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# Stellar-wind variability in Cygnus X-1 from high-resolution excess variance spectroscopy with *Chandra*

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## ABSTRACT

**Context.** Stellar winds of massive stars are known to be driven by line absorption of UV photons, a mechanism that is prone to instabilities, causing the wind to be clumpy. The clumpy structure hampers wind mass-loss estimates, limiting our understanding of massive star evolution. The wind structure also impacts accretion in high-mass X-ray binary (HMXB) systems.

**Aims.** We aim to analyse the wavelength-dependent variability of X-ray absorption in the wind to study its structure. Such an approach is possible in HMXBs, where the compact object serves as an X-ray backlight. We probe different parts of the wind by analysing data taken at superior and inferior conjunctions.

**Methods.** We applied excess variance spectroscopy to study the wavelength-dependent soft (2–14 Å) X-ray variability of the HMXB Cygnus X-1 in the hard spectral state. Excess variance spectroscopy quantifies the variability of an object above the statistical noise as a function of wavelength, which allows us to study the variability of individual spectral lines. This technique was applied to high-resolution gratings spectra provided by *Chandra*, accounting for various systematic effects. The frequency dependence is investigated by changing the time binning.

**Results.** The strong orbital phase dependence we observe in the excess variance is consistent with column-density variations predicted by a simple model for a clumpy wind. We identify spikes of increased variability with spectral features found by previous spectroscopic analyses of the same data set, most notably from silicon in over-dense clumps in the wind. In the silicon line region, the variability power is redistributed towards lower frequencies, hinting at increased line variability in large clumps. In prospect of the microcalorimetry missions that are scheduled to launch within the next decade, excess variance spectra present a promising approach to constraining the wind structure, especially if accompanied by models that consider changing ionisation.

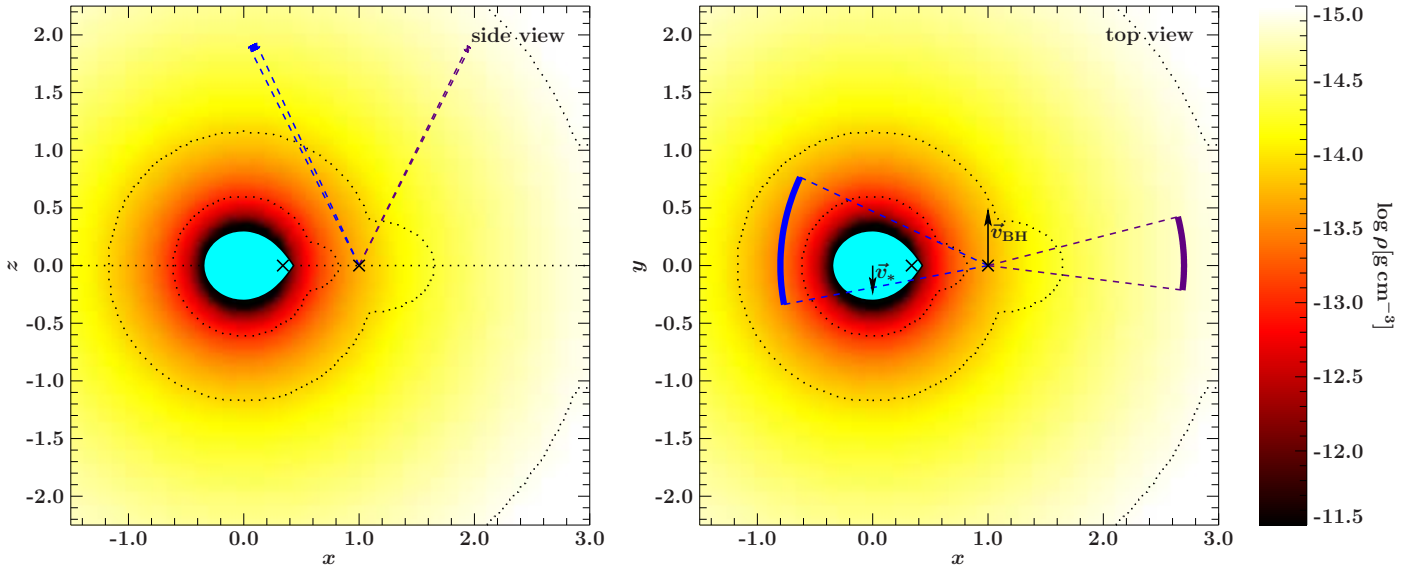
**Key words.** stars: winds, outflows – accretion, accretion disks – X-rays: binaries – stars: individual: Cygnus x-1 – stars: individual: HDE 226868 – techniques: spectroscopic

## 1. Introduction

Accretion onto compact objects is a dynamically complex phenomenon and releases enormous amounts of highly energetic radiation, which strongly impacts the environment of the accretor through feedback processes. The complex dynamics and, in particular, inhomogeneities in the accretion flow often induce variability, which can span many orders of magnitude (e.g. Oskinova et al. 2012). Understanding accretion processes on all scales, in Galactic and extragalactic sources, therefore requires precise measurements of both the variability and the environmental characteristics (e.g. densities, ionisations, and element abundances), which in turn calls for a joined spectral and timing analysis.

Excess variance spectroscopy excels at combining spectral and timing information. The excess variance is the variance of

a light curve above the expected statistical noise (Edelson et al. 2002; Vaughan et al. 2003). If applied to a set of light curves taken in different bands, the spectral distribution of the variability can be studied. Excess variance spectroscopy can reveal the variability behaviour of individual spectral lines, provided sufficient resolution and signal. This presents a clear advantage over other tools such as colour–colour diagrams (Nowak et al. 2011; Hirsch et al. 2019; Grinberg et al. 2020). So far, excess variance spectra have mainly been applied to study extragalactic sources (see, e.g. references in Parker et al. 2020). In particular, Parker et al. (2017a, 2018) introduced a method to detect ultra-fast outflows of active galactic nuclei (AGNs), which are fast, wide-angle accretion disc winds. They possess a large amount of mechanical power and therefore influence AGN evolution via feedback processes (e.g. Tombesi et al. 2010). In recent years, excess variance spectroscopy has proven valuable in detecting



**Fig. 1.** Stellar wind density in Cyg X-1 according to the isotropic clumpy wind model by El Mellah et al. (2020). The average density is shown for clarity instead of the clumpy wind structure. The dotted contours denote densities of  $\log \rho / (\text{g cm}^{-3}) = -13, -14,$  and  $-15$  in the focused wind model by Gies & Bolton (1986a). The left panel shows a side view (dotted line: orbital plane) and the right a top view (arrows: orbital motion). The line of sight to the black hole and orbital phase covered is highlighted for Obs. 3814 (dashed, blue) and 11044 (dashed, purple). Masses and orbital separation were set according to Miller-Jones et al. (2021).

ultra-fast outflows and in independently confirming and refining known results (Parker et al. 2017a, 2018; Igo et al. 2020; Härer et al. 2021), demonstrating their advantages: excess variance spectra are easy to calculate, provide less biased detections, and show more pronounced features than count spectra. Nevertheless, they have seldom been applied to Galactic sources, where high-resolution gratings data present an opportunity to study the wavelength dependence of variability at a resolution above  $0.1 \text{ \AA}$ . We demonstrate the capabilities of excess variance spectroscopy for studying the structure of stellar winds by applying it to *Chandra* observations of the high-mass X-ray binary (HMXB) Cygnus X-1 (Cyg X-1).

As binary systems consisting of an O or B star and neutron star or black hole, HMXBs are invaluable laboratories to study accretion, compact objects, and the strong winds of massive stars. Cyg X-1 is one of the most studied HMXBs. As a bright and persistent source, it was discovered in 1964 (Bowyer et al. 1965). The compact object is dynamically constrained to be a black hole (Gies & Bolton 1982), and recently Miller-Jones et al. (2021) refined the mass estimate to  $21.2 \pm 2.2 M_{\odot}$ , making Cyg X-1 the most massive known stellar mass black hole in an X-ray binary. The companion star HDE 226868 is an O9.7 Iab supergiant (Walborn 1973) with a mass of  $\sim 41 M_{\odot}$  (Miller-Jones et al. 2021). As a blue supergiant star, HDE 226868 has a strong stellar wind with a mass-loss rate of  $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$  (Herrero et al. 1995; Gies et al. 2003) and a terminal velocity of  $\sim 2100 \text{ km s}^{-1}$  (Herrero et al. 1995). Figure 1 depicts the system and wind geometry of Cyg X-1. The system is seen under an inclination of  $27\text{--}28^{\circ}$  (Orosz et al. 2011). Due to the low orbital separation (0.244 AU, Miller-Jones et al. 2021) and short orbital period (5.6 d, Webster & Murdin 1972; Brocksopp et al. 1999; Gies et al. 2003), the donor star is close to filling its Roche lobe, which gives rise to a focused accretion stream along the line connecting the supergiant and the black hole. This geometry was first verified in the optical by Gies & Bolton (1986b,a), with an analysis based on Friend & Castor (1982), and is consistent with X-ray measurements of, for example, the orbital phase

dependence of the column density (see Miškovířová et al. 2016 and references therein).

Winds of massive stars, such as HDE 226868 in Cyg X-1, are driven by resonant line-absorption of stellar UV photons by partly ionised metal ions (Lucy & Solomon 1970; Castor et al. 1975). This physical mechanism is prone to the line-deshadowing instability, the development of which produces over-dense small-scale regions called clumps (Owocki & Rybicki 1984; Owocki et al. 1988; Sundqvist et al. 2018). Most of the wind mass is contained in the clumps, making these winds notoriously inhomogeneous (Hamann et al. 2008; Sundqvist et al. 2012; Puls et al. 2015). Our limited knowledge of wind clumpiness hampers the accuracy of the mass-loss rates deduced from all available diagnostics (Fullerton et al. 2006; Sundqvist & Puls 2018). Mass loss, however, plays a key role in the evolution of massive stars, especially in the late stages (Puls et al. 2008). Consequentially, the inaccuracy of mass-loss diagnostics limits our understanding of the role radiative, mechanical, and chemical feedback of massive stars plays in many contexts. In HMXBs specifically, the mass loss and the wind structure influence the accretion flow. in't Zand (2005) first suggested that, in HMXBs, clumpiness could be constrained from the variability of the mass accretion rate onto the compact objects. This claim was challenged by El Mellah et al. (2018) who showed that accreted clumps tend to mix inside the shocked region surrounding the compact object, which smears out the variability induced by stochastic clump capture. Alternatively, the variability of the column density induced by unaccreted wind clumps passing by the line of sight can be used (Oskinova et al. 2012). Motivated by Grinberg et al. (2015), who constrained clump properties in Cyg X-1 with this ansatz, El Mellah et al. (2020, EG20 hereafter), devised a model that connects the statistical properties of the column density variations to the clump size and mass, that is, the model quantitatively links variability and clump properties.

We applied excess variance spectroscopy to study the stellar wind variability in Cyg X-1. Our aim is both to test the results obtained previously with an independent approach and to

establish excess variance spectroscopy both as an approach for wind studies in HMXBs and as a tool that can be used for high resolution X-ray data, such as those obtainable today with the High-Energy Transmission Grating (HETG) on-board *Chandra*, or those that will become available with the launch of the XRISM and *Athena* X-ray missions. We analyse *Chandra*/HETG observations at superior and inferior conjunctions, of which detailed spectral analyses were performed in Hanke et al. (2009), Miškovičová et al. (2016), and Hirsch et al. (2019). The existing studies constitute an excellent test case for constraining the stellar wind structure with excess variance spectroscopy and are summarised in Sect. 2. We took advantage of the predictions of column density variability expected in such a system recently introduced by EG20. Section 3 provides more details on the observations, the calculation of the excess variance spectra, the treatment of systematic variability, and the selection of lines we checked our results against. The resulting excess variance spectra and the frequency dependence of the excess variance are shown in Sect. 4. In Sect. 5, we explore the driving mechanism behind the observed variability, model the strong orbital phase dependence based on EG20 and discuss implications for the wind geometry and structure and the role of varying ionisation, before summarising our conclusions in Sect. 6.

