Ups and downs in the X-ray emission of the colliding wind binaries HD 168112 and HD 167971

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ABSTRACT

Context. The long-period O-star binary system HD 168112 and the triple O-star system HD 167971 are well-known sources of non-thermal radio emission that arises from a colliding wind interaction. The wind-wind collisions in these systems should result in phase-dependent X-ray emissions. The presence of a population of relativistic electrons in the wind interaction zone could affect the properties of the X-ray emission and make it deviate from the behaviour expected for adiabatic shocks.

Aims. We investigate the X-ray emission of these systems with the goals of quantifying the fraction of the X-ray flux arising from wind interactions and determining whether these emissions follow the predictions for adiabatic wind-wind collisions.

Methods. Six X-ray observations were collected with XMM-Newton. Three observations were scheduled around the most recent periastron passage of HD 168112. Spectra and light curves were analysed and compared with simple predictions of model calculations for X-ray emission from colliding wind systems.

Results. The X-ray emission of HD 168112 varies as the inverse of the orbital separation, as expected for an adiabatic wind interaction zone. The relative contribution of intrinsic X-ray emission from wind-embedded shocks varies between 38% at periastron to 81% at apastron. The wind-wind collision zone remains adiabatic even around periastron passage. The X-ray emission of HD 167971 displays variations on the orbital timescale of the inner eclipsing binary. The existing data of this system do not allow us to probe variations on the timescale of the outer orbit.

Conclusions. Shock modification due to the action of relativistic electrons does not seem to be efficiently operating in the HD 168112 system. In the existing observations, a significant part of the emission of HD 167971 must arise in the inner eclipsing binary. The origin of this emission is as yet unclear.

Key words. binaries: close – stars: early-type – stars: individual: HD 168112 – stars: individual: HD 167971 – radio continuum: stars – X-rays: stars

1. Introduction

Though massive OB stars are rare objects, they are nonetheless key players in many processes in the evolution of galaxies and the Universe as a whole. One of their most remarkable properties is the existence of a powerful radiation-driven stellar wind that combines huge mass-loss rates with highly supersonic outflow velocities (e.g. Vink 2022). Most massive stars are found in binary or higher-multiplicity systems (e.g. Sana et al. 2012).

In such systems, the stellar winds of the components interact, and this interaction can impact the observational properties of these systems over a broad range of wavelengths, from X-rays into the radio domain. The head-on collision of the highly supersonic winds leads to the formation of an interaction region contained between a pair of oppositely faced, strong hydrodynamic shocks (Stevens et al. 1992). At the shock fronts, the kinetic energy normal to the shock is converted into heat, which may result in post-shock plasma temperatures of ~10 MK. This makes colliding wind binaries interesting targets for observations in the X-ray domain (for reviews see Rauw & Nazé 2016; Rauw 2022). However, observations of large samples of massive stars indicate that very strong X-ray emission is only observed for a subset of the massive binaries (e.g. Nazé 2009).

Another observational signature of wind interactions that is relevant in the context of our present work is synchrotron non-thermal radio emission. Whilst thermal radio emission is naturally expected due to free-free emission from the stellar wind (Wright & Barlow 1975), about 15–25% of the massive stars in a distance-limited sample were instead found to display a clearly non-thermal radio spectrum (Abbott et al. 1984; Bieging et al. 1989). This synchrotron emission reveals the presence of a population of relativistic electrons inside the stellar winds. Theoretical models of synchrotron emission from single O-type stars were unable to explain the observed non-thermal radio emission (van Loo et al. 2005). Intense optical spectroscopic monitoring or interferometric surveys of these non-thermal radio emitter massive stars unveiled the binary or higher-multiplicity nature of these objects (e.g. Dougherty & Williams 2000; Nazé et al. 2010; Sana et al. 2014; Rauw et al. 2016). In colliding wind binaries, relativistic electrons are accelerated via the diffusive shock acceleration process at the strong hydrodynamic shocks between the stellar winds of the binary components (e.g. Reiterberger et al. 2016).
7803 system. Based on interferometric measurements, Le Bouquin et al. (2017) detected a near-equal brightness companion ($\Delta m = 0.74 \pm 0.05$) for the outer orbit of the tertiary component. However, the physical link between the inner binary and the third star was uncertain at first. Blomme et al. (2007) analysed the existing radio observations of HD 167971, finding a timescale of variation of about 20 years, which they suggested is the orbital period of the third component.

Apellániz et al. (2019) classified the components of the eclipsing inner binary as O4-Iaf and O5-Iaf respectively for HD 168112 (Putkuri et al. 2023; Blomme et al. 2024), the eclipsing inner binary of HD 167971 (Ibanoglu et al. 2013) and the orbit of the outer component of HD 167971 (Le Bouquin et al. 2017).

The presence of a third component has been known for quite some time (Leitherer et al. 1987; Davis & Forbes 1988; Mayer et al. 2010; Ibanoglu et al. 2013) with an orbital period of 3.32 days (Ibanoglu et al. 2013, and references therein). The third body has an eccentricity of roughly 0.87, a 514 days (= 1.4 yr) orbital period and reveal two nearly equal-mass stars in a highly eccentric orbit (e ≳ 0.74–0.75). According to these orbital solutions, HD 168112 went through its periastron in March 2023. We monitored this event by means of three coordinated XMM-Newton and Karl G. Jansky Very Large Array (VLA) observations in the X-ray and radio domains, respectively. In the present paper, we analyse the X-ray data in light of our current knowledge of HD 168112 and HD 167971. The new radio observations of HD 168112 are discussed in detail in Blomme et al. (2024).

2. Observations and data processing

2.1. X-ray observations

Our targets were observed six times with the XMM-Newton satellite (Jansen et al. 2001), which carries three mirror modules that focus X-rays onto three European Photon Imaging Cameras (EPIC; Turner et al. 2001; Strüder et al. 2001) and two Reflection Grating Spectrometer (RGS; den Herder et al. 2001) instruments (RGS1 and RGS2). Two of the EPIC instruments use Metal Oxide Semi-conductor (MOS; Turner et al. 2001) charge-coupled device (CCD) arrays whilst the third camera uses a p-n junction CCD (pn; Strüder et al. 2001).

