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USING VELA X-1 TO UNDERSTAND ACCRETION AND WIND STRUCTURE IN HIGH-MASS X-RAY BINARIES (HMXB)

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Abstract. The spectral and timing behaviour of high-mass X-ray binaries (HMXBs) offers a unique opportunity for the investigation of accretion onto compact objects and of wind structure in massive stars. The bright and persistent neutron star HMXB Vela X-1 is one of the key systems for such studies. It has a complex clumpy stellar wind, prominent cyclotron resonant scattering features (CRSFs) and thus high magnetic field. We analyse two new observations taken with *NuSTAR* and *XMM-Newton* at orbital phases ∼0.68–0.78 and ∼0.36–0.52. We follow the evolution of spectral parameters down to the pulse period time-scale to model the continuum and local absorption variability. Modelling *NuSTAR* data, we observe parameter correlations that are flux dependent and imply a change in properties of the Comptonising plasma. The observed drop of the CRSF energy following a strong flare may indicate a change in the accretion geometry. The strong variability of the absorption observed along the orbit is due to the presence of a large-scale wind structure, such as accretion- and photoionisation wakes, combined with the variable line of sight as the neutron star moves along the orbit. However, the main spectral features of the stellar wind are imprinted on the spectrum at lower energies than those covered by *NuSTAR*. We thus also present time- and absorption-resolved *XMM-Newton* spectral analysis based on our *NuSTAR* results and that we use to disentangle emission and absorption features imprinted onto the intrinsic spectrum by the wind.

Keywords: X-rays binaries, neutron stars, stellar winds, outflows

1 Introduction

1.1 The Vela X-1 system

The bright and persistent eclipsing HMXB Vela X-1 is one of the key sources for stellar wind analyses. We refer to the review by Kretschmar et al. (2021) and references therein for more details about the orbital parameters of the Vela X-1 system that we mention here. The system consists of a B0.5 Ib supergiant, HD 77581 (Hiltner et al. 1972), and an accreting neutron star with an orbital period of ∼9 d. Due to a small orbital separation of $\sim 1.7\,R_\star$ between the two components, the neutron star is deeply embedded in the stellar wind of its supergiant companion and significantly influences the surrounding material via X-ray radiation. The strong stellar wind with a mass loss rate of $\sim 10^{-6} M_\odot\,\mathrm{yr}^{-1}$ (Giménez-García et al. 2016) drives the accretion of material onto the neutron star and the pulsating X-ray emission characterised by a variable pulse period of 283 s.

The system is seen almost edge-on from the Earth which facilitates its analysis through the observation of eclipses in the light curves and allows us to span different geometries of the wind as modified by the orbital motion of the accreting neutron star. In particular, we can measure the absorption as function of the orbital phase, which was found to be highly variable in the past (see the overview Fig. 5 of Kretschmar et al. 2021).

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There is a typical decrease after the eclipse followed by a steep increase when the neutron star is in inferior conjunction (around orbital phase ∼0.5). However, no identical values for the absorption can be found at the same orbital phases at different times implying changes in the structure of the wind.

1.2 Absorption from the stellar wind

Theoretical hydrodynamical models (Manousakis et al. 2012) suggest a wake structure, known as the accretion wake, trailing the neutron star and is attributed to its supersonic motion around the companion star. Additionally, the ionisation of the wind by the X-ray source leads to the formation of a photoionisation wake, where local and large-scale instabilities with filamentary structures occur (Blondin et al. 1990). The presence of those wakes, in particular when they cross or block our line of sight, deeply affects the average X-ray emission from the neutron star by absorbing photons at low energies ($\lesssim$ 10 keV). Short-term variability of the flux and spectral parameters have been associated to the clumpiness of the companion wind by many authors (e.g. Martínez-Núñez et al. 2014; Grinberg et al. 2017), in particular to local absorption by or accretion of clumps.

1.3 CRSFs

Due to the intense magnetic field of the neutron star ($\sim10^{12}$ G , Kreykenbohm et al. 2008) in Vela X-1, electrons are accelerated off the neutron star's surface along the magnetic field lines. Since electrons are quantised intro Landau levels, incoming photons can excite them to higher levels. The excited electrons then emit photons (cyclotron radiation) as they spiral around the magnetic field lines with the peak of the emission at the frequency (or energy) of its orbit, known as the cyclotron frequency (or energy), and corresponding to the energy gap between the Landau levels. Consequently, resonant scattering of incoming X-ray photons against electrons embedded in the magnetic field can occur and appears as an absorption line called cyclotron line or CRSF at the cyclotron energy. The CRSFs are called fundamental if the resonance is between the ground state and the first Landau level, harmonics for higher levels. In the spectrum of Vela X-1, two cyclotron lines have been confirmed (e.g. Kreykenbohm et al. 2008): a prominent harmonic line at ∼55 keV and a weaker fundamental line at ∼25 keV.

