Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **447,** 1299–1303 (2015) doi:10.1093/mnras/stu2533

Probing large-scale wind structures in Vela X–1 using off-states with *INTEGRAL*

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Accepted 2014 November 28. Received 2014 November 28; in original form 2014 October 17

ABSTRACT

Vela X–1 is the prototype of the class of wind-fed accreting pulsars in high-mass X-ray binaries hosting a supergiant donor. We have analysed in a systematic way 10 years of *INTEGRAL* data of Vela X–1 (22–50 keV) and we found that when outside the X-ray eclipse, the source undergoes several luminosity drops where the hard X-rays luminosity goes below $\sim 3 \times 10^{35}$ erg s^{-1}, becoming undetected by *INTEGRAL*. These drops in the X-ray flux are usually referred to as 'off-states' in the literature. We have investigated the distribution of these off-states along the Vela X–1 $\sim$ 8.9 d orbit, finding that their orbital occurrence displays an asymmetric distribution, with a higher probability to observe an off-state near the pre-eclipse than during the post-eclipse. This asymmetry can be explained by scattering of hard X-rays in a region of *ionized* wind, able to reduce the source hard X-ray brightness preferentially near eclipse ingress. We associate this ionized large-scale wind structure with the photoionization wake produced by the interaction of the supergiant wind with the X-ray emission from the neutron star. We emphasize that this observational result could be obtained thanks to the accumulation of a decade of *INTEGRAL* data, with observations covering the whole orbit several times, allowing us to detect an asymmetric pattern in the orbital distribution of off-states in Vela X–1.

Key words: stars: neutron – X-rays: binaries – X-rays: individual: Vela X–1.

1 INTRODUCTION

Vela X–1 is an eclipsing and detached high-mass X-ray binary (HMXB) hosting an X-ray pulsar ($P_{\rm spin} \sim 283$ s; McClintock et al. 1976) that accretes matter from the wind of its B0.5Ib companion HD 77581 (see Rawls et al. 2011 and references therein). Located at a distance of 1.9 kpc (Sadakane et al. 1985), the orbital period of the system is 8.96 d (van Kerkwijk et al. 1995; Kreykenbohm et al. 2008), implying that the neutron star orbit is embedded in the companion wind.

The structure of the supergiant wind has been studied at different wavelengths, by means of ultraviolet and optical spectroscopy (Kaper, Hammerschlag-Hensberge & Zuiderwijk 1994; van Loon, Kaper & Hammerschlag-Hensberge 2001) and X-ray spectroscopic studies at different orbital phases (Eadie et al. 1975; Nagase et al. 1986; Sato et al. 1986; Haberl, White & Kallman 1989; Lewis et al. 1992; Sako et al. 1999; Schulz et al. 2002; Goldstein, Huenemoerder & Blank 2004; Watanabe et al. 2006; Fürst et al. 2010; Doroshenko et al. 2013; Martínez-Núñez et al. 2014 and references therein). These studies indicate the presence of both cold and hot gas components in the system, consistent with photoionization of the stellar wind produced by the X-ray pulsar, leading to the formation of a so-called photoionization wake trailing the neutron star (Fransson & Fabian 1980; Kaper et al. 1994; Feldmeier et al. 1996; van Loon et al. 2001), confirmed by simulations (Blondin et al. 1990; Blondin, Stevens & Kallman 1991; Mauche et al. 2008).

The X-ray emission of Vela X–1 is persistent at a level of 10^{36} erg s^{-1}, although variable (within a factor of $\sim$10), showing rare giant flares together with so-called off-states, that manifest themselves as flux drops lasting a few pulse periods (Kreykenbohm et al. 2008; Doroshenko, Santangelo & Suleimanov 2011). The