Under favourable spacecraft orientations, HD 168112 and HD 167971 fall into the same field of view of at least two EPIC cameras. This was the case for all our observations. However, RGS spectra are only available for the source located on-axis. During the first two observations, none of the stars was positioned on-axis. During the third observation, HD 167971 was observed on-axis, whilst HD 168112 was positioned on-axis for the three most recent observations. All EPIC observations were taken with the cameras operating in full frame mode; the thick filter was used to reject optical and UV radiation from the targets except for observation 3, for which the medium filter was used. Table 1 provides a journal of the XMM-Newton observations. The scheduling of the three most-recent observations was optimised to sample orbital phases around HD 168112’s periastron passage in March 2023.

We processed the data with the Science Analysis System (SAS) software version 19.1.0 using the current calibration files available in January 2024. The first and third observations were affected by soft proton background flares and we discarded the corresponding time intervals. EPIC spectra were extracted from circular regions of radius 30′′ centred on the Gaia coordinates of the two stars. The background was evaluated over an annulus of inner radius 30′′ and outer radius 50′′. For observation 3, we further extracted first and second order RGS1 and RGS2 spectra of HD 167971. For the last three observations, we did the same for HD 168112.

Table 1. XMM-Newton observations of HD 168112 and HD 167971.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Obs. ID.</th>
<th>Duration (ks)</th>
<th>JD-2 450 000</th>
<th>EPIC filter</th>
<th>Target on axis</th>
<th>ϕHD 168112</th>
<th>Putkuri</th>
<th>Blomme</th>
<th>ϕinner</th>
<th>ϕouter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0008820301</td>
<td>9.1</td>
<td>2372.56</td>
<td>Thick</td>
<td>–</td>
<td>0.096</td>
<td>0.063</td>
<td>0.49</td>
<td>0.697</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0008820601</td>
<td>13.4</td>
<td>2526.78</td>
<td>Thick</td>
<td>–</td>
<td>0.396</td>
<td>0.364</td>
<td>0.92</td>
<td>0.717</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0740990101</td>
<td>23.8</td>
<td>6909.73</td>
<td>Medium</td>
<td>HD 167971</td>
<td>0.931</td>
<td>0.921</td>
<td>0.45</td>
<td>0.278</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0920040401</td>
<td>12.5</td>
<td>10009.81</td>
<td>Thick</td>
<td>HD 168112</td>
<td>0.968</td>
<td>0.974</td>
<td>0.75</td>
<td>0.676</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0920040501</td>
<td>11.5</td>
<td>10025.98</td>
<td>Thick</td>
<td>HD 168112</td>
<td>0.000</td>
<td>0.006</td>
<td>0.62</td>
<td>0.678</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0920040601</td>
<td>11.5</td>
<td>10042.45</td>
<td>Thick</td>
<td>HD 168112</td>
<td>0.032</td>
<td>0.038</td>
<td>0.38</td>
<td>0.680</td>
<td></td>
</tr>
</tbody>
</table>

Notes. The durations indicated in the third column correspond to the effective exposure time of the EPIC-MOS camera (i.e. after removing the time interval affected by a flare in the first and third observation). The Julian day given in Col. 4 is evaluated at mid-exposure. The last four columns yield the orbital phases respectively for HD 168112 (Putkuri et al. 2023; Blomme et al. 2024), the eclipsing inner binary of HD 167971 (Ibanoglu et al. 2013) and the orbit of the outer component of HD 167971 (Le Bouquin et al. 2017).
Finally, we built background-corrected light curves of both targets over the 0.5–10.0 keV band for each of the available EPIC instruments and for each observation. For this purpose, we adopted temporal bin sizes of 100, 500 and 1000 s. The light curves were corrected to get full point spread function equivalent on-axis count rates using the epicleccor SAS task.

Beside the XMM-Newton data, we also analysed an 8.7 ks ROSAT observation (Obs. ID rp500298n00) taken with the Position Sensitive Proportional Counter (PSPC) instrument between 13 and 15 September 1993. The data were retrieved from the High Energy Astrophysics Science Archive Research Center (HEASARC). We processed these data using the xselect software (version 2.4c) and extracted background-corrected spectra for both targets. The source spectrum was obtained from a circular region of 50″ radius, whilst the background was extracted from an annulus with inner and outer radii of respectively 50″ and 90″. The HEASARC archive further quotes High Resolution Imager (HRI) count rates for both targets obtained during another 36.0 ks ROSAT observation (Obs. ID rh201995n00) performed between 12 September 1995 and 9 October 1995.

3.2. Spectral fits

To characterise the spectral energy distributions of both targets in the X-ray domain, we adjusted their XMM-Newton spectra using version 12.9.0i of the xspec code (Arnaud 1996). For each observation, all available spectra (EPIC and RGS) of a given target were fitted simultaneously. To avoid biases due to the fact that the RGS spectra exist only for a subset of the observations, we also performed fittings of the sole EPIC data for those observations where RGS data were available. We found that the EPIC only and EPIC+RGS spectral fits were fully consistent with each other and all model parameters overlapped well within their error bars.

High-resolution X-ray spectra of O-type stars unveil a wealth of emission lines of highly ionised species. These spectra indicate that the X-ray emission arises from an optically thin thermal plasma. We thus tested models of the kind

\[ \text{TBars} \times \text{phabs} \times \sum_{i=1}^{N} \text{apec}(kT). \] (1)

The apec components yield the X-ray emission of collisionally ionised, optically thin thermal plasma components (Smith & Brickhouse 2001). In our models we used \( N = 2 \) and \( N = 3 \) as we found that a single temperature plasma model \( (N = 1) \) was unable to provide a good fit over the full energy range of the data. The TBars model (Wilms et al. 2000) accounts for the photoelectric absorption by the interstellar medium (ISM) along our sightline towards the source. For HD 167971, Gudennavar et al. (2012) quoted a total interstellar neutral hydrogen column density of \( (5.4 \pm 4.0) \times 10^{21} \text{ cm}^{-2} \). Whilst the error bar on this column density is large, we note that the value is fully consistent with the mean relation between \( N(H) \) and \( E(B-V) \). Indeed, for \( E(B-V) = 0.87 \), the Bohlin et al. (1978) relation yields \( 5.0 \times 10^{21} \text{ cm}^{-2} \), whilst the relation of Gudennavar et al. (2012) yields \( 5.3 \times 10^{21} \text{ cm}^{-2} \). In our models, we thus fixed the ISM column of HD 167971 to \( 5.15 \times 10^{21} \text{ cm}^{-2} \), which is the mean of the values obtained with the two \( N(H) \)–\( E(B-V) \) relations. For HD 168112, no direct measurements of the neutral hydrogen column are available. For \( E(B-V) = 0.97 \) the same relations yield columns of \( 5.6 \times 10^{21} \text{ cm}^{-2} \) and \( 5.9 \times 10^{21} \text{ cm}^{-2} \). In our fits, we therefore fixed the ISM column of HD 168112 to \( 5.75 \times 10^{21} \text{ cm}^{-2} \). Our spectral models further included a phabs multiplicative absorption component to account for additional photoelectric absorption within the stellar winds, with the corresponding hydrogen column density considered a free parameter of the model. We stress here that the main objective of our spectral fits is to obtain a good description of the overall X-ray spectral energy distribution. Whilst the model parameters likely reflect the mean properties of the plasma, they should not be over-interpreted, especially because of the model degeneracies between the action of absorbing material and the intrinsic hardness of the emitting plasma. This remark is especially relevant for the lower temperature plasma component and explains the large error bars on the normalisation of the softest apec component. However, since this component contributes only a small fraction of the overall flux, this large error has little impact on the flux derivation.

