the actual time measured by two global positioning system (GPS) pulse-per-second (PPS) signals that are used to mark the beginning and end of each observation. Following Ambrosino et al. (2017), the arrival times recorded by SiFAP2, , were corrected assuming the linear relation \( t_{\text{arr}} = t_{\text{SiFAP2}} \times (\Delta t_{\text{GPS}}/\Delta t_{\text{SiFAP2}}) \), where \( \Delta t_{\text{GPS}} \) and \( \Delta t_{\text{SiFAP2}} \) are the total elapsed time measured by the GPS and SiFAP2 clocks, respectively. In January 2019, we had \( \Delta t_{\text{SiFAP2}} - \Delta t_{\text{GPS}} = -1.164 \text{ ms} \), with the value of \( \Delta t_{\text{GPS}} \) reported in Table. During the observations of June 2019, we had \( \Delta t_{\text{SiFAP2}} - \Delta t_{\text{GPS}} = -2.323, -1.156, \) and \(-1.511 \text{ ms} \). Finally, for January 2020 observations, we had \( \Delta t_{\text{SiFAP2}} - \Delta t_{\text{GPS}} = +0.580, +0.751, +0.822, \) and +0.663 ms.

2.2.2. Copernicus/Aqueye+

Aqueye+ is an ultra-fast optical single photon counter mounted at the Asiago 1.8-meter Copernicus Telescope with the capability of time-tagging the detected photons with subnanosecond time accuracy (Zampieri et al. 2015). The chosen Aqueye+ observations (Table) were reduced with the QUEST software (v. 1.1.5, see Zampieri et al. 2015). The arrival times of each photon were referred to the SSB through the TEMPO2 package, using the JPL ephemerides DE405.

3. Data analysis

For each data set, we first corrected the photon arrival times for the pulsar orbital motion in the binary system. We set the orbital period and the projected semimajor axis equal to the values found in the timing solution of Jaodand et al. (2016) (see Table), and we performed a search on the epoch of passage at the ascending node, . We used a grid of values spaced by 0.37 s (Calandri et al. 2012) around the estimate extrapolated from Jaodand et al. (2016). We carried out an epoch-folding search on each time series by sampling each spin period, , with 16 phase bins. The final best was determined by fitting the peak of the distribution with a Gaussian function. We considered the half width at half maximum (HWHM) of the Gaussian as the uncertainty to associate with . To improve the spin period estimate obtained from the search, we corrected the photon arrival times with the best-fitting values of the orbital parameters and performed an epoch-folding search with 16 phase bins. The best value was then estimated by modeling the peak of the distribution with a Gaussian function. The associated error was calculated using Eq. (6a) from Leahy (1987). Table summarizes the best-fitting values of and for each data set. We verified that the timing results were compatible between simultaneous X-ray and optical observations. This allowed us to use the values of and from the X-ray timing (which are more accurate than those obtained from the analysis of optical observations due to the higher root mean square (rms) pulse amplitude of the signal, i.e., the pulse amplitude divided by the square root of 2) to correct the photon arrival times for the pulsar orbital motion and to perform the phase analysis of simultaneous optical and X-ray observations. Since the folded pulse profiles are double-peaked (see, e.g., Archibald et al. 2015) Ambrosino et al. 2017 Papitto et al. 2019, we modeled them using a decomposition function with two harmonic terms,

\[
F(\phi) = K \left( 1 + \sum_{i=1}^{2} r_i \sin \left( 2 \pi i (\phi - \phi_i) \right) \right),
\]
Table 1. Log of the (quasi-)simultaneous X-ray/optical observations of PSR J1023+0038.