2 Our analysis

2.1 The datasets

Vela X-1 was observed in our targeted campaigns on 10–11 January 2019 by *NuSTAR* and on May 3–5 May 2019 by both *XMM-Newton* and *NuSTAR*, referred as observation I and observation II respectively (see Fig.1). For the first observation we have a total exposure of ∼36 ks with *NuSTAR* covering $\phi_{\rm orb} \approx 0.68$–$0.78$ when the wakes cover our line of sight. For the second observation we have ∼40 ks with *NuSTAR* and ∼109 ks with *XMM-Newton*, covering $\phi_{\rm orb} \approx 0.36$–$0.52$ during the onset of the wakes on our line of sight. Data from FPMA and FPMB (onboard *NuSTAR*) and from EPIC-pn (onboard *XMM-Newton*, timing-mode) were analysed during this work. The *XMM-Newton* EPIC-pn suffered from important pile-up that we corrected during the extraction of the data.

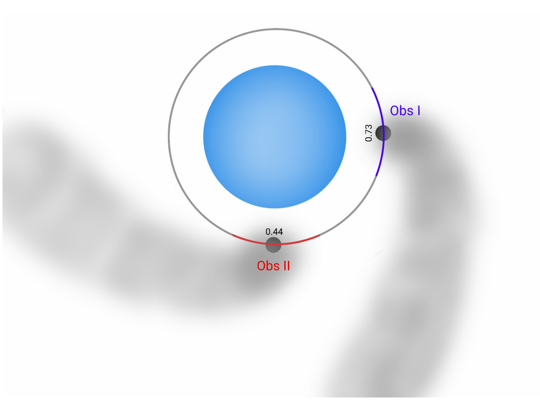

Fig. 1. Sketch of Vela X-1 showing the orbital phases covered during the two observations. In this image, the observer is located facing the system at the bottom of the picture. Figure from Diez et al. (2022).

We first extracted the *XMM-Newton* EPIC-pn and *NuSTAR* time-averaged spectra for both observations to constrain the parameters of our model before proceeding to the time-resolved spectroscopic analysis. The quality of the data was good enough with both observatories that we could extract a spectrum for each pulse of the neutron star giving us access to very short term variability in the spectral parameters (see e.g. Fig 4).

2.2 Partial covering model

For this work, we used a partial covering model. The covering fraction CF quantifies the clumpiness of the wind and ranges from 0 (X-ray source not covered) to 1 (source fully obscured). This enables us to assess both the emission from the neutron star and the absorption from the stellar wind separately as can be seen from Fig. 2. The neutron star's continuum consists of a powerlaw with a high-energy Fermi-Dirac cutoff, two cyclotron lines CRSF,F (fundamental) and CRSF,H (first harmonic), the FeKα and FeKβ lines inherent to accreting pulsars at 6.4 keV and 7.1 keV respectively, and a 10 keV feature to account for an emission-like feature in the spectrum at this energy (for more details, see Diez et al. 2022). We also modelled a plethora of ionisation lines present in the *XMM-Newton* EPIC-pn spectra of the source between 0.5 and 4 keV (see Fig. 3).

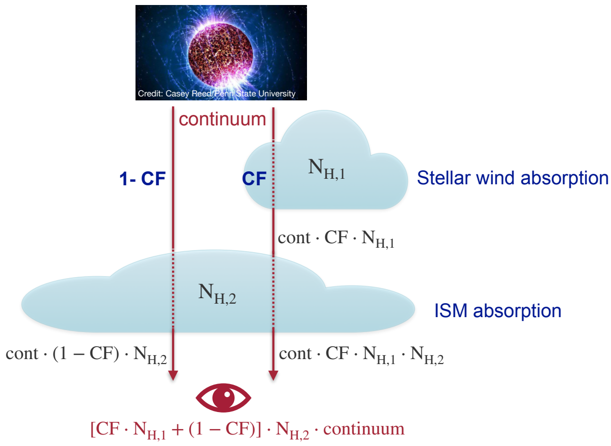

Fig. 2. Scheme of the partial covering model used in this work. The X-ray emitting source is at the top of the figure and the observer is located at the bottom. $N_{H,1}$ is the hydrogen absorption column density of the stellar wind, $N_{H,2}$ the hydrogen absorption column density of the interstellar medium between the source and the Earth fixed at its known value (NASA's HEASARC N_H tool `https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl`). Figure from Diez et al. (2022).

