

Letter to the Editor

A puzzling 2-hour X-ray periodicity in the 1.5-hour orbital period
black widow PSR J1311−3430

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ABSTRACT

Time-domain analysis of an archival XMM-Newton observation unveiled a very unusual variability pattern in the soft X-ray emission of PSR J1311−3430, a black widow millisecond pulsar in a tight binary (Pb ≈ 93.8 min) with a very low-mass (M ≈ 0.01 Ms) He companion star, known to show flaring emission in the optical and in the X-rays. A series of six pulses with a regular recurrence time of 124 min is apparent in the 0.2–10 keV light curve of the system, also featuring an initial, bright flare and a quiescent phase lasting several hours. The X-ray spectrum does not change when the pulses are seen and is consistent with a power law with photon index Γ ≈ 1.6, also describing the quiescent emission. The peak luminosity of the pulses is of several 10³⁴ erg s⁻¹. Simultaneous observations in the U band with the Optical Monitor onboard XMM and in the g' band from the Las Cumbres Observatory do not show any apparent counterpart of the pulses and only display the well-known orbital modulation of the system. We consider different hypotheses to explain the recurrent pulses: we investigate their possible analogy with other phenomena already observed in this pulsar and in similar systems and we also study possible explanations related to the interaction of the energetic pulsar wind with intrabinary material, but we found none of these pictures to be convincing. We identify simultaneous X-ray observations and optical spectroscopy as a possible way to constrain the nature of the phenomenon.

Key words. X-rays: stars – pulsars: individual: PSR J1311−3430 – binaries: close

1. Introduction

The population of rotation-powered millisecond pulsars (MSP) features a sizeable fraction of binary systems (slightly less than 60%, according to the ATNF pulsar database¹). Among them, of particular interest are those with very tight orbits (Pb ≪ 1 day) and very low-mass companion stars, classified (see e.g. Roberts [2013] as “black widows” (BW, companion star mass < 0.1 Ms) and “redbacks” (RB, companion star mass 0.1–0.3 Ms). BW have heavily degenerate companions, being evaporated by the pulsar radiation, and are in the path of becoming isolated MSP, while RB have partially degenerate companion stars and are supposed to be systems in the transition between the accretion-powered and the rotation-powered phase, in which the mass transfer from the companion has temporarily halted (see Roberts [2013], for a review). A recent, important achievement has been the discovery of transitional systems, switching between a rotation-powered regime in which they behave as a “canonical” RB MSP, and an accretion-powered regime, in which they behave as a peculiar, subluminous low-mass X-ray binary (see Papitto & de Martino [2023], for a recent review). All of these systems are crucial to understand the overall pulsar recycling scenario and the ablation process (see Bhattacharya & van den Heuvel [1991], for a review); they are formidable laboratories for studying the acceleration, composition and shock dynamics of the highly relativistic pulsar winds (see e.g. van der Merwe et al. [2020]).

The target of this investigation, PSR J1311−3430, was discovered in the γ-rays (E > 100 MeV) thanks to a blind search for pulsations in Fermi LAT data (Pletsch et al. [2012]) and soon after it was also detected as an eclipsing radio pulsar (Ray et al. [2013]). It is an energetic millisecond pulsar with P = 2.5 ms and spin-down luminosity Eot = 5 × 10³⁴ erg s⁻¹, in a tight (Pb ~ 93.8 min) binary system (Pletsch et al. [2012]) with a very low-mass star (M ≈ 0.01 Ms). The companion star’s rotation is tidally locked at the orbital period; the star side facing the pulsar is heated to ~ 14,000 K, while the far side is much cooler (~ 4500 K, see Romani et al. [2012]). This, coupled to ellipsoidal variations due to the tidal deformation of the star, produces a very large (~ 4 mag) modulation in flux and in colour of the optical counterpart at the orbital period (Kataoka et al. [2012]; Romani [2012]). The pulsar radiation is also powering an intense and highly variable evaporative wind from the companion star, which appears to be fully stripped of hydrogen (H abundance n(H) < 10⁻⁵, see Romani et al. [2012]; 2015). Steady X-ray emission is observed from the system in the 0.2−10 keV energy range, with a power law spectrum (photon index Γ ~ 1.6) and little or no orbital variability, generally interpreted as produced at the intrabinary shock between the pulsar and the companion star winds (Kataoka et al. [2012]; Romani et al. [2012]; An et al. [2017]).

