Optical pulsations from a transitional millisecond pulsar

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Millisecond pulsars are neutron stars that attain their very fast rotation during a 10^8–10^9-yr-long phase of disk accretion of matter from a low-mass companion star1,2. They can be detected as accretion-powered millisecond X-ray pulsars if towards the end of this phase their magnetic field is strong enough to channel the in-falling matter towards their magnetic poles3. When mass transfer is reduced or ceases altogether, pulsed emission generated by magnetospheric particle acceleration and powered by the star rotation is observed, preferentially in the radio4 and gamma-ray5 bands. A few transitional millisecond pulsars that swing between an accretion-powered X-ray pulsar regime and a rotationally powered radio pulsar regime in response to variations of the mass inflow rate have been recently identified6,7. Here, we report the detection of optical pulsations from a transitional millisecond pulsar. The pulsations were observed when the pulsar was surrounded by an accretion disk, and originated inside the magnetosphere or within a few hundreds of kilometres from it. Energy arguments rule out reprocessing of accretion-powered X-ray emission and argue against a process related to accretion onto the pulsar polar caps; synchrotron emission of electrons in a rotation-powered pulsar magnetosphere8 seems more likely.

PSR J1023+0038 is a 1.69-ms-spinning neutron star in a 4.75-h orbit around a 0.2 M☉ main-sequence-like companion, located at a distance of 1.37 kpc. It was discovered in 2008 as a rotationally powered radio pulsar8,10 releasing a spin-down power9 of 4.3 × 10^33 erg s^-1, corresponding to the mass accretion rate required to overcome the centrifugal barrier of the pulsar rotating magnetosphere and its propelling effect (assuming matter reaches the neutron star). Its gamma-ray10 and flat-spectrum continuum radio emission, consistent with a jet-like outflow10, add to the complex phenomenology of PSR J1023+0038 in the accretion disk state, possibly being manifestations of the interaction between the disk, the pulsar magnetosphere and its wind11,12,13,14. Archival observations15 indicate that PSR J1023+0038 was in a similar state in 2001. The optical counterpart of PSR J1023+0038, AY Sex, in the disk state is a g = 16.7 mag blue object that emits an average luminosity\(^{15,16}\) of \(L_{\text{opt}} \approx 10^{34}\) erg s^-1 in the 320–900-nm band. Most of the optical/UV emission originates from the outer regions of the disk, and from the companion star’s face illuminated by the pulsar’s high-energy radiation, which drives a \(\Delta g \approx 0.4\) mag modulation25 of the optical flux at the orbital period of the system.

During a 4-h-long observation carried out on 2–3 March 2016 with SiFAP, a fast photometer with 25-ns time resolution that was mounted at the 3.58 m INAF’s Telescopio Nazionale Galileo (TNG) in La Palma, Spain (see Methods), we discovered optical (320–900 nm) pulsations at the spin period of PSR J1023+0038 (Fig. 1). To detect the signal, we corrected the arrival times of the optical photons for the light travel time delays introduced by the pulsar orbit by using the ephemeris derived from the X-ray pulsations20 (Table 1). PSR J1023+0038 was in a disk-dominated state at the time of the SiFAP measurement, as inferred from Swift X-ray Telescope (XRT) observations performed within a few days of the optical observations (see Methods). The optical pulse profile comprises two peaks with a fractional amplitude that varied significantly over 20-min-long time intervals between a maximum value of \(A = (0.80 \pm 0.07)\%\) of the total average emission and values below the detectability level (\(A < 0.19\%\); Fig. 2). The maximum observed pulsed flux corresponds to \(L_{\text{opt}} \approx 0.01\)\(L_{\text{opt}} \approx 10^{34}\) erg s^-1. The lack of simultaneous X-ray observations prevented us from searching for possible changes taking place at the timescales set by the variability of the X-ray pulse amplitude21.