3.2.1. HD 168112

The X-ray spectra of HD 168112 can be reasonably well described by a two-temperature (2-T) plasma model. The above-mentioned degeneracy between wind column density and plasma

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2 The NRAO is a facility of the US National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
temperature is especially apparent when comparing the parameters of observation 2 with those of the other exposures. Adding a third plasma component significantly improves the quality of the fits for the most recent exposures that have the best statistics (see Table 2). The improvement is marginal for observations 1 and 2, which have the poorest statistics. Since the 3-T fits yield a better adjustment of the overall spectral energy distribution, we use the flux values inferred from those fits in what follows. The total X-ray flux of HD 168112 exhibits highly significant variations between the various observations (see Table 2 and Fig. 1).

This result is independent of the model (2-T or 3-T), although, as indicated before, the 3-T models better represent the true flux of the source.

Owing to the smaller energy range covered by the ROSAT-PSPC instrument, the PSPC spectrum was fitted using a 1-T model. Assuming the same set of 1-T model parameters (except for the normalisation) describes the properties of the source during the ROSAT-HRI observation, we used the HEASARC WebPIMMS tool3 to convert the HRI count rates into fluxes in the 0.5–1.0 keV and 1.0–2.0 keV energy domains.

As outlined in Sect. 1, HD 168112 and HD 167971 are known as synchrotron non-thermal radio emitters. This synchrotron emission reflects the presence of a population of relativistic electrons accelerated by diffusive shock acceleration in the colliding wind region. In principle, inverse Compton (IC) scattering of stellar UV photons by those relativistic electrons could result in a non-thermal X-ray emission with a power law photon index \( \Gamma \). Since the index of the energy distribution of the relativistic electrons is \( \Gamma \) (Chen & White 1991). To check for the existence of such a non-thermal X-ray emission, we adjusted models of the kind

\[
T_{\text{Babs}} \times \text{phabs} = \sum_{i=1}^{2} \text{apec}(kT_{i}) + \text{power},
\]

where the power component stands for a non-thermal emission described by a power law relation. This model usually resulted in fits of very similar quality as for the 3-T thermal plasma model. The best-fit photon index of the power law turned out to be highly variable between exposures, changing from 2.2 to

![Fig. 1. Observed X-ray and radio flux of HD 168112 as a function of the orbital phase evaluated with the ephemerides of Blomme et al. (2024). The top four panels correspond to the different energy bands in the X-ray domain: soft (0.5–1.0 keV), medium (1.0–2.0 keV), hard (2.0–4.0 keV), and total (0.5–10 keV). Violet filled symbols correspond to XMM-Newton observations, and the red open circles indicate the ROSAT data. The error bars on the X-ray fluxes correspond to the 90% confidence intervals. The bottom panel presents the 6 cm radio flux data from Blomme et al. (2005).](http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl)

Notes. The model was defined according to Eq. (1) with \( N = 3 \). The ISM column was fixed to 5.75 \times 10^{21} \text{cm}^{-2}. Abundances were fixed to solar following Asplund et al. (2009). The plasma normalisation parameters are equal to \( 10^{14} \text{erg cm}^{-2} \) with \( D \) the distance of the source and \( f_n, n_{\text{H}} \text{d}V \) the emission measure of the plasma. The last column yields the observed flux in the 0.5–10 keV band. The quoted errors correspond to the 90% confidence intervals. The uncertainties on the observed fluxes were evaluated using the cfux command of the xspec software.

<table>
<thead>
<tr>
<th>Obs. Instruments</th>
<th>( N_{\text{H}} )</th>
<th>( kT_{1} )</th>
<th>( \text{norm}_{1} )</th>
<th>( kT_{2} )</th>
<th>( \text{norm}_{2} )</th>
<th>( kT_{3} )</th>
<th>( \text{norm}_{3} )</th>
<th>( \chi_{\nu}^{2} )</th>
<th>d.o.f.</th>
<th>( f_{\nu} ) (0.5–10 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOS1+2</td>
<td>0.54220.11 0.20 13</td>
<td>(4.41576) \times 10^{-3}</td>
<td>0.56220.19 0.36 19</td>
<td>(7.3405) \times 10^{-4}</td>
<td>\geq 2.8</td>
<td>(2.312) \times 10^{-4}</td>
<td>0.94</td>
<td>66</td>
<td>51.49 0.4 2.9</td>
<td></td>
</tr>
<tr>
<td>MOS1+2</td>
<td>0.26210.20 0.14 14</td>
<td>(2.72975) \times 10^{-3}</td>
<td>0.6060.08 12 0.36 19</td>
<td>(4.522) \times 10^{-4}</td>
<td>\geq 2.5</td>
<td>(1.010) \times 10^{-4}</td>
<td>0.76</td>
<td>61</td>
<td>38.77 0.4 0.5</td>
<td></td>
</tr>
<tr>
<td>EPIC</td>
<td>0.59210.13 0.26 15</td>
<td>(4.443) \times 10^{-3}</td>
<td>1.26210.38 0.28 38</td>
<td>(5.114) \times 10^{-4}</td>
<td>\geq 2.7</td>
<td>(2.522) \times 10^{-4}</td>
<td>0.85</td>
<td>162</td>
<td>71.2 \pm 4.9</td>
<td></td>
</tr>
<tr>
<td>EPIC+RGS</td>
<td>0.28210.20 0.33 12</td>
<td>(9.410) \times 10^{-4}</td>
<td>0.94210.09 0.64 19</td>
<td>(3.911) \times 10^{-4}</td>
<td>2.910.54 0.41</td>
<td>(5.910.9) \times 10^{-4}</td>
<td>0.96</td>
<td>451</td>
<td>84.3 \pm 3.7</td>
<td></td>
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<tr>
<td>EPIC+RGS</td>
<td>0.33210.11 0.31 19</td>
<td>(2.014) \times 10^{-3}</td>
<td>0.98210.07 0.66 19</td>
<td>(5.814) \times 10^{-4}</td>
<td>2.910.64 0.41</td>
<td>(6.313) \times 10^{-4}</td>
<td>1.11</td>
<td>493</td>
<td>103.1 \pm 2.3</td>
<td></td>
</tr>
<tr>
<td>EPIC+RGS</td>
<td>0.52210.11 0.30 18</td>
<td>(2.227) \times 10^{-3}</td>
<td>0.76210.16 0.07 13</td>
<td>(6.510) \times 10^{-4}</td>
<td>3.211.16 0.63</td>
<td>(4.310.9) \times 10^{-4}</td>
<td>1.03</td>
<td>414</td>
<td>74.0 \pm 3.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Fits of the X-ray spectra of HD 168112 using 3-T plasma models.