Dramatic flaring activity is seen in the optical and near infrared (up to 6 times the flux at the peak of the orbital modulation), originating on the companion star surface and likely powered by the star’s magnetic field. Intense flares are also observed in the soft X-rays (up to ~ 10 times the quiescent level, Kataoka et al. [2012]; An et al. [2017]), possibly as a further
manifestation of the release of energy stored in the companion star’s magnetic field. Flares in different energy ranges are correlated and may occur at any orbital phase, with a duty cycle in the 10%-20% range (An et al. 2017).

We are carrying out a large project aimed at studying the temporal properties of soft X-ray sources (see De Luca et al. 2021) listed in the X-ray Multi-mirror Mission (XMM-Newton) serendipitous source catalog. In this context, we discovered a very unusual phenomenon in an archival observation of PSR J1311–3430. We describe the peculiar, observed variability pattern in the next section. Section 3 gives detail on the behaviour of the source in the optical and near ultraviolet band, as derived from simultaneous observations. Possible interpretations and implications of the phenomenon are discussed in Section 4.

2. Peculiar X-ray pulses from PSR J1311–3430

We analyzed an XMM-Newton observation of PSR J1311–3430 performed on 2018, February 9 (72 ks exposure time). Results from an older observation XMM-Newton will be given in Sect. 2.3. We used data collected from the pn camera (Strüder et al. 2001) and from the two MOS cameras (Turner et al. 2001) of the European Photon Imaging Camera (EPIC) instrument. Using an updated version of the EXTraS software (De Luca et al. 2021), we generated a background-subtracted light curve of the source in the 0.2–10 keV energy range using all exposure time – the EXTraS pipeline features a detailed modelling and subtraction of the time-variable EPIC instrumental background. As shown in Figure 1 (top panel), PSR J1311–3430 undergoes an initial, rapidly decaying trend. After a phase of quiescence with little or no variability, the behaviour changes and a very peculiar series of six “pulses” is seen in the second half of the light curve, the last pulse being truncated at the very end of the observation. We may safely exclude an instrumental origin, as the profile of the pulses does not correlate with the variability of the particle background, and no similar pulses are seen in the light curves of other sources in the EPIC field of view. The regular time spacing between the pulses is apparent, in spite of variability in the peak flux and in the time profile of different pulses.

2.1. Temporal properties

To better characterise the temporal properties of the pulses, we extracted the Power Density Spectrum (PDS) from the light curve of 2018, February after excluding the first portion (about 10 ks of data), dominated by the bright flare. Fitting a Lorentzian function to the main peak in the resulting PDS yields a central frequency $f_c = 1.346 \pm 0.007 \times 10^{-4}$ Hz, corresponding to a time scale of $\sim 7430$ s ($\sim 124$ min) – this is the recurrence time of the pulses. The full width at half maximum (FWHM) of the Lorentzian is $1.8 \pm 0.2 \times 10^{-5}$ Hz, which yields a nominal quality factor $Q = f_c / \Delta f = 7.5$, where $\Delta f$ is the FWHM of the peak in the PDS. We note that the FWHM of the peak is consistent with the frequency resolution of the data ($\sim 1.7 \times 10^{-5}$ Hz), so that results on the coherence of the signal should be taken with caution.

We also performed epoch folding of the same portion of the light curve (the initial flare being excluded), with different trial periods. We fitted a $\sin^2$ function (appropriate for a sinusoidal signal) to the very prominent peak in the resulting periodogram and we evaluated $P = 7450 \pm 50$ s, the error being computed according to Leahy (1987) and to be taken with caution because of the non-sinusoidal shape of the pulse. The coherence of the modulation was investigated by measuring peak time delays along the light curve by correlating a one-period long data segment with a template of the pulse shape produced by folding the light curve at $P = 7450$ s. The rms variation relative to a fully coherent modulation is $\sim 440$ s, a factor $\sim 10$ larger than the $1\sigma$ statistical uncertainty on the determination of each pulse time delay. Although the data are consistent with a strictly periodic signal, considering the small number of pulses and their variable profile we cannot exclude that the phenomenon is quasi-periodic.