The region responsible for the optical pulsations cannot be larger than \(c P_{\text{orb}} \approx 500\) km, as delays introduced by light propagation at the speed of light in vacuum, \(c\), would smear them out. Comparison of the projected semi-major axis \(a\) sin(i) and epoch of the pulsar passage at the ascending node \(T_{n}\) derived from the orbital modulation of the optical pulse period with the ephemeris derived from X-ray pulsations, showed that the region emitting the optical pulsation must be centered within \(\delta T_{\text{p}} \approx 3\) sin(i)/30 km and \(\delta R_{\text{p}} \approx 2\pi a\sin(i)\sigma_{\text{p}}/P_{\text{orb}}\sin(i)\approx 300\) km of radial and azimuthal distance from the X-ray pulsar, respectively (see Table 1 and Methods). These values are comparable to or larger than both the \(r_{\text{cov}} \approx 24\) km corotation radius (for a 1.4 M☉ neutron star) of PSR J1023+0038, that is, the radius where the angular velocity of the pulsar magnetosphere equals the Keplerian velocity, and the \(r_{\text{w}} \approx 80\) km...
Fig. 1 | Coherent optical pulsations of PSR J1023+0038. Average Fourier power spectral density of the 320–900 nm optical photons observed by SiFAP mounted at the TNG, during four almost consecutive observations starting on 2 March 2016 at 23:40 (Coordinated Universal Time, UTC), for an exposure of 13.2 ks. The power spectrum was obtained sampling the time series at a time resolution of 0.1 ms and averaging the density measured in eight intervals, each 1.65 ks long. The times of arrival of optical photons were corrected for a known systematic drift of the SiFAP clock (see Methods), and converted to the barycentre of the Solar System and to the line of nodes of the binary system hosting PSR J1023+0038, using the parameters listed in Table 1. The peaks at 592.4 and 1184.4 Hz represent the first and the second harmonic of the coherent signal detected at the pulsar spin frequency. Inset: average, background-subtracted pulse profile obtained by folding the optical photons detected during the four TNG observations around $P_{\text{opt}}=1.687987444 \text{ ms}$ (Table 1). The pulse profile is sampled by 32 phase bins, error bars show uncertainties at 1σ confidence level, and two cycles are plotted for clarity. The dashed solid line is a Fourier decomposition with two harmonic components with fractional amplitudes $A_1=0.08\pm0.02\%$ and $A_2=0.34\pm0.02\%$ (giving a total amplitude $A=(A_1^2+A_2^2)^{1/2}$ 0.38±0.03% with respect to the net optical flux of PSR J1023+0038 averaged over an orbital cycle, $K=8.185\pm76\times10^{-6}$). The variance of the profile with respect to a constant is $\chi^2=438$ for 31 degrees of freedom. The probability of observing a pulse profile with such a high variance if it were due to a statistical fluctuation was just $\chi^2=0.19$, allowing us to rule out such a null hypothesis at a high confidence.

light cylinder radius, where closed magnetic field lines travel at the speed of light.

Reprocessing of the X-ray pulsations at the surface of the companion star and/or in the outer disk region, as observed in some X-ray binaries hosting a strongly magnetized and slowly rotating accreting pulsar2, is ruled out as the origin of the optical pulsations from PSR J1023+0038; the reprocessing regions would have a very different light travel time-delay orbital signature than that of a region $\delta r \approx 30–300 \sin(i)/\text{km}$ away from the neutron star, and their size would greatly exceed the maximum beyond which pulsations are washed out ($c P_{\text{spin}} \approx 500 \text{ km}$). The above problems could be circumvented if the X-ray pulsations were reprocessed in the innermost regions of the disk close to the boundary with the pulsar magnetosphere at $r_{\text{out}}$. However, reprocessing of the X-ray luminosity of PSR J1023+0038 ($L_{\text{x}}=7 \times 10^{33} \text{ erg s}^{-1}$) by an area of $\pi r_{\text{out}}^2$ located at a distance $r_{\text{out}}$ from the pulsar would convert to a brightness temperature of $T_{\text{B}}=(L_{\text{x}}/4\pi r_{\text{out}}^2)^{1/4} \approx 1.1 \times 10^5 \text{ K}$. The optical output would be more than a thousand times smaller than the observed pulsed flux, also ruling out this interpretation.