## 2. The clumpy wind in Cyg X-1

Highly variable absorption is observed from Cyg X-1 especially in the hard state of the black hole (e.g. Feng & Cui 2002; Ibragimov et al. 2005; Boroson & Vrtilek 2010; Grinberg et al. 2015)<sup>1</sup>. In particular, dips in the light curve are observed in soft X-rays preferentially at superior conjunction and interpreted as signatures of the clumps in the wind (see Grinberg et al. 2015, and references therein). At superior conjunction, the line of sight passes closer to the star, potentially sampling a highly structured wind region (see Fig. 1).

A paper series by Hanke et al. (2009), Miškovičová et al. (2016), and Hirsch et al. (2019) used high-resolution *Chandra* spectra to study the wind in the hard state in great detail. Hanke et al. (2009) investigated the non-dip spectrum at superior conjunction, identifying absorption lines from several H- and He-like ions and L-shell iron at low velocity shifts. Miškovičová et al. (2016) expanded this study to other orbital phases. They observed P-Cygni line profiles at inferior conjunction, which point to weak absorption and a high projected velocity. As the last paper in the series, Hirsch et al. (2019) investigated the above-mentioned absorption dips in the light curve, which are believed to be caused by clumps in the wind. Using time-resolved spectra, they studied how absorption from silicon and sulphur ions evolves in the dips, finding that lower ionisation species appear and increase in relative strength with dip depth. From this result, Hirsch et al. (2019) concluded that material in the clumps has a lower ionisation than its surroundings and that deeper dips correspond to larger clumps. In other words, the clumps have a layered ionisation structure, with large clumps reaching lower ionisations in their centres. An open question that remains from these studies is whether the dips are caused by individual, big clumps passing through the line of sight or by groups of

several smaller ones. The geometry (spherical or pancake-like) and typical masses also remain to be constrained.

## 3. Observations and methods

### 3.1. *Chandra* HETG observations of Cyg X-1

We analysed two *Chandra* observations (ObsIDs 3814 and 11044) of Cyg X-1 in the hard state taken with the High-Energy Transmission Grating (HETG; Canizares et al. 2005) and the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The observations cover the superior (3814, orbital phase  $\varphi = 0.93-0.03$ ) and inferior (11 044,  $\varphi = 0.48-0.54$ ) conjunction passages, during which the line of sight probes different parts of the wind (see Fig. 1). At superior conjunction, the line of sight intercepts the wind close to the stellar photosphere and grazes the focused stream. At inferior conjunction, the wind is probed at a greater distance to the companion. We note that the classification of these observations as belonging to the hard state follows Grinberg et al. (2013) and the orbital phases were assigned according to the ephemeris provided by Gies et al. (2003).

Detailed spectral analysis of both data sets has been performed in the studies mentioned in Sect. 2 (Hanke et al. 2009; Miškovičová et al. 2016; Hirsch et al. 2019). The existing results provide an opportunity to assess the capabilities of our approach against those of conventional analysis techniques. The observations were performed in timed exposure mode (TE); that is, events are accumulated on the CCDs, transferred in the frame store, and read out. A full read-out cycle of the ACIS-S in TE mode usually takes 3.2 s; however, in our case the time is halved to 1.7 s, because only 512 of the 1024 available pixel rows were in use. We used the extracted event files provided by Miškovičová et al. (2016), but analysed the entirety of Obs. 3814, including dipping and non-dipping stages. The extractions were created using CIAO version 4.2, consistently with previous work by Miškovičová et al. (2016) and Hirsch et al. (2019), in order to facilitate direct comparison with their spectral results. We include all four first-order spectra from the high and medium energy gratings (HEG and MEG, orders  $\pm 1$ ) of the HETG. We refer the reader to Miškovičová et al. (2016) and Hirsch et al. (2019) for further details on the data collection, extraction, and processing.

We performed spectral and time binnings on the extracted events separately for the four first orders of the HEG and MEG. The spectral binning covers the 2–14 Å band with a 0.05 Å resolution and a 500 s step is used for the time binning. For a closer inspection later on, we increased the spectral resolution three-fold and varied the time step in the 50–2000 s range. The excess variance spectrum was then calculated as described in Sect. 3.2. While the spectral resolution and smallest time step are constrained by the signal strength, the maximal time step should be chosen such that the light curve has a sufficient number of bins to obtain an accurate estimate of the variance ( $\geq 20$ , Vaughan et al. 2003). One-sigma uncertainties are given unless otherwise noted.

### 3.2. Calculating the excess variance spectrum

The excess variance quantifies the variability of an object and is defined as (Edelson et al. 2002; Vaughan et al. 2003):

$$\sigma_{\text{XS}}^2 = S^2 - \overline{\sigma_{\text{err}}^2}, \quad (1)$$

<sup>1</sup> In the hard state, the intrinsic emission from close to the black hole is dominated by a hard, Comptonised component, with comparatively little contribution from the thermal emission of the accretion disc (for a discussion of accretion states in Cyg X-1 see, e.g. Wilms et al. 2006; Grinberg et al. 2013).

where  $S^2$  is the variance of the light curve and  $\overline{\sigma_{\text{err}}^2}$  the arithmetic mean of the squared measurement uncertainty, that is, the variability introduced by the statistical nature of the measurement process. Subtracting this statistical noise makes the excess variance a quantity that is indicative of only the physical variability of the source, in other words, if no variability is present, the excess variance is zero. The excess variance depends on source flux, which is avoided by normalising it to the square of the mean number of counts per bin,  $\bar{x}$ :

$$F_{\text{var}}^2 = \frac{\sigma_{\text{XS}}^2}{\bar{x}^2}. \quad (2)$$

We write the normalised excess variance in terms of the square of the fractional quantity,  $F_{\text{var}}$ , also called root-mean-square (RMS) variability.  $F_{\text{var}}$  is often used as it is linear in number of counts. However, the squared quantity,  $F_{\text{var}}^2$ , is preferable if the variability is low, because  $F_{\text{var}}$  contains a square root and becomes imaginary if the uncertainty,  $\overline{\sigma_{\text{err}}^2}$ , is larger than the signal,  $S^2$ . This case is relevant to our analysis because working at gratings resolution makes it necessary to divide the signal over a large number of bins, in comparison to CCD data, to which the excess variance is usually applied.

One advantage of using the excess variance as a measure for variability is the straightforward application to spectral data, that is, the calculation of an excess variance spectrum. As discussed in the introduction, studying the wavelength dependence of variability can provide unique physical insights that cannot be obtained from static count spectra. To judge the significance of features in the excess variance spectrum, an error estimate is required. We used the expression computed by Vaughan et al. (2003) from a Monte Carlo approach, which accounts for Gaussian and Poissonian measurement uncertainties:

$$\text{err}(F_{\text{var}}^2) = \sqrt{\frac{2\sigma_{\text{err}}^2}{N\bar{x}^2} \left( \frac{\sigma_{\text{err}}^2}{\bar{x}^2} + 2F_{\text{var}}^2 \right)}, \quad (3)$$

where  $N$  is the number of photons in the respective bin.

The band pass of frequencies contributing to the excess variance is determined by the time binning of the light curve and the length of the observation. By choosing the time binning, it is therefore possible to probe the frequency dependence of  $F_{\text{var}}^2$  and investigate if there is a variability timescale intrinsic to the system. Hirsch et al. (2019) state that the passage of a clump across the line of sight takes 0.5–5 ks, assuming that the observed dips in the spectrum are caused by single clumps and not multiple small clumps. We chose a time step of 500 s for our initial investigation to capture all clump variability in this timescale range. The frequency dependence of the detected features was investigated in a second step.

### 3.3. Eliminating systematic variability

As detailed in Sect. 3.1, we analysed *Chandra* HETG data taken with the ACIS-S detector. For a variability study such as that presented in this work, a solid understanding of the timing and read-out properties of the detector and associated systematic effects is vital.

The ACIS-S detector consists of a row of six CCDs, which are read out in sequence. As a consequence, photons arriving simultaneously on different CCDs are registered at slightly different times. This effect becomes relevant if data from multiple

gratings or orders, that is, locations on the detector, are combined. We avoid systematic effects of this kind by calculating  $F_{\text{var}}^2$  separately for each grating and order,  $i$ , and taking their weighted mean,

$$F_{\text{var}}^2 = \frac{1}{\sum_i \bar{x}_i^2} \sum_i F_{\text{var},i}^2 \cdot \bar{x}_i^2. \quad (4)$$

Weighting by the square of the mean number of counts,  $\bar{x}_i^2$ , gives equal weight to each count, regardless of which grating or order it belongs to. As the errors  $\text{err}(F_{\text{var},i}^2)$  are independent, they can be propagated according to

$$\text{err}(F_{\text{var}}^2) = \frac{1}{\sum_i \bar{x}_i^2} \sqrt{\sum_i \bar{x}_i^4 \cdot \text{err}(F_{\text{var},i}^2)^2}. \quad (5)$$

A second systematic effect is the increase in  $F_{\text{var}}^2$  due to the photon loss in gaps between CCDs and rows of dead pixels in *Chandra*'s ACIS-S detector. The photon loss is averaged over a range of wavelengths by dithering the telescope pointing<sup>2</sup>, which causes the count rate to vary periodically within dithering range of CCD gaps and dead rows, increasing the variability in this range. In the  $F_{\text{var}}^2$  spectrum, this increase manifests itself as spikes at specific wavelengths, which are not, per se, distinguishable from genuine features. Gap-induced  $F_{\text{var}}^2$  spikes constitute the largest systematic effect in our analysis, exceeding genuine features up to about an order of magnitude. We detect and filter out affected wavebands separately for each grating and order, before calculating and averaging their  $F_{\text{var},i}^2$  as described above. The resulting reductions in sensitivity strongly vary between wavelength bands (for a detailed description, see Appendix A).

While gaps produce spikes at certain wavelength, the discrete nature of the read-out increases the continuum variability for binned spectra. From Monte Carlo simulations detailed in Appendix B, we conclude that the effect on our analysis is negligible but can be significant on timescales approaching the read-out time of the instrument.

### 3.4. Line selection

We compiled atomic data from various sources to compare to observed features (see Sect. 4). Most of the data were taken from ATOMDB<sup>3</sup> and XSTARDB (Mendoza et al. 2021). The full list of references is shown in Table 1. We only considered transitions from astrophysically abundant elements (e.g. C, N, O, Ne, Mg, Si, S, Fe, etc.), which include the ground state. The final selection encompasses 719 lines with energies of 0.1–14.7 keV. For more than one transition at a given wavelength, line identification is based on elemental abundance, oscillator strength, and initial state population. However, fine structure splitting cannot be resolved for most of the lines.

## 4. Results

### 4.1. Overview: $F_{\text{var}}^2$ continuum and spike features

Figure 2 shows the  $F_{\text{var}}^2$  spectrum for both investigated data sets, Obs. 3814 and 11044, taken during the superior and inferior conjunction passage, respectively, in the 2–14 Å range.

<sup>2</sup> <https://cxc.cfa.harvard.edu/proposer/POG/html/ACIS.html> (The *Chandra* Proposer's Observatory Guide, Sect. 6.12).