| Telescope/Instrument (Obs. ID) | Start Time (MJD) | Exposure (s) | Band         |
|-------------------------------|------------------|--------------|--------------|
| **2017 May**                  |                  |              |              |
| TNG/SiFAP2                   | 57896.9700580    | 3298         | white filter |
| TNG/SiFAP2                   | 57897.890820     | 8397         | white filter |
| XMM-Newton/EPIC-pn (0794580801) | 57896.929380     | 24914        | 0.3–10 keV   |
| XMM-Newton/EPIC-pn (0794580901) | 57897.7392740    | 23413        | 0.3–10 keV   |
| **2018 December 11 - 12**    |                  |              |              |
| Copernicus/Aqueye+           | 58464.0446059    | 1799         | white filter |
| Copernicus/Aqueye+           | 58464.0686652    | 1799         | white filter |
| Copernicus/Aqueye+           | 58464.0925580    | 2699         | white filter |
| Copernicus/Aqueye+           | 58464.1329206    | 2699         | white filter |
| Copernicus/Aqueye+           | 58464.1667650    | 2699         | white filter |
| Copernicus/Aqueye+           | 58464.2083977    | 1799         | white filter |
| XMM-Newton/EPIC-pn (0823750301) | 58463.8833467    | 30000        | 0.3–10 keV   |
| **2018 December 13**         |                  |              |              |
| Copernicus/Aqueye+           | 58467.0313365    | 1199         | white filter |
| Copernicus/Aqueye+           | 58467.0504218    | 3599         | white filter |
| Copernicus/Aqueye+           | 58467.0951940    | 1799         | white filter |
| Copernicus/Aqueye+           | 58467.1306531    | 1799         | white filter |
| Copernicus/Aqueye+           | 58467.1566119    | 1799         | white filter |
| Copernicus/Aqueye+           | 58467.1820657    | 1799         | white filter |
| Copernicus/Aqueye+           | 58467.2137354    | 1199         | white filter |
| XMM-Newton/EPIC-pn (0823750401) | 58467.9157557    | 34000        | 0.3–10 keV   |
| **2019 January**             |                  |              |              |
| TNG/SiFAP2                   | 58514.9781481    | 3300         | u filter     |
| NICER (1034060118)           | 58514.9150460    | 2268         | 0.2–12 keV   |
| NICER (1034060119)           | 58514.9805560    | 6785         | 0.2–12 keV   |
| **2019 February**            |                  |              |              |
| Copernicus/Aqueye+           | 58520.0611407    | 4499         | white filter |
| Copernicus/Aqueye+           | 58520.8774590    | 3599         | white filter |
| Copernicus/Aqueye+           | 58520.9395999    | 3599         | white filter |
| NICER (1034060120)           | 58519.8725930    | 4265         | 0.2–12 keV   |
| NICER (1034060121)           | 58520.0084100    | 3709         | 0.2–12 keV   |
| **2019 June**                |                  |              |              |
| TNG/SiFAP2                   | 58636.8837037    | 2400         | white filter |
| TNG/SiFAP2                   | 58636.9135648    | 1200         | white filter |
| TNG/SiFAP2                   | 58636.9194676    | 1560         | white filter |
| NICER (2034060101)           | 58636.8678240    | 1185         | 0.2–12 keV   |
| **2020 January**             |                  |              |              |
| Copernicus/Aqueye+           | 58879.0814000    | 1799         | white filter |
| Copernicus/Aqueye+           | 58879.1064600    | 1799         | white filter |
| TNG/SiFAP2                   | 58878.9843981    | 3600         | white filter |
| TNG/SiFAP2                   | 58879.0284954    | 3600         | white filter |
| TNG/SiFAP2                   | 58879.0722454    | 3600         | white filter |
| NICER (2034060110)           | 58878.9268060    | 2265         | 0.2–12 keV   |
| NICER (2034060111)           | 58878.9921300    | 11533        | 0.2–12 keV   |
| **2022 January-February**    |                  |              |              |
| Copernicus/Aqueye+           | 59608.0382707    | 13395        | white filter |
| Copernicus/Aqueye+           | 59609.0113612    | 13750        | white filter |
| Copernicus/Aqueye+           | 59609.9358742    | 13465        | white filter |
| Copernicus/Aqueye+           | 59611.9862628    | 5955         | white filter |
| NICER (4034060110)           | 59607.9890106    | 4771         | 0.2–12 keV   |
| NICER (4034060111)           | 59609.0265844    | 2496         | 0.2–12 keV   |
| NICER (4034060112)           | 59609.9946040    | 2910         | 0.2–12 keV   |
| NICER (4034060113)           | 59611.9905482    | 1480         | 0.2–12 keV   |
| NICER (4034060114)           | 59613.0439361    | 617          | 0.2–12 keV   |

\(a\): Barycentric dynamical time at exposure start.

\(b\): SDSS u filter with \(\Delta\lambda_{\text{eff}} = 349\) nm and \(\Delta\lambda_{\text{FWHM}} = 68\) nm. This observation was part of a campaign in which u, g, and r filters were used to investigate any dependences of the pulse amplitude on the spectral band.
where $K$ is the average count rate, and the free parameters, $r_i$ and $\phi_i$ ($i = 1, 2$), are the fractional amplitude and the phase of the two harmonics, respectively. Uncertainties of our best-fitting values were estimated from the parameter range required to increase the $\chi^2$ from the fit of a quantity $\Delta x^2(\alpha = 68\%) = 1.0$ [Lampton et al. 1976; Avni 1976; Yaqoob 1998].

### 3.1. Evolution of the time of passage at the ascending node

Figure 1 shows the difference $\Delta T_{\text{asc}}$ between our values of $T_{\text{asc}}$ in NICER observations (Table 2), and that computed using the radio timing solution [Archibald et al. 2013; Jaodand et al. 2016] as a function of the number of orbital cycles since $T_{\text{ref}} = 57897.027668$ MJD. A similar approach was adopted in previous works (see, e.g., Jaodand et al. 2016; Papitto et al. 2019; Burtovoi et al. 2020). NICER observations in addition to those chosen in this paper simultaneously with optical data (Table 1) were analyzed to study the $T_{\text{asc}}$ long-term evolution (Table 3).

We selected observations with an exposure $> 10$ ks in order to have good statistics for the timing analysis and at least two measurements of $T_{\text{asc}}$ per year. We found an increasing trend of $\Delta T_{\text{asc}}$ with time, as already inferred since May 2017 by Burtovoi et al. 2020, who emphasized that the steady increase may indicate a systematic underestimation of the orbital period of the system. We modeled the second part of the data in Fig. 1 that is, from $T_{\text{ref}} = 57897.027668$ MJD, with the following expression:

$$\Delta T_{\text{asc}}(N_{\text{orb}}) = A + B \frac{N_{\text{orb}}}{2} P_{\text{orb}} C N_{\text{orb}}^2.$$  

$P_{\text{orb}}$ is the orbital period, which was fixed at the value given in Table 2, while $A$, $B$, and $C$ are free parameters. The integer number of orbital cycles since $T_{\text{ref}}$ is $N_{\text{orb}} = \text{int}[(T - T_{\text{ref}})/P_{\text{orb}}]$. We obtained $A = (-2.73 \pm 0.8) \text{s}$, $B = (5.0 \pm 0.4) \times 10^{-3} \text{s}$, and $C = (1.7 \pm 0.5) \times 10^{-11} \text{s/s}$. In general, redbacks, that is, millisecond pulsars in a close orbit with a low-mass companion star such as the source under consideration, show unpredictable variations of the orbital phase (see, e.g., Jaodand et al. 2016 Fig. 2). Therefore, we caution that the $B$ term might be related to the correction

