Looking through the photoionisation wake: Vela X-1 at $\varphi_{\text{orb}} \approx 0.75$

with \textit{Chandra}/HETG

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ABSTRACT

\textbf{Context.} The Supergiant X-ray binary Vela X-1 represents one of the best astrophysical sources to investigate the wind environment of a O/B star irradiated by an accreting neutron star. Previous studies and hydrodynamic simulations of the system revealed a clumpy environment and the presence of two wakes: an accretion wake surrounding the compact object and a photoionisation wake trailing it along the orbit.

\textbf{Aims.} Our goal is to conduct, for the first time, high-resolution spectroscopy on \textit{Chandra}/HETGS data at the orbital phase $\varphi_{\text{orb}} \approx 0.75$, when the line of sight is crossing the photoionisation wake. We aim to conduct plasma diagnostics, inferring the structure and the geometry of the wind.

\textbf{Methods.} We perform a blind search employing a Bayesian Block algorithm to find discrete spectral features and identify them thanks to the most recent laboratory results or through atomic databases. Plasma properties are inferred both with empirical techniques and with photoionisation models within CLOUDY and SPEX.

\textbf{Results.} We detect and identify five narrow radiative recombination continua (Mg x–xii, Ne ix–x, O viii) and several emission lines from Fe, S, Si, Mg, Ne, Al, and Na, including four He-like triplets (S xv, Si xiii, Mg xi, and Ne ix). Photoionisation models well reproduce the overall spectrum, except for the near-neutral fluorescence lines of Fe, S, and Si.

\textbf{Conclusions.} We conclude that the plasma is mainly photoionised, but more than one component is most likely present, consistent with a multi-phase plasma scenario, where denser and colder clumps of matter are embedded in the hot, photoionised wind of the companion star. Simulations with the future X-ray satellites \textit{Athena} and \textit{XRISM} show that a few hundred seconds of exposure will be sufficient to disentangle the lines of the Fe K doublet and the He-like Fe xxv, improving, in general, the determination of the plasma parameters.

\textbf{Key words.} X-rays: binaries – stars: massive – stars:winds, outflows

1. Introduction

The eclipsing high-mass X-ray binary (HMXB) Vela X-1 (4U 0900-40) consists of a $\sim 283$ s period pulsar (McClintock et al. 1976) and a blue supergiant companion star (HD 77851, a B0.5ia class star, Hiltner et al. 1972). With an X-ray luminosity of $\sim 4 \times 10^{36}$ erg s$^{-1}$ and a distance of 2 kpc from Earth (Jiménez-García et al. 2016), it is one of the brightest HMXBs in the sky. It is a high inclination system ($\approx 73^\circ$, Joss & Rappaport 1984), with an orbital period of $\sim 8.9$ d (Forman et al. 1973; Kreykenbohm et al. 2008) and an orbital separation of $\sim 53 R_\odot$ (Quaintrell et al. 2003). The donor star has a radius of about $30 R_\odot$ (Quaintrell et al. 2003), so that the pulsar is constantly embedded in the wind environment of the companion. The geometry of the accreting stream of matter onto the compact object is complex, being made up of an accretion wake, a photoionisation wake, and possibly a tidal stream, as both simulations (e.g., Blondin et al. 1990; Manousakis 2011) and observations in different wavebands show (e.g., Kaper et al. 1994; van Loon et al. 2001; Malacaria et al. 2016). A sketch of the binary system with the main features is given in Fig. 1. The line of sight intersects the different elements at different orbital phases, so that the observational data show strong changes in absorption along the whole orbital period (Doroshenko et al. 2013).

X-ray emission from Vela X-1 has already been detected and studied for several different orbital phases with different instruments (e.g., Haberl & White 1990; Goldstein et al. 2004; Watanabe et al. 2006; Fürst et al. 2010; Grinberg et al. 2017). High resolution X-ray studies of the system are of special interest, as they allow to draw conclusions on the properties of the complex plasma. High-resolution data from the High-Energy Transmission Grating Spectrometer (HETGS) of the \textit{Chandra} X-ray Observatory (Weisskopf et al. 2000) of Vela X-1 during eclipse ($\varphi_{\text{orb}} \approx 0$) were studied by Schulz et al. (2002), who discovered and identified a variety of emission features, including radiative recombination continua (RRCs) and fluorescent lines, that led to the idea of the coexistence of a hot optically thin photoionised plasma and a colder optically thick one. Goldstein et al. (2004) investigated \textit{Chandra}/HETGS data of the system at three different orbital phases ($\varphi_{\text{orb}} \approx 0$, $\varphi_{\text{orb}} \approx 0.25$, $\varphi_{\text{orb}} \approx 0.5$), finding that the emission features revealed during the eclipse are obscured at $\varphi_{\text{orb}} \approx 0.25$, but then they appear again at $\varphi_{\text{orb}} \approx 0.5$, when the soft X-ray continuum...
uum diminishes. The simultaneous presence of H- and He-like emission lines and fluorescent lines of near-neutral ions can be explained by contributions from different regions: the warm photoionised wind of the companion star and smaller cooler regions, or clumps, of gas. Watanabe et al. (2006) compared the same Chandra/HETGS data sets to 3D Monte Carlo simulations of X-rays photons propagating through a smooth, undisturbed wind. Based on this assumption, they deduced that highly ionised ions, which give rise to the emission lines, are located mainly in the region between the neutron star (NS) and the companion star, while the fluorescent lines are produced in the extended stellar wind, from reflection of the stellar photosphere, and in the accretion wake. More recent results on the same orbital phase by Odaka et al. (2013) with Suzaku and by Martínez-Núñez et al. (2014) with XMM-Newton, respectively, highlighted flux variability and strong changes in absorption over periods of the order of ks. The same variability is found in Chandra/HETGS data at $\phi_{\text{orb}} \approx 0.25$ from Grinberg et al. (2017), who attributed the changes in the overall absorption necessarily to the clumpy nature of the winds from the companion. Moreover, the high energy resolution of Chandra allowed the detection of line emission features from several ionised elements, corroborating the idea of a co-existence of cool and hot gas phases in the system.

Hydrodynamic simulations (Manousakis & Walter 2015; El Mellah et al. 2018, 2019) suggest the presence of a more complex structure around the neutron star (NS), with a bow shock and eventually the formation of a transient wind-captured accretion disk (Liao et al. 2020). Such features can influence the way clumps accrete onto the compact objects, i.e., reducing the amount of transferred angular momentum or introducing time lags and phase mixing when the clumps are stored in such structures.

In this work we present, for the first time, a high-resolution spectroscopic study of Chandra/HETGS archival data of Vela X-1 at orbital phase $\phi_{\text{orb}} \approx 0.75$, i.e., when the line of sight is intersecting the photoionisation wake (see Fig. 1). The study of the X-ray spectrum at this specific orbital phase, where the absorption from the wind of the X-rays coming from the NS is high, allows the detection of a large number of lines from different elements in high ionisation states and, thus, the application of plasma diagnostic techniques to characterise the accretion environment. The paper is structured as follows: we first look for changes in the hardness of the flux in Section 2, finding none; then we proceed with a blind search for spectroscopic absorption/emission features, applying a Bayesian Block algorithm to the unbinned spectrum; we present the identification of all the detected features in Section 3, while in Section 4 we compare the observational data with two different photoionisation codes; in Section 5 we discuss the plasma properties and the geometry of the wind of the companion star; in Section 6 we perform simulations with future X-ray satellites; we present our conclusions in Section 7.

2. Data reduction and temporal analysis

We analysed the High Energy Grating (HEG) and Medium Energy Grating (MEG) data sets of the Chandra/HETGS ObsID 14654, taken on 2013-07-30, with ACIS-S, in FAINT mode, for a total exposure time of 45.88 ks. According to the ephemeris of Kreykenbohm et al. (2008), the data set covers the orbital phase $\phi_{\text{orb}} \approx 0.72–0.78$, where $\phi_{\text{orb}} = 0$ is defined as mid-eclipse. Data were reprocessed using CIAO 4.11, with CALDB 4.8.2. We followed the standard Chandra data analysis threads, but we chose a narrower sky mask to avoid the overlapping of the extraction region and to improve the flux at the shortest wavelengths.