If X-ray pulsations observed in the disk state are due to channelled accretion onto the magnetic polar regions of the neutron star1,2, one may wonder whether the same polar hotspots could give rise to the observed optical pulses. The X-ray spectrum of accreting millisecond pulsars is modelled with unsaturated Comptonization of soft 0.5–1 keV photons emitted from the polar hotspots, by thermal electrons with temperature of tens of keV presumably located in the accretion column1. Cyclotron emission by the same electrons in the $B_0 \approx 10^9 \text{ G}$ magnetic field of this pulsar takes place at $E_{\text{cyc}} \approx (B_0/10^9 \text{ G})^2 \text{ eV}$ energies. Optical pulsed flux might result from self-absorbed cyclotron emission in the optically thick regime, with a Rayleigh–Jeans spectrum at the temperature of the Comptonizing electrons extending over a range of cyclotron harmonics2. For PSR J1023+0038, we use an electron temperature $kT_{\text{el}}$ of 100 keV, where $k$ is the Boltzmann constant, (photons up to $\sim80 \text{ keV}$ have been detected from it1,2) and an accreting polar region of conservatively large area $A \approx \pi R_\text{el}^2 (R_\text{in}/R_\text{el}) \approx 100 \text{ km}^2$ (refs 24,29), where $R_\text{el}=10 \text{ km}$ is the neutron star radius. The maximum pulsed luminosity in the visible band is

$$L_{\text{cyc}} \approx 3 \times 10^{29} \left( \frac{A}{100 \text{ km}^2} \right) \left( \frac{kT_{\text{el}}}{100 \text{ keV}} \right) \text{ erg s}^{-1}$$

which is more than ~30 times lower than the observed pulsed luminosity, $L_{\text{pulsed}} \approx 10^{31} \text{ erg s}^{-1}$. This does not favour an interpretation of the optical pulses in terms of cyclotron emission from electrons in the accretion columns; a detailed modelling will assess whether a larger optical efficiency can be achieved.

Finally, we explore the rotation-powered regime of pulsars. Synchronotron radiation from secondary relativistic electrons and positrons in the magnetosphere of pulsars is generally believed to produce non-thermal pulsed emission from the optical to the X-ray band1,2. Pulsed emission in the visible band has been detected from five rotation-powered pulsars20. They are all isolated, high-magnetic-field (>10^12 G) pulsars with young to moderate ages of 10^3–10^5 yr. Their efficiency in converting spin-down power to optical pulsed luminosity (measured in the B-band) spans a broad range from $\eta_{\text{opt}} \sim 5 \times 10^{-9}$ (for example, the Crab pulsar) to ~2 \times 10^{-7} \text{ (red circles in Fig. 3 and Supplementary Table 1)} . The efficiency of PSR J1023+0038, $\eta_{\text{opt}} \sim 2 \times 10^{-7}$, is higher; note that two middle-aged

| Parameter | X-rays | Optical (this work) |
|-----------|--------|---------------------|
| Right ascension, $\alpha$ (J2000) | 10:23:47.687198 | – |
| Declination, $\delta$ (J2000) | +00:38:40.84551 | – |
| Reference epoch, $T_0$ (MJD) | 57449.9028346 | – |
| Spin period, $P_0$ (ms) | 1.68798744420(13) | 1.687987444(6) |
| Orbital period, $P_{\text{orb}}$ (s) | 17115.5216924 | 17116.1±5.5 |
| Projected semi-major axis, $a$ (lt-s) | 0.343356(3) | 0.3434(1) |
| Epoch of ascending node | 57449.7258(3) | 57449.72579(9) |

$^a$Astrometric position determined from radio interferometry and referred to the standard equinox epoch J2000 (1 January 2000 at 12:00 Terrestrial Time). MJD is modified Julian date.

$^b$Extrapolation to the reference epoch $T_0$ of the period of the X-ray pulse1 estimated at $T_0=56458$ MJD, $P_0=1.68798744442521(3)$, taking into account the spin period derivative, $P_0=(8.665 \pm 0.026) \times 10^{-7}$. Values set by ref. 22 to be equal to those derived from radio pulsar timing.

$^c$The projected semi-major axis is expressed in light-seconds (lt-s), i.e. the distance travelled by light in the time interval reported. Extrapolation to the reference epoch $T_0$ of the epoch of passage at the ascending node determined from the formal orbital solution that models the epochs of passage at the ascending node determined from X-ray pulsations with a quadratic function $T_{\text{asc}, X}=56490.9694374476$ MJD, $P_0(T_0, T_{\text{asc}, X})=(-165.5 \pm 0.19)/T_{\text{asc}, X}$.

The slight difference with respect to the radio-derived epoch was attributed by ref. 22 to non-deterministic orbital variations.