2.2. Spectral properties

We studied the energy spectrum of the source and its variability as a function of the time, to search for possible spectral changes associated with the series of pulses (as well as with the initial flare).

As a first step, we generated energy-resolved light curves in the $0.2$–$1.5$ and $1.5$–$10$ keV energy ranges (each including about 50% of the overall source photons) and we computed the hardness ratio as a function of the time. This turned out to be fully consistent with a constant (p value $> 95\%$), suggesting that no significant spectral changes occur in spite of the peculiar, large flux variability. We also folded the hardness ratio curve at $P = 7450$ s, but no hints of modulation were found.

Then, we performed time-resolved spectroscopy. Source photons were selected from a circle with a radius of $25''$. Background photons were extracted from a source-free region located in the same CCD as the source. Ad-hoc response and effective area files were generated with the SAS software. Spectral modelling was performed with Xspec. We quote uncertainties at the 68% confidence level for a single parameter of interest. First, we studied the time-averaged spectrum, which turned out to be well described (p value $= 2.2 \times 10^{-7}$) by a power law with photon index $\Gamma = 1.53 \pm 0.04$, absorbed by a column $N_H = (5 \pm 1) \times 10^{20}$ cm$^{-2}$. The observed flux in the $0.2$–$10$ keV energy range is $(1.9 \pm 0.1) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Then, we selected time intervals corresponding to the initial flare, to the peaks of individual pulses and to the low-flux, quiescent level, based on a simple count rate threshold, and we extracted three spectra. No significant spectral changes could be detected. We show in Table 1 results from a simultaneous fit to the three spectra, linking the column density to be the same and leaving the photon index and normalization as free parameters (p value$=0.83$). The emission is always consistent with the time-averaged spectrum.

2.3. Older, archival X-ray observations

We also studied the only previous XMM-Newton observation of the system, performed on 2014, August 2 (120 ks). The source background-subtracted light curve features a rather bright flare at the beginning of the observation, but does not show any hint of recurring pulses with a regular time spacing (Figure 5b of An et al. 2017, shows the source light curve from that dataset). We repeated both the PDS analysis and the folding analysis on

\[\text{Results do not change if the quiescent phase is also excluded.}\]
that light curve. No significant periodic or quasi-periodic signals were detected in either method.

For completeness, we also performed spectroscopy of the 2014, August observation, following the same procedure described above. In this case, the spectra of the flaring period (~15 ks) and of the quiescent period (~100 ks) turned out to be different. A simultaneous fit where both the normalizations and the photon indexes were allowed to vary between the two intervals results in an acceptable fit (p-value = 10⁻³) with $N_H = (2±2)\times10^{20}$ cm⁻², $\Gamma_{\text{flare}} = 1.23±0.05$ and $\Gamma_{\text{quiesce}} = 1.57±0.07$. Our results are fully consistent with those of [An et al. (2017)].

We note that the flaring period caught by this observation is remarkably longer (~10 times), although fainter, than the one seen in the 2018 observation and this results in smaller errors on the best fit parameters. The photon index of the two flaring periods is compatible at the 2σ level.

Other X-ray observations of PSR J1311–3430 were performed with Chandra, Suzaku and Swift/XRT, but they lack the sensitivity and/or the uninterrupted exposure time needed to firmly identify similar X-ray pulses (see [Kataoka et al. 2012; Arumugasamy et al. 2015; An et al. 2017]).

### 3. Optical and近 Ultraviolet behaviour

We investigated the multiwavelength properties of the pulses, taking advantage of available data collected simultaneously with the XMM-Newton observation of 2018.