<sup>3</sup> <http://www.atomdb.org>

**Table 1.** List of spike features in the  $F_{\text{var}}^2$  spectrum of Obs. 3814 with a significance  $>2\sigma$  and associated lines, which are defined as having a distance of  $<0.05 \text{ \AA}$  to the features.

Spike ( $\text{\AA}$ )	$\sigma$	Ion	Line(s)	Wl. ( $\text{\AA}$ )	Ref.	Spike ( $\text{\AA}$ )	$\sigma$	Ion	Line(s)	Wl. ( $\text{\AA}$ )	Ref.
4.37	2.0					9.48	2.1	Fe XXVI	2s $\rightarrow$ 3p	9.536	1
5.30	2.0	S X	L-shell	5.275	<b>5, b</b>	9.50	3.4	Fe XXVI	2p $\rightarrow$ 3d	9.532	1
5.32	2.3							Mg I	K $\beta$	9.521	<b>2</b>
6.18	2.5	Si XIV	Ly $\alpha$	6.182	<b>6, b</b>			Ne X	Ly $\delta$	9.481	<b>4, a</b>
6.65	3.8	Si XIII	i [em.]	6.685	<b>3, b</b>	10.01	2.1	Fe XVII	2s <sup>2</sup> 2p <sup>6</sup> $\rightarrow$ 2s2p <sup>6</sup> 5p	10.102	1
		Si XIII	He $\alpha$	6.648	<b>3, b</b>			Fe XXV	2s $\rightarrow$ 3p	10.037	1
		Al XII	He $\beta$	6.64	<b>a</b>			Na XI	Ly $\alpha$	10.025	<b>6, a</b>
6.78	2.8	Fe XXIV	2p $\rightarrow$ 7d	6.809	1	10.63	2.2	Fe XIX	2p <sup>4</sup> $\rightarrow$ 2p <sup>3</sup> 4d	10.664	1
		Fe XXIV	2s $\rightarrow$ 6p	6.787	1			Fe XXIV	2s $\rightarrow$ 3p	10.663	1
		Si XI	L-shell	6.784	<b>5, b</b>			Fe XVII	2p <sup>6</sup> $\rightarrow$ 2p <sup>5</sup> 6d	10.658	1
		Si I	K $\beta$	6.753	<b>2</b>			Ne IX	He $\epsilon$	10.643	<b>8, a</b>
		Fe XXIV	2p $\rightarrow$ 7d	6.751	1			Fe XXIV	2s $\rightarrow$ 3p	10.619	1
		Si XIII	f [em.]	6.740	<b>3, a</b>	11.57	2.8	Na I	K $\beta$	11.575	<b>2</b>
		Mg XII	Ly $\gamma$	6.738	<b>4</b>			Ne IX	He $\beta$	11.546	<b>7, a</b>
6.83	2.3	Si X	L-shell	6.856	<b>5, b</b>			Fe XVIII	2p <sup>5</sup> $\rightarrow$ 2p <sup>4</sup> 4d	11.539	1
6.85	4.5	Fe XXIV	2p $\rightarrow$ 7d	6.809	1			Fe XVIII	2p <sup>5</sup> $\rightarrow$ 2p <sup>4</sup> 4d	11.524	1
		Fe XXIV	2s $\rightarrow$ 6p	6.787	1	12.47	2.1	Fe XX	2p <sup>4</sup> $\rightarrow$ 2p <sup>3</sup> 3d	12.475	1
6.90	2.5	Fe XXIV	2p $\rightarrow$ 6s	6.982	1			Fe XXI	2p <sup>2</sup> $\rightarrow$ 2p3d	12.445	1
6.92	5.7	Fe XXIV	2p $\rightarrow$ 6d	6.970	1	12.57	2.2	Fe XX	2s <sup>2</sup> 2p <sup>3</sup> $\rightarrow$ 2s 2p <sup>3</sup> 3p	12.576	1
6.93	4.4	Si IX	L-shell	6.928	<b>5, b</b>			Fe XXI	2p <sup>3</sup> $\rightarrow$ 2p <sup>2</sup> 3d	12.602	1
6.98	2.1	Fe XXIV	2p $\rightarrow$ 6d	7.033	1			Fe XX	2p <sup>4</sup> $\rightarrow$ 2p <sup>3</sup> 3d	12.592	1
		Si VIII	L-shell	6.996	<b>5, b</b>			Fe XX	2s <sup>2</sup> 2p <sup>3</sup> $\rightarrow$ 2s2p <sup>3</sup> 3p	12.570	1
		Fe XXIV	2p $\rightarrow$ 6s	6.982	1			Fe XX	2s <sup>2</sup> 2p <sup>3</sup> $\rightarrow$ 2s2p <sup>3</sup> 3p	12.569	1
		Fe XXIV	2p $\rightarrow$ 6d	6.970	1			Fe XX	2s <sup>2</sup> 2p <sup>3</sup> $\rightarrow$ 2s2p <sup>3</sup> 3p	12.558	1
8.05	2.2	Fe XXII	2p $\rightarrow$ 5d	8.059	1	12.70	2.3	Fe XXII	2p <sup>2</sup> $\rightarrow$ 2p3s	12.710	1
		Na XI	Ly $\gamma$	8.021	<b>4, a</b>			Fe XVII	2p <sup>6</sup> $\rightarrow$ 2p <sup>5</sup> 4s	12.702	1
9.28	2.2	Mg XI	f [em.]	9.314	<b>3, a</b>	12.85	3.2	Fe XX	2p <sup>3</sup> $\rightarrow$ 2p <sup>2</sup> 3d	12.867	1
		Ne X	Ly $\zeta$	9.29	<b>a</b>			Fe XX	2p <sup>3</sup> $\rightarrow$ 2p <sup>2</sup> 3d	12.809	1
		Ne X	Ly $\eta$	9.25	<b>a</b>			Fe XVIII	2s <sup>2</sup> 2p <sup>5</sup> $\rightarrow$ 2s2p <sup>5</sup> 3p	12.801	1
		Ne IX	i [em.]	9.23	<b>a</b>						
9.37	3.3	Ne X	Ly $\epsilon$	9.36	<b>a</b>						

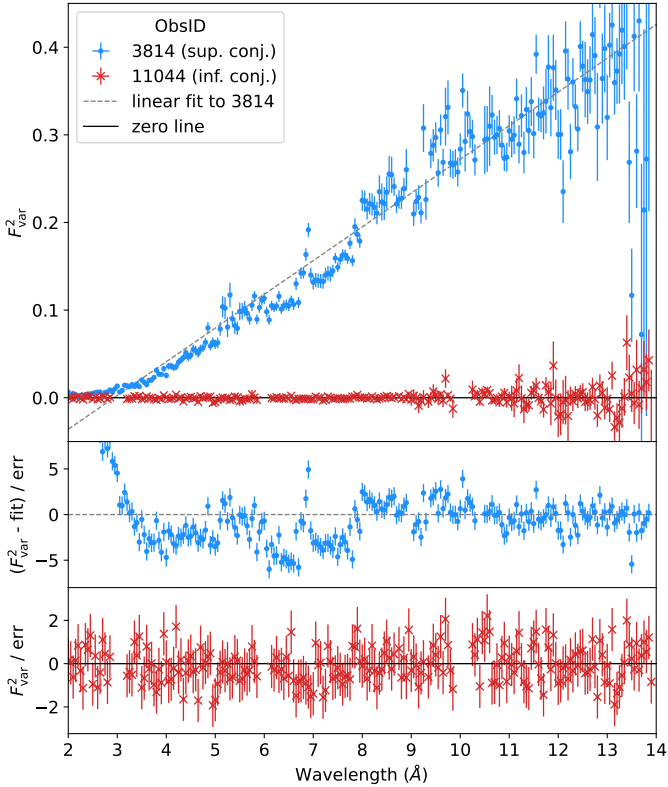
**Notes.** The listed lines are compiled the selection described in Sect. 3.4 and previous analyses of the data: (a) Hanke et al. (2009) and (b) Hirsch et al. (2019). Primary references are numbered and given below. (a) obtain line energies from (1, 8). (5) measure blended line complexes ('L-shell' for short in the table). Lines listed multiple times with different wavelengths differ in the fine structure. Emission lines are marked with [em.]. Iron lines are exclusively from AtomDB.

**References.** (1) AtomDB (<http://www.atomdb.org/>), (2) Bearden (1967), (3) Drake (1988), (4) Garcia & Mack (1965), (5) Hell et al. (2016), (6) Johnson & Soff (1985), (7) Liao et al. (2013), (8) Verner et al. (1996).

A major difference exists between the two: at inferior conjunction, the variability is consistent with zero, while a continuum is present at superior conjunction, which linearly increases with wavelength above  $\sim 3 \text{ \AA}$ . The linear fit shown in Fig. 2 serves to qualitatively characterise this trend and the significance of the superimposed features, the most prominent of which is a spike-like increase in variability just below  $7 \text{ \AA}$ . In contrast, the observation at inferior conjunction shows no clear features.

Figure 3 shows the  $F_{\text{var}}^2$  spectrum at superior conjunction for a higher resolution, relative to the linear fit. All data points that lie more than  $2\sigma$  above a piece-wise running average over 101 bins are highlighted in bold and listed in Table 1 with associated transitions. The clear feature seen in Fig. 2 just below  $7 \text{ \AA}$

corresponds to the silicon line region. At the increased resolution, the feature splits into multiple spikes at positions corresponding to those of the lines. A similar group of spikes is seen in the sulphur region, but it is less prominent, which is likely due to a reduction in signal caused by gap filtering strongly increasing the uncertainty (see Sect. 3.3 and Appendix A). An alignment of lines and spike features exists outside the silicon and sulphur regions as well; hints of neon (e.g. Ne X Ly  $\delta$ - $\eta$  at  $9.2$ - $9.5 \text{ \AA}$ ), magnesium (e.g. Mg XII Ly  $\gamma$  at  $6.74 \text{ \AA}$ ), aluminium (Al XII He  $\beta$  at  $6.64 \text{ \AA}$ ), and iron (e.g. at  $12.4$ - $12.9 \text{ \AA}$ ) features can be seen in Fig. 3. In general, more spikes seem to be present close to known lines than in line-free regions (see black and blue in Fig. 3). However, due to the low signal-to-noise ratio and strength of the  $F_{\text{var}}^2$  features, such detections are tentative. As previously mentioned,



**Fig. 2.**  $F_{\text{var}}^2$  spectrum of Obs. 3814 (blue) and 11044 (red) during which Cyg X-1 passed through superior and inferior conjunction, respectively. Residuals to a continuum estimate (a linear fit for 3814, the zero line for 11044) are shown in the bottom panels. The gaps in the  $F_{\text{var}}^2$  spectrum of Obs. 11044 around 3 Å, 6 Å, and 10 Å are due to the filtering of systematic variability from CCD gaps in *Chandra*'s HETG detector (see Sect. 3.3 and Appendix A).

the  $F_{\text{var}}^2$  spectrum of Obs. 11044 shows far fewer features. A higher resolution  $F_{\text{var}}^2$  spectrum can be found in Fig. C.1.

In Sect. 4.2, we discuss the silicon and sulphur line regions in Obs. 3814 in more detail, as these contain the most prominent features. Their time dependence will be investigated in Sect. 4.3. As this work is among the first studying  $F_{\text{var}}^2$  spectra at grating resolution (predated only by Mizumoto & Ebisawa 2017, to our knowledge), we aim to assess the prospects of this approach and did not perform a rigorous search and identification of spike features. In addition, a quantitative analysis is challenging because it requires an accurate description of the continuum.