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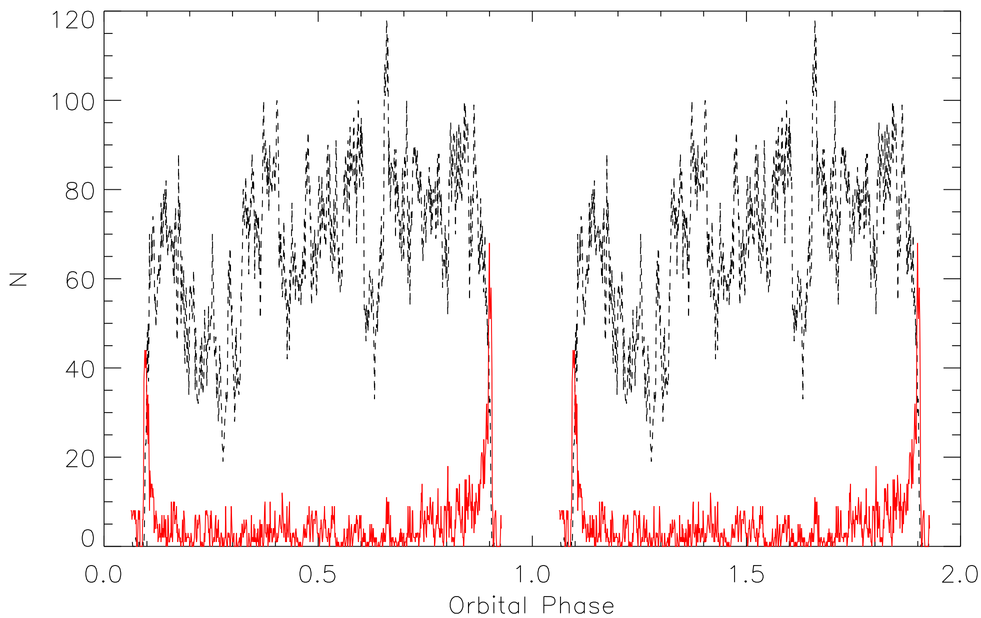

Figure 1. Histogram of the orbital distribution of the 100 s off-states in Vela X–1 (red solid curve, bin size $\Delta\phi = 0.001$, that is ∼774 s), compared to the orbital distribution of the detections (black dashed curve). Data are in the energy band 22–50 keV. Two orbits are shown for clarity. Eclipses are evident around $\phi = 0, 1, 2$, where Vela X–1 is not detected by *INTEGRAL* (see text for details).

observed variability is indicative of the presence of massive clumps in the supergiant wind (Nagase et al. 1986; Fürst et al. 2010). The global variability of Vela X–1 at hard X-rays with *INTEGRAL* has been studied by different authors (Fürst et al. 2010; Paizis & Sidoli 2014), pointing to a log-normal luminosity distribution.

Here, we present the first study of the orbital dependence of the *off-states* in Vela X–1, as observed in a decade of *INTEGRAL* observations (22–50 keV).

2 DATA ANALYSIS

In orbit for more than a decade, *INTEGRAL* enables an important long-term study of the hard X-ray properties of high-energy sources. In this paper, we used *INTEGRAL* archival public data of Vela X–1, from the beginning of the mission in 2002, up to revolution 1245, for a total of about 10.2 years of data. We have considered only the pointings in which Vela X–1 was within 12° from the centre and with a duration >1 ks. The raw data were downloaded from the ISDC Data Centre for Astrophysics into our local *INTEGRAL*/IBIS data base (Paizis et al. 2013). Standard analysis has been applied using OSA 10.0 software package.[1]

We produced individual pointing images (∼ks) and the associated detected source lists in the 22–50 keV energy band, as well as light curves binned over 100 s in the 22–50 keV band. The energy range was chosen to maximize the signal-to-noise ratio while minimizing the instrumental low threshold fluctuations (Caballero et al. 2012). We consider a threshold of 5σ for a detection in the imaging analysis and of 3σ for a detection in the light-curve analysis. In the obtained data set, Vela X–1 is within 12° from the centre for about 4.84 Ms, and it is detected at the imaging level in about 3.98 Msec (∼82 per cent of the time).

The analysis of the Vela X–1 cumulative luminosity distribution of a significantly overlapping data set (9 years of *INTEGRAL* data, instead of 10.2 years) has been reported in Paizis & Sidoli (2014). We refer to that paper for more details on the hard X-ray emission properties of Vela X–1, as observed by *INTEGRAL*. Here, we concentrate on the orbital distribution of the source's off-states.

[1] http://www.isdc.unige.ch/integral/analysis

3 RESULTS

We considered all *INTEGRAL* data (spanning about 10 years) where Vela X–1 was detected at the imaging level (∼ks). Indeed, non-detections at imaging level are found only during X-ray eclipses. We then extracted the hard X-ray light curves (22–50 keV) from these pointings, adopting a bin time of 100 s.