Following the work of Grinberg et al. (2017), who observed a change in the hardness of the source during phase $\phi_{\text{orb}} \approx 0.25$, we extracted the light curve in two different energy bands, 0.5–3 keV (soft) and 3–10 keV (hard), and computed the hardness ratio, defined as the ratio between the counts in the hard and soft bands. Fig. 2 shows the results, with data binned to the neutron star spin period of 283 s (errors at 1$\sigma$). The hardness ratio values at $\phi_{\text{orb}} \approx 0.75$ are higher than the ones obtained by Grinberg et al. (2017) by at least a factor of ten, which is not surprising considered the high absorption expected at this orbital phase. Moreover, the hardness ratio is almost flat for the whole observation, in contrast to Grinberg et al. (2017), where a variability of a factor of three was observed. Hence, we extract only one spectrum, in the full energy range of 0.5–10 keV (Fig. 3).

3. High-resolution spectroscopy

We used the Interactive Spectral Interpretation System (ISIS) 1.6.2-43 (Noble & Nowak 2008a,b) to perform the spectroscopic
analysis of the data, with the ISIS functions (ISISscripts) provided by ECAP/Remis observatory and MIT, cross sections from Verner et al. (1996), and solar abundances from Wilms et al. (2000). We used Cash statistic (Cash 1979) with the spectrum binned to the MEG resolution. All uncertainties are given at 90% confidence level.

We performed a blind search of spectral features, using a Bayesian Block (BB) algorithm (Scargle et al. 2013), as described in Young et al. (2007) and as applied to Chandra/HETGS data by Grinberg et al. (2017). To optimise the line detection algorithm, we divided the whole spectrum into five regions of interest, named after the most significant element detected in each of them, as reported in Table 1. These spectral regions were analysed one by one. We locally modelled the continuum with a simple power law and then looked for significant deviations in the residuals. Given the narrow wavelength ranges of individual regions, the continuum is always adequately well fitted by a power law. Similar piece-wise approaches have been previously repeatedly used for line searches and modelling (see, e.g., Yao et al. 2008; van den Eijnden et al. 2019).

The BB algorithm determines whether a data point is far from the model above a certain significant threshold, defined by a parameter, α, such that each detection has a significance of \( p \sim \exp(-2\alpha) \), corresponding to a probability of \( P \sim 1 - \exp(-2\alpha) \) of positive detection. For each new detection, we added to the model one or more Gaussian components for emission/absorption lines and the XSPEC (Arnaud 1996) functions edge and edge for the RRCs and the Fe K-edge (Sect. 3.1, 5.1), respectively. After each addition, we fit the data and apply the algorithm once more. We iterate the process until the significance drops to 95%, corresponding to \( \alpha \sim 1.5 \). All the line detections with their corresponding values of \( \alpha \) are listed in Tables 2–6, while Table 1 shows the best-fit values of the power law parameters for each spectral region and the goodness of the fit. Table 7 displays the best-fit values of the RRCs.

In some cases, lines that are too close to be clearly resolved by the algorithm, such as for example He-like triplets, are detected as a single block. In such cases, we use our knowledge of atomic physics to add the proper number of lines to the model. Moreover, to improve the fit, we fixed the distance of known lines, since the BB per se is a blind algorithm, i.e., it does not take into account known line distances. We did this for the H-like Lyα and Lyβ lines (Erickson 1977) and the He-like triplets (Drake 1988), assuming that Doppler shifts are the same within the same ionic species.

Whenever a line appeared unresolved, we fixed its width to 0.003 Å, corresponding to about one third of the MEG resolution (0.023 Å FWHM). Line identification for S and Si ions accounts for the most recent laboratory measurements from Hell et al. (2016), while for the other elements we use the AtomDB database (Foster et al. 2012, 2017).

For every detected He-triplet, we computed the density-sensitive ratio \( R = f/i \) and the temperature-sensitive ratio \( G = (i + f)/r \), where \( f \) represents the intensity of the forbidden line (1s2s 3S1–1s2 1S0), \( i \) the intensity of the intercombination line (1s2p 3P1–1s2 1S0) and \( r \) the intensity of the resonant line (1s2 1P1–1s2 1S0) (Gabriel & Jordan 1969; Porquet & Dubau 2000).

In our case, the intensities of the lines are linked to reproduce \( G \) and \( R \) as free parameters in the fit. Results are reported in Table 8.

In the following subsections, we present in detail the results of the BB procedure for each spectral region of interest.

### 3.1. Iron region

In the Fe region (wavelength range 1.6–2.5 Å, cf. Table 1), the BB method found only one strong line, that we identified with Fe Kα and one edge, identified with the Fe K-edge. Best-fit values for these features are reported in Table 2. Although the strong Fe Kα line implies the presence of a strong Fe Kβ component, our approach did not detect it. We discuss the possible reasons in Sect. 5.

Given the overall strength of the Fe Kα line, we attempted an additional fit, letting the line width free. We obtained a best-fit value of \( \sigma = (5.4^{+0.5}_{-0.4}) \times 10^{-3} \) Å, consistent with our previous assumption and with results by Tzanavaris & Yaqoob (2018).

### 3.2. Sulphur region

We studied the S region in the wavelength range 4.5–6.0 Å (Table 1). Line identification is based on the recent laboratory measurements from Hell et al. (2016). The BB algorithm detected a single block between 5 Å and 5.4 Å, with \( \alpha \sim 27 \). We model this block with the S xvi He-like triplet, the S xiv, the S xi and the blended fluorescence S i–vii lines. The second run of the algorithm resulted in the detection of the S xvi Lyα, with \( \alpha = 12 \). Lastly, three more lines were detected: the Si xvi Heβ (\( \alpha = 8 \)), the S x (\( \alpha = 2.7 \)) and an unidentified absorption line at \( \sim 5.457 \) Å (\( \alpha = 2.2 \)). No reference wavelength was found for this last absorption line. Considering the low value of the parameter \( \alpha \) and the lack of any other absorption feature in the whole spectrum, it is most likely that the line is just a statistical fluctuation.

In the same region we could also expect to find the Si xvi Lyβ line, at 5.217 Å (Erickson 1977). The lack of a significant detection of this line is probably due to the strong continuum.
Table 1. Best-fit values of the power laws used to model the continuum and values of the Cash statistic per degrees of freedom (d.o.f.) for each region of the spectrum.

| Region   | Wavelength range (Å) | $\Gamma$       | Norm. (keV s$^{-1}$ cm$^{-2}$) | Cash(d.o.f.) |
|----------|----------------------|----------------|-------------------------------|--------------|
| Fe       | 1.6–2.5              | $-0.083^{+0.004}_{-0.008}$ | $0.0158^{+0.0023}_{-0.0018}$ | 1.03(179)    |
| S        | 4.5–6.0              | $-5.38 \pm 0.05$ | $(1.04^{+0.06}_{-0.16}) \times 10^{-5}$ | 1.14(279)    |
| Si       | 6.0–7.4              | $-0.3 \pm 0.1$  | $(3.4 \pm 0.2) \times 10^{-4}$ | 1.19(247)    |
| Mg       | 7.5–10.0             | $2.31^{+0.15}_{-0.16}$ | $(1.27 \pm 0.07) \times 10^{-3}$ | 1.26(468)    |
| Ne       | 10.0–14.5            | $0.1 \pm 0.7$   | $(6.9^{+0.7}_{-0.6}) \times 10^{-4}$ | 0.99(892)    |

Table 2. Features detected in the Fe region (1.6–2.5 Å) with the detection parameter $\alpha$ and the best-fit values. The width of the Fe K$\alpha$ line was fixed to 0.003 Å.

| Line          | BB | Ref. wavelength ($\alpha$) (Å) | Det. wavelength ($\alpha$) (Å) | Line flux (ph s$^{-1}$ cm$^{-2}$ x 10$^{-4}$) | $\tau$ |
|---------------|----|-------------------------------|-------------------------------|-----------------------------------------------|-------|
| Fe K$\alpha$  | 157| 1.9375$^a$                     | 1.9388 $\pm$ 0.0006           | 9.4 $\pm$ 0.8                                 | –     |
| Fe K edge     | 47 | 1.7433$^b$                     | 1.742 $\pm$ 0.003             | –                                             | 0.31 $\pm$ 0.03 |

Notes. $^a$ Drake (1988). $^b$ Bearden & Burr (1967).

Fig. 4. Fe-region spectrum and best-fit model (red line), with residuals shown in the bottom panel. The only line detected by the BB algorithm is identified and marked as a FeK$\alpha$ emission line, as well as the detected Fe K-edge. Arrows mark the position of the expected Ni K$\alpha$, Fe K$\beta$ and He-like Fe xxv lines (in grey).