6.9. These indices differ significantly from the value expected for a population of relativistic electrons (\( \Gamma \sim 1.5 \)) if the shocks responsible for the acceleration have the usual compression ratio \( \sim 4 \). Moreover, their erratic variations further indicate that there currently is no clear evidence for the existence of a non-thermal component in the X-ray emission of HD 168112. Moreover, the best quality EPIC-pn spectra (observations 4, 5 and 6) display an Fe XV line at 6.7 keV, which is a clear indication that the harder X-ray emission arises inside a very hot thermal plasma. We come back to this point in Sect. 4.1.
Table 3. Fits of the X-ray spectra of HD 167971 using 3-T plasma models.

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Instruments</th>
<th>$N_H$ (10$^{22}$ cm$^{-2}$)</th>
<th>$kT_1$ (keV)</th>
<th>norm$_1$</th>
<th>$kT_2$ (keV)</th>
<th>norm$_2$</th>
<th>$kT_3$ (keV)</th>
<th>norm$_3$</th>
<th>$\chi^2_\nu$</th>
<th>d.o.f.</th>
<th>$f_X$ (0.5–10 keV)</th>
<th>\text{erg cm$^{-2}$ s$^{-1}$}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MOS1+2</td>
<td>0.72$^{+0.11}_{-0.12}$</td>
<td>0.31$^{+0.07}_{-0.03}$</td>
<td>(11.9$^{+7.9}_{-6.0}$) $\times$ 10$^{-3}$</td>
<td>0.86$^{+0.12}_{-0.15}$</td>
<td>(12.8$^{+7.7}_{-6.6}$) $\times$ 10$^{-3}$</td>
<td>3.0$^{+2.0}_{-0.9}$</td>
<td>(6.5$^{+4.1}_{-2.1}$) $\times$ 10$^{-4}$</td>
<td>0.85</td>
<td>111</td>
<td>16.6 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>EPIC</td>
<td>0.64$^{+0.06}_{-0.07}$</td>
<td>0.30$^{+0.03}_{-0.02}$</td>
<td>(6.8$^{+3.3}_{-2.6}$) $\times$ 10$^{-3}$</td>
<td>0.98$^{+0.07}_{-0.07}$</td>
<td>(12.9$^{+2.6}_{-2.0}$) $\times$ 10$^{-4}$</td>
<td>3.1$^{+2.8}_{-0.8}$</td>
<td>(4.4$^{+2.1}_{-1.8}$) $\times$ 10$^{-4}$</td>
<td>1.11</td>
<td>231</td>
<td>14.1 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>EPIC+RGS</td>
<td>0.60$^{+0.04}_{-0.04}$</td>
<td>0.32$^{+0.02}_{-0.01}$</td>
<td>(6.3$^{+1.3}_{-0.4}$) $\times$ 10$^{-3}$</td>
<td>0.81$^{+0.04}_{-0.01}$</td>
<td>(16.9$^{+7.2}_{-6.4}$) $\times$ 10$^{-4}$</td>
<td>2.0$^{+0.2}_{-0.1}$</td>
<td>(8.4$^{+4.0}_{-3.5}$) $\times$ 10$^{-4}$</td>
<td>1.13</td>
<td>967</td>
<td>15.8 ± 0.4</td>
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</tr>
<tr>
<td>4</td>
<td>EPIC</td>
<td>0.53$^{+0.09}_{-0.09}$</td>
<td>0.31$^{+0.08}_{-0.03}$</td>
<td>(6.6$^{+4.4}_{-3.3}$) $\times$ 10$^{-3}$</td>
<td>0.84$^{+0.12}_{-0.08}$</td>
<td>(16.6$^{+6.0}_{-2.9}$) $\times$ 10$^{-4}$</td>
<td>1.9$^{+0.5}_{-0.3}$</td>
<td>(10.8$^{+2.6}_{-2.7}$) $\times$ 10$^{-4}$</td>
<td>1.09</td>
<td>180</td>
<td>19.1 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>EPIC</td>
<td>0.40$^{+0.09}_{-0.15}$</td>
<td>0.15$^{+0.22}_{-0.06}$</td>
<td>(10.2$^{+6.8}_{-7.4}$) $\times$ 10$^{-3}$</td>
<td>0.65$^{+0.33}_{-0.05}$</td>
<td>(21.0$^{+6.1}_{-5.7}$) $\times$ 10$^{-4}$</td>
<td>1.3$^{+0.1}_{-0.1}$</td>
<td>(19.3$^{+2.4}_{-2.9}$) $\times$ 10$^{-4}$</td>
<td>1.22</td>
<td>186</td>
<td>20.0 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>EPIC</td>
<td>0.47$^{+0.16}_{-0.17}$</td>
<td>0.34$^{+0.21}_{-0.17}$</td>
<td>(3.9$^{+7.5}_{-2.9}$) $\times$ 10$^{-3}$</td>
<td>0.79$^{+0.13}_{-0.09}$</td>
<td>(16.3$^{+7.2}_{-9.4}$) $\times$ 10$^{-4}$</td>
<td>1.9$^{+0.5}_{-0.3}$</td>
<td>(12.5$^{+3.1}_{-3.1}$) $\times$ 10$^{-4}$</td>
<td>1.15</td>
<td>143</td>
<td>19.1 ± 0.9</td>
<td></td>
</tr>
</tbody>
</table>

Notes. Same as Table 2, but the ISM column was here fixed to 5.15 $\times$ 10$^{22}$ cm$^{-2}$. For observation 5, a few deviating energy bins of the EPIC-pn spectrum below 0.4 keV were excluded from the fitting procedure.