We found that, outside the eclipses, the source was not detected by *INTEGRAL* (implying a hard X-ray observed luminosity, $L_{\rm X} \lesssim 3 \times 10^{35}$ erg s^{-1}) during short time intervals (lasting from 100 s to a few hundred seconds). We will refer to these non-detections as 'off-states' or 'dips', regardless of the cause of diminished flux (similarly to the definition assumed by Kreykenbohm et al. 2008, who studied a subsample of *INTEGRAL* data of Vela X–1, at early times of the mission).

Assuming the ephemeris reported in Kreykenbohm et al. (2008), we studied the distribution of these off-states along the orbit. In Fig. 1, we compare the off-states distribution with the occurrences of the source detections (both at 100 s level) along the orbit. We found two remarkable features in the off-state distribution (red solid curve in Fig. 1): the first is that off-states occur at any orbital phase; the second and, more important, is that they cluster near the eclipse, but with an asymmetric profile: at late orbital phases, approaching the eclipse, the off-states are more numerous and span a broader phase interval than during the eclipse egress, where the peak in the off-states distribution is narrower.

To quantify this effect, we rebinned the off-states orbital distribution adopting a bin size of $\Delta\phi = 0.01$, and fitted this distribution (assuming an uncertainty on the N axis of $\sqrt{N}$) with a model consisting of two exponential functions (proportional to $e^{-\alpha_1\phi}$ and $e^{+\alpha_2\phi}$) together with a constant function, finding two significantly different exponents: $\alpha_1 = 32 \pm 2$ and $\alpha_2 = 79 \pm 4$, near eclipse

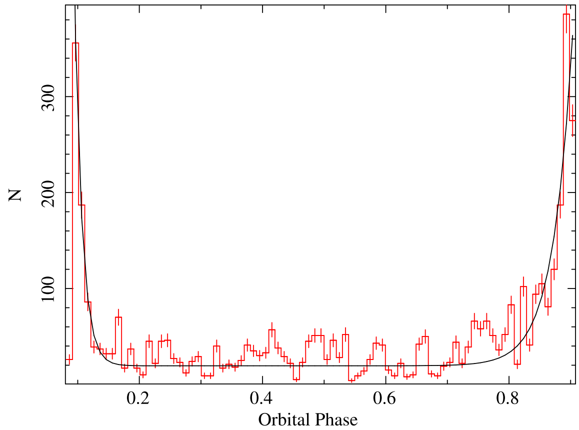

Figure 2. Histogram of the orbital distribution of the 100 s off-states in Vela X-1 (bin size $\Delta\phi = 0.01$, that is ~7740 s), fitted with a constant and two exponential functions. The exponents of the two exponential functions ($e^{-\alpha_1\phi}$ and $e^{+\alpha_2\phi}$) describing the enhanced frequency of off-states near eclipse egress and eclipse ingress are significantly different (see text).

egress ($\phi = 0.1$–0.2) and eclipse ingress ($\phi = 0.7$–0.9), respectively (Fig. 2).

Our analysis demonstrates that two different types of off-states co-exist in Vela X–1: the ones uniformly distributed along the orbit and the ones more concentrated near the X-ray eclipse, with a broader coverage in orbital phases near eclipse ingress than near eclipse egress.

The first kind of dips occurring at any orbital phase can be explained by intrinsic X-ray variability that causes the source to be undetected by *INTEGRAL*. When observed with more sensitive instruments below 10 keV, off-states usually show a spectral softening, thus suggesting that they are not simply due to obscuration by a dense wind clump passing in front of the X-ray pulsar, but by a change in the accretion regime or by the onset of a propeller effect. These dips have been studied in detail by several authors (e.g. Kreykenbohm et al. 2008; Doroshenko et al. 2011, 2012; Odaka et al. 2013; Shakura, Postnov & Hjalmarsdotter 2013; Fürst et al. 2014) and have been found also in other accreting X-ray pulsars (even in Supergiant Fast X-ray Transients; e.g. Drave et al. 2014).

The second kind of dips, asymmetric and clustered around the eclipses, could be discovered only by taking advantage of the long-term observations of Vela X–1 available with IBIS/ISGRI. This result points to a different mechanism, not intrinsic to the X-ray source. Indeed, the orbit is almost circular and cannot induce any variability in the accretion rate leading to dips preferentially seen at certain phases. Moreover, eclipse in Vela X–1 occurs near periastron (e.g. fig. 1 in Martínez-Núñez et al. 2014).