However, since the Si xiv Ly$\alpha$ line is strong in the Si region (see Sect. 3.3), the Si xiv Ly$\beta$ is most likely present and blended with the Si xi line. In Fig. 5, we marked the line at 5.224 Å with both its possible identifications. Given this line confusion, the Ly$\beta$/Ly$\alpha$ ratio for Si xiv cannot be easily constrained. Only an upper limit of 0.55 can be derived, assuming the minimum flux for Ly$\alpha$ (cf. Sec. 3.3) and that all flux of the discussed blend is due to Si xiv Ly$\beta$. Moreover, the high absorption constitutes a source of additional uncertainty as it influences the line ratio (Kaastra & Mewe 1995).

For this region, all the line widths were fixed to 0.003 Å. Best-fit values are reported in Table 3, together with the Doppler velocities computed with respect to laboratory reference values (Hell et al. 2016). Fig. 5 shows the spectrum, the best-fit model and the residuals of the fit. From the S xiv triplet, we obtained the best fit ratios $R = 9.9^{+2.4}_{-2.2}$ and $G = 0.48^{+0.14}_{-0.10}$ (Table 8).

3.3. Silicon region

We searched for Si lines in the region 6.0–7.4 Å (Table 1). The BB algorithm highlighted at the first trial ($\alpha = 190$) the Si xiv Ly$\alpha$ line and a whole block in the range 6.6–6.8 Å that we modelled with the He-like triplet Si xii, at first. The fluorescent line blend Si iii-vi is detected with $\alpha = 121$, while a whole block is detected at the wavelengths 6.9–7.1 Å, with $\alpha = 32$. We added three Gaussians to model this block, according to the laboratory measurements by Hell et al. (2016) (see also Grinberg et al. 2017), corresponding to the Si vi, Si vii, and Si ix lines. The last detections are identified as the Al xiii Ly$\alpha$ line ($\alpha = 9$), the Si x and Si xi lines ($\alpha = 5$) and the Si xii line ($\alpha = 1.8$).
Table 3. Spectral features detected in the S region. For each feature we report the detection parameter $a$, the best-fit values (wavelength and line flux) and the Doppler velocities, computed using reference wavelengths measured by Hell et al. (2016). Line widths fixed to 0.003 Å for all the lines.

| Line                | BB Ref. wavelength | Det. wavelength | Line flux (ph s$^{-1}$ cm$^{-2}$ x10$^{-5}$) | Velocity (km s$^{-1}$) |
|---------------------|--------------------|-----------------|---------------------------------------------|------------------------|
| $S_{\text{xxvi}}$ Ly$_{\alpha}$ | 12                 | 4.7329$^{a}$    | $4.731 \pm 0.003$                          | $3.5^{+1.1}_{-0.9}$ $-50^{+180}_{-170}$ |
| $S_{\text{xxv}}$ r | 27                 | 5.0386          | $5.042^{+0.0018}_{-0.0014}$               | $3.18^{+0.09}_{-0.07}$ $210^{+110}_{-140}$ |
| $S_{\text{xxv}}$ i | 27                 | 5.0666          | $5.066^{+0.0016}_{-0.0014}$               | $0.14 \pm 0.03$ $= v(5 \text{ sv r})$ |
| $S_{\text{xxv}}$ f | 27                 | 5.1013          | $5.104^{+0.0016}_{-0.0014}$               | $0.06^{+0.04}_{-0.07}$ $= v(5 \text{ sv r})$ |
| $S_{\text{xxv}}$  | 27                 | 5.0858          | $5.081 \pm 0.003$                         | $2.3 \pm 0.8$ $-310^{+180}_{-160}$ |
| $S_{\text{xi}}/S_{\text{xxiv}}$ Ly$_{\beta}$ | 27    | 5.2250          | $5.224 \pm 0.002$                         | $2.3^{+0.8}_{-0.7}$ $-70 \pm 140$ |
| $S_{\text{ix}}$    | 2.7               | 5.3163          | $5.320^{+0.006}_{-0.009}$                 | $1.3^{+0.0}_{-0.7}$ $210^{+340}_{-510}$ |
| $S_{\text{ii-viii}}$ | 27      | 5.3616          | $5.365 \pm 0.003$                         | $2.8^{+0.9}_{-0.8}$ $200 \pm 150$ |
| $S_{\text{xxiv}}$  | 22               | –               | $5.457^{+0.002}_{-0.003}$                 | $-0.69^{+0.01}_{-0.24}$ $- $ |
| $S_{\text{iii}}$ He$_{\beta}$ | 8     | 5.681$^{a}$    | $5.683 \pm 0.003$                         | $1.4^{+0.0}_{-0.5}$ $80^{+150}_{-160}$ |

Notes. Hell et al. (2016) reports the statistical uncertainties for each energy, which correspond to an error in wavelength of the order of $10^{-4} \sim -10^{-3}$ Å. However, authors state that there is also a systematic uncertainty of 0.23 eV for S lines, which results in an error on the wavelength of 0.0008 Å. $^{a}$Garcia & Mack (1965). $^{b}$Distances between the $r$ line and the $i$ and $f$ lines computed from Drake (1988). $^{c}$The reference wavelength of Si xiv Ly$_{\beta}$ is 5.217 Å (Erickson 1977). $^{d}$Kelly (1987).

In the same region, also the RRC of Mg xi is detected, at 6.321 Å (1.961 ± 0.002 keV), with a temperature of $4.5^{+5.8}_{-3.2}$ eV. Lastly, we added one more redge function to model the Mg xi RRC, expected at 7.037 Å (Drake 1988). It results in a temperature of $3.1^{+1.6}_{-1.1}$ eV, consistent with the one of Mg xi RRC (Table 7).

The width of the lines was fixed to 0.003 Å, except for the Si xiv Ly$_{\alpha}$ line, which has a slightly larger width of $(7.3^{+1.2}_{-1.1}) \times 10^{-3}$ Å. For each line, we computed the Doppler velocities with respect to the laboratory or literature reference wavelengths. All the best-fit values of the emission lines and RRCs are reported in Table 4 and Table 7, respectively, while the spectrum, the best-fit model and the residuals are shown in Fig. 6. The best fit values of the $R$ and $G$ ratios of the $S_{\text{xxiv}}$ triplet resulted in $R = 6.0 \pm 0.6$ and $G = 0.8^{+0.10}_{-0.09}$ (Table 8). The BB algorithm did not detect the Mg xi Ly$_{\beta}$ emission line expected at ~ 7.1037 Å (Erickson 1977). Also in this case, the line is most likely embedded in the (near-)neutral fluorescence Si ii-vi lines.

3.4. Magnesium region

The region we took into account to look for Mg emission lines ranges from 7.5 Å to 10 Å (Table 1). The first line detected corresponds to the Mg xi Ly$_{\alpha}$ ($\alpha = 220$). The successive detection ($\alpha = 89$) consisted in a block in the range ~9-9.4 Å, which we modelled with three Gaussians for the He-like triplet Mg xi. In the same block, we insert the Ne x RRC (Schulz et al. 2002; Watanabe et al. 2006; Goldstein et al. 2004). We also detected and identified the Mg xi He$_{\beta}$ ($\alpha = 48$), the Ne x Ly$_{\gamma}$ ($\alpha = 15$), the Al xii r Heo ($\alpha = 7$), the Ne x Heo$_{\delta}$ ($\alpha = 4.4$), the Fe xx ($\alpha = 3.4$), and the Fe xxiv ($\alpha = 2.9$) emission lines. Best-fit values are reported in Table 5, while the spectrum, the best-fit model and the residuals are shown in Fig. 7. A few lines show a broadening that required to let their widths free. This is the case for Mg xi Ly$_{\alpha}$ whose width of $(7.4 \pm 1.2) \times 10^{-3}$ Å is in agreement with those of Si xiv (Sect. 3.3) and Ne x Ly$_{\alpha}$ (Sect. 3.5) lines. Other broadened lines are the Mg xi $r$ and the Ne x Heo, ~0.01 Å width, and a Fe xiii line (~0.025 Å width). The Ne x RRC, at a wavelength of ~9.116 Å (1.3600$^{+0.0012}_{-0.0010}$ keV) indicates a temperature of $10.8^{+1.2}_{-3.3}$ eV (Table 7) consistent with previous findings at different orbital phases (Schulz et al. 2002; Goldstein et al. 2004). Doppler shifts of the Ly$_{\alpha}$, the He$_{\beta}$ and the triplet lines are around 150 km s$^{-1}$. From the intensities of the Mg xi triplet we obtained the ratios $R = 1.20^{+0.28}_{-0.23}$ and $G = 0.74^{+0.13}_{-0.14}$ (Table 8) for plasma diagnostic.