#### 4.2. Silicon and sulphur line regions at superior conjunction

Figure 4 shows a zoomed-in view of the silicon and sulphur regions. In addition to the 500 s binning investigated before, a 50 s binning is shown to investigate if there is additional variability at higher frequencies. The bottom panels of Fig. 4 show the count spectra from Hirsch et al. (2019), summed for all dip stages, relative to local power-law fits in the given bands, to allow for a direct visual comparison to the  $F_{\text{var}}^2$  spectrum.

For silicon, a spike is clearly detected for each corresponding line, except Si XII, which might be because it cancels with the neighbouring He-like Si forbidden emission line. Line emission typically decreases variability because, when looking at an object, the observer sees the sum of emission from all regions in which variability in individual regions is averaged out

(Parker et al. 2017a). Visually, the spike positions and strengths directly correspond to those of the lines. The asymmetries present in some of the absorption lines in the analyses of the count spectra by Miškovičová et al. (2016) and Hirsch et al. (2019) are also hinted at in the spikes, albeit with greater uncertainties and lower resolution. The heights and widths of the spikes are slightly larger in the 50 s binning, but this increase is not enough to exceed the uncertainty.

The analysis of the sulphur region is complicated by greatly reduced signal, as laid out in Sect. 4.1. Nevertheless, there is a small but visible increase in overall variability. Spike features are resolved and approximately coincide with line positions, with the best agreement for S XI and S XII. S XIII and S XIV cannot be resolved in the  $F_{\text{var}}^2$  spectrum, resulting in a joined spike. A spike feature with no corresponding line is present at  $\sim 5.33$  Å, but it does not challenge the general conclusion that spike and line positions coincide, due to the large uncertainties and the clear result for silicon. As for silicon,  $F_{\text{var}}^2$  slightly increases for the shorter, 50 s time step, but remains within the uncertainty.

#### 4.3. Frequency dependence at superior conjunction

The timescale of the variability can give an insight into its producing mechanism, for example the typical sizes of overdensities in a stellar wind that produces variability by obscuration (e.g. EG20). We investigated this timescale by changing the upper bound of the frequency range over which  $F_{\text{var}}^2$  integrates, while keeping the lower bound fixed at the length of the observation. In practice, the upper bound is set by the binning time step of the light curves from which  $F_{\text{var}}^2$  is calculated (see Sect. 3.2). The result in Fig. 5 therefore effectively shows an integrated frequency spectrum; that is to say, its slope indicates the variability power added to  $F_{\text{var}}^2$  at any given frequency.

In the figure, bands containing the bulk of detected silicon (6.6–7.2 Å) and sulphur (5–5.35 Å) lines are compared to a reference band, spanning the range in between them (5.4–6.6 Å), but excluding a region of  $\pm 0.05$  Å around the Si XIV line. The bottom panel shows the ratio of  $F_{\text{var}}^2$  in the line regions to the reference band. The  $F_{\text{var}}^2$  in each band is rescaled to its value at  $t = 500$  s:  $0.137 \pm 0.001$ ,  $0.105 \pm 0.002$ , and  $0.082 \pm 0.004$ , for the silicon, sulphur, and the reference band, respectively. We note that these values are not normalised to the linear continuum fit, which means that  $F_{\text{var}}^2$  is highest in the silicon region due to the continuum, not the line variability. For the choice of time steps, we refer the reader to Sect. 3.1.

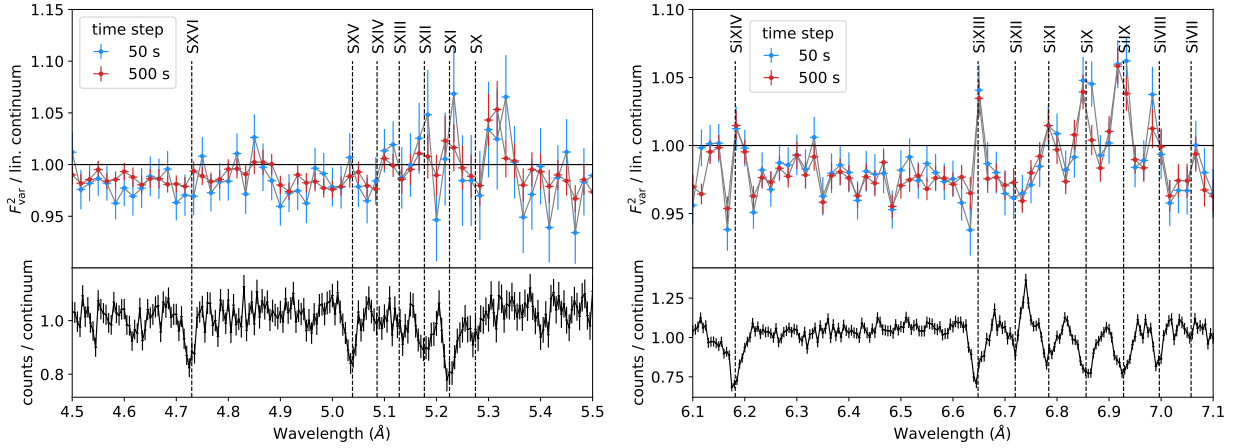
Overall,  $F_{\text{var}}^2$  declines approximately linearly with binning time step in the logarithmic scaling, which is consistent with an underlying red noise process. The silicon line region shows a flatter trend than the reference band; in other words, the power is distributed more towards lower frequencies in this region. For sulphur, the behaviour is consistent with the continuum, but subject to large uncertainties.

A possible systematic effect is the periodicity of the dither in the telescope pointing. The light grey band in Fig. 5 indicates the range where such an effect would be expected<sup>4</sup>. As no significant increase in  $F_{\text{var}}^2$  relative to the overall trend is present in this region, we conclude that the dither periodicity is not an issue in our analysis.

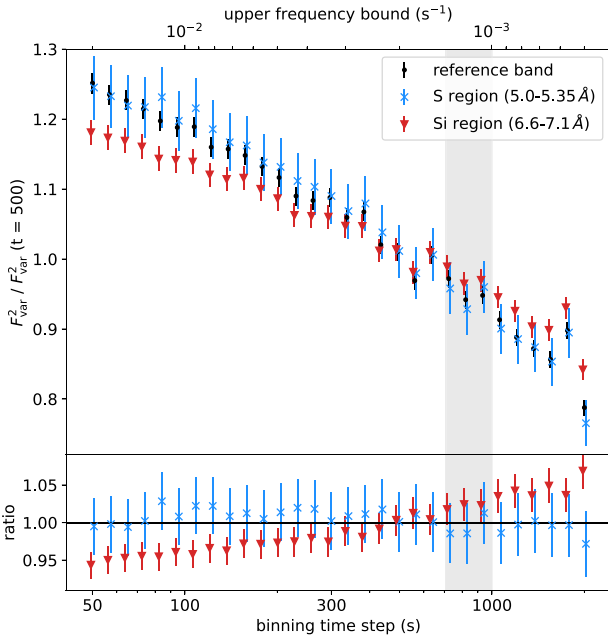
<sup>4</sup> <https://cxc.cfa.harvard.edu/ciao/why/dither.html> (*Chandra* CIAO supplemental information on dither).







**Fig. 4.** Sulphur (left) and silicon (right) line regions. The  $F_{\text{var}}^2$  spectrum of Obs. 3814 is shown relative to the linear fit from Fig. 2 (black) and compared to the count spectrum (lower panels) from Hirsch et al. (2019) and the rest-wavelength of detected lines. The count spectrum is given relative to a local power-law fit in the wavelength bands indicated in the figure and is the sum of spectra of all dip stages. Two time binnings are displayed for the  $F_{\text{var}}^2$  spectrum, 50 s (blue) and 500 s (red), to investigate the effect of the added higher frequencies. Lines connect the data points for clarity. Overall, there is a good correspondence between  $F_{\text{var}}^2$  spike features and known line positions.



**Fig. 5.** Total variability in Obs. 3814 in terms of  $F_{\text{var}}^2$  as a function of the binning time step; in other words, the figure effectively shows integrated frequency power. The sulphur (blue, 5–5.35 Å) and silicon (red, 6.6–7.2 Å) line regions are compared to a reference band (black, 5.4–6.6 Å, excluding a region of  $\pm 0.05$  Å around the Si XIV line), with the ratio shown in the bottom panel.  $F_{\text{var}}^2$  is normalised to its value at 500 s in each respective band. The light grey band indicates a range where systematic effects due to the dither of the telescope would arise, if they were present.

## 5. Discussion

### 5.1. Clump-driven variability

Variability can be caused by intrinsic changes in flux, originating close to the compact object, or be a result of obscuration by material passing through the line of sight. In the latter case, the variability can be greatly sensitive to the line of sight. We observe that while the continuum variability at superior

conjunction increases linearly with wavelength, it is constant and consistent with zero at inferior conjunction. Additionally, while the light curve is constant at inferior conjunction, strong transient dipping events are present at superior conjunction (Miškovičová et al. 2016). It is well established (see Sect. 2) that the dipping events are caused by clumps in the stellar wind. During both observations, Cyg X-1 was in the hard state at very similar fluxes. Jointly, these results strongly support the conclusion that the observed variability is driven by clumps crossing the line of sight.

On the continuum, spikes of increased variability are observed, with a clear correspondence between their properties, such as their position and strength, and those of absorption lines in the silicon line region and, also, at reduced significance due to lower sensitivity, in the sulphur line region (see Sect. 4.2). This result suggests that the spikes are caused by an increased variability inherent to the absorption lines, which is also observed in ultra-fast outflows of AGNs (e.g. Parker et al. 2017b, 2018; Igo et al. 2020). A general prevalence of spikes near known lines outside the silicon and sulphur regions further supports this conclusion. Both intrinsic and absorption variability can cause enhanced  $F_{\text{var}}^2$  in lines. In ultra-fast outflows, the enhancement is consistent with the ionisation responding to intrinsic luminosity changes (e.g. Pinto et al. 2018; Parker et al. 2020). Considering again that Cyg X-1 has a clumpy wind and that the clumps have a layered ionisation structure (see Sect. 2), it seems plausible that ionisation could also be driving the variability in Cyg X-1. However, in an optically thin medium such as the wind, the line strength can directly respond to a change in the column density, without requiring an associated ionisation change. It is likely that both mechanisms contribute to the observed enhancement of the line variability. The role of ionisation is discussed further in Sect. 5.6.

### 5.2. Modelling the orbital phase dependent variability of a clumpy stellar wind

In the last section, clumps passing through the line of sight were identified as a main driver of the variability. We now compare the results of the  $F_{\text{var}}^2$  analysis to a model based on a prescription for a clumpy stellar wind by EG20. This model does not take into account X-ray photoionisation effects, but instead calculates the total

column density of material along the line of sight. We therefore approximate the ionisation effects using an XSTAR (Kallman & Bautista 2001) table model as described below. At the moment, no model exists that simultaneously incorporates both clumping and ionisation.

EG20 modelled the X-ray absorption by a clumpy wind in a binary system consisting of a massive star and a compact object, described as an X-ray point source. The mass is assumed to be contained in spherical clumps, with a radius  $R_{\text{cl}}$  at two stellar radii,  $2R_{\star}$ , from the stellar centre, growing in size and accelerating as they move outwards according to the canonical velocity law for stellar winds,

$$v(r) = v_{\infty}(1 - R_{\star}/r)^{\beta}, \quad (6)$$

where  $\beta$  is a factor determining how quickly the terminal wind velocity,  $v_{\infty}$ , is reached. We employed the smooth expansion law for the clump size (Eq. (4) in EG20) but note that the impact of the clump expansion law on the variability is expected to be small (see EG20). The wind is assumed to be spherically symmetric and fast enough to be unaffected by the gravity of the compact object, which is a valid assumption for Cyg X-1 for two reasons: the terminal wind speed ( $2100 \text{ km s}^{-1}$ ) is high compared to the orbital speed ( $500 \text{ km s}^{-1}$ ), and, more importantly, the bulk of material intercepting the line of sight is above the orbital plane.