More likely, the two peaks in the off-states distribution near $\Delta\phi = 0.1$ and 0.9 probe the innermost denser regions of the supergiant wind. The larger orbital extent of dip occurrence in the pre-eclipse region can be induced by the passage into the line of sight of a large-scale *ionized* wind structure, able to produce a drop in the X-ray flux by scattering. This structure can be naturally associated with the photoionized wake (see below; e.g. Kaper et al. 1994).

4 DISCUSSION

Dips in the light curve of Vela X–1 have been observed since the early 1970s: in two orbital cycles observed with *Ariel V* (1.2–19.8 keV), four irregular dips were detected (with two dips at similar late orbital phases in both cycles) and an association with the obscuration by an accretion wake was proposed (Eadie et al. 1975; Charles et al. 1978).

Simulations by Blondin et al. (1990, 1991) have shown that three different wind structures are present in the stellar wind, excited by the presence of the accreting neutron star: the *accretion wake*, the *tidal stream* and the *photoionization wake*. A sketch of these three wind structures in Vela X–1 can be found in Kaper et al. (1994). The *accretion wake* around the neutron star can affect the column density variations along the orbit only around $\phi = 0.4$–0.5 orbital phases. The *tidal stream* is a permanent wind enhancement structure that is a source of strong orbital phase-dependent attenuation of soft X-rays, expected to produce a higher hydrogen column density from phase $\phi = 0.5$ up to the X-ray eclipse at phases $\phi = 0.9$–1.1. The production of the tidal stream depends on the orbital separation, being more evident in closer orbits (Blondin et al. 1991). An enhancement of the neutral absorption column density towards the neutron star at late orbital phases has been indeed observed in Vela X–1 (e.g. Nagase et al. 1986; Doroshenko et al. 2013 and references therein). Finally, the wind structure is strongly influenced by the neutron star orbit not only because of gravity but also because of the accretion X-ray emission produced by the compact object, that photoionizes the wind reducing the ability of the wind to be radiatively driven (Castor, Abbott & Klein 1975). This effect decreases the wind velocity near the neutron star and produces a wake of gas trailing behind the ionized wind, where faster wind collides with slower wind, leading to the formation of a so-called *photoionization wake* (Fransson & Fabian 1980; Blondin et al. 1990; Feldmeier et al. 1996). Evidence for a photoionization wake in Vela X–1 has been found also from optical spectroscopy (Kaper et al. 1994).

The orbital distribution of off-states we observed with *INTEGRAL* is consistent with the orbital phases spanned by the tidal stream discussed by Blondin et al. (1991) and by the photoionization wake (Kaper et al. 1994), that somehow overlap.

Thanks to the accumulation of a huge amount of *INTEGRAL* data, able to cover the entire orbit several times, we could study the orbital dependence of the occurrence of the off-states, finding an asymmetric distribution. We explain it with the presence of a large-scale *ionized* wind structure that scatters hard X-rays out of the line of sight, producing short off-states.

Scattering by the ambient wind is also the physical mechanism explaining both the residual X-ray emission observed during the eclipse and the soft X-rays excess visible in Vela X–1 spectrum (Haberl & White 1990; Haberl 1991; Lewis et al. 1992; Feldmeier et al. 1996).

Our finding of an asymmetry in the off-state distribution, with an enhanced number of off-states at late orbital phases, complements previous studies on the circumstellar matter in Vela X–1, starting from Eadie et al. (1975), Nagase et al. (1986), Haberl et al. (1989), Lewis et al. (1992) to the most recent works on the neutral hydrogen column density variations along the orbit as observed by ASM/*RXTE* (Fürst et al. 2010) and MAXI data (Doroshenko et al. 2013) in much softer X-ray bands. A hardening of the X-ray emission at late orbital phases was found by these authors, explained with denser gas into the line of sight due to the presence of a photoionization wake, with a column density, $N_{\rm H} = 1$–3×10^{23} cm^{-2}. Here, we were able to map the ionized component of this gas stream that produces a significant scattering effect at hard X-rays, outside the eclipse, only detectable after the accumulation of a decade of *INTEGRAL* observations.