3.2.2. HD 167971

HD 167971 is a few times brighter in X-rays than HD 168112. Its X-ray spectra are again reasonably well described by means of 2-T plasma models. However, including a third plasma component significantly improves the quality of the fits for the majority of the exposures (see Table 3). We observe significant variations in the total flux between the different exposures, although they are of lower amplitude than in the case of HD 168112 (see Table 3). The highest quality EPIC-pn spectrum (observation 3) displays a clear Fe XXV emission near 6.7 keV consistent with a rather high plasma temperature. The ROSAT data were analysed in the same way as for HD 168112.

As for HD 168112, we also adjusted models including a power law component as of Eq. (2). Compared to the 3-T models, the 2-T + power law model resulted in a slight improvement of the quality of the fits in 4 cases out of 6. We found again best-fit photon indices that were quite different from the expected value of 1.5. For all observations, except the third one, $\Gamma$ was found to be in the range 2.6–3.4. For the third observation, the best agreement with the data was achieved for $\Gamma = 7.9$. Again, we conclude that there is currently no evidence for the existence of a genuine non-thermal component in the X-ray emission of HD 167971. We return to this point in Sect. 4.2.

4. Discussion

The properties of the hot plasma in a colliding wind interaction zone depend strongly on the efficiency of radiative cooling (Stevens et al. 1992). If the plasma density is high, collisional recombinations will be frequent resulting in a fast radiative cooling. As a result, the plasma temperature drops rapidly before the material escapes the system. This situation applies notably to massive binaries with short orbital periods such as the inner eclipsing binary in HD 167971. On the contrary, in wide massive binaries, such as HD 168112 or the outer system of HD 167971, the density of the plasma in the post-shock region of the colliding winds interaction is comparatively low. As a result, radiative cooling should be negligible and the hot shocked plasma only cools adiabatically. Under these circumstances, the X-ray luminosity is expected to scale with $1/r$ where $r$ is the instantaneous orbital separation between the stars (Stevens et al. 1992; Pittard & Dawson 2018).

The efficiency of radiative cooling is usually quantified through the ratio between the radiative cooling time and the escape time from the shock region $\chi = \frac{\tau_{\text{esc}}}{\tau_{\text{cool}}} = \frac{\rho v}{\sigma T}$ (Stevens et al. 1992). Here, $r$ stands for the instantaneous orbital separation of the stars, $\rho$ and $v_0$ are the wind mass-loss rate and wind terminal velocity (assuming the wind has the time to accelerate to its terminal velocity before the collision). Adopting the spectral types inferred by Maíz Apellániz et al. (2019) or those quoted by Putkur et al. (2023) along with the corresponding mass-loss rates and wind velocities fromMuijres et al. (2012), we infer $\chi \geq 22$ for both shocked winds of HD 168112. This result holds at all orbital phases, with the lowest value being reached at periastron. Hence, the radiative cooling via collisional recombination should be negligible at all orbital phases.

Collisional recombination might not be the sole cooling mechanism affecting the post-shock plasma. Mackey et al. (2023) drew attention to the importance of IC cooling that can become the primary cooling mechanism notably in eccentric binary systems with large wind momentum ratios. IC cooling of the thermal electrons could make the shocked winds strongly radiative near periastron despite the fact that the Stevens et al. (1992) criterion would indicate them to be in the adiabatic regime. Mackey et al. (2023) therefore formulate a specific criterion to evaluate the importance of IC cooling: $\chi_{\text{IC}} = \frac{1.61 \rho v_0^2}{\pi} L_{\text{bol}}$. Here $\chi_{\text{IC}}$ stands for the distance from the centre of the star to the shock in units 10$^{12}$ cm, $\rho$ is the pre-shock velocity in units 1000 km s$^{-1}$ and $L_{\text{bol}}$ the bolometric luminosity of the star in units 10$^5$ $L_\odot$. If $\chi_{\text{IC}} < 1$, then IC cooling makes the shock radiative. Applying this criterion to HD 168112 at periastron, we infer $\chi_{\text{IC}} \geq 8$ for both components of the system. Hence, we conclude that both criteria suggest that the wind interaction zone remains in the adiabatic regime all around the orbital cycle.

Applying the same calculations to the inner binary of HD 167971 yields $\chi = 3.2 (v/v_0^2)$ and $\chi_{\text{IC}} = 0.9 (v/v_0)$. Because of the proximity of the two stars and their mutual radiation fields, their winds do not accelerate to $v_0$ before they collide. Assuming that they reach $v_0/2$, which seems rather optimistic, we would find $\chi \approx 0.2$ and $\chi_{\text{IC}} = 0.4$, indicating that the shocked winds should be in the radiative regime. For the wind interaction between the inner binary and the tertiary component, the cooling parameters vary with phase because of the changing orbital separation. In this case, we find $\chi \geq 295$ and $\chi_{\text{IC}} \geq 75$.

Wide eccentric binaries offer an ideal testbed for the theory of adiabatic wind interactions, and more specifically for the predicted $1/r$ dependence of the X-ray flux. Evidence for such a behaviour was found in several O + O and Wolf–Rayet (WR) + O binaries.
elements. We focus on the results obtained with the Blomme et al. (2024) orbital solution from Blomme et al. (2024). The position angle is measured in the orbital plane and is defined here as the angle between the line joining the two stars and the direction of conjunction with the primary star (labelled component A in Blomme et al. 2024) in front. Phase 0.0 corresponds to periastron passage. Bottom panel: X-ray flux of HD 168112 in the 0.5–10 keV energy band corrected for absorption by the ISM as a function of orbital phase along with the best fit 1/r scaling of the colliding wind X-ray emission given by Eq. (3).