### Table 2. Summary of the orbital parameter estimates for different observations of PSR J1023+0038.

| Telescope/Instrument | $P$ $(\text{ms})$ | $T_{\text{asc}}$ $(\text{MJD})$ | $T_{\text{start}}$ $(\text{MJD})$ |
|----------------------|-----------------|-----------------|-----------------|
| 2017 May             |                 |                 |                 |
| XMM-Newton/EPIC      | 1.6879874455(24)| 57896.829263(13)| 57896.92939840  |
| TNG/SiFAP2           | 1.6879874449(58)| 57896.829275(38)| 57896.97005780  |
| 2018 December 11 - 12|                 |                 |                 |
| XMM-Newton/EPIC      | 1.6879874440(48)| 58463.781107(14)| 58463.88334670  |
| Copernicus/Aqueye+   | 1.6879874257(27)| 58463.781111(27)| 58464.04460940  |
| 2018 December 15     |                 |                 |                 |
| XMM-Newton/EPIC      | 1.6879874445(42)| 58467.743034(14)| 58467.91575570  |
| Copernicus/Aqueye+   | 1.6879874399(25)| 58467.743029(22)| 58467.03133470  |
| 2019 January         |                 |                 |                 |
| NICER                | 1.6879874474(19)| 58514.889969(18)| 58514.92190000  |
| TNG/SiFAP2           | 1.6879875334(48)| 58515.088033(17)| 58514.98403960  |
| 2019 February        |                 |                 |                 |
| NICER                | 1.6879874424(11)| 58519.8423788(99)| 58519.87965120  |
| Copernicus/Aqueye+   | 1.6879873897(60)| 58519.842377(28)| 58519.87965120  |
| 2019 June            |                 |                 |                 |
| NICER                | 1.6879874466(96)| 58636.91735124(2)| 58636.86910000  |
| TNG/SiFAP2           | 1.6879874467(70)| 58636.917367(18)| 58636.88410956  |
| 2020 January         |                 |                 |                 |
| NICER                | 1.6879874464(13)| 58878.991096(21)| 58878.93440000  |
| TNG/SiFAP2           | 1.6879874844(69)| 58878.9911009(12)| 58878.99024860  |
| Copernicus/Aqueye+   | 1.6879874511(24)| 58878.991044(11)| 58877.98782000  |
| 2022 January-February|                 |                 |                 |
| NICER                | 1.6879874474(22)| 59067.985869(18)| 59067.98901060  |
| Copernicus/Aqueye+   | 1.6879874574(85)| 59067.985862(33)| 59067.98901060  |

$a$: From Jaodand et al. (2016).

$b$: From Deller et al. (2012).

### Table 3. Additional observations of PSR J1023+0038 that were used to study the evolution of the epoch of passage at the ascending node.

| Telescope (Obs. ID) | $T_{\text{asc}}$ $(\text{MJD})$ | $T_{\text{start}}$ $(\text{MJD})$ |
|---------------------|-----------------|-----------------|
| NICER (3515010101)  | 58949.1172388(14)| 58949.1224730  |
| NICER (3515010802)  | 59209.0196900(17)| 59209.0096634  |
| NICER (4531010203)  | 59311.039315(19)| 59311.0334708  |
| NICER (4531010601)  | 59533.303528(13)| 59533.3494883  |
we should apply to the orbital period to have constant residuals over time and C as the orbital period derivative. Since the orbital period difference would not significantly affect the results of the analysis presented here, we retained the value reported by Jaodand et al. (2016). Future studies will allow us to firmly establish the binary evolution.

3.2. Nonselection of intensity modes

Except for the May 2017 data set, we did not distinguish among low, high, and flaring modes, differently from what was done in other works (see, e.g., Bogdanov et al. 2015; Papitto et al. 2019). As we show in the following, the nonselection of modes does not change the phase of our signal. The reason for this choice lies in the fact that different modes are typically identified in the X-ray band: just a fraction of the optical data considered in this work is strictly simultaneous to X-ray observations, differently from the case of the 2017 observations analyzed in Papitto et al. (2019) (hereafter P19). It is not possible to precisely distinguish high and low modes in the optical band because the corresponding variations in intensity are fainter than those observed in the X-rays and are preferentially observed in the red part of the visible spectrum (see, e.g., Shahbaz et al. 2015; Shahbaz et al. 2018; Kennedy et al. 2018; Papitto et al. 2018).