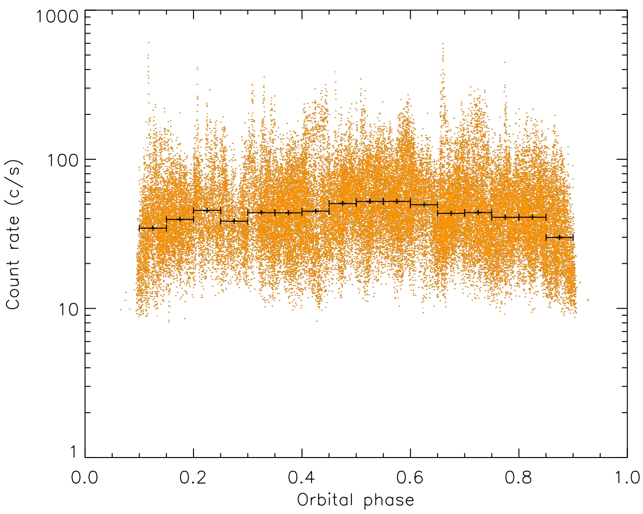

Figure 3. Long-term orbital light curve of Vela X–1 at hard X-rays (22–50 keV, 10.2 years of *INTEGRAL* data) outside the eclipses. The orange points show the Vela X–1 detection count rates in 100 s bins. Uncertainties on the source count rates are not shown, for clarity (average error on count rate is about 4 counts s^{-1}). The thick black line marks the median count rate in each phase bin.

We note that a similar effect was observed in *INTEGRAL* hard X-ray data of Cyg X–1: this HMXB black hole was simultaneously observed at soft and hard X-rays, finding that dips are mainly present in the soft X-ray band at upper conjunction due to photoelectric absorption in the focused stellar wind, whereas in *INTEGRAL* simultaneous data, a scattering effect is evident (Hanke et al. 2010). These authors suggested that these features are due to clumps in the focused wind which are both highly ionized and with (near-)neutral cores. The neutral clump cores produce dips by photoelectric absorption in the soft X-rays, while their ionized halo produces the attenuation at hard X-rays. We conclude here that a similar scattering effect is indeed at work in Vela X–1 too.

For completeness, we show in Fig. 3 the long-term orbital light curve of Vela X–1 at hard X-rays (22–50 keV), as obtained by IBIS/ISGRI in this work. The curve is consistent with what found by Fürst et al. (2010) who analysed a more contained *INTEGRAL* data set in the similar energy band 20–60 keV. The comparison of this long-term folded light curve with the off-states orbital distribution (Fig. 1) shows that the pattern we discovered and present in this work is clearly visible *only plotting the off-states distribution*, rather than the more standard orbital light curve that is dominated by the source variability.

5 CONCLUSIONS

We have analysed about 10 years of Vela X–1 *INTEGRAL* data. We have reported here on the first evidence at hard X-rays (22–50 keV) of an orbital dependence of the off-states distribution in Vela X–1 (time intervals when the source is undetected by *INTEGRAL* , i.e. $L_X \lesssim 3 \times 10^{35}$ erg s^{-1}). Their orbital distribution is asymmetric: the off-states cluster near the X-ray eclipse, with a broader orbital distribution before the eclipse than after it, covering the orbital phase range $\phi = 0.7$–0.9.

We exclude an intrinsically fainter X-ray flux producing more non-detections with *INTEGRAL* at these orbital phases, given the orbital (almost circular) geometry. Moreover, the periastron, and not the apastron, is located near the eclipse phases, thus potentially producing the opposite effect of an enhanced X-ray luminosity.

More likely, the orbital asymmetry of the off-states distribution is indicative of a higher density of ionized material trailing the neutron star along its orbit, causing an attenuation of hard X-ray flux into the line of sight at late orbital phases. We associated this extra scattering with an ionized large-scale wind structure, very likely the so-called photoionization wake, which is expected to lie at similar orbital phases.

Our analysis demonstrates that *INTEGRAL* archival observations, mapping the off-states distribution along the Vela X–1 orbit many times, can provide meaningful information on the structure of the supergiant *ionized* wind at large scales.

ACKNOWLEDGEMENTS

Based on observations with *INTEGRAL*, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Spain and Switzerland), Czech Republic and Poland, and with the participation of Russia and the USA. This work has made use of the *INTEGRAL* archive developed at INAF-IASF Milano, http://www.iasf-milano.inaf.it/~ada/GOLIA.html. We acknowledge support from ISSI through funding for the International Team on 'Unified View of Stellar Winds in Massive X-ray Binaries' (PI: S. Martínez-Nuñez). LS thanks L. Oskinova for interesting discussions. JMT acknowledges grant AYA2010-15431. LS and AP acknowledge the Italian Space Agency financial support INTEGRAL ASI/INAF agreement no. 2013-025.R.0.

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