The model calculates the total equivalent hydrogen column density,  $N_{\text{H}}$ , resulting from the clumpy wind for a given line of sight parameterised by the inclination,  $i$ , and orbital phase,  $\varphi$ , without taking into account possible ionisation effects. We adopted the parameters that are given in EG20 for Cyg X-1:  $i = 27.1^{\circ}$ , mass-outflow rate,  $\dot{M} = 3 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ ,  $v_{\infty} = 2100 \text{ km s}^{-1}$ , and the orbital separation  $a = 2.5 R_{\star}$ . Orbital phases of  $\pm 0.1$  around superior and inferior conjunction are covered, with a resolution of 20 000 points, resulting in a time step of  $\sim 5 \text{ s}$ . For further details on the model and its application to Cyg X-1, we invite the reader to consult EG20.

The  $N_{\text{H}}$  light curve obtained from the clumpy wind model was then used to create absorbed model spectra, from which  $F_{\text{var}}^2$  can be calculated. We did this by faking an absorbed power-law for each value in the  $N_{\text{H}}$  light curve with the ISIS command `fakeit`. The power-law index and normalisation were fixed to the values obtained by Hanke et al. (2009) for the *Chandra* and RXTE joined continuum of Obs. 3814 ( $\Gamma = 1.60$ ,  $\text{norm} = 1.33$ ; see Table 2 in the reference). For the absorption, we used a custom XSTAR table model, following the approach detailed in Hirsch et al. (2019). The model is based on a calculation of the ionisation balance in a spherical gas cloud irradiated from the centre. The SED describing the source of incident continuum at the centre of the cloud includes a `nthcomp` continuum model, combined with lamp-post model relativistic reflection (`relxillpcp`) and a small contribution from a non-relativistic reflection (`xillvercp`). The model reflects the idea that the primary X-ray radiation of the BH is already reprocessed by reflection of the accretion disc before interacting with the stellar wind of the donor. For this study, we chose  $\Gamma = 1.67$ ,  $kT_{\text{e}} = 400 \text{ keV}$  and an inclination of  $36^{\circ}$ <sup>5</sup> for both

reflection components. The height of the primary component in the `relxillpcp` component is  $6.1 r_{\text{g}}$ , and the spin of the BH is 0.998. The ionisation parameters  $\log \xi$  are 3.1 and 0 for `relxillpcp` and `xillvercp`, respectively, and the reflection fractions are 0.27 and  $-1^6$ . The reflection parameters represent a reasonable assumption for the conditions in Cyg X-1 in the typical hard state. The results of our qualitative discussion, which is concerned with the overall effects of ionisation, are not sensitive to slight changes in the conditions.

The  $F_{\text{var}}^2$  spectra resulting from this approach are shown in Fig. 6. We investigated the dependence on  $\beta$ , the line of sight, the ionisation parameter of the XSTAR model<sup>7</sup>,  $\xi$ , and the ratio  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$ , where  $m_{\text{cl}}$  and  $R_{\text{cl}}$  are given as multiples of  $m_0 = 1.1 \times 10^{18} \text{ g}$  and  $R_{\star} = 17 R_{\odot}$ <sup>8</sup>. The clump mass,  $m_{\text{cl}}$ , takes values of 0.4 and 10 and  $R_{\text{cl}}$  ranges over 0.005–0.08. This range overlaps with the result of Feng & Cui (2002;  $R_{\text{cl}} = 0.01$ –0.6), who obtained clump sizes by analysing the duration of the dips in the light curve. The choice of the combined parameter  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  is motivated by EG20, who found that it is proportional to the spread of the column density,  $\delta N_{\text{H}}$ . If variability is caused by  $N_{\text{H}}$  changes, as our model assumes, then  $\delta N_{\text{H}}$  directly translates in  $F_{\text{var}}^2$  variability. We considered two values for  $\beta$ , 0.5, and 2. The former is widely used in the literature and believed to be representative of winds of early O supergiants (Sundqvist et al. 2019), while the latter corresponds to the velocity profiles computed by Sander et al. (2018), showing a more gradual acceleration. Unless otherwise indicated, the ionisation is fixed at  $\log \xi = 3$ ,  $\beta = 0.5$ , and variability at inferior conjunction is shown. The ionisation,  $\xi$ , is always given in units of  $\text{erg cm s}^{-1}$ .

### 5.3. Line-of-sight dependence of the variability continuum

The employed model is able to qualitatively reproduce the data by predicting an approximately linear continuum and spikes of increased  $F_{\text{var}}^2$  (Fig. 6, upper panel). The model also shows a strong line-of-sight effect, with higher variability at superior conjunction. The effect is especially strong for the higher  $\beta$  value,  $\beta = 2$ , and is a direct consequence of how  $\delta N_{\text{H}}$  depends on the orbital phase. The clumps probed at superior conjunction are smaller, because the line of sight runs closer by the star than at inferior conjunction and the clumps expand as they move outwards. As  $\delta N_{\text{H}} \propto m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$ , the variability is higher at superior conjunction if the clump mass is fixed. A high  $\beta$  increases this effect because the slower acceleration requires a higher density if  $\dot{M} = \text{const.}$  and therefore more clumps. The variability increases with wavelength, because lower energy photons are more sensitive to changes in absorption.

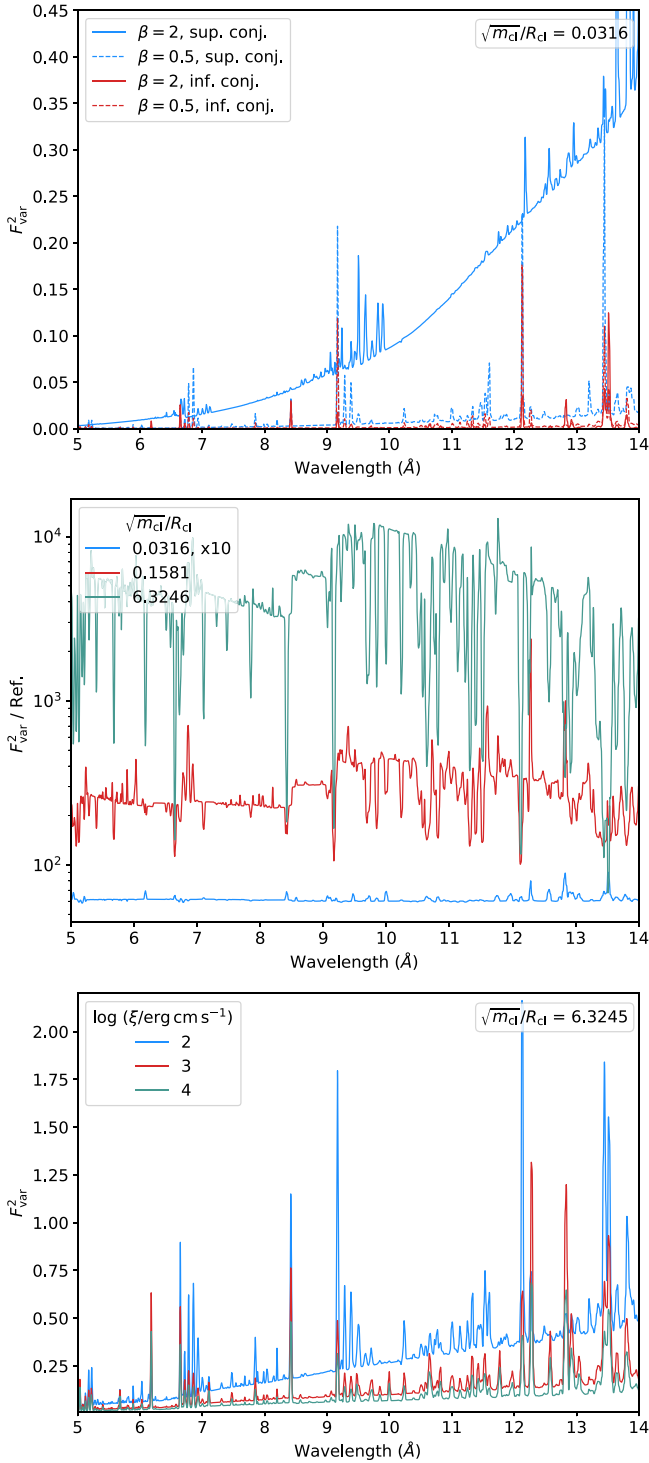
For  $\beta = 2$  and  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1} = 0.0316$ , the model predicts  $F_{\text{var}}^2 \sim 0.37$  at  $14 \text{ \AA}$  at superior conjunction and an inferior conjunction continuum that is consistent with zero within the measurement accuracy. These values agree very well with the measurement (Fig. 2). However, the slope of the superior conjunction continuum is too steep, which causes  $F_{\text{var}}^2$  to be underestimated below  $14 \text{ \AA}$ . Larger  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  reduce this discrepancy, but require a non-zero inferior conjunction continuum.

<sup>5</sup> A misalignment of the inner disc inclination to the inclination of the system has been inferred for Cyg X-1 in several studies when not using high-density reflection models (Tomsick et al. 2014, 2018; Parker et al. 2015; Walton et al. 2016) and is also supported by polarimetry measurements (Krawczynski et al. 2022). The value we employ here corresponds to the measurements of inner disc inclination in the hard state in Tomsick et al. (2018).

<sup>6</sup> See <http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/> for the definition of the parameters.

<sup>7</sup> As defined by Tarter et al. (1969):  $\xi = L_{\text{X}} \rho^{-1} r^{-2}$ .

<sup>8</sup> We note that we adopt the stellar radius given in EG20 here, instead of the updated value of  $R_{\star} = 22.3 R_{\odot}$  (Miller-Jones et al. 2021). The results are unaffected by this slight inconsistency, because  $R_{\star}$  only functions as a scaling factor for the  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  ratio.



**Fig. 6.**  $F_{\text{var}}^2$  expected for absorption in a clumpy wind following EG20. Details on the model generation can be found in the text. Upper panel: Dependence on the line of sight (blue: superior conjunction, red: inferior conjunction) and the  $\beta$  value of the wind velocity law (Eq. (6)); solid:  $\beta = 2$ , dashed:  $\beta = 0.5$ ), highlighting their strong impact on the continuum. Middle panel: Ratio to a baseline model with  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1} = 0.0079$ , showing the increase in continuum variability and with  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  and the reduced increase of the line variability (dips in the ratio). The lowest ratio model (blue) has been multiplied by a factor of ten for better visibility. Bottom panel: Ionisation dependence. A high  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1} = 6.3245$  is shown to highlight the continuum changes. The increase in  $F_{\text{var}}^2$  with ionisation is weaker for higher ionisations. For clarity, the model is only shown above  $5 \text{ \AA}$ .