Table 1 | X-ray and optical ephemerides of PSR J1023+0038

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pulsars with a spin-down power comparable to that of PSR J1023+0038 (for example, Geminga) have $\eta_{\text{opt}} \lesssim 10^{-6}$. A few more pulsar optical counterparts were proposed based on the positional coincidence of an optical source (blue circles in Fig. 3 and Supplementary Table 1); an increasingly higher efficiency is observed for a system with decreasing spin-down power and ages exceeding 10$^9$ yr.

Comparison of PSR J1023+0038—the first optical millisecond pulsar ever detected—with other rotation-powered millisecond pulsars is necessarily limited. A recent search$^{29}$ did not detect optical pulses down to a magnitude of $g \sim 25$ from PSR J0337+1715, a millisecond radio pulsar of similar spin-down power and distance as PSR J1023+0038, whose average optical pulses correspond to $g \gtrsim 22.5$. A candidate optical counterpart of PSR J2124-3358, a close-by 4.4-ms binary radio pulsar with spin-down power ~6 times lower than that of PSR J1023+0038, has been recently reported$^{31}$; its optical luminosity of $\sim 10^{26}$ erg s$^{-1}$ gives $\eta_{\text{opt}} \sim 10^{-6}$. Therefore, the optical efficiency of PSR J1023+0038 appears to be orders of magnitude higher than that of other millisecond pulsars, and lower only than the efficiency of the proposed optical counterpart$^{31}$ of the old (1.7$\times$10$^9$ yr), isolated 0.8 s pulsar, PSR J0108-1431.

The feature that singles out PSR J1023+0038 among rotation-powered pulsars is the presence of an accretion disk. If the disk does not prevent rotation-powered pulsar mechanisms from working, the interaction between pulsar magnetosphere$^{24,25}$ and/or its wind$^{26,27,28}$ with the disk plasma may evaporate enough material to disperse radio pulsations, which may not be observable (radio pulsations have not been detected$^{26,27,28}$ since an accretion disk formed in 2013). Moreover, it would form a shock where electrons and positrons could be accelerated to the energies (1–20 MeV) required to radiate optical synchrotron photons, in the field of $B \approx 2 \times 10^8$–10$^9$ G of the magnetospheric region inward of the light cylinder of PSR J1023+0038. This might be the reason for the higher $\eta_{\text{opt}}$ of PSR J1023+0038. The absence of a dramatic change of the spin-down rate when the source transitioned from a radio pulsar to a disk-dominated state$^{29}$ might provide additional evidence that a rotation-powered mechanism is working in PSR J1023+0038, despite the presence of a disk.

Our discovery of optical pulsations from PSR J1023+0038 demonstrates that the magnetosphere of old, weakly magnetic and quickly spinning neutron stars can give rise to such signals when surrounded by an accretion disk. This new observational window provides a promising diagnostic to probe the physics of millisecond pulsars in close binary systems, and to discover new millisecond pulsars in low-mass X-ray binaries and in unidentified gamma-ray sources obscured in the radio band by matter enshrouding the system. The optical pulsations observed from PSR J1023+0038 are still open to different interpretations. The pulsed optical luminosity rules out disk reprocessing of accretion-powered X-ray emission and is also hard to reconcile with cyclotron emission from matter accreting onto the neutron star polar caps. We argued that the observed optical pulse emission could be due to synchrotron emission by relativistic electrons in the magnetosphere of a rotation-powered pulsar. We note that the observed optical efficiency of PSR J1023+0038 exceeds by about three decades that of pulsars of comparable spin-down luminosity. That may be due to the shocked magnetized environment that results from the interaction between the rotation-powered pulsar magnetosphere and the accretion disk, a characteristic of PSR J1023+0038 and of other transitional millisecond pulsars. Future observations will assess whether the process responsible for optical pulsations from PSR J1023+0038 coexists or alternate with accretion-powered X-ray pulsations.

