Precise optical timing of PSR J1023+0038, the first millisecond pulsar detected with Aqueye+ in Asiago

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ABSTRACT
We report the first detection of an optical millisecond pulsar with the fast photon counter Aqueye+ in Asiago. This is an independent confirmation of the detection of millisecond pulsations from PSR J1023+0038 obtained with SiFAP at the Telescopio Nazionale Galileo. We observed the transitional millisecond pulsar PSR J1023+0038 with Aqueye+ mounted at the Copernicus telescope in January 2018. Highly significant pulsations were detected. The rotational period is in agreement with the value extrapolated from the X-ray ephemeris, while the time of passage at the ascending node is shifted by $11.55 \pm 0.08$ s from the value predicted using the orbital period from the X-rays. An independent optical timing solution is derived over a baseline of a few days, that has an accuracy of $\sim 0.007$ in pulse phase ($\sim 12$ $\mu$s in time). This level of precision is needed to derive an accurate coherent timing solution for the pulsar and to search for possible phase shifts between the optical and X-ray pulses using future simultaneous X-ray and optical observations.

Key words: accretion, accretion discs – stars: neutron – pulsars: general – pulsars: individual: PSR J1023+0038 – X-rays: binaries

1 INTRODUCTION
Millisecond radio pulsars were discovered in 1982 (Alpar et al. 1982; Backer et al. 1982). The first confirmation of the long sought evolutionary link between these sources and accreting Low Mass X-ray Binaries (LMXBs) came in 1998 with the discovery of pulsations at 2.5 ms in SAX J1808.4-3658 (Wijnands & van der Klis 1998). This showed that old, low magnetic field pulsars are re-accelerated (“recycled”) through mass and angular momentum transfer from a companion star in a previous LMXB phase.

However, it was only recently that direct evidence that some of these systems can swing between a rotation-powered millisecond pulsar phase and an accretion phase was gathered, thanks to the amazing discovery of an ordinary radio millisecond pulsar switching off and turning on as an accretion-powered, X-ray millisecond pulsar (PSR J1824-2452; Papitto et al. 2013). At present, we know other two systems that behave in a similar way: PSR J1023+0038 (Archibald et al. 2009) and PSR J1227-4853 (de Martino et al. 2010). These fast spinning, weakly magnetized neutron stars (NSs) are called transitional millisecond pulsars (tMSPs) and typically have low mass companion stars ($\sim 0.5 M_\odot$).

PSR J1023+0038, located at a distance of $1.37 \pm 0.04$ kpc (Deller et al. 2012), was initially classified as a Cataclysmic Variable (Bond et al. 2002). Subsequent observations carried out with the Green Bank Telescope showed that in 2007 the source was, in fact, a radio pulsar with a rotational period of 1.69 ms orbiting a $\sim 0.2 M_\odot$ companion with a period of 4.75 hours (Archibald et al. 2009). It was then realized that, between 2000 and 2001, the source had an accretion disc, which subsequently disappeared following the appearance of the radio millisecond pulsar. In June 2013 an inverse transition took place, with the disappearance of the radio pulses and the reappearance of the accretion disc, with a strong double-peaked Hα emission observed in the optical spectrum (Halpern et al. 2013; Patruno et al. 2014; Stappers et al. 2014). In the disc state the average optical and X-ray fluxes increase by a factor of $\sim 2 - 3$ (Coti Zelati et al. 2014) and $\sim 10$ (Stappers et al. 2014), respectively.
GeV γ-ray flux is 3-5 times higher (Torres et al. 2017), while only an upper limit exists on the TeV γ-ray flux (Aliu et al. 2016). As for the radio emission, bright continuum emission with a flat spectrum is observed, with radio flares occurring at certain phases (Deller et al. 2015; Bogdanov et al. 2018).

During the accretion phase significant X-ray variability is observed in PSR J1023+0038 on time scales of tens of seconds. XMM-Newton observations show a puzzling trimodal behaviour in the 0.3-10 keV band. PSR J1023+0038 spends about 70-80% of the time in a stable high mode with a X-ray luminosity $L_X \sim 7 \times 10^{33}$ erg s$^{-1}$. The source then unpredictably switches to a low mode with a much lower luminosity ($L_X \sim 10^{33}$ erg s$^{-1}$; Bogdanov et al. 2015; Campana et al. 2016; Coti Zelati et al. 2018), often correlated with enhancements of the radio emission (Bogdanov et al. 2018). Sporadic X-ray flaring episodes are also observed reaching luminosities $L_X \sim 10^{34}$ erg s$^{-1}$ (flaring mode). Coherent X-ray pulsations at the NS spin period are detected only when the system is in the high mode (Archibald et al. 2015). The luminosity in this mode is lower than that of a typical LMXB. Notably, the spin rate of the pulsar during the accretion state is close to the value measured during the radio LMXB. Notably, the spin rate of the pulsar during the accretion state is close to the value measured during the radio