Blomme et al. (2024). Here, \(a\) stands for the orbital semi-major axis, whilst \(r\) is the instantaneous orbital separation. The straight line yields a least square fit to these data given by

\[
 f_X(10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}) = (3.16 \pm 0.42) (a/r) + (7.75 \pm 1.05). \tag{3}
\]

Using instead the Putkuri et al. (2023) orbital solution yields a very similar relation with the numerical values of 3.30 ± 0.45 and 7.41 ± 1.10. The best-fit relation of Eq. (3) is illustrated in Fig. 3 along with the phase dependence of \(r/a\) and of the position angle \(\theta\) defined as the true anomaly variation between the conjunction with the O4.5IV primary star in front and the actual direction of the line joining the two stars. We observe no obvious dependence of the X-ray fluxes on \(\theta\), which indicates that the observed variations are not due to absorption effects.

In shorter period systems (e.g. WR 21a, \(P_{\text{orb}} = 31.7\) days and Cyg OB2 #8a, \(P_{\text{orb}} = 21.9\) days), the X-ray emission displays an asymmetric behaviour between phases before and after periastron (e.g. Gosset & Nazé 2016; Mossoux et al. 2020). This was attributed to disruptions of the shock at periastron, and the shock subsequently needing some time to recover as the orbital separation increased again. Our observations of HD 168112 at \(\phi = 0.974\) (observation 4) and \(\phi = 0.038\) (observation 6) allowed us to check for the existence of such a hysteresis-like behaviour. Table 2 clearly shows the similarity in properties of these two phases. Therefore, we find no significant evidence for such a phenomenon in the HD 168112 system: the variations in the X-ray flux appear rather symmetrical around periastron passage.

As described above, the presence of relativistic electrons in the wind interaction zone of HD 168112 could result in shock modification (Pittard & Dougherty 2006). This should in turn lower the X-ray luminosity (compared to the 1/r relation) and the post-shock temperature and, hence, the temperature of the X-ray emitting plasma (Pittard & Dougherty 2006). Figures 2 and 3 do not show any evidence for a significant deviation of the X-ray flux from the 1/r relation.

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4 We focus on the results obtained with the Blomme et al. (2024) orbital solution as it contains significantly more data points around periastron passage and should thus result in better constrained orbital elements.
As outlined in Sect. 1, HD 168112 displays a non-thermal radio emission that is most likely associated with the wind interaction zone. De Becker et al. (2024) presented European Very Long Baseline Interferometry Network (EVN) radio observations of HD 168112 collected in November 2019 with an angular resolution of 12 × 22 mas°. The data of the EVN observations corresponds to phase $\phi = 0.598$ of HD 168112 according to the Blomme et al. (2024) ephemerides. The radio emission of HD 168112 was partially resolved and found to be elongated, consistent with the emission expected from a colliding wind interaction.

The bottom panel of Fig. 1 illustrates the variations in the observed radio emission at 6 cm wavelength (using our new VLA radio observations along with the radio light curve of Blomme et al. 2005). This radio emission displays a pronounced minimum around periastron passage. This minimum could reflect a genuine disruption of the shock around periastron passage. Indeed, if the shock were disrupted (as seen in WR 21a or Cyg OB2 #8a), the particle acceleration mechanism would be temporarily switched off, resulting in a strong attenuation of the synchrotron radio emission. However, the symmetrical variations in the X-ray flux around periastron clearly indicate that the shock is not disrupted. Instead, the most likely explanation of the radio minimum is the substantial free-free absorption by the stellar wind material. Indeed, as the stars approach periastron, the colliding wind interaction moves deeper into the optically thick winds and the synchrotron radio emission is strongly attenuated (Blomme et al. 2005). From the variations in the position angle in Fig. 3, we also see that the wind interaction zone remains partially hidden behind the radio photosphere of the secondary until about phase 0.35 and fully emerges only once the orbital separation increases as the stars approach apastron. This situation is quite reminiscent of the behaviour observed for the orbital separation increases as the stars approach apastron. The presence of a population of relativistic electrons in the wind interaction region of HD 168112 further opens up the possibility that IC scattering of stellar UV photons by these relativistic electrons could result in a non-thermal X-ray or $\gamma$-ray emission (Pittard et al. 2021). Indeed, the $\eta$ Car colliding wind system was detected at energies above 20 keV with the International Gamma Ray Astrophysics Laboratory (INTEGRAL) and NuSTAR (Leyder et al. 2010; Hamaguchi et al. 2018), and up into the GeV domain with Agile and Fermi (Farnier et al. 2011; Reitberger et al. 2015). So far all attempts to detect such a non-thermal X-ray emission over the 0.5–10 keV band in other particle accelerating colliding wind binaries failed (e.g. Rauw et al. 2002; Mossoux et al. 2020). This indicates that any non-thermal X-ray emission must be significantly weaker than the thermal emission from the colliding winds binary, at least at energies below 10 keV.

Pittard et al. (2021) estimated that IC energy losses by relativistic electrons are important for systems with orbital separation of less than $10^{10}$ cm. For HD 168112, the orbital separation varies between 248 $R_\odot$ (1.73 × 1013 cm) at periastron and 1766 $R_\odot$ (1.23 × 1014 cm) at apastron adopting the Blomme et al. (2024) orbital elements and taking $i = 63^\circ$. Hence, IC scattering by relativistic electrons should be relevant for this system over most orbital phases, and certainly around periastron. Our spectral fitting tests including a power law component yielded photon indices that varied over a wide range and were usually quite different from the expected value of 1.5. In this context, it is interesting to note that Pittard et al. (2021) drew attention to the large variations in the spectral indices of the relativistic particles in their models of colliding wind binaries, which make the usual $N(E) \propto E^{-2}$, where $N(E)$ stands for the number of photons emitted with an energy $E$, too simplistic. In the energy range between 1 and 10 keV, where non-thermal emission is dominated by IC scattering, their models always predict a photon index $\Gamma$ in the range 1.5–2. Hence, we performed another series of X-ray fittings adopting a model as given by Eq. (2), but this time keeping the photon index fixed to $\Gamma = 1.5$. These fits were of significantly poorer quality than those described in Sect. 3.2.1. Nevertheless, the normalisation of the power-law component was usually significant at the $\sim \sigma$ level and its intrinsic flux in the 0.5–10 keV band would be typically of order $3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to $\sim 10\%$ of the total intrinsic flux. However, we note that these spectral fits failed to properly reproduce the Fe XXV line at 6.7 keV, which requires a high-temperature thermal plasma (see Table 2). Therefore, we conclude that the existing data do not provide any evidence for a significant non-thermal X-ray emission in HD 168112. The above quoted flux associated with such a component is thus to be considered as a very conservative upper limit.
correspond to separations differing by only a few percent, the values are very similar and the ensuing X-ray emissions should with the above X-ray fluxes corrected for the interstellar absorption range between 2.75 × 10⁻¹² erg cm⁻² s⁻¹ and 4.17 × 10⁻¹¹ erg cm⁻² s⁻¹. The bolometric luminosities of the eclipsing binary components were evaluated as log L₁bol/L⊙ = 5.383 and 5.102, whilst the third light contribution was found to be near 40% of the total light of the triple system (Ibanoglu et al. 2013). Evaluating the sum of these bolometric luminosities, assuming a 2 kpc distance and comparing with the above X-ray fluxes corrected for the interstellar absorption results in L₁bol between 3.8 × 10⁻⁷ and 5.7 × 10⁻⁷. Using instead the typical bolometric magnitudes as quoted by Martins et al. (2005) for stars of equal spectral types yields L₁bol between 2.0 × 10⁻⁷ and 3.1 × 10⁻⁷. HD 167971 thus appears mildly over-luminous in X-rays compared to the canonical L₁/X₁ relation.