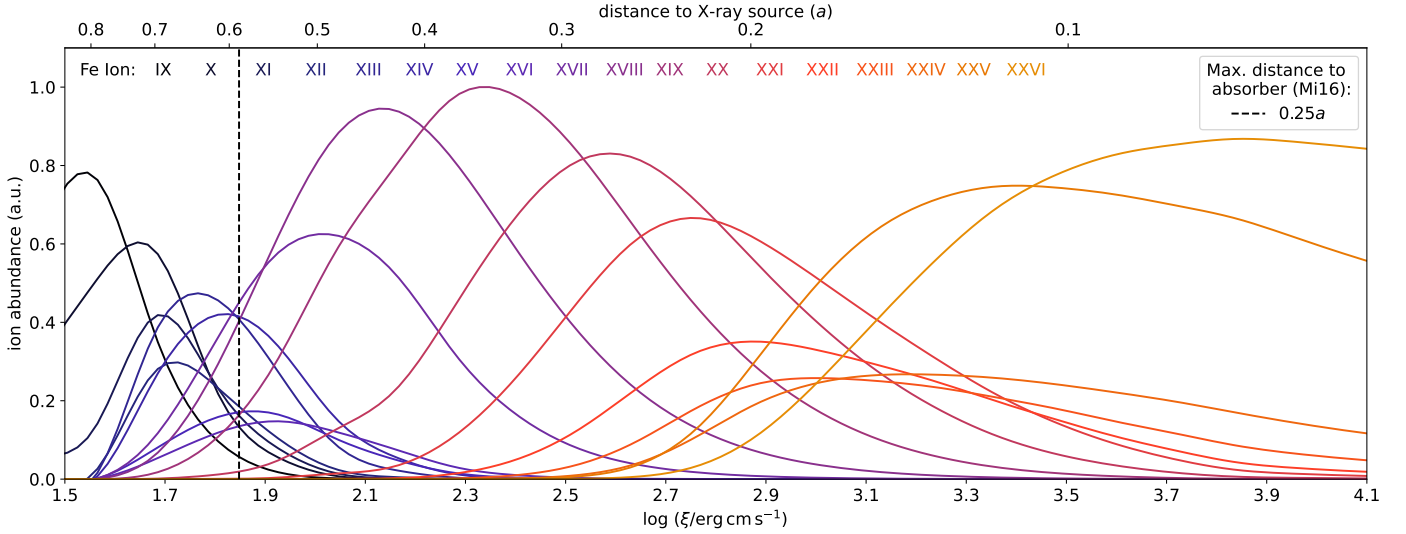
The fact that the model is able to reproduce the qualitative behaviour of the data consistently at both conjunctions shows that varying absorption in an ionised clumpy wind is a viable explanation for the observed variability. Discrepancies, such as those mentioned above, are expected given that the model is in an early state and we thus discuss two noteworthy model caveats and their effect on the variability continuum and line-of-sight dependence. First is the spherical wind assumption, which disregards the focused stream between star and black hole, whose higher density could lead to an increase in variability at superior conjunction. At inferior conjunction, the line of sight passes through the bow shock trailing the black hole, which could disrupt the wind structure and smooth out the absorption variability. A similar effect is expected from interaction with the jet, through which the wind inevitably passes before crossing the inferior conjunction line of sight. Perucho & Bosch-Ramon (2012) showed that wind structures are usually destroyed in interactions with a jet. Second is the use of the canonical velocity law (Eq. (6)), especially considering that the wind is ionised by the X-ray emission from the black hole, resulting in a change in the populations of the driving lines. The X-ray luminosity in Cyg X-1 ( $L_x \gtrsim 10^{37} \text{ erg s}^{-1}$ , Miškovičová et al. 2016; Hirsch et al. 2019) is in a regime where it could significantly inhibit the wind acceleration (Krtićka et al. 2018), although the net effect of X-ray photoionising feedback is still uncertain (see Sander et al. 2018, for the insightful example of Vela X-1, another HMXB). The inhibiting effect would be largest towards the black hole where the X-ray irradiation is strongest. It could therefore increase  $F_{\text{var}}^2$  at superior conjunction, as a slower wind must have a higher density if  $\dot{M}$  is fixed. Even without an ionising source, Sander et al. (2017) predicted a slower onset of the acceleration from a model that calculates a self-consistent hydrodynamic stratification of the wind.

#### 5.4. Suppressed line variability at inferior conjunction

The line variability predicted by the model is of a similar strength at superior and inferior conjunction (Fig. 6, upper panel), yet the observations show line variability only at superior conjunction. This discrepancy is due to the wind moving and becomes apparent from the discussion of the count spectra in Miškovičová et al. (2016). While the superior conjunction spectrum shows absorption, mainly P-Cygni profiles are observed at inferior conjunction. Miškovičová et al. (2016) ascribe this difference to the fact that the absorption at inferior conjunction is highly blueshifted because of the line-of-sight projection of the wind velocity, separating it from the ubiquitous emission component. Emission lines are suggested to reduce  $F_{\text{var}}^2$  instead of increasing it (Parker et al. 2017b). It is likely that the variability of the absorption and emission components cancels out, given that the absorption component is weak at inferior conjunction and that our resolution is lower than that of the count spectra. In addition, narrow spikes appear smaller at lower resolution, because of the averaging effect. The resolution effect also applies at superior conjunction and plausibly explains why the reported variability is slightly lower than in the model (compare the  $F_{\text{var}}^2$  spikes in Figs. 2 and 6, upper panel).

#### 5.5. Clump mass and radius

The middle panel of Fig. 6 shows the behaviour of our model with  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$ , by taking a low value as a baseline (0.0079; big, light clumps:  $m_{\text{cl}} = 0.4 m_0$ ,  $R_{\text{cl}} = 0.08 R_*$ ) and showing the ratio of models with higher values to it. As mentioned in Sect. 5.2,



**Fig. 7.** Relative abundances of iron K to M-shell ions as a function of the ionisation parameter,  $\xi$  (lower  $x$ -axis) or, equivalently, the distance absorber–X-ray source,  $d$  (upper  $x$ -axis). The dashed line marks the maximum value of  $d$  according to Miškovičová et al. (2016), given in terms of the semi-major axis of the binary system,  $a = 2.35 R_*$  (Miller-Jones et al. 2021). For details, see Sect. 5.6.

$m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  is proportional to  $\delta N_{\text{H}}$  and therefore also to  $F_{\text{var}}$ . For the investigated ratios, the variability spans several orders of magnitude, making  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  an influential parameter. For low ratios, the increase in the lines is stronger than in the continuum (light blue curve), but as higher ratios are approached, the increase is reduced (dips in the red and green curves). This relative reduction in line variability is an averaging effect. As  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1} \propto \delta N_{\text{H}}$ , the absorption varies over a larger range for higher values of the ratio. Less absorbed spectra are brighter and therefore have a higher weight in the average that is contained in the definition of  $F_{\text{var}}^2$  (see Eqs. (1) and (2)). They also show weaker lines, because the line strength responds to the absorbing column. As a consequence, the line variability relative to the continuum is weaker for higher  $\delta N_{\text{H}}$ , resulting in the dips in the model ratio. In addition to this effect, the continuum variability gets more linear, as seen by comparing the upper to the bottom panel in Fig. 6, where a high  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  ratio was chosen.

An independent approach to obtain information on  $R_{\text{cl}}$  is measuring the timescale of the variability, as small structures cross the line of sight more quickly than large ones, causing the timescale to depend on  $R_{\text{cl}}$ . Our analysis of the time binning dependence in Sect. 4.3 revealed that the distribution of variability power is shifted towards lower frequencies in the silicon line region compared to the continuum. Such a result is explained by the response of the line region to the column density changes driving the variability: the line depths vary across a wider range in bigger clumps, which enhances their variability and therefore flattens the frequency trend. This mechanism is likely complemented by the layered ionisation structure of the clumps. Bigger clumps allow for a lower ionisation in their centre (see Sect. 2), which also increases the range across which line depths vary. In addition, the larger ionisation range gives rise to more lines. This interpretation is in line with our conclusion from Sect. 5.1 that column density changes might drive ionisation variability. As a general conclusion, timescale measurements can independently reveal  $m_{\text{cl}}$  and  $R_{\text{cl}}$ , if  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  can be constrained. In principle, the clump size can also be obtained from the duration of dips in the light curve, as demonstrated in Feng & Cui (2002) and Ness et al. (2012). In case of Cyg X-1, the necessity to account for the orbital speed, the progressive acceleration of the wind, and

projection effects complicates this approach (see discussion in EG20).

### 5.6. Ionisation

The bottom panel of Fig. 6 shows  $F_{\text{var}}^2$  model spectra for  $\log \xi = 2-4$  (the  $m_{\text{cl}}^{0.5} R_{\text{cl}}^{-1}$  ratio was chosen to be high in this plot to explicitly show the continuum changes). Ionisation acts mainly as a scaling factor for both the continuum and line variability. The effect is stronger at lower ionisations.

We therefore do not expect the choice of  $\log \xi = 3$  to impact the conclusions we reached so far. To illustrate the effect of  $\xi$  on spectral features in more detail, we show Fe ion abundances from an XSTAR photoionisation model in Fig. 7. The lower  $x$ -axis shows the maximum value of  $\xi$  reached in the absorber. The corresponding minimum distance of the absorber from the X-ray source (upper  $x$ -axis) is obtained by inverting the definition of  $\xi$  (Tarter et al. 1969),

$$d = \sqrt{\frac{L_{\text{X}}}{\xi \rho}}, \quad (7)$$

where  $L_{\text{X}} = 10^{37} \text{ erg s}^{-1}$  for Cyg X-1 and  $\rho$  is taken from the clumpy wind model by EG20 evaluated at superior conjunction (adopting  $\beta = 2$  and a mean molecular weight of  $\mu = 1 \text{ u}$ ). Miškovičová et al. (2016) estimated the distance between absorber and black hole to be  $d \lesssim 0.25 a$ , which gives  $\log \xi \gtrsim 1.8$ . This lower limit does not constrain the ion abundances well (see Fig. 7) and a conclusion on which lines dominate the spectrum is difficult to draw without better constraints on the absorber position. Considering that the absorber likely has a significant extension, is clumpy, and that the ion abundances strongly depend on  $\xi$  (see Fig. 7), it is expected to have a complex ionisation structure.

Despite the discussed limitations, fixing the ionisation to a single value has proven to be a successful first step, considering the good qualitative agreement of data and model. However, this simple approach inevitably results in an incomplete picture, because varying ionisation is known to contribute to the variability (see Sect. 5.1), and even the clumps themselves have a layered

ionisation structure. Examples for the behaviour that might arise from this structure were given in Sects. 5.1 and 5.5.

In the general case, the response of variability to changes in  $\xi$  is non-trivial: for example, variability in absorption lines is not necessarily enhanced. The decisive question is how it correlates with the continuum variability. If line strength decreases with increasing flux, the total flux change is higher in the line than in the continuum, causing  $F_{\text{var}}^2$  to spike. In the contrary case, the change in the line counteracts that in the continuum, resulting in an  $F_{\text{var}}^2$  dip. For ionisation-driven variability, both cases are possible, even within the same observation because a change in ionisation shifts the ion balance, which means that abundances rise for some ions while they decrease for others. Only in specific regimes can the situation be simpler: for example, in an almost fully ionised environment, the responses of the lines to ionisation changes are more uniform. This special case is thought to apply to ultra-fast outflows of AGNs and result in the observed anti-correlation between line strength and flux (Parker et al. 2017b, 2018; Igo et al. 2020). In Cyg X-1, the situation is likely to be complex, because of the wide range of ionisations. Adding to that, lines can show different responses in different regions in the source from which we observe the sum, as we argue in Sect. 5.4 for P-Cygni profiles. As a result of this complex behaviour, a comprehensive model will require radiative transfer modelling, which is outside the scope of this work.

## 6. Summary and outlook

We present an analysis of high-resolution excess variance spectra of Cyg X-1 calculated from *Chandra*/HETG observations during the hard state at superior and inferior conjunction (ObsID 3814 and 11044, respectively), which enabled us to discuss the impact of the accretion geometry and wind structure on the excess variance. We match features in the excess variance to their counterparts in the count spectra comparing to previous spectral analysis by Hanke et al. (2009), Miškovičová et al. (2016), and Hirsch et al. (2019), and to a selection of significant iron lines in the 2–14 Å range. To complement the data analysis, we modelled excess variance spectra from X-ray absorption in a clumpy stellar wind based on EG20 and an XSTAR table model to incorporate ionisation effects.