## 2 OBSERVATIONS AND DATA ANALYSIS

We observed PSR J1023+0038 with Aqueye+ mounted at the Copernicus telescope in Asiago, Italy. Aqueye+ is a fast photon counter with a field of view of few arcsec and the capability of time tagging the detected photons with a sub-nsec time accuracy (Barbieri et al. 2009; Naletto et al. 2013; Zampieri et al. 2015). A total of 30 acquisitions were performed between January 22 and 25, 2018, each lasting either $\sim 900$ s or $\sim 1800$ s. The overall on-source observing time is $\sim 44.1$ ks. The log of the observations is shown in Table 1. The sky background was regularly monitored between on-target observations. The average background-subtracted rate of PSR J1023+0038 varied between $\sim 800$ and $\sim 2000$ c/s, mostly because of intrinsic source variability (flares).

The data reduction is performed with a dedicated software. The whole acquisition and reduction chain ensures an absolute accuracy of $\sim 0.5$ ns relative to UTC (Naletto et al. 2009). The photon arrival times are barycentred using TEMPO2 in TDB time units (Edwards et al. 2006; Hobbs et al. 2006), using the position of Jaodand et al. (2016) (RA=10:23:47.687198, DEC=+0:38:40.84551 at MJD 54995) and the JPL ephemerides DE405. We corrected for the motion of the NS along the orbit using the orbital period $P_{orb} = 0.1980963155$ days and projected semi-major axis $a = 0.343356$ light-seconds of Jaodand et al. (2016).

### Table 1. Log of the 2018 observations of PSR J1023+0038 taken with Aqueye+ at the 1.8 m Copernicus telescope in Asiago.

| Observation ID | Start time (UTC) | Start time (MJD) | Duration (s) |
|----------------|------------------|-----------------|-------------|
| 20180122-011224 | Jan 22 00:20:10.2 | 58140.014007 | 899.4 |
| 20180122-012903 | 00:36:48.3 | 58140.025559 | 899.4 |
| 20180122-014725 | 00:55:10.3 | 58140.038314 | 899.4 |
| 20180122-020320 | 01:11:05.4 | 58140.049368 | 899.4 |
| 20180122-022214 | 01:29:59.5 | 58140.062494 | 899.4 |
| 20180122-023844 | 01:46:29.5 | 58140.073953 | 899.4 |
| 20180122-030122 | 02:09:07.6 | 58140.080671 | 1799.4 |
| 20180122-034854 | 02:56:39.7 | 58140.122682 | 1799.2 |
| 20180122-042617 | 03:34:02.9 | 58140.146645 | 1799.4 |
| 20180122-050133 | 04:09:20.0 | 58140.173149 | 1799.4 |
| 20180123-013839 | Jan 23 00:46:30.3 | 58141.032295 | 899.4 |
| 20180123-015619 | 01:04:10.4 | 58141.044565 | 899.4 |
| 20180123-021846 | 01:26:36.4 | 58141.060144 | 899.4 |
| 20180123-023447 | 01:42:38.5 | 58141.071279 | 899.4 |
| 20180123-025439 | 02:02:30.6 | 58141.085076 | 1799.4 |
| 20180123-033110 | 02:39:01.7 | 58141.110436 | 1799.4 |
| 20180124-011222 | 02:09:07.6 | 58142.080303 | 1799.4 |
| 20180124-014447 | 02:12:37.8 | 58142.133771 | 1799.3 |
| 20180124-023519 | Jan 24 01:41:14.4 | 58142.070086 | 1799.4 |
| 20180124-031307 | 02:21:02.5 | 58142.099746 | 1799.4 |
| 20180124-034843 | 02:56:39.6 | 58142.122681 | 1799.4 |
| 20180124-042332 | 03:31:27.8 | 58142.146849 | 1799.4 |
| 20180124-045838 | 04:06:33.9 | 58142.171726 | 1799.4 |
| 20180124-053343 | 04:41:39.0 | 58142.195590 | 1799.4 |
| 20180125-014934 | Jan 25 00:57:35.0 | 58143.039898 | 1799.4 |
| 20180125-024737 | 01:55:38.2 | 58143.080303 | 1799.4 |
| 20180125-034559 | 02:54:00.4 | 58143.126838 | 1799.4 |
| 20180125-042058 | 03:28:58.5 | 58143.145122 | 1799.4 |
| 20180125-045849 | 04:06:50.6 | 58143.171419 | 1799.4 |
| 20180125-051440 | 04:49:40.7 | 58143.201166 | 899.4 |

Start times refer to the Solar system barycenter.