Figure 4 displays the variations in the X-ray flux as a function of the orbital phase of the tertiary component (left panel) and of the orbit of the inner eclipsing binary (right panel). The observed X-ray emission of HD 167971 is a combination of (i) the intrinsic emission of the three components of this triple system, (ii) a possible contribution from the wind interaction zone of the short-period binary, and (iii) the collision between the combined winds of the inner binary and the wind of the third component. The third of these contributions is expected to undergo a 1/r modulation similar to the one observed for HD 168112. However, Fig. 4 unveils very little coherent variations with the phase of the outer orbit. This could primarily be due to the rather scarce phase coverage. Indeed, existing XMM-Newton data only sample phases φout between 0.3 and 0.7. Because these phases are roughly symmetrical with respect to periastron (φout = 0.0) and correspond to separations differing only by a few percent, the 1/r values are very similar and the ensuing X-ray emissions should thus display a similar level, as observed. By far, the largest variations in the X-ray emission from the outer colliding wind interaction are expected around periastron, but such data are currently lacking. The data points collected around φout = 0.7 display significant variations, but this variability occurs with a timescale that is too short to be due to a 1/r modulation. The right panel of Fig. 4 shows instead that these variations probably arise on the timescale of the inner orbit. Indeed, the existing data suggest a modulation that is reminiscent of eclipses in the inner binary (see Fig. 5). This is especially true for the soft and medium energy bands, whilst the variations in the hard band are more erratic. In the medium energy band, the variations have peak-to-peak amplitudes of 40%.

The part of HD 167971’s X-ray emission that undergoes a short-term modulation consistent with the orbital period of the inner eclipsing binary must therefore arise inside this short period binary. There are three possibilities to explain the origin of this emission:

- It could arise from the intrinsic emission due to wind-embedded shocks (Feldmeier et al. 1997). The modulation of the X-ray flux would then result from eclipses by the stars and their winds, as was suggested, for instance, for the case of 29 CMa (Berghöfer & Schmitt 1995). Observationally, the intrinsic emission of O-type stars typically amounts to 10⁻² Lbol and is mostly soft with kT ~ 0.6 keV (e.g. Berghöfer et al. 1996; Nazé 2009). Based on the spectral types proposed by Maíz Apellániz et al. (2019), and the calibration of Martins et al. (2005), we estimate log (Lbol/L⊙) ≃ 5.91 for the primary and log (Lbol/L⊙) ≃ 5.69 for the secondary component. Assuming a distance of 2 kpc, the X-ray flux due to wind-embedded shocks is estimated as ~6.5 × 10⁻¹³ erg s⁻¹ cm⁻² for the primary and ~3.9 × 10⁻¹³ erg s⁻¹ cm⁻² for the secondary. Each star contributes a non-negligible fraction (~15% and ~9% respectively for the primary and secondary star) of the maximum

4.2. Colliding winds in HD 167971

The X-ray fluxes of HD 167971 in the 0.5–10 keV band corrected for the interstellar absorption range between 2.75 × 10⁻¹² erg cm⁻² s⁻¹ and 4.17 × 10⁻¹¹ erg cm⁻² s⁻¹. The bolometric luminosities of the eclipsing binary components were evaluated as log L₁bol/L⊙ = 5.383 and 5.102, whilst the third light contribution was found to be near 40% of the total light of the triple system (Ibanoglu et al. 2013). Evaluating the sum of these bolometric luminosities, assuming a 2 kpc distance and comparing with the above X-ray fluxes corrected for the interstellar absorption results in L₁bol between 3.8 × 10⁻⁷ and 5.7 × 10⁻⁷. Using instead the typical bolometric magnitudes as quoted by Martins et al. (2005) for stars of equal spectral types yields L₁bol between 2.0 × 10⁻⁷ and 3.1 × 10⁻⁷. HD 167971 thus appears mildly over-luminous in X-rays compared to the canonical L₁/X₁ relation.
The uncertainties on the folded with the ephemerides from Ibanoglu et al. (2013). We note that the intrinsic flux in the 0.5–10 keV band corrected for the interstellar absorption and with the ephemerides of the inner eclipsing binary. Bottom panel: X-ray

Fig. 5. Comparison between optical and X-ray light curve of HD 167971. Top panel: V-band photometry of HD 167971 (Mayer et al. 2010) folded with the ephemerides of the inner eclipsing binary. Bottom panel: X-ray flux in the 0.5–10 keV band corrected for the interstellar absorption and folded with the ephemerides from Ibanoglu et al. (2013). We note that the uncertainties on the \( \phi_{\text{inner}} \) of the X-ray data are smaller than the size of the symbols. They range between 1.6 \( \times \) 10\(^{-3} \) for the oldest data and 2.8 \( \times \) 10\(^{-3} \) for the most recent observation.

total ISM-corrected X-ray emission, but these contributions fall short by about a factor of 2 to 4 compared to what is needed to explain the observed ~40\% peak to peak variations by occultation and eclipse effects.