3.5. Neon region

The region for Ne emission lines goes from 10 Å to 14.5 Å (Table 1). We detected and identified 11 lines and two RRCs. Best-fit values are reported in Table 6 and 7, the spectrum, best-fit
Table 4. Spectral features detected in the Si region. For each of them, we report the detection parameter $\alpha$, the best-fit values (wavelength and line flux). Line widths fixed to 0.003 Å, if not stated otherwise. Doppler velocities of the Si lines, computed with respect to the reference wavelengths measured by Hell et al. (2016).

| Line       | BB | Ref. wavelength $\alpha$ (Å) | Det. wavelength (Å) | Line flux (ph s$^{-1}$ cm$^{-2}$ × 10$^{-5}$) | Velocity (km s$^{-1}$) |
|------------|----|-------------------------------|---------------------|---------------------------------|-----------------------|
| Si xiv Ly$\alpha$ | 190 | 6.1817$^{+a}$ | 6.184 ± 0.001 | 6.2 ± 0.6$^{+b}$ | 100 ± 50 |
| Si xiii r  | 190 | 6.6483 | 6.6506 ± 0.0007 | 4.5$^{+0.8}_{-0.7}$ | 100 ± 30 |
| Si xiii i  | 190 | 6.7195 | 6.6887 ± 0.0007$^{+c}$ | 0.51$^{+0.05}_{-0.04}$ | $\approx \nu$(Si xiii r) |
| Si xiii f  | 190 | 6.7405 | 6.7427 ± 0.0007$^{+c}$ | 3.1 ± 0.4 | $\approx \nu$(Si xiii r) |
| Si xi      | 1.8 | 6.7197 | 6.722 ± 0.003 | 0.9 ± 0.3 | 110 ± 110 |
| Si x       | 5   | 6.7841 | 6.788 ± 0.004 | 0.42$^{+0.18}_{-0.16}$ | 170 ± 180 |
| Si x       | 32  | 6.9279 | 6.930 ± 0.003 | 1.1 ± 0.3 | 80 ± 120 |
| Si vi      | 32  | 7.0008 | 7.006 ± 0.005 | 1.6 ± 0.3 | 220±210 |
| Si vii     | 32  | 7.0577 | 7.057$^{+0.005}_{-0.004}$ | 0.5 ± 0.2 | $\approx$40$^{+10}_{-170}$ |
| Si xi-ii$^{d}$ | 121 | 7.1172 | 7.115 ± 0.001 | 2.6 ± 0.4 | $\approx$120 ± 40 |
| Al xxiv Ly$\alpha$ | 9   | 7.1764$^{+a}$ | 7.177 ± 0.003 | 0.6 ± 0.2 | 20$^{+10}_{-120}$ |

Notes. Hell et al. (2016) report a systematic uncertainty of 0.13 eV for Si lines, corresponding to an error on the wavelength of 0.0005 Å.  
(a) Garcia & Mack (1965). (b) This line results in a best line width of $7.3^{+1.2}_{-1.0}$ Å. (c) Distances between the r line and the i and f lines computed from Drake (1988). (d) The Mg Ly$\beta$ (7.1037 Å, Erickson 1977) might be blended with the Si x-ii line. (e) Erickson (1977).

Table 5. Spectral features detected in the Mg region (7.5–10 Å). For each of them, we report the detection parameter $\alpha$, the best-fit values (wavelength and line flux) and the Doppler velocities, computed with respect to reference wavelength from literature. Line widths fixed to 0.003 Å, if not stated otherwise.

| Line      | BB | Ref. wavelength $\alpha$ (Å) | Det. wavelength (Å) | Line flux (ph s$^{-1}$ cm$^{-2}$ × 10$^{-5}$) | Velocity (km s$^{-1}$) |
|-----------|----|-------------------------------|---------------------|---------------------------------|-----------------------|
| Al xii He$\alpha$ | 7   | 7.7573$^{+a}$ | 7.782$^{+0.012}_{-0.011}$ | 0.9 ± 0.3$^{+b}$ | 960$^{+40}_{-190}$ |
| Mg xi He$\beta$ | 48  | 7.850$^{+d}$ | 7.8565 ± 0.0017 | 1.2 ± 0.3 | 250 ± 70 |
| Fe xxiv    | 2.9 | 7.985$^{+a}$ | 7.980$^{+0.008}_{-0.005}$ | 0.30$^{+0.17}_{-0.14}$ | $\approx$190$^{+30}_{-190}$ |
| Mg xii Ly$\alpha$ | 220 | 8.42101$^{+c}$ | 8.4226 ± 0.0011 | 5.3$^{+0.06}_{-0.05}$ | 180 ± 40 |
| Mg xi r   | 89  | 9.16896$^{+a}$ | 9.1728 ± 0.0015 | 3.7 ± 0.8$^{+e}$ | 130 ± 50 |
| Mg xi i   | 89  | 9.2312$^{+a}$ | 9.2343 ± 0.0015$^{+a}$ | 1.51$^{+0.14}_{-0.23}$ | $\approx$0(Mg xi r) |
| Mg xi f   | 89  | 9.3143$^{+a}$ | 9.3188 ± 0.0015$^{+a}$ | 1.5 ± 0.4 | $\approx$0(Mg xi r) |
| Fe xx$^{b}$ | 3.4 | 9.282$^{+a}$ | 9.290 ± 0.004 | 1.0 ± 0.4 | 260 ± 130 |
| Ne x Ly$\delta$ | 4.4 | 9.481$^{+a}$ | 9.485 ± 0.006 | 0.6 ± 0.3 | 130 ± 190 |
| Ne x Ly$\gamma$ | 15  | 9.708$^{+a}$ | 9.708 ± 0.005 | 1.3$^{+0.5}_{-0.4}$ | 0 ± 150 |

Notes. (a) Drake (1988). (b) Line width of 0.025$^{+0.002}_{-0.008}$ Å. (c) Kelly (1987). (d) Wargelin et al. (1998). (e) Erickson (1977). (f) For this line the best-fit line width value was $(7.4 ± 1.2) × 10^{-3}$ Å. (g) Line width of 0.011 ± 0.003 Å. (h) Close to the same wavelength there is also the Ne x Ly$\gamma$ emission line at 9.291 Å, but with a lower intensity ratio. In this case the resulting Doppler velocity would be $(\approx 32 ± 129)$ km s$^{-1}$. (i) Unpublished atomic data from Liedahl (1997). (j) Line width of 0.010$^{+0.005}_{-0.004}$ Å.

model and residuals are shown in Fig. 8. The first line to be detected by the BB procedure ($\alpha = 49$) was the Ne x Ly$\alpha$, at a wavelength of 12.1398 Å and with a width of $(9.6^{+3.0}_{-1.9}) × 10^{-3}$ Å. The successive detection ($\alpha = 29$) was a line at $\approx 10.24$ Å, that we identified with the Ne x Ly$\beta$. Hence, we fixed the distance of the latter line with respect to the corresponding Ly$\alpha$ according to Erickson (1977). The next detection ($\alpha = 17$) was a block from 13.4 Å to 13.9 Å, that we modelled with the Ne x triplet (Grinberg et al. 2017; Goldstein et al. 2004; Watanabe et al. 2006).

Lastly, we detected six more lines, corresponding to Ne xi He$\beta$, at 11.549 Å ($\alpha = 8$), Ne xi He$\gamma$ at 11.005 Å ($\alpha = 7$), Ne xi He$\delta$ at 10.644 Å ($\alpha = 3.2$), Na x Ly$\beta$ at 10.023 Å ($\alpha = 2.5$), Fe xix at 10.814 Å ($\alpha = 1.8$) and Fe xxvi at 12.285 Å ($\alpha = 1.7$). The Ne xi RRC at 10.374 Å was detected with $\alpha = 8$ and resulted in a best-fit temperature of $4.5^{+1.4}_{-1.2}$ eV, while the O vii RRC at 14.2 Å was detected with $\alpha = 2.8$ with a best-fit temperature of $0.9^{+4.2}_{-0.6}$ eV (Table 7). This is the first detection of the O vii RRC in Chandra data for Vela X-1. It was implied in ASCA observa-
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![Fig. 7. Mg-region spectrum and best-fit model (red line), with residuals shown in the bottom panel.]

![Fig. 8. Ne-region spectrum and best-fit model (red line), with residuals shown in the bottom panel.]