#### 3.1. Near-ultraviolet observations with XMM/OM

During the XMM-Newton observation of 2018, February 9, the Optical Monitor observed PSR J1311–3430 in Fast Mode with the U filter ($\lambda = 344$ nm, $\Delta \lambda = 84$ nm). We performed a standard data reduction and analysis using the dedicated SAS software. Count rate to flux conversion was performed using the conversion factors derived from observations of white dwarf standard stars provided by the calibration team.

The resulting light curve (see Figure 1 middle panel) shows the well-known modulation at the orbital period of the system, with maxima corresponding to the companion star superior conjunction (i.e. its heated side seen face-on). The only apparent deviation from this trend is an obvious counterpart of the X-ray flare occurring at the beginning of the observation (the recovery from the flare having a different time profile in the two energy ranges).

We searched for possible UV variability correlated to the X-ray pulses. We selected time intervals corresponding to the peaks

### Table 1. Results of XMM-Newton time-resolved spectroscopy for the time intervals of the initial flare, the peaks of pulses (combined) and the low-flux, quiescent level. The three spectra are simultaneously fitted linking the $N_H$ value. The time-averaged results are also shown for comparison.

| Interval   | Exp.(pn/MOS) | $N_H$ $10^{20}$ cm⁻² | $\Gamma$ |
|------------|--------------|----------------------|---------|
| Flare      | 0.5/1.9      | 5±1 (linked)         | 1.60±0.13 |
| Pulses     | 13.1/15.1    | 5±1 (linked)         | 1.54±0.07 |
| Quiescence | 39.3/44.7    | 5±1 (linked)         | 1.55±0.07 |
| Total      | 60.7/70.1    | 5±1                  | 1.53±0.04 |

3.2. Optical observations with LCO

Ground-based observations of PSR J1311–3430 were performed simultaneously with the XMM-Newton, 2018 February 9 observation, with the Sinistro camera at the 1m telescope at Las Cumbres Observatory (LCC), in the $g'$ band ($\lambda = 477$ nm, $\Delta \lambda = 150$ nm). 103 observations with 300 s exposure time were performed. We retrieved images reduced with the BANZAI pipeline from the LCO data archive. We ran a standard source detection using the Sextractor software ([Bertin & Arnouts 1996]). The target was detected in part of the observations only, thus we also performed forced aperture photometry at its position. With the main aim of investigating the flux variability as a function of the time, we performed a quick photometric calibration using a set of USNO-B1 stars.

The resulting light curve is shown in Figure 1 (bottom panel). The orbital modulation is clearly visible, minima being poorly constrained because of a low signal-to-noise. The recovery from the initial bright flare is also apparent. Unfortunately, there is only partial LCO coverage of the time intervals where the X-ray pulses are seen, because of gaps in the series of observations and/or of poor atmospheric conditions. To search for variability correlated to the X-ray pulses, we combined data from multiple observations corresponding to two different optical minima, one aligned with an X-ray pulse and the other simultaneous with X-ray quiescent emission and repeated the analysis. Although the signal to noise is low, we find some evidence of enhanced $g'$ flux associated with the X-ray pulse ($g' = 21.6 ± 0.3$) with respect to the X-ray quiescent level ($g' = 23.4 ± 0.5$). The difference between the two fluxes corresponds to a 50% ± 20% variation with respect to the average value seen during the orbital modulation. For a comparison, the X-ray fluxes in the two selected intervals differ by a factor 4.5 ± 0.8).

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[6] https://www.cosmos.esa.int/web/xmm-newton/sas-watchout-uvflux

[7] proposal ID: NOAO2018A-021

[8] https://lco.global/

[9] https://lco.global/documentation/data/BANZAIpipeline/

[10] https://archive.lco.global/
3.3. The initial flare

We also studied the multiwavelength properties of the initial flare (see Figure 1). In the first 500 s of the OM observation, the U band flux is a factor 7 ± 1 higher than the average level measured when the orbital modulation is seen. In the same time interval, the g’ light curve displays a factor 5.7 ± 0.3 increase with respect to the average level (measured across the orbital modulation, as in the case of the U band). In the X-rays, the flux in the same time interval is a factor 24 ± 3 higher than the quiescent level. In all cases, the flux variation is computed as \((F_{\text{peak}} - F_0)/F_0\) where \(F_0\) is the average or quiescent level. Results for the initial flare and for the pulses are compared in Table 2. These suggest a different spectral energy distribution for the two phenomena, the pulses having higher \(F_X/F_U\) and \(F_X/F_{g'}\) ratios than the flare.