We have demonstrated that we can deal with systematic variability introduced by the use of *Chandra* grating data, by accounting for photon loss in CCD gaps, differences in the effective areas of the gratings arms, the discreteness of the CCD read-out cycle, and the telescope dither. The fact that the inferior conjunction variability is consistent with zero and shows no features rules out the existence of further systematic effects that would increase the variability at a measurable level, highlighting the reliability of our results.

Overall, this work demonstrates that excess variance can be used to study winds of HMXBs, providing an independent new approach to previous high resolution spectral studies. Our main conclusions are as follows:

1. The excess variance is strongly dependent on the orbital phase with a linearly increasing continuum and spike features at superior conjunction and the inferior conjunction spectrum consistent with zero;
2. Modelling shows that the variability is consistent with changes in column density caused by clumps crossing the line of sight. The orbital phase dependence is slightly under-predicted, and a slowly accelerating wind is required. We suggest that the jet or the bow shock of the black hole in

the focused wind disrupts the wind structure, suppressing inferior conjunction variability, and we name effects that might increase superior conjunction variability;

3. Variability in absorption lines is enhanced at superior conjunction, with this effect being especially clear in the silicon and sulphur line regions. We suggest that no significant variability spikes are seen at inferior conjunction, because the projected wind velocity is higher, causing the count spectrum to be dominated by P-Cygni profiles, whose absorption and emission components cancel out in terms of variability;
4. The variability power in the silicon region is redistributed towards lower frequencies, compared to the nearby continuum. We argue that the line variability might be increased in big clumps, which have higher column densities and reach lower ionisations in their centres.

We have discussed that the impact of ionisation is highly non-trivial, calling for radiative transfer simulations. In future work, we aim to generate an  $F_{\text{var}}^2$  table model for clumpy stellar winds including improvements such as this one. Such a model will allow us to constrain the clump mass-size ratio,  $m^{0.5}R_{\text{cl}}^{-1}$ , which constitutes a direct approach to quantify the wind structure, when combined with an  $F_{\text{var}}^2$  timescale analysis, the feasibility of which we have demonstrated.

This outlook highlights that excess variance spectra are a versatile tool, first and foremost because they manage to combine spectral and timing information, making it easy to handle and model. In addition, excess variance features tend to be more pronounced than those in count spectra (compare the height of the silicon  $F_{\text{var}}^2$  spike to the continuum in Fig. 2), which is in line with previous results laid out in Sect. 1. This emphasizes the importance of establishing this analysis method for the future missions. The results presented here also present a sneak peak at the detail with which extragalactic sources will be able to be studied with microcalorimetry. The major challenge, and the reason why few studies have applied excess variance spectroscopy to data of high spectral resolution, is the amount of signal required to perform simultaneous energy and time binning. Within the next decades, microcalorimetry instruments such as XRISM (Tashiro et al. 2018) and *Athena* (Nandra et al. 2013) will become available to solve this issue for a range of sources. The technical difficulties we faced in this work come almost exclusively from the use of gratings and will naturally disappear when switching to microcalorimetry.

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## Appendix A: Filtering CCD gaps and dead pixel rows

In Sect. 3, we briefly discuss that the dither in *Chandra* introduces a systematic increase in  $F_{\text{var}}^2$  around CCD gaps and rows of dead pixels. In this appendix, we explain in detail how affected wavelength bins are identified.

Figure A.1 (a) shows the distribution of counts on *Chandra*'s ACIS-S detector for Obs. 11044. The ACIS-S consists of a row of six quadratic CCDs, on which photons are dispersed by the HEG and MEG, resulting in a cross-like shape. Due to this design, a small amount of photons are lost at the boundaries between CCDs, in the so-called CCD gaps (Garmire et al. 2003). Rows of dead pixels have the same effect. We jointly refer to CCD gaps and dead rows as 'gaps' in the following. To avoid the photon loss exclusively affecting specific wavelengths, the telescope pointing moves in a Lissajous pattern, periodically changing the zeroth-order position on the detector, which averages the loss over a small wavelength range (Garmire et al. 2003). As a secondary effect, the number of detected photons strongly varies with time in range of a gap, which strongly affects variability analyses. The diagonal positioning of the gratings increases the affected range, because it causes one gap to affect a range of wavelengths at any given moment.

To account for the systematic variability introduced by the dither, we exclude all bins within dither range of gaps. The first steps towards identifying these bins is finding the positions of all gaps, by searching for pixel rows with zero counts along the  $x$ -coordinate of the detector, considering all events within 2–14.5 Å. In this range, the number of counts per pixel is high enough to conclude that pixel rows with zero counts are likely an instrumental effect and not due to low signal. The detected gaps run across both the HEG and MEG spectrum, also indicating that they are instrumental.

A total of ~70 coinciding gaps were detected in Obs. 11044 and 3814, including the CCD gaps, whose positions were correctly reproduced. Eight additional gaps were picked up by the algorithm in Obs. 11044, but not in 3814, despite them being visible by eye at coinciding positions. We therefore added these gaps manually in Obs. 3814. The detected gaps were verified by comparing them to the positions of dead rows documented in the ACIS `badpix` calibration file. As shown in Fig. A (c), all dead rows in the investigated range were found and have a matching width. We note that the coloured region centred at ~3300 pixels is excluded from the analysis because it contains zeroth-order and  $\lambda < 2$  Å events, not because of a defective chip section.

The second step is to identify all wavelength bins that are in dither range of gaps. For each gratings arm, we calculated the minimal and maximal  $x$  position of all events in a given bin and check if the closest gap is at least a two-pixel distance below the minimal or above the maximal value. If not, the bin is discarded. By requiring a distance of at least two pixels, we correctly rejected bins that are half covered by a gap, which cannot be distinguished from bins directly adjacent to a gap.

As an example, a result of this selection is shown in Fig. A.1 (b) and (d) for the first-order MEG spectrum. In panel (b), the spread of all bins that passed the filtering is shown in transparent blue and the gaps are marked in red. As intended, the filtered bins do not overlap with the gaps. Panel (d) compares the filtered and unfiltered  $F_{\text{var}}^2$  spectra. CCD gaps cause huge, often double-peaked spikes. The shape results from the fact that the amount of arriving photons varies more strongly for bins around the gap edge than for bins largely covered the

gap. Dead pixel rows give rise to smaller features because they are narrower. The filtering algorithm succeeds in cutting out the large CCD gap spike, as well as several smaller ones caused by the gaps indicated in the figure above.

Figure A.1 (e) shows the effect of filtering on the number of counts available for the analysis in each wavelength bin. Depending on how the filtered wavelengths align across the gratings arms, the number of counts fluctuates greatly. In a small number of bins no signal is left, which results in the gaps in the data in Fig. 2. We note that the slightly visible two hump structure is a result of *Chandra*'s effective area (compare to, e.g. Canizares et al. 2005) and that the higher number of counts in Obs. 3814 is due to a higher exposure time.

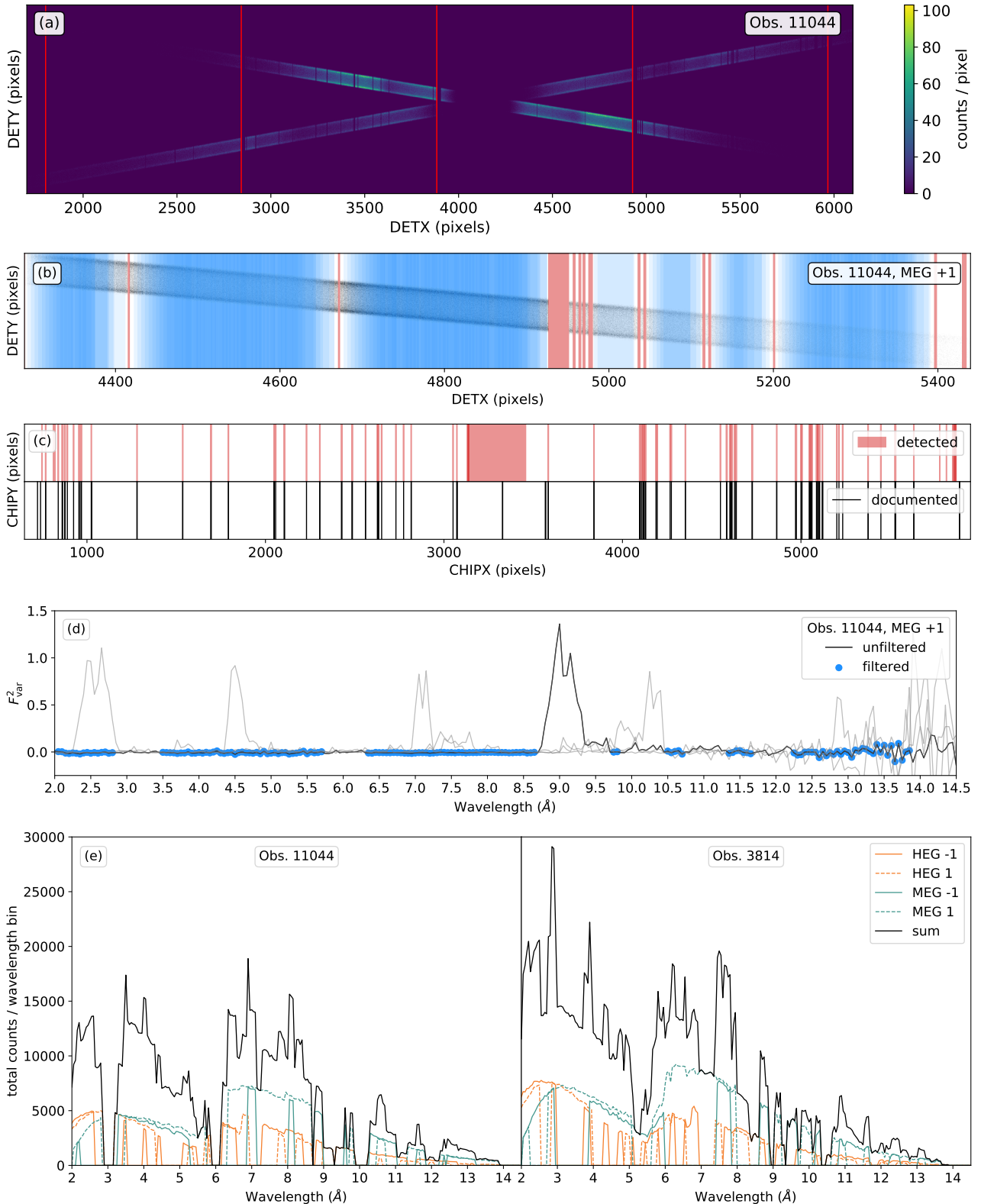


Fig. A.1: Dead pixel rows and CCD gaps in *Chandra*'s ACIS-S detector are a major source of systematic variance. This figure illustrates our filtering procedure. Panel (a) shows the distribution of counts on the ACIS-S CCD array, against which CCD gaps (marked in red) and dead pixel rows clearly stand out. Panel (b) shows the filtered bins (blue) and gaps (red) as an overlay on a cut-out of the top panel (first order MEG spectrum). Only bins a minimum distance of two pixels from the detected gaps pass the filtering. Panel (c) compares the positions of detected gaps to those of dead pixel rows documented in the ACIS `badpix` calibration file. The gap at  $\sim 3300$  pixels is not excluded because of a detector defect, but because it contains zeroth-order and  $\lambda < 2 \text{ \AA}$  events. In panel (d), the resulting  $F_{\text{var}}^2$  is shown, with the filtered bins highlighted in blue and MEG  $-1$  and HEG  $\pm 1$  spectra (all light grey) for comparison. Details on the filtering procedure can be found in the text. (e) Total counts per wavelength bin in Obs. 11044 (left) and 3814 (right) after filtering, for all gratings arms (orange and green, straight and dashed lines) and their sum (black line). For clarity, data in panels (d) and (e) are displayed with lines and no errors are given.