4. Photoionisation models with CLOUDY and SPEX

We attempted a more physical modelling of the detected features using photoionisation models with the latest release of CLOUDY (Ferland et al. 2017; Chakraborty et al. 2020) and SPEX (v3.05, Kaastra et al. 1996, Kaastra et al. 2018). In both cases we used proto-Solar abundances from Lodders et al. (2009). Both these codes require an input ionising continuum. We approximated such a continuum with a sum of two components, as previously done in Grinberg et al. (2017) and Lomaeva et al. (2020). The emission from the star, that dominates in the UV, was modelled with a black body, while the emission from the accretion onto the NS with a power law modified by a Fermi-Dirac cutoff. Both components have the same parameters as employed in Lomaeva et al. (2020). In particular, the shape of the power law continuum cannot be well constrained at energies below 10 keV, especially when strongly affected by absorption, as is the case with our observations. We thus used parameters derived from non-simultaneous NuSTAR observations (Fürst et al. 2014). We note that there are some indirect hints that the illuminating continuum assumed here may not reflect the true continuum seen by the plasma in the system, such as, in particular, the large ratio between the Fe and Si/S fluorescence lines and the stability curves, which are unstable over wide ranges, especially at the ionisation parameters of interest. This emphasises the importance of strictly simultaneous observations at high resolution below 10 keV and at energies above this range for the future.

In our modelling, we left free to vary the electron density $n_e$ (cm$^{-3}$), the ionisation parameter $\xi$ (erg cm s$^{-1}$), the absorption coefficient $N_H$ (10$^{22}$ cm$^{-2}$), and the turbulent velocity $v_{turb}$ (km s$^{-1}$). We explored the parameter space with CLOUDY in the ranges $5.0 \leq \log n_e \leq 11.5$, $0.0 \leq \log \xi \leq 4.0$, $20.9 \leq \log N_H \leq 22.3$, and $80$ km s$^{-1} \leq v_{turb} \leq 160$ km s$^{-1}$. For SPEX we assume a much larger parameter space since its PION model calculates the ionisation balance instantaneously and does not require a pre-defined grid of models.

We modelled the data with an absorbed partially covered power law, with spectral index $\Gamma = 1$, corresponding to the input power law of our photoionisation models (Fürst et al. 2014), in addition to the CLOUDY/SPEX photoionisation model. The absorption due to the interstellar medium was fixed to $3.7 \times 10^{21}$ cm$^{-2}$ (HI4PI Collaboration et al. 2016), while the local absorption was left free to vary. The local partial absorption was applied only to the continuum, since both the geometry of the system, with localised wakes of material, and previous high resolution studies (Schulz et al. 2002; Watanabe et al. 2006; Grinberg et al. 2017; Lomaeva et al. 2020) imply that the line producing region is not experiencing the same high absorption as the vicinity of the neutron star, where the continuum is produced. We further added three more Gaussians for the fluorescence Fe K$\alpha$ line, centred at 1.9388 Å (cfr. Sect. 4), and for the near-neutral fluorescence emission lines of Si ii-vi and Si ii-vii, which are not reproduced by CLOUDY and SPEX.

The best fit CLOUDY model resulted in $\log n_e = 8.19984^{+0.0017}_{-0.01696}$, $\log \xi = 3.728 \pm 0.009$, with $\log N_H = 22.175 \pm 0.020$ cm$^{-2}$ and a turbulent velocity of $\sim 160$ km s$^{-1}$. The model required a redshift, with a best fit value of $z \sim 10^{-4}$, corresponding to a velocity of $v \sim 100$ km s$^{-1}$, consistent with the Doppler shifts previously obtained. The Cash (d.o.f.) statistic value was 1.58 (2584). The modelling of the whole spectrum with SPEX resulted in the best fit values of $\log \xi = 3.867^{+0.005}_{-0.009}$ and $\log N_H = (4.3 \pm 0.3) \times 10^{21}$ cm$^{-2}$, with a line broadening of $160 \pm 16$ km s$^{-1}$ and a Cash (d.o.f.) value of 1.57 (2382). Also in this case the model is redshifted with respect to the data, with a best fit velocity along the line of sight of $130^{+15}_{-25}$ km s$^{-1}$. Best fits are shown in Fig. 9. We also tried to add a second CLOUDY component, obtaining no statistical significant improvement of the fit.

We noticed that the electron density $n_e$ is degenerate with the absorption of the interstellar medium (ISM): the larger the ISM $N_H$, the larger the $n_e$ (see discussion in Sect. 5.2).
Table 6. Spectral features detected in the Mg region (10-14 Å). For each of them, we report the detection parameter $\alpha$, the best-fit values (wavelength and line flux) and the Doppler velocities, computed with respect to reference wavelength from literature. Line widths fixed to 0.003 Å, if not stated otherwise.

| Line     | BB    | Ref. wavelength (Å) | Det. wavelength (Å) | Line flux ($\text{ph s}^{-1} \text{cm}^{-2} \times 10^{-5}$) | Velocity (km s$^{-1}$) |
|----------|-------|---------------------|---------------------|-------------------------------------------------|-------------------------|
| Na x Ly$\alpha$ | 2.5   | 10.023$^b$           | 10.023 ± 0.005      | 0.5$^{+0.1}_{-0.2}$                             | 0 ± 150                 |
| Ne x Ly$\beta$ | 29    | 10.23887$^c$         | 10.2408 ± 0.0017    | $^{+2.1}_{-0.5}$                               | 60 ± 50                 |
| Ne ix He$\epsilon$ | 3.2   | 10.643$^b$           | 10.644 ± 0.006      | 0.7$^{+0.4}_{-0.3}$                             | 30 ± 170                |
| Fe xix   | 1.8   | 10.816$^b$           | 10.814$^{+0.006}_{-0.005}$ | 0.4$^{+0.3}_{-0.2}$                             | $^{−60}_{−140}$         |
| Ne ix Ne$\gamma$ | 7     | 11.001$^a$           | 11.005$^{+0.006}_{-0.007}$ | 1.0$^{+0.5}_{-0.4}$                             | $^{110}_{−190}$        |
| Ne ix He$\delta$ | 8     | 11.544$^a$           | 11.549$^{+0.005}_{-0.006}$ | 2.1$^{+0.6}_{-0.5}$                             | $^{130}_{−130}$        |
| Ne x Ly$\alpha$ | 49    | 12.132$^c$           | 12.1398 ± 0.0017    | 5.3$^{+1.1}_{-1.2}$                             | 190 ± 40                |
| Fe xxi   | 1.7   | 12.284$^b$           | 12.285$^{+0.008}_{-0.007}$ | 0.5$^{+0.5}_{-0.4}$                             | 20$^{+200}_{−200}$     |
| Ne ix r  | 17    | 13.447$^b$           | 13.454 ± 0.005      | 1.3$^{+1.6}_{-0.7}$                             | 140 ± 110               |
| Ne ix i  | 17    | 13.553$^i$           | 13.557 ± 0.005      | 2.2$^{+0.8}_{-0.6}$                             | $^{0}_{\text{Ne ix r}}$ |
| Ne ix f  | 17    | 13.699$^b$           | 13.706 ± 0.005      | 2.6$^{+1.3}_{-1.3}$                             | $^{0}_{\text{Ne ix r}}$ |

Notes. ($^a$) Possible line blends include Fe xx at 10.024 Å and Ni xxiv at 10.027 Å. ($^b$) Reference wavelength taken from AtomDB database (http://www.atomdb.org/index.php). ($^c$) Erickson (1977). ($^d$) Computed from the Ne x Ly$\alpha$ best-fit wavelength, as from Erickson (1977). ($^e$) Another possible identification is the Fe xix at 10.648 Å. ($^f$) Possible line blends are: Fe xx at 11.007 Å, Na x He$\alpha$ at 11.003 Å and Fe xix at 11.002 Å. ($^g$) Kelly (1987). ($^h$) Another possible line is Fe xx at 11.546 Å. ($^i$) Best-fit value of the line width of (9.6$^{+1.8}_{−2.5}$) × 10$^{-3}$ Å. ($^k$) Drake (1988).