4. Discussion

Interpretation of the periodic X-ray pulses is challenging. First, their recurrence time of \(\sim 124\) min is puzzling and requires the identification of a characteristic frequency in the system different from the \(\sim 94\) min orbital periodicity of the binary. Second, the phenomenon is transient in nature. The series of pulses starts in the middle of the 2018 XMM-Newton observation, after a phase of quiescent X-ray emission lasting several hours. It
The possible enhanced g' emission associated to the pulses could be related to He I line emission from the wind, as observed by Romani et al. (2015).

Table 2. Multiwavelength properties of the pulses and of the initial flare. For each energy range, we computed the relative flux variation for the pulses as \( (F_{\text{peak}} - F_0) / F_0 \), where \( F_{\text{peak}} \) is the flux at the peak of the pulses and \( F_0 \) is the quiescent flux level (see Sect.3.1 and 3.2). The same relative flux variation was computed for the initial flare (see Sect.3.3).

| Energy band | Pulses | Flare |
|-------------|--------|-------|
| X-rays      | \( 5.00 \pm 0.35 \) | \( 24 \pm 3 \) |
| U band      | \( 0.32 \pm 0.19 \) | \( 7 \pm 1 \) |
| g' band     | \( 0.5 \pm 0.2 \) | \( 5.7 \pm 0.3 \) |

is not seen in the longer XMM-Newton observation performed in 2014. Third, the pulses are seen in very different geometric configurations of the binary system, occurring at either the companion star superior conjunction, inferior conjunction, a descending configuration of the binary system, occurring at either the co-moving rotating frame or producing quasi-periodic flares. Such flares are seen to occur on a variety of time scales, from few s to ~ 1 hr, and occasionally display a quasi-periodic pattern, somehow reminiscent of the series of pulses seen from PSR J1311−3430 (see e.g. Jaodand et al. 2021, Strader et al. 2021). As a matter of fact, the physics of the flaring mode in transitional systems is not understood. Are the X-ray pulses from PSR J1311−3430 powered by the same (unknown) mechanism? Multiwavelength phenomenology does not support this picture. Transitional pulsars in their flaring mode show correlated emission in the X-rays and in the near infrared to near ultraviolet range, which is not seen in the case of our pulses (see Sect.4). The luminosity of X-ray flares from transitional pulsars \( (2 - 7 \times 10^{34} \text{erg s}^{-1}) \) is also higher by \( \sim 2 \) orders of magnitude than that of the pulses of PSR J1311−3430. Should this analogy be proven by future observations, it would have extremely interesting implications since a common mechanism would be at work in very different contexts. In fact the flaring mode in transitional MSPs is seen when they are accreting, while accretion is not occurring in PSR J1311−3430, where the momentum flux of the pulsar overwhelms that of the companion’s wind.

We may also explore other possible explanations for the pulses within the standard picture for BW systems. The lack of X-ray spectral changes across the complex variability pattern suggests that pulses could be produced by the same process generating the “quiescent” emission: synchrotron emission at the intrinsic shock (IBS) between the pulsar’s relativistic wind and the companion star’s massive wind. The position and shape of the IBS depend on the momentum balance between the pulsar and companion winds, as well as on the orbital velocity (Arons & Tavani 1993). These quantities also determine the observed high-energy flux from the IBS, depending on the fraction of the pulsar spin-down power intercepted by the IBS (setting the IBS luminosity) and on Doppler boosting of the X-ray emission when the mildly relativistic post-shock plasma flow is directed along the line of sight (see e.g. Arons & Tavani 1993, Kandei et al. 2019, van der Merwe et al. 2024, Cortes & Sironi 2022). Interpretation of the pulses within this scenario is not easy. Large inhomogeneities in the companion star wind would be required to trigger major changes in the IBS luminosity and/or in its emission pattern. Explaining the periodicity would be more difficult: on the one side, an unknown (transient) mechanism producing periodic variations in the companion star wind properties would be required; on the other side, it seems hardly conceivable to observe pulses with similar properties associated with totally different orbital phases of the system, in view of the major role of the geometry of sight in shaping the IBS observed phenomenology.