To verify whether the pulse phase changes depend on either selecting or not selecting the different modes, we analyzed the optical observation acquired in May 2017 (Table 1) in three different ways: by selecting only the high modes; by using the whole observation, therefore without distinguishing between low, high, and flaring modes; and by visually selecting and removing flares, hence keeping both low and high modes. We first selected high modes only in simultaneous intervals with the X-ray observation, adopting the definition of X-ray modes from Bogdanov et al. (2015). Because our values of $T_{\text{asc}}$ and $P$ (Table 2) are compatible with those used by P19, equal to $P_{\text{ref}} = 1.687987446019$ ms and $T_{\text{asc}} = 57896.82926(1)$ MJD, we used the latter values for a better comparison. The first and second harmonics of the optical pulsation lag the X-ray harmonics by $\delta T_1 = (223 \pm 31) \mu s$ and $\delta T_2 = (195 \pm 7) \mu s$ (Table 2), respectively. Our results are compatible with those of P19. We note that the phases of the optical pulse profile obtained by selecting only the high modes are $\phi_1 = 0.4726 \pm 0.0053$ and $\phi_2 = 0.5500 \pm 0.0023$ (Table 2). Second, analyzing the entire optical observations of May 2017 without selecting the different intensity modes, we obtained $\phi_1 = 0.4714 \pm 0.0070$ and $\phi_2 = 0.5615 \pm 0.0034$. These differ by 0.2$\sigma$ and 3$\sigma$, respectively, from the phases estimated when only high-mode intervals were selected. When we removed the flaring intervals (i.e., analyzing both high and low modes), the results are compatible with those obtained by selecting only high modes. In this third case, we indeed obtained $\phi_1 = 0.4666 \pm 0.0064$ and $\phi_2 = 0.5501 \pm 0.0029$, both compatible within 3$\sigma$ with the results from the data set in which only the high modes were analyzed. This is expected because optical (and X-ray) pulsars are not detected during the low modes, whereas optical pulsations appear during flares, although the pulse amplitude is six times smaller than in the high modes (Papitto et al. 2019). For this reason, we paid special attention to removing flaring intervals in the remainder of this work, but we did not distinguish between high and low modes. Optical flares are indeed easy to identify (see, e.g., Bogdanov et al. 2015; Papitto et al. 2018; 2019). As an example, Fig. 2 shows the visual selection of flares in the Aqueye+ observation of January 2020. We conclude that, with these caveats, the decision not to distinguish high and low modes does not produce different results in the phase analysis.

3.3. Phase analysis results

We summarize our main results in Tables 4 and 5. We filtered X-ray and optical observations to analyze simultaneous intervals. The cases in which this was not possible are marked in the tables with an asterisk. The reason was either the absence of exact simultaneity or the short duration of these intervals, which made the statistics insufficient to detect the pulsed profile. Table 4 lists the best values for the phases and amplitudes, $\phi_i$ and $r_i$, with $i = 1, 2$, obtained by modeling the pulse profiles with a function consisting of two harmonics (Eq. (1)). $T_{\text{ref}}$ denotes the reference epoch (the same for simultaneous optical/X-ray observations) against which we calculated the phases. Fractional amplitudes were converted to background-subtracted rms amplitudes, that is, $r' = (1/\sqrt{2}) r c_{\text{tot}} (c_{\text{tot}} - c_{\text{bkg}})$, where $r$ is the pulse amplitude, $c_{\text{tot}}$ is the total count rate, and $c_{\text{bkg}}$ is the count rate associated with the sky background. $R = (r_1^2 + r_2^2)^{1/2}$ is the total rms amplitude. We associated the statistical errors computed through the least-squares method, setting $\Delta x^2(\alpha = 68\%) = 1.0$ (Sect. 3). The absolute timing accuracies for XMM-Newton and SiFAP2 are $\sim 100$ $\mu$s and $\sim 60$ $\mu$s, respectively, while systematic errors are negligible for NICER and Aqueye+. Table 5 shows the corresponding lags between optical and X-ray pulsations.

Figure 3 focuses on the results from the second harmonic, whose power spectral densities are more than three times higher than those of the first harmonic. Colored error bars represent 1$\sigma$ statistical uncertainties, and the black error bars indicate the total error. We note the influence of the absolute timing accuracy.

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Fig. 1. Long-term evolution of $T_{\text{asc}}$ as a function of the number of orbital cycles since $T_{\text{ref}} = 57897.027668$ MJD. Red points are the values found by Jaodand et al. (2016), which deviate from the almost linearly increasing trend found in this work. Blue points are from Papitto et al. (2019), and lighter blue points are from Burtovoi et al. (2020). Triangles, associated in the legend with the different NICER observations, are from this work. The thick dashed line indicates our increasing roughly linear trend. The dotted gray line indicates the sinusoidal trend that is similar to the trend found in previous work (e.g., Jaodand et al. 2016, Papitto et al. 2019).
In this section, we discuss the results of (quasi-)simultaneous observations acquired over five years.

3.3.1. NICER and Aqueye+ simultaneous observations

In this section, we discuss the results of (quasi-)simultaneous observations between Aqueye+ and NICER. They are most valuable for our analysis because the absolute timing uncertainties are negligible compared with the effects we aim to measure. They were also taken with a different set of instruments than in P19, thus with disconnected systematics and of a much smaller magnitude. We have simultaneous observations between these two instruments in February 2019, January 2020, and January-February 2022 (Table 1).