– It could arise from a wind interaction between the components of the inner binary. Indeed, short-period massive binaries may display a phase shift in their X-ray light curve with respect to the optical light curve. This is due to the Coriolis deflection of the wind interaction region (e.g. V444 Cyg, \( P_{\text{orb}} = 4.21 \) d, Lomax et al. 2015; WR 21 and WR 31, \( P_{\text{orb}} = 8.25 \) d and 4.83 d, Nazé et al. 2023). De Becker (2015) argued that because of the radiative nature of the wind interaction in the inner binary, the total X-ray emission of HD 167971 should be dominated by this contribution. However, from the observational viewpoint, wind interactions in such short-period O-star binaries are often X-ray faint (e.g. 29 CMa; Bergfors & Schmitt 1995, and HD 149404, Rauw et al. 2024). From a theoretical viewpoint, radiative wind interaction zones are expected to be subject to thin shell instabilities that considerably lower their X-ray emission (Stevens et al. 1992; Kee et al. 2014). The problem would be even worse if the inner eclipsing binary is in an overcontact configuration as suggested by Mayer et al. (2010) and Ibanoglu et al. (2013) based on their photometric light curve analyses. In such cases, the strong head-on collision of the winds along the line of centres is lacking and the wind interaction region has an annular shape, which would make it less prone to eclipsing effects (Montes et al. 2013).

– It could form in a magnetically confined wind of one of the components of the inner binary. In magnetic massive stars, the mostly dipolar magnetic field channels the wind material towards the magnetic equator where the flows from the two hemispheres collide, leading thereby to an enhanced X-ray emission (for a review see ud-Doula & Nazé 2016). The eclipse of such a magnetically confined wind by the companion star could indeed lead to a modulation of the observed X-ray emission. Hubrig et al. (2023) reported the detection of a strong (1324 + 582 G) longitudinal magnetic field in one of the components of the eclipsing binary. However, given the large error bar, this 2.3 \( \sigma \) detection requires confirmation. We note that Neiner et al. (2015) had previously analysed the same observation, reporting a non-detection. Again, more evidence needs to be gathered to check the validity of this scenario.

Whilst the above discussion highlights the fact that the X-ray emission of HD 167971 arises from several regions, one obviously expects a contribution coming from the interaction between the winds of the inner binary and the wind of the tertiary component. In fact, the non-thermal radio emission of this system is clearly ruled by the outer orbit (Blomme et al. 2007), pointing towards an energetic wind-wind collision. Blomme et al. (2007) estimated that the tertiary star was at its closest position to the inner binary in 1988 in good agreement with the ephemerides of Le Bouquin et al. (2017)\(^3\). Sanchez-Bermudez et al. (2019) discussed two very long baseline interferometry (VLBI) observations in 2006 and 2016. These data unveiled a change in orientation of the elongated emission region, consistent with the orbital motion of the tertiary component. These results demonstrate that the non-thermal radio emission from HD 167971 arises from the wind-wind collision between the inner eclipsing binary and the tertiary component. The location of the emitting region between the positions of the inner binary and the tertiary further indicates that the combined wind of the inner binary is stronger than the wind of the tertiary star. The next periastron passage of the tertiary component should take place in 2030. From the 0.44 \( \pm \) 0.02 eccentricity derived by Le Bouquin et al. (2017), one can then estimate that the contribution of the outer colliding wind interaction should increase by more than a factor of 2 between the existing data around \( \phi_{\text{outer}} = 0.3 \) or \( \approx 0.7 \) and periastron if there is no impact of shock modification.

The VLBI data of Sanchez-Bermudez et al. (2019) yielded a radio spectral index of \( \alpha = -1.1 \), significantly steeper than expected for synchrotron emission in an optically thin environment (\( \alpha = -0.5 \)). Sanchez-Bermudez et al. (2019) interpreted this as a consequence of efficient IC cooling leading to a softening of the electron energy spectrum or as a consequence of modified shocks. While the current sampling of the outer orbit is insufficient to search for evidence for or against shock modification, we tried to look for evidence of non-thermal X-ray emission arising from the IC scattering by the relativistic electrons. As for HD 168112, we repeated the fits of a model including beside a 2-T thermal plasma a power-law component with \( \Gamma \) fixed to 1.5. These fits were again of poorer quality than those described in Sect. 3.2.2. The normalisation of the power-law was only significant at the \( \sim 3.5 \sigma \) level. The intrinsic flux in the 0.5–10 keV band of the power-law component would be typically of order \( 4 \times 10^{-13} \) erg cm\(^{-2} \) s\(^{-1} \), corresponding to \( \sim 3\% \) of the total ISM-corrected X-ray flux. We stress that these models failed to reproduce the Fe XXV line at 6.7 keV clearly seen

\(^3\) This is also confirmed by the EVN radio data of De Becker et al. (2024) that were collected near apastron of the tertiary component at a time when the synchrotron emission of this system was at a low level. The radio emission of HD 167971 remained unresolved in this observation.
in the EPIC-pn spectrum from observation 3. Hence, as in the case of HD 168112, we conclude that the flux quoted for the non-thermal X-ray emission must be seen as a strict upper limit and that currently, there is no detection of a genuine non-thermal high-energy emission in HD 167971.

5. Conclusions

In this study we used a new set of XMM-Newton observations to gain further insight into the X-ray properties of two colliding wind systems that are well-known non-thermal radio emitters. Taking advantage of the orbital elements that were recently established for HD 168112, we find that the X-ray spectra of this highly eccentric 1.4 yr binary unveil a clear phase-dependent X-ray over-luminosity. The X-ray fluxes display variability consistent with the expected 1/r modulation for an adiabatic wind interaction. We show that the shocks remain adiabatic at peri-astro and do not collapse, unlike what has been observed in other eccentric massive binaries. Despite the presence of a population of relativistic electrons, as revealed by the synchrotron radio emission, we find no evidence of a significant shock modification due to the action of these relativistic electrons. We also failed to detect any clear indication of a non-thermal X-ray emission that could arise from IC scattering by relativistic electrons. Our analysis indicates that wind-embedded shocks in the individual winds of the binary contribute between 38% and 81% of the X-ray flux at periastro and apastron, respectively.

The existing X-ray data of the triple system HD 167971 were not sufficient to look for a 1/r modulation locked to the orbit of the tertiary component. This is mostly because observations of the outer orbit near periastro are still missing. From the current best knowledge of the outer orbit, the next opportunity to fill this gap is expected around 2030. Meanwhile, the existing data hint at a modulation of the X-ray emission on the orbital period of the inner eclipsing binary. This suggests that a significant fraction of the observed X-ray emission must arise inside this inner binary, although its exact origin remains uncertain. Whilst the emission from wind-embedded shocks is probably not sufficient to explain the observed modulation, colliding winds possibly coupled with a magnetically confined wind of one of the components of the inner binary could provide an explanation. However, a better sampling of the inner orbital cycle would be needed to determine the constraints needed to guide future models of this system.

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References


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