1 Seeing on 21-23, 25-27, 29-31.
2 QUEST v. 1.1.5, see Zampieri et al. (2015).

1 \cite{Ambrosino2017}
2 \cite{quest2015}
3 RESULTS

When J1023+0038 transited to the accretion state, the time of passage of the pulsar at the ascending node $T_{\text{asc}}$ showed a ~20 – 30 s shift from the value measured during the radio pulsar phase. In addition to that, variations of a few seconds around an approximately sinusoidal modulation are observed (Jaodand et al. 2016; Papitto & et al. 2019). Thus, following Ambrosino et al. (2017) we performed an accurate epoch folding search for the value of $T_{\text{asc}}$ for our epoch by folding the corrected event lists of January 25, 2018 with the spin period extrapolated from the X-ray ephemeris ($P_X = 1.6879874462$ ms at $t_0 = 58140.0$ MJD; Jaodand et al. 2016) and with 16 bins per period. The maximum of the $\chi^2$ is obtained for $T_{\text{asc}} = 58140.0915932 \pm 9 \times 10^{-7}$ MJD, shifted by $11.55 \pm 0.08$ s from that predicted using the orbital period from the X-ray ephemeris (see Fig. 1). For this value of $T_{\text{asc}}$ the variance of the pulse profile with respect to a constant ($\chi^2 = 100$ for 15 degrees of freedom) gives a probability < $10^{-14}$ that the pulsation is caused by a statistical fluctuation, corresponding to a detection significance of 7.7σ.

Using the actual value of $T_{\text{asc}}$, we then performed a phase fitting of the Aqueye+ data, corrected for the binary motion, following the approach presented in previous works (Germanà et al. 2012; Zampieri et al. 2014; Spolon et al. 2019). We folded separately the four nights of observations reported in Table 1 using as reference rotational period the value $P_{\text{min}} = 1.6879874400$ ms and 16 bins per period. We detected the two peaks of the pulse profile in each night. They were fitted with the sum of two harmonically-related sinusoids plus a constant (Ambrosino et al. 2017). To improve the accuracy of the measurement, we performed the fit fixing the separation $\Delta \phi$ and ratio $\rho$ of the two sinusoids at the values obtained from fitting the pulse shape of the best observing night (Jan 25, 2018): $\Delta \phi = 0.419$, $\rho = 1.27$. The typical uncertainty on the phase measurement of each single night is ~ 0.007 (or 12 µs).

The measured phases show a drift $\psi(t)$ with respect to a uniform rotation with period $P_{\text{min}}$ (Fig. 2). We fitted it with a second-order polynomial and obtained the timing solution reported in Table 2. The rotational period ($P = 1/\nu_0 = 1.68798744596 \pm 3.9 \times 10^{-10}$ ms) is consistent within the uncertainties with the value extrapolated at $t_0 = 58140$ MJD from the X-ray ephemeris ($P_X = 1.68798744620 \pm 4 \times 10^{-12}$ ms; Jaodand et al. 2016). Only an upper limit to the first derivative of frequency could be obtained. Timing noise is present at a level of ~ 0.01 in phase. We note that additional terms accounting for the phase residuals induced by the orbital motion were not included in the fit because the reduced $\chi^2$ of the second-order polynomial fit is smaller than unity (0.9) and because of the limited number of phase measurements available.

The final background-subtracted pulse shape obtained from folding all the January 2018 Aqueye+ observations with the timing solution reported in Table 2 and with 32 phase bins is shown in Fig. 3. A fit with the same model (two sinusoidal components plus a constant) adopted by Ambrosino et al. (2017) and Papitto & et al. (2019) leads to consistent values of the parameters. The amplitudes of our two sinusoidal components are $A_1 = 0.0033 \pm 0.0002$ and $A_2 = 0.0046 \pm 0.0002$, and the phases are $\phi_1 = 0.671 \pm 0.012$ and $\phi_2 = 0.261 \pm 0.004$. The total fractional amplitude of the

As defined in Zampieri et al. (2014) and Spolon et al. (2019).
signal is $A = (A_1^2 + A_2^2)^{1/2} = 0.6\%$. The variance of the pulse profile with respect to a constant ($\chi^2 = 440$ for 31 degrees of freedom) gives a probability $< 10^{-73}$ that the pulsation is caused by a statistical fluctuation, corresponding to a detection significance of $18.2\sigma$.

We used the same model to investigate possible night-to-night variations of the pulse shape, keeping the relative phases of the two sinusoidal components fixed at the value inferred from the previous fit ($\Delta\phi = 0.41$). The amplitudes of the two fitting sinusoids are in the interval $A_1 = 0.002 - 0.005$ and $A_2 = 0.003 - 0.007$. The corresponding curves are shown in Fig. 4. There are some differences in the quality of the pulse profiles in the various nights, but they do not appear to be caused by variations of the seeing conditions and/or depend in a straightforward way on the average source rate. Indeed, the night with the best seeing and the highest background-subtracted average rate (Jan 24; see Table 1 and Fig. 4) is not the one with the best pulse quality. Despite the different quality of the pulse profiles, we find evidence that the height of the second peak (defined as maximum minus minimum of the corresponding peak of the fitting function) varies significantly compared to that of the first peak. From Jan 22 through Jan 25 the ratio of the two peaks is $0.68 \pm 0.07$, $0.35 \pm 0.08$, $0.56 \pm 0.09$, $0.49 \pm 0.05$, respectively.