From January 29 to February 2, 2022 an observational campaign was carried out with Aqueye+ and NICER. However, optical data were affected by the bad weather conditions, and the

Table 4. Properties of the X-ray and optical pulses.

| Telescope/Instrument | $T_{\text{ref}}$ (MJD) | $\phi_1$       | $\phi_2$       | $r_1$ (%) | $r_2$ (%) | $R$ (%) |
|----------------------|------------------------|----------------|----------------|-----------|-----------|---------|
| 2017 May - overlap: 11.0 ks |                       |                |                |           |           |         |
| XMM-Newton/EPIC      | 57896.0                | 0.340(18)      | 0.4346(39)     | 3.34(39)  | 7.69(38)  | 8.38(38) |
| TNG/SiFAP2           | 57896.0                | 0.4726(53)     | 0.5500(23)     | 0.391(13) | 0.449(13) | 0.595(13) |
| 2018 December, 11/12 - overlap: 10.8 ks |                       |                |                |           |           |         |
| XMM-Newton/EPIC      | 58463.0                | 0.474(24)      | 0.1177(42)     | 2.01(32)  | 5.86(31)  | 6.29(31) |
| Copernicus/Aqueye+   | 58463.0                | 0.564(29)      | 0.164(14)      | 0.145(48) | 0.159(48) | 0.215(48) |
| 2018 December, 15 - temporal gap: 41 ks* |                       |                |                |           |           |         |
| XMM-Newton/EPIC      | 58467.0                | 0.256(34)      | 0.4271(43)     | 1.30(28)  | 5.11(28)  | 5.27(28) |
| Copernicus/Aqueye+   | 58467.0                | 0.315(23)      | 0.434(16)      | 0.167(39) | 0.128(39) | 0.210(39) |
| 2019 January - overlap: 2.3 ks |                       |                |                |           |           |         |
| NICER                | 58514.0                | 0.048(34)      | 0.1665(78)     | 2.78(61)  | 6.12(60)  | 6.72(60) |
| TNG/SiFAP2           | 58514.0                | 0.153(98)      | 0.197(20)      | 0.30(17)  | 0.70(17)  | 0.76(17) |
| 2019 February - overlap: 1.1 ks |                       |                |                |           |           |         |
| NICER                | 58519.0                | 0.288(26)      | 0.3831(76)     | 3.01(50)  | 5.12(49)  | 5.94(49) |
| Copernicus/Aqueye+   | 58519.0                | 0.385(32)      | 0.534(16)      | 0.122(60) | 0.118(59) | 0.170(60) |
| 2019 June - overlap: 340 s* |                       |                |                |           |           |         |
| NICER                | 58636.0                | 0.560(87)      | 0.353(16)      | 2.6(1.3)  | 6.8(1.3)  | 7.3(1.3) |
| TNG/SiFAP2           | 58636.0                | 0.775(42)      | 0.426(13)      | 0.085(22) | 0.139(22) | 0.163(22) |
| 2020 January - overlap: 4.6 ks |                       |                |                |           |           |         |
| NICER                | 58878.0                | 0.117(56)      | 0.234(12)      | 2.77(98)  | 6.53(96)  | 7.09(96) |
| TNG/SiFAP2           | 58878.0                | 0.1917(55)     | 0.2823(12)     | 0.265(95) | 0.328(95) | 0.422(95) |
| 2020 January - overlap: 520 s |                       |                |                |           |           |         |
| NICER                | 58878.0                | 0.207(65)      | 0.221(12)      | 3.9(1.5)  | 10.1(1.6) | 10.8(1.6) |
| Copernicus/Aqueye+   | 58878.0                | 0.204(30)      | 0.292(14)      | 0.240(57) | 0.256(57) | 0.351(57) |
| 2022 January - overlap: 1.7 ks |                       |                |                |           |           |         |
| NICER                | 59607.0                | 0.058(75)      | 0.717(10)      | 1.19(55)  | 4.13(54)  | 4.30(54) |
| Copernicus/Aqueye+   | 59607.0                | 0.031(82)      | 0.781(19)      | 0.064(57) | 0.135(57) | 0.149(57) |

*: Cases in which it was not possible to analyze exactly simultaneous intervals between optical and X-ray observations.

of XMM-Newton (∼ 100 µs) and SiFAP2 (∼ 60 µs). The time lags of optical and X-ray pulsations are always within the range (0 – 250) µs, that is, a phase lag of $\delta \phi \in (0 – 0.15)$, even in observations acquired over five years.
X-ray pulse profiles. In the main analysis of this work (see Tables 4 and 5, and Fig. 3), we report the results from the first X-ray statistics was often low due to short NICER exposure. The top and middle panels of Fig. 3 show the X-ray and optical rms amplitudes in February 2019, in January 2020, and over the five-day observational campaign in 2022. When optical pulsations were not detected, we estimated upper limits on the pulse amplitude by computing the Fourier power spectral density and measuring the power of the first and second harmonics of the spin frequency. We then converted these power pairs into rms amplitudes at 3σ confidence level according to the procedure described by Vaughan et al. (1994) to take into account that the probability distribution of total power in a frequency bin of a Fourier spectrum containing both signal and noise is more complicated than a χ² distribution. The bottom panel shows the phase of the two harmonic components of the corresponding optical and X-ray pulse profiles. In the main analysis of this work (see Tables 4 and 5, and Fig. 3), we report the results from the first day of the 2022 observational campaign (January 29), when we had the longest X-ray observation that was suitable to provide statistically acceptable results and the weather conditions were good enough to detect optical pulsations. The phase of the second harmonic term of optical pulses lags that in the X-rays by δτ₂ = (108 ± 36) µs.

Special attention was paid to filtering out flare intervals present in the optical data of February 2019 and January 2020. We obtained time lags from the second harmonic component of δτ₂ = (254 ± 47) µs and (119 ± 31) µs, respectively (Table 5).

Figure 5 shows the pulsed profiles of the NICER/Aqueye+ simultaneous observations discussed here.