Table 7. Best-fit values of the RRCs in each region, with temperature reported in K and eV. The wavelengths in the last column are simply the conversion of the threshold energy from keV to Å and are meant just for convenience to the reader.

| RRC | Region | Threshold energy (keV) | Temperature ($10^4$ K) | Temperature (eV) | Wavelength (Å) |
|-----|--------|------------------------|------------------------|-----------------|----------------|
| Mg xi | Si     | 1.961 ± 0.002          | 5.2$^{+6.7}_{−2.9}$    | 4.5$^{+5.2}_{−2.5}$ | 6.321          |
| Mg xi | Si     | 1.768 ± 0.001          | 3.6$^{+1.9}_{−1.3}$    | 3.1$^{+1.6}_{−1.1}$ | 7.022          |
| Ne x  | Mg     | 1.3600$^{+0.012}_{−0.010}$ | 12.5$^{+2.9}_{−2.9}$   | 10.8$^{+3.4}_{−1.2}$ | 9.116          |
| Ne ix | Ne     | 1.1950$^{+0.0006}_{−0.0007}$ | 5.2$^{+3.9}_{−2.4}$    | 4.5$^{+3.4}_{−2.1}$ | 10.374         |
| O vii | Ne     | 0.8720 ± 0.0006        | 1.0$^{+4.8}_{−0.7}$    | 0.9$^{+4.2}_{−0.6}$ | 14.218         |

Table 8. Best-fit values of the $G$ and $R$ ratios of the He-like triplets and correspondent electron temperatures and densities (Porquet & Dubau 2000). The electron density of the He-like Si xv triplet (marked as $*$) is an upper limit.

| Element | $G$       | $R$       | Temperature (K) | Temperature (eV) | Electron density $n_e$ (cm$^{-3}$) |
|---------|-----------|-----------|-----------------|-----------------|----------------------------------|
| S xv    | 0.48$^{+0.14}_{−0.10}$ | 9.9$^{+2.4}_{−2.2}$ | -               | -               | -                                |
| Si xiii | 0.80$^{+0.09}_{−0.09}$  | 6.0 ± 0.6 | 1 × 10$^7$      | 860             | 1 × 10$^{12}$*                   |
| Mg xi   | 0.74$^{+0.14}_{−0.13}$  | 1.2$^{+0.3}_{−0.2}$ | 7 × 10$^6$      | 600             | 2 × 10$^{13}$                   |
| Ne ix   | 3.7$^{+4.4}_{−3.7}$     | 1.2$^{+0.6}_{−0.5}$ | 1 − 3 × 10$^6$  | 90–260           | 1.5 × 10$^{12}$                |

5. Discussion

We performed, for the first time, high-resolution spectroscopy analysis of Chandra/HETGS data of Vela X-1 at the orbital phase $\phi_{orb} \approx 0.75$. A first look at the hardness ratio (Fig. 2) revealed no significant continuum spectral variability during the observation. The mainly flat shape of the hardness ratio is not surprising, since the line of sight at this orbital phase is expected to lie well within the photoionisation wake, a denser stream-like region that trails the NS (Doroshenko et al. 2013; Malacaria et al. 2016) and acts as a constant absorber (see Fig.1).

The analysis pointed out the presence of Fe, S, Si, Mg and Ne, as well as of less intense emission lines from Al and Na. Contrary to previous observations (Schulz et al. 2002; Goldstein et al. 2004; Watanabe et al. 2006), there is no evidence of the presence of Ar ($\lambda \sim 3.359$ Å), Ca ($\lambda \sim 4.186$ Å) and Ni ($\lambda \sim 1.660$ Å) fluorescence lines. Upper limits of their fluxes resulted in $5.2 \times 10^{-5}$ ph s$^{-1}$ cm$^{-2}$ for Ar, $2.3 \times 10^{-5}$ ph s$^{-1}$ cm$^{-2}$ for Ca, and $3.1 \times 10^{-4}$ ph s$^{-1}$ cm$^{-2}$ for Ni, respectively.

In the next subsections, we discuss in details the Fe region (Sect. 5.1), carry out plasma diagnostic (Sect. 5.2), and investigate the geometry of the wind of the companion star (Sect. 5.3).
5.1. The Iron complex

The Fe region (1.6–2.5 Å) is dominated by a Fe Kα line, centred at 1.9388 ± 0.0006 Å. Assuming no Doppler shift for the line, the corresponding maximum ionisation state is Fe x (Palmeri et al. 2003), consistent with the results of Grinberg et al. (2017) (below Fe xi), and different from the case of an irradiated wind, as showed by the hydrodynamic simulations of Sander et al. (2018) (where the wind is mainly driven by Fe m ions). However, the line may be redshifted so that a higher ionisation state could be expected. A more refined calculation is beyond the goal of this paper.

The only other relevant feature detected in this region is the Fe K-edge at 1.742 ± 0.003 Å (see Table 2), which is not significantly Doppler shifted.

The BB algorithm did not detect the Fe Kβ line, expected at 1.758 Å, most likely because of the proximity of the Fe K-edge. However, since the average flux ratio between the Fe Kβ and Fe Kα lines is 0.13–0.14 (Palmeri et al. 2003), for the charge states Fe ii–ix, we can estimate an expected flux of (1.32 ± 0.11) × 10−10 ph cm−2 s−1 Å−1, which might not be sufficient to let the line emerge from the continuum underneath. To verify this assertion, we generated 1000 Monte Carlo simulated spectra adding to the best fit model a Gaussian at the correspondent wavelength of the Fe Kβ with the expected flux. We then run the BB algorithm on all the simulated spectra (cf. Sect. 3.1). In no case the line was detected, confirming its weakness with respect to the X-ray continuum and the K-edge, which precluded a detection in the observational data. The Fe Kβ/Kα ratio depends on the ionisation of iron (see the detailed discussions in Molendi et al. 2003; Bianchi et al. 2005). For higher charge states, the expected line ratio is even smaller, i.e., the Fe Kβ line would be even weaker than what our simulation showed as undetectable. Therefore, we cannot rule out that the ionisation state is higher than what we assumed. We discuss the prospects of detecting Fe Kβ with future instruments in Sect. 6.

Results from Goldstein et al. (2004) at φorb ≈ 0 and φorb ≈ 0.5 show, in the same spectral region, the presence of the Ni Lyα line at λ ~ 1.660 Å, while Schulz et al. (2002) propose the presence of a Fe xxv emission line at λ ~ 1.85 Å (φorb ≈ 0). The BB procedure did not detect any feature at those wavelengths, but after a visual inspection, we noted a marginal presence of residuals in emission. So we add two more Gaussians to the best fit model of the Fe region, at λ ~ 1.66 Å and λ ~ 1.86 Å, for the Ni Lyα and a Fe xxv respectively, and fit the spectrum again. The Fe XXV is actually a He-like triplet, but the resolution of the MEG of 0.023 Å FWHM, adopted consistently through the paper, is not good enough to resolve the lines individually. Hence, we use just one Gaussian to fit the whole ion, letting the width free to vary. The width of the Ni Lyα line was fixed to the usual value of 0.003 Å. The fluxes of these latter Gaussians resulted in (1.8 ± 1.3) × 10−14 ph cm−2 s−1 Å−1 for the Ni Lyα and (3.1 ± 1.2) × 10−15 ph cm−2 s−1 Å−1 for the Fe xxv lines, while the width of the He-like Fe xxv had a best fit value of 0.018 ± 0.003 Å.

From the Fe edge (Table 2), we computed the equivalent hydrogen column as NHI = τedge/(ZFeσFe), where ZFe = 2.69 × 10−5 is the solar Fe abundance (Wilms et al. 2000) and σFe = 3.4 × 10−20 cm2 is the photoelectric absorption cross section for Fe xxv at the wavelength of the K-edge (Verner et al. 1996). Using the best-fit value optical depth τedge = 0.31 ± 0.03, we derive NHI = (3.4 ± 0.3) × 1023 cm−2, which is nearly consistent with the best-fit value of NHI = (2.68 ± 0.07) × 1023 cm−2 obtained fitting the spectrum in this region with a simple absorbed power law, with solar abundances and cross sections as specified in Sect. 3. These values are of the same order of magnitude as the best fit values found for observations using MAXI (Matsuoka et al. 2009) by Doroshenko et al. (2013) and NuSTAR (Harrison et al. 2013) by Fürst et al. (2014) at the same orbital period. However, we must bear in mind here that the model we used does not account for the Fe Kβ line, which may contribute to larger uncertainties on the Fe K-edge parameters.

5.2. Plasma properties

The presence of five narrow RRCs (Mg xi, Mg xii, Ne ix, Ne x, and O vii) suggests that the plasma is photoionised, with a temperature between ~1 and 10 eV (Table 7). A further indication of a photoionised plasma might be the value of G = 3.7±1.5, the Ne ix triplet (Table 8), consistent with 4 in spite of the large uncertainties (Porquet & Dubau 2000).