Methods

The optical dataset. We observed PSR J1023+0038 with the Silicon Fast Astronomical Photometer (SiFAP) mounted at the Nasmyth B focus of the 3.58 m Telescopio Nazionale Galileo (TNG), in La Palma Spain$^{12}$, exploiting the focal plane of the Device Optimized for the LOw RESolution (DOLORES) instrument$^{11}$. SiFAP is a two-channel ultrafast optical photometer developed at the Department of Physics of the University of Rome (La Sapienza)$^{13,14}$. It comprises two multi pixel photon counters (MPPCs) modules manufactured by Hamamatsu Photonics, one aimed at measuring photon counting rates from the target and the other at
monitoring a reference star in the field of view (FoV). These MPPCs integrate signals in configurable time windows from 100 ms down to 1 ms via a standard USB interface. They also provide an analog output that can tag the time of arrival of individual photons with a time resolution of 25 ns and a discriminated output capable of counting photons in time bins of 20 μs, through two independent custom electronic chains. A global positioning system (GPS) unit yields a reference time marker via the pulse per second (PPS) signal with 25 ns resolution at 50% of the rising edge of the pulse itself. Observations of PSR J1023+0038 were performed starting on 2 March 2016 at 21:40 (UTC), each lasting 3.3 ks (Supplementary Table 2). A white filter covering the 320–900 nm band was used in all the observations (Supplementary Fig. 1). The airmass ranged between 1.13 and 1.74, while seeing conditions varied from 0.8 arcsec up to 3 arcsec. The FoV of the sensor is ~30 arcsec, ensuring that signal loss was negligible. A reference star, UCAC 454-048424 (ϖ = 10.23 ± 0.39, δ = +54.80 ± 0.08, and PSR J1023+0038 was simultaneously observed, at a lower time resolution (1 ms). We estimated the sum of the sky background and of the dark count rate by observing a region located 25 arcsec away from the target towards the east direction for 120 s (between the third and the fourth exposure), which yielded an average count rate of 8.85 ± 0.9, amounting to roughly 50% of the total photons recorded while pointing at the direction of PSR J1023+0038. The contribution of the dark count rate alone was ~2.5 × 10^{-4} of the total.

**Temporal analysis.** We considered data taken by the SiFAP at the maximum possible time resolution of 25 ns. A systematic effect introduced a significant difference between the actual photon arrival times and those measured by the SiFAP system quartz clock. In each of the four observations, the total time elapsed between the two GPS-PPS signals marking the beginning and the end of each exposure, which we took as a reference, ∆GPS = 3 ± 0.03 s, was slightly longer than the time interval measured by the SiFAP clock, ∆SiFAP = ∆GPS + ∆t, with ∆t = 6 ± 10^{-4} s. We assumed that this difference was due to a constant drift of the time recorded by the SiFAP clock with respect to the actual time, yielding a cumulative linear effect on the recorded times of arrival, ∆t_{corr}. We corrected the arrival times by using the following relation, t_{corr} = t_{SiFAP} + (∆GPS/∆SiFAP) × ∆t_{corr}.

We checked this procedure by applying it to the arrival times recorded during an observation of the Crab pulsar performed with the 1.52 m Cassini telescope (https://davide2.bsaastro.it/loiano/152cm-telescope/) of the Bologna Astronomical Observatory on 2 December 2016 at 00:56 (UTC), with the same equipment. Using the uncorrected arrival times, a spin period of P_{Crab} = 33.7296127(23) ms was obtained; by applying the correction above we recovered a period of P_{Crab} = 33.7298827(23) ms, fully compatible with that extrapolated from the monthly radio ephemeris provided by the Jodrell Bank Observatory (http://www.jb.man.ac.uk/pulsar/crab/crab2.txt), P_{Crab} = 33.7298810(1) ms. This proved the robustness of the SiFAP clock correction. We also determined through laboratory tests (using a frequency/period counter) the maximum jitter of the system quartz clock period (∆P_{48} = 8.000009873(1) × 10^{-6}) determined by a thermal drift, ∆P_{th} = 8.000000000(4) × 10^{-6} s. The relative uncertainty on the measured period introduced by the thermal drift is thus 6 × 10^{-7}, that is, about 60 times smaller than the relative accuracy of our determination of the spin period of PSR J1023+0038 (Table 1). The effect of thermal drift could be safely neglected.

We reported the times of arrival of the corrected photons to the Solar System Barycentre, using the JPL DE431 ephemeris (http://ssd.jpl.nasa.gov/horizons.cgi) and the source radio astrometric position9. A search for periodicities at the known Barycentre, using the JPL DE431 ephemeris (https://ssd.jpl.nasa.gov/horizons.cgi) showed no significant signals smaller than the relative accuracy of our determination of the spin period of PSR J1023+0038 (ref. 1), allowing us to safely conclude that the source was in such state during the TNG observations performed less than a day before the second Swift observation considered here (id. 33012, seq. no. 113).

### Data availability

The barycentered SiFAP data that support the findings of this study are available in figshare with the identifier doi:10.6084/m9.figshare.5341192.

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