4 DISCUSSION AND CONCLUSIONS

We analyzed the January 2018 Aqueye+ observations of PSR J1023+0038 and detected, for the first time with Aqueye+, a highly significant millisecond pulsation. The rotational period ($P = 1/\nu_0 = 1.68798744596 \pm 3.9 \times 10^{-10}$ ms) is consistent within the uncertainties with the value extrapolated from the X-ray ephemeris of Jaodand et al. (2016) and the properties of the pulse shape are similar to those reported by Ambrosino et al. (2017). Night-to-night variations of the pulse shape are observed, with the height of the second peak varying significantly (compared to that of the first peak).

The accuracy of our timing and acquisition system allowed us to derive an independent timing solution for PSR J1023+0038 and to measure its absolute rotational phase with high accuracy ($\sim 12 \mu$s) using 4 consecutive observing nights. This level of accuracy is needed to search for possible phase shifts between the optical and X-ray pulses, as done for other optical pulsars as the Crab pulsar (e.g. Zampieri et al. 2014) or the Vela pulsar (Spolon et al. 2019). For the Crab pulsar, the optical pulse clearly leads the radio peak, but is in phase with the X-ray one (within $\sim 0.003$). A similar evidence for a phase alignment of the optical and X-ray peaks that correspond to the radio peak is found in the Vela pulsar. If the optical and X-ray peaks of PSR J1023+0038 are in phase, this would then suggest that the emission mechanism is the same, likely a rotation powered pulsar. Conversely, finding a significant phase shift between the optical and X-ray peaks would provide independent evidence that a different emission mechanism is at work. For PSR J1023+0038 an accuracy of $\sim 12 \mu$s, as that obtained from our timing solution, guarantees to pinpoint a phase shift as small as $\sim 0.01$.

Other optical measurements of the absolute rotational
phase of PSR J1023+0038 could be affected by systematic errors related to the drift of the internal clock of the acquisition system. To compensate for this effect, Ambrosino et al. (2017) apply a linear correction to the photon arrival times of their event lists. This linear correction is calibrated comparing the time of arrival of the main peak of the Crab pulsar from an optical observation taken in February 2016 with that reported in the Jodrell Bank monthly ephemeris4 (Lyne et al. 1993). Ambrosino et al. (2017) find that the optical peak leads the radio one by ~ 180 µs, in agreement with previous findings (e.g. Germanà et al. 2012; Zampieri et al. 2014). However, the Jodrell Bank ephemeris contains monthly averages of the phase measurements and can be affected by errors of ~ 100 µs. For Feb 2016 the reported error is 70 µs, but weekly phase excursions around the monthly ephemeris could be as large as ~ 50 – 100 µs, as shown in Cadez et al. (2016). For this reason, considering the accuracy of our timing solution, simultaneous optical measurements of the absolute phase of PSR J1023+0038 with Aqueye+ at Copernicus are desirable. They can serve not only because of their intrinsic scientific value, but also as calibrators for observations taken with other optical facilities.

As far as the X-ray observations are concerned, their timing accuracy depends on the satellite and the instrument. The EPIC-pn instrument onboard XMM-Newton in the timing mode has an uncertainty of 48 µs on the absolute timing and a clock drift of < 10^{-8} s^{-1} (Martin-Carrillo et al. 2012). The clock drift appears to be sufficiently small not to lead to a significant smearing of the pulse profile of PSR J1023+0038 during a 30 ks long observation (Jaodand et al. 2016). However, the absolute error may lead to a non-negligible uncertainty in the measurements of the phase shift with respect to other measurements at the level of 0.03. Simultaneous Aqueye+-observational data could be used to determine the optical-X-ray shift (if it is > 0.03) or to cross-calibrate the optical and X-ray measurements.

Unfortunately, because no X-ray observations were performed at the time of the Aqueye+ observations, we cannot measure directly the X-ray-optical time delay using the present dataset. Nor can we select high and low mode time intervals to improve the significance of our measurements. However, future simultaneous multiwavelength campaigns in synergy with X-ray telescopes and with SiFAP at TNG will certainly allow us to perform an accurate measurement of the relative shift between the X-ray and optical peaks in the pulse shape of PSR J1023+0038. This type of measurements provide significant constraints to the geometry of the emission region and, ultimately, to the physical mechanism producing the optical and X-ray pulses.

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