## Appendix B: Estimating binning variability

The *Chandra* ACIS-S detector has a read-out time of the order of seconds (Garmire et al. 2003), which not only limits its timing resolution, but also introduces systematic variability if the data are binned. Intuitively, some photons are assigned to time bin  $n + 1$  instead of  $n$ , because of the delay between photon arrival and read-out.

We estimated the magnitude of this effect with Monte Carlo simulations. We generated a random constant light curve by drawing photon arrival times from a constant distribution, separately for each observation, order, and grating, with their respective count numbers and exposure times. The read out is simulated by rounding the arrival times up to the next largest time stamp present in the data, imprinting the read-out times from the observation on the simulated data. We note that the average count rates of Cyg X-1 in Obs. 11044 and 3814 are  $\sim 90$  and  $\sim 70$  cts  $s^{-1}$ , respectively, which makes it very unlikely that this approach misses read-out cycles because no photons arrived. We confirmed this assumption by checking that there were no significant outliers in the time differences between consecutive events that exceed the read-out time. For each observation, order, and grating, we repeated this procedure 100 times and averaged the resulting total  $F_{\text{var}}^2$ . Combining all gratings and orders as described in Sect. 3.3 yields the systematic binning variability,  $F_{\text{var, binning}}^2$ . The one sigma error on  $F_{\text{var, binning}}^2$  is below  $2 \cdot 10^{-4}$  for both Obs. 3814 and 11044.

An example of the simulation for Obs. 11044 is shown in Fig. B.1 as a function of binning time step.  $F_{\text{var, binning}}^2$  strongly increases as the bin size approaches the read-out time, which is expected, as a smaller binning is more sensitive to a disturbance of a fixed magnitude. The periodicity in the ratio is caused by the binning time step matching an integer multiple of the duration of a read-out cycle. For a time step of 500 s, which was chosen for Fig. 2,  $F_{\text{var, binning}}^2$  is below 0.9% of the total variability over the 2–14 Å band in Obs. 11044. For Obs. 3814, we investigate time steps as short as 50 s, but due to the higher variability of this observation, the fraction stays below 0.3%. In absolute terms,  $F_{\text{var, binning}}^2$  always stays below  $2.5 \cdot 10^{-5}$  for time steps above 500 s in Obs. 11044 and below  $2.7 \cdot 10^{-4}$  for time steps above 50 s in Obs. 3814 at a one sigma confidence level. We therefore conclude that  $F_{\text{var, binning}}^2$  does not significantly impact our analysis, but we note that the effect generally should be considered when investigating the excess variance at a timing resolution approaching the read-out time of the instrument.

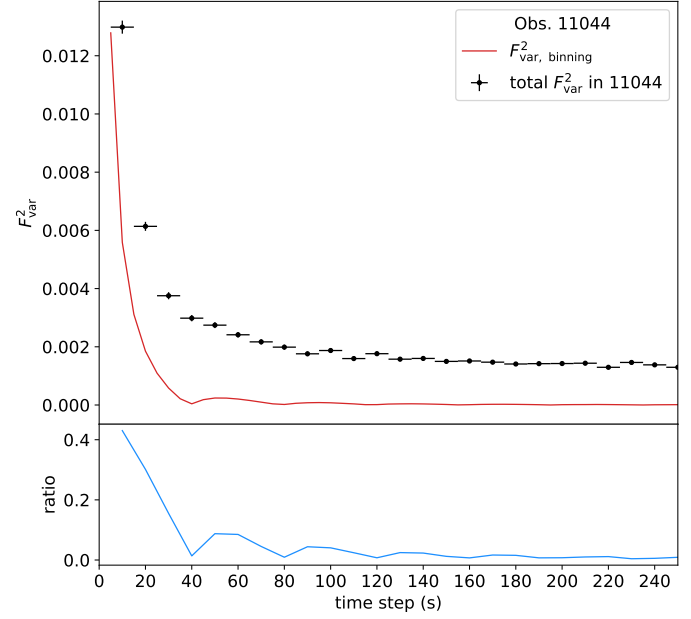


Fig. B.1: Systematic variability,  $F_{\text{var, binning}}^2$ , introduced by the timing resolution of the ACIS detector (red line) compared to total  $F_{\text{var}}^2$  in the broad band (2–14 Å, black data points) and their ratio, shown in the bottom panel. As a time step of 500 s is used for Obs. 11044, the effect is negligible in our analysis.

## Appendix C: Detailed $F_{\text{var}}^2$ spectrum of Obs. 11044

Table C.1: List of spike features in the  $F_{\text{var}}^2$  spectrum of Obs. 3814 with a significance  $>2\sigma$  and associated lines, e.g., lines that are at a distance of  $<0.05$  Å from the features.

Spike [Å]	$\sigma$	Ion	Line	Wl. [Å]	Ref.
5.82	2.2	P XIV	f [em.]	5.836	3
		P XIV	i [em.]	5.790	3
8.23	2.0	Fe XXII	$2p^2 \rightarrow 2p5d$	8.283	1
		Fe XXIV	$2p \rightarrow 4d$	8.232	1
8.58	2.2	Fe XXI	$2p^2 \rightarrow 2p5d$	8.608	1
		Fe XXIII	$2p \rightarrow 4d$	8.604	1
		Fe XXI	$2p^2 \rightarrow 2p5d$	8.555	1
		Fe XXI	$2p^2 \rightarrow 2p5d$	8.553	1
		Fe XXIII	$2p \rightarrow 4d$	8.540	1
		Fe XXIII	$2p \rightarrow 4d$	8.539	1
11.50	2.1	Ne IX	$1s \rightarrow 3p$	11.546	7
		Fe XVIII	$2p^5 \rightarrow 2p^44d1$	11.539	1
		Fe XVIII	$2p^5 \rightarrow 2p^44d$	11.524	1
		Fe XVIII	$2p^5 \rightarrow 2p^44d$	11.511	1
		Fe XVIII	$2p^5 \rightarrow 2p^44d$	11.508	1
		Fe XXII	$2s^22p \rightarrow 2s2p3p$	11.480	1
		Fe XXII	$2s^22p \rightarrow 2s2p3p$	11.471	1
		Fe XXII	$2s^22p \rightarrow 2s2p3p$	11.460	1

**Notes:** The listed lines are compiled from the selection described in Sect. 3.4. An alignment of lines detected in the previous analysis of the data set by Miškovičová et al. (2016) was searched for, but not found. References are given below. Lines listed multiple times with different wavelengths differ in the fine structure. Emission lines are marked with [em.]. Iron lines are exclusively from AtomDB.

**References:** (1) AtomDB (<http://www.atomdb.org/>), (3) Drake 1988, (7) Liao et al. 2013.

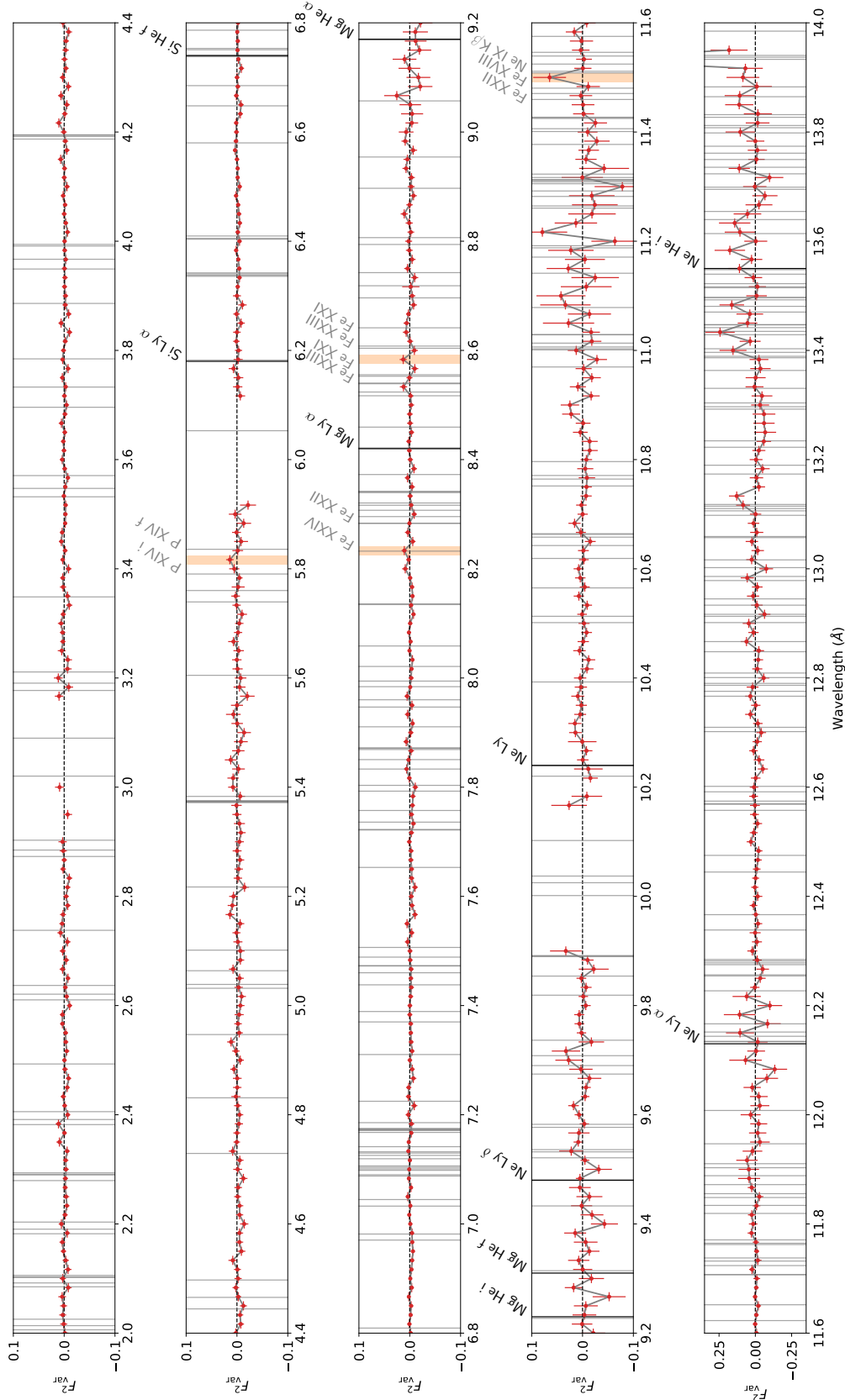


Fig. C.1: Detailed  $F^2_{\text{var}}$  spectrum of Obs. 11044, overplotted with the positions of line features identified in Miskovičová et al. (2016) (black) and transitions from the selection described in Sect. 3.4 (grey). Spikes with a significance  $\sigma > 2\sigma$  are highlighted in orange. For subsequent iron transitions belonging to the same ion the label is shown only once. A list of spikes and associated transitions can be found in Tab. C.1. In contrast to Obs. 3814, the lines identified by Miskovičová et al. (2016) are P-Cygni profiles, which makes the absence of spike features plausible (see Sect. 5.4).