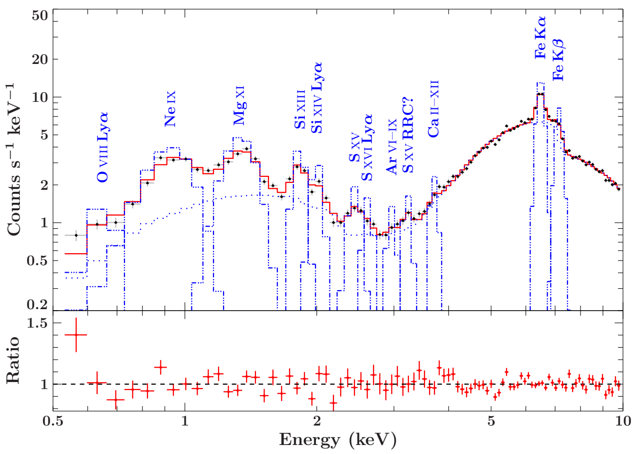

Fig. 3. Example of an *XMM-Newton* EPIC-pn spectrum (black datapoints). The individual model components including all lines detected in this dataset are indicated by blue dot-dashed Gaussians and the absorbed continuum by the blue dotted line. Figure from Diez et al. (2023).

3 Conclusions

In this work, we analysed two observations of the HMXB Vela X-1 shortly before the neutron star is in inferior conjunction and at late orbital phases when the wakes obscure our line of sight (Diez et al. 2022, 2023). We cover a broad X-ray range from 0.5 keV to 78 keV thanks to the simultaneous *XMM-Newton* and *NuSTAR* coverage we obtained for the second observation, the first one was covered by *NuSTAR* only. Using a partial covering model, we performed a detailed study of the CRSFs and observed flux/time dependent correlations among the spectral parameters of our model.

3.1 CRSFs

We confirmed the negative correlation between photon index and flux but could not confirm a previously seen positive correlation between flux and energy of the first harmonic CRSF (Fürst et al. 2014). We therefore question the accretion regime of Vela X-1 which may lie between sub- and super-critical regimes in this observation. However, we observed a drop in the CRSFs energies following a strong flare. This could be explained by a restructuring of the accretion column and consequently to a change in the location of the CRSF producing region due to sudden strong accretion of material.

3.2 Clumpy wind

The newly obtained constraints at high-energies permitted by *NuSTAR* enables us to trace the onset of the wakes in Vela X-1 using the *XMM-Newton* simultaneous coverage. This is the first time that we have such a detailed view of the wind on a broad X-ray band and with high-time resolution, down to the pulse period of the neutron star of $\sim$283 s. The wakes are characterised by a rise of the absorption column density $N_{\mathrm{H},1}$ as well as local absorption variability (see Fig. 4). There are also orbital dependencies between spectral parameters, which are observational evidences of overlapping and accretion of clumps.

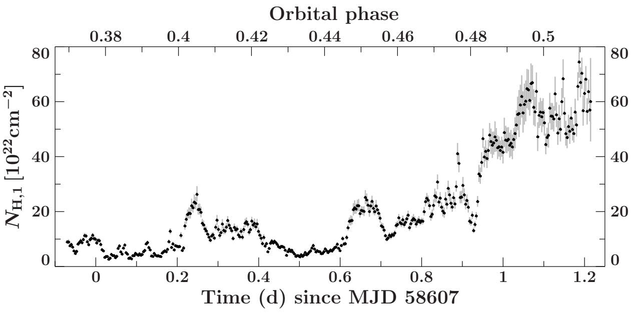

Fig. 4. Absorption column density $N_{\mathrm{H},1}$ of the stellar wind as function of time (bottom axis) or orbital phase (top axis). Each point is integrated over a pulse period ($\sim$283 s) of the neutron star. Figure from Diez et al. (2023).

3.3 Nature of the absorbers

We also conducted a high-resolution spectroscopy of the multiple fluorescent emission lines present in the Vela X-1 system (Lyα lines of O, Ne, Mg, Si and S) which show a strong photoionisation of the wind. The presence of those lines at different absorption phases implies that the sources of emission originate from both local absorbers close the neutron star (clumps) and large-scale structures (photoionisation wake).

3.4 Perspectives

From the *XMM-Newton* observation, only EPIC-pn data were explored so far. The analysis of the simultaneous *XMM-Newton* RGS data in a future work is crucial as blending with neighbouring elements with EPIC-pn can happen. Moreover, a similar analysis on other HMXBs is also in progress in order to put constraints on a bigger sample of sources and find common absorption behaviours between different HMXBs. Last but not least, the recently launched *XRISM* and upcoming *Athena* will be of utmost importance for this study thanks to their high-resolution instruments enabling a detailed X-raying of the stellar wind.

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