However, the G ratios of 5 xxv (G = 0.48±0.14), Si xiii (G = 0.80±0.10), and Mg xi (G = 0.74±0.13) are all smaller than 1, indicating that collisional processes are not negligible and may even dominate (Porquet & Dubau 2000; Porquet et al. 2010). Under the hypothesis of a collisional equilibrium plasma (CIE),
we can estimate the temperature from the $G$ ratio values (Porquet & Dubau 2000). From the He-like Si xi and Mg xi triplets we obtain temperatures of $1 \times 10^7$ K and $7 \times 10^6$ K, respectively, which are two orders of magnitude higher than the ones from the Ne RRCs.

This inconsistency between temperatures derived from the RRCs and the He-like line ratios is likely due the known issue that relative level populations between the upper levels of the He-like triplet lines can be shifted by other physical phenomena, which are likely present in HMXBs, thus making the $G$ ratio unreliable. In particular, two processes can enhance a resonant $r$ line stronger than the intercombination $i$ or forbidden $f$ lines; photoexcitation and resonance line scatter. Photoexcitation can be important in photoionisation equilibrium (PIE) plasma, when many photons with the right energy excite the electrons to the resonant level. This clearly enhances the resonance line and, then, alters the $G$ ratio with respect to the pure recombination case (see the comprehensive explanation in Kinkhabwala et al. 2002). The presence of a few weak iron L emission lines (Fe xix-xxiv) also seems to point in this direction (Sako et al. 2000).

Resonant line scattering occurs when a photon is absorbed and re-emitted in the same wavelength, but in the direction of the lowest optical depth. This phenomenon is well explained by Wojdowski et al. (2003) for the HMXB Centaurus X-3, observed during eclipse. In the case of Vela X-1, though we are not in the eclipsing phase, the dense streams of matter surrounding the NS can act as a strong absorber, enhancing the resonance line scattering into the line of sight.

Concerning the $R$ ratio, the values of Mg xi ($R = 1.2^{+0.3}_{-0.5}$) and Ne ix ($R = 1.2^{+0.6}_{-0.5}$) He-like lines implies an electron density of the plasma of $2 \times 10^{13}$ cm$^{-3}$ and $1.5 \times 10^{12}$ cm$^{-3}$, respectively, considering a plasma temperature of $7 \times 10^6$ K and $2 \times 10^6$ K, as previously estimated. On the other hand, the $R$ ratios of Si xii ($R = 6.0 \pm 0.6$) and S xv ($R = 9.9^{+2.4}_{-1.5}$) are much higher than the respective values at the low density limit, when the relative intensities of the He-like lines are in fact independent of the electron density of the plasma. In the case of Si, for instance, the low density limit value is $R = 3$, corresponding to a maximum density of the order of $10^{12}$ cm$^{-3}$ (Porquet & Dubau 2000), which can be addressed here as upper limit. On the other hand, the fit with CLOUDY and SPEX photoionisation models highlighted the degeneracy of the electron density $n_e$ with the model chosen for the continuum, and, in particular, with the absorption from the ISM. The best fit value of $n_e = 1.5 \times 10^6$ cm$^{-3}$, for instance, can be treated only as a lower limit. The analysis underlines that the estimation of the density is influenced in opposite directions by the $R$ ratio and the continuum and the real value is somewhere in between those limits.

Also the UV radiation of the companion star can alter the plasma (the so-called “UV-pumping” mechanism, Gabriel & Jordan 1969; Blumenthal et al. 1972; Mewe & Schrijver 1978; Porquet et al. 2001). UV radiation mimics a high density plasma, favouring the population of the $3P$ levels against the $3S_1$ level, leading to an increase of the intensity of the intercombination line, against the forbidden line and, hence, to smaller values of the $R$ ratio. The influence of the UV emission is taken into account in both, CLOUDY and SPEX based photoionisation models, through our choice of the continuum. Such models should also, if applicable to the given data at all, give better constrains on the underlying plasma parameters than the more empirical consideration of $G$ and $R$ ratios. The quality of our fits in Sect. 4 imply that this is the case.

Overall, both the self-consistent photoionisation codes provided a satisfactory fit of the data (Fig. 9), implying that, at this specific orbital phase, the plasma is mainly photoionised. However, a closer inspection at the residuals hints to the presence of at least another phase of the plasma. The near-neutral emission lines of Si ii-iv and Si iii-iv, as well as the Fe K line are not reproduced by the photoionisation models that are driven by the presence of highly ionised lines. This naturally suggests that the plasma cannot be a single component plasma.

In a possible scenario, colder and denser clumps of plasma, from either the wind or larger scale accretion structures such as wakes, can cross unevenly the line of sight, adding to the PIE emission of the wind of the companion star a further component with a lower ionisation. Our data do not allow to constrain the origin of this component that could be, for example, a further, colder PIE component, a collisionally ionised component or a more complex mix with a temperature gradient as is the case, e.g., in Cyg X-1 (Hirsch et al. 2019). We also note that our results emphasise the necessity of an accurate treatment of intermediate and low ionisation ions in atomic codes used for high resolution X-ray spectroscopy.

5.3. Wind geometry

Doppler velocities at different orbital phases can reveal the location and dynamics of the line emitting material. Fig. 10 shows the velocities for the ions of Si vi-ix from Schulz et al. (2002) and Goldstein et al. (2004) at the orbital phases $\phi_{orb} \approx 0$ and $\phi_{orb} \approx 0.5$, adjusted with respect to the laboratory measurements of Hell et al. (2016), together with the ones from Grinberg et al. (2017) at the orbital phase $\phi_{orb} \approx 0.25$, and with those in the present work ($\phi_{orb} \approx 0.75$). Velocities at $\phi_{orb} \approx 0.25$ are negative (blueshift), while velocities at the other orbital phases are positive (redshift) and/or consistent with no shift. The same behaviour is observed also for all the others lines of S, Si, Mg and Ne (Fig. 11), even though there are no recent laboratory measurements that allow us to validate the Doppler shifts found by the previous studies (Schulz et al. 2002; Watanabe et al. 2006; Goldstein et al. 2004; Grinberg et al. 2017). Most of the velocities are consistent with the radial velocity of the NS, as well

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5 We note here that the $R$ ratio depends upon the relative ionic abundance of the H-like and He-like ions ($\chi_{ion}$ parameter), but in the range of our interest the dependence is so small that we can neglect it (see Fig. 9 of Porquet & Dubau 2000).
Fig. 11. Doppler velocities at different orbital phases of Lyα lines and He-like triplets of S, Si, Mg and Ne from Schulz et al. (2002) (blue) and Goldstein et al. (2004) (orange), from Grinberg et al. (2017) (green) and from the present work (red). Different symbols stand for different ionisation stages. The solid and dashed lines represent the radial velocities of the NS and of the companion star, respectively.

as of the companion star (solid and dashed lines in Figs. 10-11), computed as:

\[ v_{\text{rad}} = 2 \pi a \sin \theta \cos \omega \left( 1 - e^2 \right) \]  

where \( a \) is the semi-major axis, \( \theta \) is the inclination, \( T \) is the orbital period, \( e \) is the eccentricity, \( \theta \) and \( \omega \) are the true anomaly and the argument of periapsis, respectively.

The overall behaviour is consistent with the material comoving with the NS, though the lack of more observational data for each orbital phase prevent us to assert it definitively. However, this behaviour has already been observed for the black hole HMXB Cygnus X-1 (Hirsch et al. 2019; Miškovićová et al. 2016), where the Doppler shifts show a clear modulation with the orbital phase. It has already been suggested for Vela X-1 that the wind velocity at the distance of the NS is \( \sim 100 \text{ km s}^{-1} \) and lower than typically estimated from prescribed simple β-laws (Sander et al. 2018). The large spread in the range of observed Doppler shifts within the same orbital phases may be due radiation coming from regions further downstream the wind or due to a more complex velocity structure in the accretion region.

More considerations on the geometry of the emitting region can be drawn from the ionisation state of the plasma. The ionisation parameter can be expressed as in Tarter et al. (1969):

\[ \xi = \frac{L_X}{n_e r^2} \]  

where \( L_X \) is the X-ray luminosity of the source, \( n_e \) the particle density of the plasma, and \( r \) the distance at which the lines are produced. From the photoionisation models, we computed the distributions of the relative abundances of all the ions as a function of \( \xi \). For the H-like ions, the ionisation parameter was in the range \( 3.7 \geq \log(\xi) \geq 4.2 \). Assuming that each ion is produced at the peak of its distribution, for a luminosity of \( 4 \times 10^{36} \text{ erg s}^{-1} \) and a best-fit value of \( \log(n_e) \approx 8 \), we obtained a distance in the range \( (1.6 - 2.8) \times 10^{12} \text{ cm} = 23 - 40 R_\odot \). Considering that the orbital separation of the system is \( \sim 50 R_\odot \) and the companion star has a radius of about \( 30 R_\odot \), the region where the H-like emission lines come from seems to be very close to the surface of the companion star, rather then to the surface of the NS. The other ionisation stages have lower values of \( \log(\xi) \), implying even higher distances, compatible with the idea of a wake expanding after the passage of the NS. We note, however, that this estimate assumes a constant density, that is most likely not the case for an expanding wind, even without taking into account possible clumping and wake structures.