### Table 5. Lags between optical and X-ray pulsations.

| Date               | Opt. Instrument | X-ray Telescope | ηφ₁ (× 10⁻¹) | ητ₁ (µs) | ηφ₂ (× 10⁻¹) | ητ₂ (µs) |
|--------------------|-----------------|-----------------|--------------|----------|--------------|----------|
| 2017 May           | SiFAP2          | XMM-Newton      | 1.32(18)     | 2.23(31) | 1.154(45)    | 1.950(70) |
| 2018 December, 11/12 | Aqueye+         | XMM-Newton      | 9.0(3.8)     | 1.52(64) | 4.7(1.4)     | 7.9(2.4)  |
| 2018 December, 15* | Aqueye+         | XMM-Newton      | 5.9(4.1)     | 9.9(7.0) | 0.7(1.6)     | 1.2(2.7)  |
| 2019 January       | SiFAP2          | NICER           | 1.0(1.0)     | 1.8(1.7) | 3.0(2.1)     | 5.1(3.6)  |
| 2019 February      | Aqueye+         | NICER           | 9.7(4.1)     | 1.63(69) | 1.50(18)     | 2.54(31)  |
| 2019 June*         | SiFAP2          | NICER           | 2.15(97)     | 3.6(1.6) | 7.3(2.0)     | 1.23(34)  |
| 2020 January       | SiFAP2          | NICER           | 2.15(5.6)    | 3.5(9.5) | 4.8(1.2)     | 8.1(2.0)  |
| 2020 January       | Aqueye+         | NICER           | −0.4(7.1)    | −0.1(1.2) | 7.0(1.8)     | 1.19(31)  |
| 2022 January       | Aqueye+         | NICER           | −0.3(1.1)    | −0.5(1.9) | 6.4(2.1)     | 1.08(36)  |

*: Cases in which it was not possible to analyze exactly simultaneous intervals between optical and X-ray observations.

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**Fig. 3.** Time lags relative to the second harmonic term (Table 5). The y-axis is not temporally equispaced. The purple point indicates the values for simultaneous observations between XMM-Newton and SiFAP2, blue points show values between XMM-Newton and Aqueye+, light blue points indicate values between NICER and SiFAP2, and green points show the values between NICER and Aqueye+. The dashed line indicates a zero time lag. Colored error bars represent 1σ statistical uncertainties, while the black error bars indicate the total error. The influence of the absolute timing accuracy of XMM-Newton (~ 100 µs) and SiFAP2 (~ 60 µs) is visible.
Among the three sets of NICER/Aqueye+ (quasi-) simultaneous observations discussed in this section, the February 2019 data feature the longest interval of simultaneity between NICER and Aqueye+ (Table 4), combined with the highest significance of the pulse profiles. Therefore, they can be considered most valuable for estimating the optical/X-ray time lag. This data set is also of particular interest because it shows the largest time lag with respect to the second harmonic term (Fig. 3). To strengthen the time lag measure obtained from this data set, we performed a cross-correlation analysis of the two pulse profiles as a function of the optical profile offset against that in X-rays. The cross-correlation function (Derrick 2004) was corrected for the counting statistics, and the data were wrapped around themselves to avoid leaving unmatched points. For instance, when we shifted the optical pulse profile of one phase bin to the right, the number of counts in the last bin of the optical profile was matched with the number of counts of the first bin of the X-ray profile. We folded the Aqueye+ and NICER pulse profiles of February 2019 with a 64 phase bins. Figure 6 shows that the maximum value of the correlation coefficient is at a lag of 9 phase bins. When 64 phase bins are used, each of them has a length equal to $P/64 \sim 26\mu s$, where $P$ is the spin period from the X-ray timing in $\mu s$ (Table 2). Therefore, this phase lag corresponds to a time lag of $\delta t \sim (237 \pm 13) \mu s$, where the associated error is half the bin width. This result is significantly different from zero at more than 5$\sigma$ and is fully compatible with the analysis result for the second harmonic phase. This conclusion also shows that the second component prevails in the computation of the correlation between the optical and X-ray pulse profiles.

### 3.3.2. Other observations

We report the results of the remaining data sets, including observations carried out with XMM-Newton and/or SiFAP2, which must be taken with caution as they are affected by larger absolute timing uncertainties than those of NICER and Aqueye+. Simultaneous or quasi-simultaneous observations performed between XMM-Newton and Aqueye+ in December 2018 and between NICER and SiFAP2 in January 2019 and in January-February 2020 return time lags that are compatible with the absence of a phase shift considering the systematic errors. The observational campaign of June 2019 performed with SiFAP2 and NICER provides $\delta t_2 = (124 \pm 34) \mu s$, considering the statistical errors alone. When the SiFAP2 absolute timing accuracy is added in quadrature, we obtain $\delta t_2 = (130 \pm 69) \mu s$. An improvement in the absolute timing accuracy of XMM-Newton and SiFAP2 would lead to statistically stronger results. Although the systematic errors affecting these estimates often make the lags compatible with zero, these observations are important to confirm that the time lag relative to the second harmonic term between optical and X-ray pulses is always in the $\sim (0 - 250) \mu s$ range, that is, is not randomly distributed.