To explain the regular recurrence time of the phenomenon, we could invoke the existence of a third body in the system (e.g. a planet, as in the case of PSR B1257−20, Wolszczan & Frail 1992), interacting with the pulsar radiation and wind and producing (e.g. through a shock/via non-thermal bremsstrahlung) the observed X-ray pulses. With an orbital period of ~ 124 min, it would stay on an orbit only ~ 20% larger than the one of the known companion star, which would pose severe problems in explaining the system’s long-term stability, the lack for any direct

\[ \text{erg s}^{-1} \]
evidence of the putative third body in the near infrared/optical and in the timing phenomenology of the millisecond gamma-ray pulsar, as well as the transient behaviour of the pulses. The possibility of an object sitting in a larger orbit \((P \gg 124\text{ min})\) could also be considered; in that case, one would need a mechanism “illuminating” the object once per 124 min cycle, which seems a rather contrived picture. We also note that searches for planetary companions to millisecond pulsars, taking advantage of the very accurate timing achievable for such systems, proved planets to be a rarity (see e.g. Behrens et al. 2020).

As a further alternative, we could consider an orbiting, dense “blob” of ablated gas. Such a blob, originating from inhomogeneities in the companion star wind and/or from instabilities in the post-shock flow, should be confined within the region occupied by the shocked companion star wind – expected to have the shape of the apex of an Archimedean spiral, bent by Coriolis force and radiation pressure (Rasio et al. 1989; Arons & Tavani 1993) – and would participate in the quiet outward motion of the shocked wind at a speed comparable to the star orbital velocity (Romani et al. 2015). Indeed, BW and RB systems show both regular eclipses as well as “mini-eclipses” that occur at sporadic orbital phases, are not stable in orbital phase from one orbit to the next, and likely indicate such blobs of intra-binary material (see e.g. Fig. 5 of Archibald et al. 2015). However, it would be difficult to explain the production of copious X-rays in such a slow flow, and the persistence of a regular recurrence time in the emission over ~ 8 system revolutions.

To assess the actual viability of the above hypothesis, detailed calculations and modelling would be needed, which are beyond the scope of this letter.

An important piece of information would be the evaluation of the duty cycle of the X-ray pulses. In the soft X-rays, the only available observations with the sensitivity and long, uninterrupted exposure needed to firmly identify the phenomenon are the two XMM-Newton ones. At other wavelengths, Fermi/LAT data do not have the sensitivity to detect individual pulses. Turning to lower energies, we note that Romani et al. (2015) published trailed spectra to show the spectral evolution of PSR J1311–3430 in the optical range as a function of the orbital phase, based on Keck/LRIS data, collected in 2013, February and covering ~ 3 orbital periods (see their Figure 2). A very interesting feature is a series of three bright “flares”, consisting of He I line emission only (thus, coming from circumstellar gas), clearly apparent in the red branch of the spectrum. It can be easily seen that their time spacing is about the same that we observe between our X-ray pulses. Thus, it is very tempting to relate these three He I line emission “flares” to the same phenomenon we observe in XMM-Newton 2018 data – He I line emission being possibly excited by X-ray periodic pulses. Under this assumption, on the one side study and modelling of the Keck 2013 data could constrain the position and velocity of the gas illuminated by the X-ray pulses, possibly constraining the emitting region of the pulses themselves. On the other side, the periodic mechanism triggering the pulses would have a larger duty cycle and thus there could be important chances to re-observe it. Simultaneous X-ray observations and optical spectroscopy could confirm the picture and shed light on this puzzling phenomenon, potentially very relevant for our understanding of BW systems and of the overall evolution of MSP.

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12 Possible evidence for a very low-mass third body gravitationally tied to the Black-widow Pulsar PSR J1555−2908 based on accurate γ-ray timing was recently reported by Nieder et al. (2022).

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