Our result is in agreement with simulations of X-ray photons in a smooth wind from Watanabe et al. (2006), for H-like Si, in the case of a mass loss rate \( M \leq 1.0 \times 10^{-6} M_\odot \text{ yr}^{-1} \), consistent with the latest estimation for Vela X-1 of \( \sim 0.7 \times 10^{-6} M_\odot \text{ yr}^{-1} \) (Sander et al. 2018). In the end, our simple calculation would suggest that the photoionised plasma is produced at the orbital separation of the system, in a region close to the surface of the companion star.

Nonetheless, given the uncertainty in the electron density driven by the continuum, we repeated the calculation using instead the \( n_e \) derived from the \( R \) ratio (\( n_e \sim 10^{13} \text{ cm}^{-3} \)). This \( n_e \) value, however, does not take into account the presence of the strong UV radiation from the stellar wind (Sec. 5.2) and thus has to be considered as an overestimate. For the same values of the ionisation parameter as before, the resulting distance is \( r \leq 0.5 R_\odot \), comparable with the Bondi-Hoyle-Littleton radius of the NS in Vela X-1 of \( \sim 10^{10} \text{ cm} \) (Manousakis & Walter 2015). The assumption of using the same ionisation parameters holds because \( \log(\xi) \) is primarily driven by the ionisation state and thus hardly changes with the electron density, which is instead driven by the absolute line strength (i.e., distance and continuum) and the triplet shape, if the lines are well resolved. In this case, of course, the ionisation of the wind would be due almost entirely to the gravitational pulling of the NS.

From this analysis, we cannot infer the presence of clumps.

6. Future perspectives with \( \text{XRISM/Resolve and Athena/X-IFU} \)

High-resolution spectroscopy is a powerful tool to study X-ray emission from any kind of astrophysical plasma. Currently, limitations of X-ray satellites are due, for instance, to their intrinsic resolution and sensibility. New generation X-ray satellites will go beyond these limits. The X-Ray Imaging Spectroscopy Mission (\( \text{XRISM, formerly XARM, Tashiro et al. 2018} \)) and the Advanced Telescope for High Energy Astrophysics (\( \text{Athena, Nandra et al. 2013} \)) will host on-board microcalorimeters with an energy resolution down to a few eV, thus exceeding the resolution of Chandra gratings in the Fe K region.

We performed simulations of this region (1.6–2.2 Å, cfr. Sect. 5.1), including the Fe K-edge and the Fe Kα as detected in the Chandra observation, and the Fe Kβ, the He-like Fe xxv and the Ni Kα with the upper limit on the flux as in Sect. 5.1. Both microcalorimeters should be able to resolve the Fe Kα doublet and the Fe xxv triplet. To assess this in more detail, the input spectrum of our simulation included two Gaussians for the Fe Kα, at 1.9399 Å for the Fe Kα1 and at 1.9357 Å for Fe Kα2, respectively, with a 1:2 ratio (Kaastra & Mewe 1993), and four Gaussians for the Fe xxv, with line centroids as in Drake (1988) and a flux ratio of 2:1:1:2 \((w:\alpha:Fe:Fe)\). The width of all the lines was fixed to 0.0007 Å (\( \sim 2 \text{ eV} \)).

\( \text{XRISM} \) will be provided with the soft X-ray spectrometer Resolve, with a nominal energy resolution of 5–7 eV in the 0.3–12 keV bandpass. We used the ancillary and response files of Hitomi/SXS (Kelley et al. 2016) for the energy resolution requirement of 7 eV. Simulations show that an exposure of only 300 s (comparable with the pulse period of 293 s) is sufficient to clearly detect the Fe Kβ line with a significance of \( \alpha = 1.8 \), corresponding to 83% of positive detection probability, with a
measured Fe Kβ/Feα ratio of 0.17$^{+0.11}_{-0.09}$. With an exposure of 2.5 ks, the probability of a positive detection of the Fe Kβ line raises up to $> 99.99\%$ ($\alpha = 22$). The Fe Kα doublet is resolved, while amongst the lines of Fe xxv only the f line is clearly resolved.

*Athena* will be equipped with the X-ray Integral Field Unit (X-IFU, Barret et al. 2018), a cryogenic X-ray spectrometer working in the energy range 0.2–12 keV, with a nominal energy resolution of 2.5 eV up to 7 keV. Moreover, thanks to the higher collecting area of *Athena* (1.4 m$^2$ at 1 keV), high quality spectra will be acquired in much shorter exposures. Also for the *Athena*/X-IFU, we performed a 300 s simulation of the Fe region (Fig. 12). Running the BB algorithm on the simulated spectrum, the Kβ line is detected with $\alpha = 9$, corresponding to 99.99% probability of positive detection. If the exposure times is increased up to 2.5 ks, then the Kβ line is detected with a significance of $\alpha = 69$. The measured intensity ratio between the Fe Kβ and Fe Kα is $0.16^{+0.09}_{-0.10}$. The Fe Kα doublet is fully resolved, as well as the f line of Fe xxv. The i line, which is made by two lines ($(x + y)$ in the nomenclature of Gabriel 1972), is partially resolved, with the most energetic one blended with the r line.

*Athena*'s capabilities will significantly improve also plasma diagnostic, even at shorter exposures. To test how well we can determine $R$ and $G$ ratios, we performed simulations with *Athena*/X-IFU at different exposure times. Fig. 13 shows the ratios of the Si regions at different exposures, in comparison with the ratios obtained from the analysis of the 45.88 ks *Chandra*/HETGS observational data set. With an exposure of only 2.5 ks the uncertainties on $R$ and $G$ are reduced of the $\sim50\%$. Longer exposures reduce consistently the errors on $R$ and $G$, from $\sim10\%$ up to 2% of their absolute values.

All the discussed simulations with *Athena*/X-IFU were performed using standard response matrices and background files. A more thorough exploration of possibilities to observe Vela X-1 with *Athena*, including a detailed modelling of the effects of defocussing necessary to avoid pile-up for bright X-ray binaries and the right choice of event grades to address certain scientific questions, is beyond the scope of this work and will be addressed in a dedicated publication.

Overall, the achievement of good-quality spectra with such short exposure times imply that the lines can be traced on shorter timescales, i.e., of the same order of magnitude as the pulsar period. Moreover, because of *Athena*’s resolution, the energy of the Fe Kα line can be better constrained so that we can be able to determine the ionisation stage of iron with a higher precision. It is clear, then, that upcoming X-ray satellites will considerably improve the knowledge of HMXBs, of stellar winds and, in general, of any kind of astrophysical plasma, as well remarked by XRISM Science Team (2020).

### 7. Conclusions

We conducted, for the first time, X-ray high-resolution spectroscopy of Vela X-1 at the orbital phase $\phi_{\text{orb}} \approx 0.75$, i.e., when the line of sight is going through the photoionisation wake that trails the neutron star along the orbit.

The data did not show any significant variability of the continuum for the duration of the observation. A blind search for spectral features lead us to detect emission lines from Fe, Si, Mg, Ne, and, to a lesser degree, from Al and Na. We detected and identified five narrow RRCs (Mg i-xii, Ne ix-x, O viii) and He-like triplets of S, Si, Mg and Ne.

From plasma diagnostic techniques and from fits with photoionisation models from CLOUDY and SPEX, we conclude that the plasma at this orbital phase is mainly photoionised, but data suggest the presence of at least another component, with a smaller ionisation parameter. The presence of a collisional component cannot be excluded, as well as a mixture of ionised and collisional phases. This is in agreement with the idea of colder and denser clumps of matter, embedded in the hot, optically-thin wind of the donor star. The complex geometry of the system is also reflected by the spread of the distribution of the Doppler velocities, as well as in the indetermination of the emission region.

The future X-ray instruments *Athena*/X-IFU and XRISM/Resolve will considerably enhance the detection and the resolution of spectral features. We showed through simulations that, thanks to higher energy resolutions, they will resolve single lines in the Fe Kα doublets and Fe xxv triplet and,
thanks to higher collecting areas, will allow plasma diagnostic for time scales as short as few hundreds of seconds.

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