### 4. Discussion

This paper presented a detailed timing analysis of optical/X-ray (quasi-)simultaneous observations of the tMSP PSR J1023+0038, focusing on the study of the time lags between the pulses in the optical and X-ray bands. We folded the data at the spin periods found in the X-ray timing, compatible with the values estimated in the simultaneous optical observations (Table 2), and we modeled the pulse profiles with two harmonic terms. The optical pulses have total rms pulsed amplitudes of $\sim 0.1 - 0.8\%$, while the X-ray total rms pulsed amplitudes are in the
range 4.3 – 10.8% (Table A, in agreement with what was found in previous works (Archibald et al. 2015; Bogdanov et al. 2015; Ambrosino et al. 2017; Papitto et al. 2019; Zampieri et al. 2019; Miraval Zanon et al. 2022). Moreover, the rms pulsed fraction is variable over time (e.g., top and middle panels of Fig. 4), as was also found in Miraval Zanon et al. (2022). Although the estimated time lags (Table 5) are not consistent with being modeled by a single value, we report the weighted averages obtained from the studies of the first and second harmonic terms, respectively: \( \delta \tau_1 = (175 \pm 22) \mu s \) and \( \delta \tau_2 = (162 \pm 6) \mu s \). These results are compatible with each other within 1\( \sigma \).

By focusing on the second harmonic of the pulse profiles (because their power spectral densities are higher than those of the first harmonic), we found that the time lag between optical and X-ray pulsations always lies in the limited range of \( (0 – 250) \mu s \), also taking into account observations acquired over about five years (Fig. 3). We note the large total errors due to the absolute timing accuracy of \( XMM-Newton \) (\( \sim 100 \mu s \)) and SiFAP2 (\( \sim 60 \mu s \)), highlighting the value of the results from \( NICER/Aqueye \) simultaneous observations.

A timescale of \( \sim 250 \mu s \) is virtually equal to the light cylinder radius light-crossing time (for a NS spin frequency of \( v \approx 592.42 \) Hz, \( R_{LC} \approx 80 \) km), indicating that the optical pulsed luminosity might be produced by the reprocessing of accretion-powered X-ray emission. However, the observed pulsed luminosity in the visible band is too high to be explained in this way (Ambrosino et al. 2017; Papitto et al. 2019). The properties of optical and X-ray pulsations, such as their simultaneous detection during the X-ray high modes and their disappearance in the low modes (Papitto et al. 2019), the similar pulse shape, and the very limited range of the estimated time lags might indicate that they are related, either by originating in the same region or in a region that lies very near, or that they are connected to the same emission process.

X-ray pulsations observed in the high modes of J1023+0038 were at first interpreted as due to the accretion of matter channeled along the magnetic field lines of the pulsar (Archibald et al. 2015). However, this model fails to explain the observed optical pulsed luminosity of\( \approx 10^{11} \) erg s\(^{-1} \). When we assume that optical pulsations result from cyclotron emission by electrons that are in-falling in the accretion columns on the NS hotspots, the luminosity produced in this way is about 40 times lower than the observed one (Ambrosino et al. 2017; Papitto et al. 2019).

On the other hand, indicating the efficiency in converting the spin-down power into the optical pulsed luminosity as \( \eta_{opt} = L_{opt}/E_{sd} \), where \( E_{sd} \) is the pulsar spin-down power, the measured values for the five rotation-powered pulsars from which optical pulses were detected (Cocke et al. 1969; Mignani 2011) are in the range from \( \eta_{opt} \approx 5 \times 10^{-6} \) down to \( \sim 2 \times 10^{-9} \) (see red points in Fig. 3 from Ambrosino et al. 2017). These NSs are all young (10\(^{-3} – 10^{-5} \) years), isolated, and possess high-magnetic fields (\( \sim 10^{12} \) G). A higher value, equal to \( \eta_{opt} \sim 2 \times 10^{-5} \), is found for J1023+0038. In addition, the fraction of the spin-down power converted into X-ray pulses would be much higher than that of almost all rotation-powered pulsars (Papitto et al. 2019). The rotation-powered mechanism can hardly be the only common source of X-ray and optical pulsations from J1023+0038.

A model was thus proposed in which, despite the presence of an accretion disk, a rotation-powered pulsar is active in the system. In the shock-driven mini pulsar nebula scenario (Papitto et al. 2019; Veleldina et al. 2019), optical and X-ray pulses are produced via synchrotron emission from a shock that is formed where the pulsar wind meets the accretion disk, within a few light cylinder radii from the pulsar. Inside the light cylinder, the magnetic field is described in terms of a split-monopole (Bo恪valov 1999). The two monopoles with opposite sign give rise to a current sheet on the equatorial plane, which expands as an Archimedean spiral until it reaches the shock in two opposite spots where electrons are accelerated to relativistic speeds. Indicating the shock distance from the pulsar as \( \sim k R_{LC} \), for low values \( k \approx 1 – 2 \), just beyond the light cylinder radius, the magnetic field is still so intense that synchrotron emission provides the dominant cooling mechanism for shock-accelerated electrons. This model is compatible with the presence of two harmonics. For quite large inclination angles, the emission from the spot on the observer’s side is obscured by the disk. In contrast, the emission from the farthest spot, which is modulated sinusoïdally during its rotation, is more easily observed (see Fig. 14 of Papitto et al. 2019). The higher intensity of the second compared to the first harmonic may derive from an asymmetry of the system that causes them to be obscured in a different way.

We used a parametric value of the time lag between optical and X-ray pulsations to estimate some physical quantities of the system within this model. Based on our most accurate results, that is, those from \( NICER/Aqueye \) simultaneous observations (Sect. 3.3.1), we adopted \( \delta \tau_p \sim 150 \mu s \). Synchrotron photons are emitted by the shock-accelerated electrons on a timescale (Eq.
The electron energy is \( y m_e c^2 \) and \( P_{\text{sync}} \approx 4/3 \sigma r c^2 U_B^2 \) is the average synchrotron power per relativistic electron in a source with an isotropic pitch-angle distribution. Here \( \sigma r \) is the Thomson scattering cross section, \( U_B \) is the magnetic energy density, and we used the typical energy of synchrotron photons written as \( \varepsilon = \mu_0 r c^2 = 3heB_p^2/(2mc^2) \). The magnetic field intensity in the post-shock region is given by (Arons & Tavani 1993)

\[
B_p = 3 \left( \frac{\sigma}{1 + \sigma} \right)^{1/2} \left( \frac{E}{\epsilon f_p r_p} \right)^{1/2} \approx 4.5 \times 10^5 \frac{k}{\nu} f_p^{-1/2} \text{G},
\]

(4)

where \( E = 4.43 \times 10^{34} \text{erg s}^{-1} \) is the total spin-down power (Archibald et al. 2013) and \( r = k R_{\text{LC}} \) is the shock distance. The magnetization parameter \( \sigma \) (Kennel & Coroniti 1984; Bogdanov et al. 2011) is \( \gg 1 \) close to the light cylinder where the wind is released (Arons 2002), and \( f_p \) represents a geometric factor indicating the sky fraction in which the pulsar wind is emitted (\( f_p = 1 \) for an isotropic pulsar wind; Bogdanov et al. 2011). We assumed \( 1 \leq k \leq 2 \), that is, the shock region where optical and X-ray pulsations are produced is just beyond the light cylinder (for \( k < 1 \) the matter of the disk would enter the light cylinder, preventing the formation of a relativistic wind from the pulsar).

From Eq. (4), we found that it takes to emit X-ray photons. We assumed the average energy of NICER photons to be \( \epsilon = 5 \text{keV} \). On the other hand, the synchrotron timescale for optical photons, with \( \epsilon = 1 \text{eV} \), is \( \sim 70 \) times longer, such that the time lag between optical and X-ray pulsations is

\[
\delta T \approx 220 \left( \frac{B_p}{4.5 \times 10^5 \text{G}} \right)^{3/2} \text{ms}.
\]

(6)

Similarly, we can predict the time lags with UV and near-infrared (NIR) pulsations from J1023+0038. Assuming an energy of \( \epsilon \sim 5 \text{eV} \) for UV photons, we would have a time lag of \( \sim 122 \) ms between optical and UV pulsations, and of \( \sim 95 \) ms between UV and X-ray pulsations. For a NIR observation in the K band, the photon energy is \( \epsilon \sim 0.6 \text{eV} \). NIR pulsations would lag optical pulsations by \( \sim 64 \) ms, UV pulsations by \( \sim 186 \) ms, and X-ray pulsations by \( \sim 281 \) ms. When we use our parametric value of the time lag, \( \delta T_{\nu} \sim 150 \) ms, and invert Eq. (6), the intensity of the magnetic field behind the shock is

\[
B_p \approx 5.8 \times 10^5 \hat{T}^{-2/3} \text{G}.
\]

(7)

where \( \hat{T}_{p,150} \) is in unit of 150 ms. For a surface magnetic field of \( B_{\text{surf}} \approx 9.6 \times 10^7 \text{G} \) (Deller et al. 2012), we computed the dipole decrease at the light cylinder radius as \( B_{\text{LC}} \approx B_{\text{surf}} \left( R_{\text{LC}}/R_{\text{NS}} \right)^3 \), assuming a NS radius of about \( R_{\text{NS}} \approx 10 \) km. Since the magnetic

\[https://heasarc.gsfc.nasa.gov/docs/nicer/mission_guide\]

5. Conclusions

We presented a detailed timing analysis of (quasi-)simultaneous observations in the X-rays and in the optical band of the transitional millisecond pulsar PSR J1023+0038. The analyzed data cover the time interval from May 2017 to January 2022, when the system was in a subluminous disk state. They were acquired with XMM-Newton and NICER X-ray satellites, and with the fast optical photometers SiFAP2 and Aqueye+. Our main results are summarized below.
Although the estimated time lags between optical and X-ray pulsations are not consistent with being modeled by a single value, the weighted averages obtained from the studies of the first and second harmonic terms are $\delta t_1 = (175 \pm 22) \mu s$ and $\delta t_2 = (162 \pm 6) \mu s$, respectively. When we focus on the second harmonic because of its higher power spectral densities, the time lag lies in a limited range of values, $0 - 250 \mu s$. This is maintained over the years, supporting the hypothesis that both pulsations originate from the same region and that their emission mechanisms are intimately linked.

2. From NICER/Aqueeye+ simultaneous observations, we found that the second harmonic of the optical pulse lags that of the X-ray pulse by $\delta t_2 = (254 \pm 47) \mu s$ in February 2019, $(119 \pm 48) \mu s$ in January 2020, and $(108 \pm 36) \mu s$ in January 2022. These results are not affected by the systematic errors, while the previous measurement by Papitto et al. (2019) was affected by the absolute timing uncertainty of SiFAP2 and XMM-Newton.

3. Our results find a convincing interpretation in the shock-driven mini pulsar nebula scenario (Papitto et al. [2019] Veclina et al. [2019]), which suggests an origin of optical and X-ray pulses based on synchrotron radiation emitted from a shock formed where the striped pulsar wind meets the accretion disk, within a few light cylinder radii from the pulsar. The time lag is interpreted in terms of the different timescale that synchrotron X-ray and optical photons take to be emitted.

Within the proposed model, variations of the estimated time lags of optical pulses relative to the X-ray pulses may be due to the variability in disk truncation radius and of optical pulses relative to the X-ray pulses may be due to the X-ray pulses may be due to

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