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Evidence for colliding winds in WR 25 from *XMM-Newton* observations of X-ray variability[*]

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ABSTRACT

The Wolf-Rayet star WR 25 in the Carina Nebula is a surprisingly bright X-ray source, and amongst the brightest WR stars in X-rays. It is a suspected binary star, though its binary nature has been a matter of controversy. We report here observations of WR 25 from the *XMM-Newton* archive which showed an increase in X-ray luminosity of more than a factor of two. The X-ray absorption also increased. Such a large change in X-ray output is unknown in single massive stars, though large changes in X-ray brightness are seen in binaries. The most likely explanation of the observed X-ray variability is as a result of colliding-wind emission in a moderately eccentric binary with a period of about 4 years. The next periastron passage is expected in 2007. The X-ray spectrum is similar to that of the archetype colliding-wind binary WR 140.

Key words. X-rays: stars – stars: Wolf-Rayet – stars: individual: WR 25 – stars: winds, outflows – stars: binaries: general

1. Introduction

WR 25, or HD 93162, is a rather controversial object in the Carina Nebula. It is one of 3 Wolf-Rayet stars in the Nebula, which is also home to the enigmatic object η Carinae, and of the 3 it is by far the brightest in X-rays. The origin of the large X-ray flux is uncertain, but suggestive of colliding-wind emission in a binary system (Pollock 1987; Raassen et al. 2003). However, the binary nature of the star has been a matter of debate. The star possesses an X-ray overluminosity of $L_x/L_{bol} \approx 20 \times 10^{-7}$ (Seward & Chlebowski 1982) and a high X-ray temperature, similar to other known or suspected massive binaries, in contrast to values including $L_x/L_{bol} \approx 2 \times 10^{-7}$ typical of single massive stars. The optical spectrum is a composite of a diluted Wolf-Rayet emission-line spectrum of subtype WN6-7 and strong early-type absorption (Walborn et al. 1985). More recently, van der Hucht (2001) attributed a classification of WN6h+O4f to the star. However no radial velocity variations have ever been observed, indicating either a long-period or low-inclination binary, or a single star. The X-ray emission could arise from colliding-wind emission in a massive binary, or perhaps from the interaction of a strong wind from a single star with a nearby circumstellar cloud or dust lane, though

Raassen et al. (2003) argued that the presence of Fe XXV emission in the X-ray spectrum was indicative of colliding-wind emission and hence binarity. On the other hand, as Raassen et al. (2003) noted, the X-ray luminosity of WR 25 had remained relatively stable over a 10-year timespan, with variations <15%, and this lack of large variability in X-rays has been taken as evidence of the singular nature of the star.

Here we report a series of archived observations of WR 25 obtained with the European Photon Imaging Counter (EPIC) aboard *XMM-Newton*. In most of these observations the X-ray flux from WR25 in the EPIC band showed modest variations consistent with Raassen et al. (2003). However, more recently, there has been an episode of a few weeks during which both the X-ray luminosity and absorption of WR 25 temporarily increased considerably.

2. Observations

Table 1 lists the *XMM-Newton* observations considered here. The first five were reported by Raassen et al. (2003) while the remainder were obtained as part of a campaign to monitor the X-ray emission of η Carinae, which is about 7′ from WR 25. The observations mostly follow a pattern in which a group of several was spread over a few days in seasons separated by about 6 months or a year until the η Carinae periastron campaign, which covered a few weeks of the summer in 2003. Most

Table 1. *XMM-Newton* EPIC observations of WR 25.

Date	MJD	Target	rev_ObsID	MOS1 m^a+f^b	MOS1 Count rate (s^{-1})	MOS2 m^a+f^b	MOS2 Count rate (s^{-1})	pn m^a+f^b	pn Count rate (s^{-1})
2000-07-26	51751	η Carinae[k]	0115_0112580601	FF+T	0.387 ± 0.003	SW+T	0.439 ± 0.004	FF+T	1.214 ± 0.007
2000-07-27	51752	η Carinae[k]	0116_0112580701	FF+T	0.384 ± 0.006	SW+T	0.457 ± 0.008	FF+T	1.237 ± 0.014
2001-06-25	52085	WR 25[k]	0283_0112560101	FF+T	0.463 ± 0.006	FF+T	0.469 ± 0.006	...	...
2001-06-28	52088	WR 25[k]	0284_0112560201	FF+T	0.460 ± 0.004	FF+T	0.468 ± 0.004	FF+T	1.385 ± 0.007
2001-06-30	52090	WR 25[k]	0285_0112560301	FF+T	0.460 ± 0.004	FF+T	0.471 ± 0.004	FF+T	1.389 ± 0.007
2003-01-25	52664	η Carinae[c]	0573_0145740101	FF+T	0.368 ± 0.008	FF+T	0.342 ± 0.007	SW+T	...
2003-01-27	52666	η Carinae[c]	0574_0145740201	FF+T	0.365 ± 0.008	FF+T	0.341 ± 0.007	SW+T	...
2003-01-27	52666	η Carinae[c]	0574_0145740301	FF+T	0.366 ± 0.008	FF+T	0.353 ± 0.007	SW+T	...
2003-01-29	52668	η Carinae[c]	0575_0145740401	FF+T	0.354 ± 0.007	FF+T	0.346 ± 0.007	SW+T	...
2003-01-29	52668	η Carinae[c]	0575_0145740501	FF+T	0.372 ± 0.008	FF+T	0.333 ± 0.007	SW+T	...
2003-06-08	52798	η Carinae[c]	0640_0160160101	SW+T	0.487 ± 0.004^g	FF+T	0.487 ± 0.004^g	SW+T	...
2003-06-19	52809	η Carinae[c]	0643_0160160901	SW+T	0.093 ± 0.002^x	FF+T	0.331 ± 0.003^x	SW+T	...
2003-07-22	52842	η Carinae[c]	0662_0145780101	SW+T	0.581 ± 0.009	FF+M	0.672 ± 0.009	SW+T	...
2003-08-02	52853	η Carinae[c]	0668_0160560101	SW+T	0.346 ± 0.005	FF+M	0.401 ± 0.005	SW+T	...
2003-08-09	52860	η Carinae[c]	0671_0160560201	SW+T	0.375 ± 0.006	FF+M	0.442 ± 0.006	SW+T	...
2003-08-18	52869	η Carinae[c]	0676_0160560301	SW+T	0.316 ± 0.004	FF+M	0.433 ± 0.005	SW+T	...

[a] EPIC mode: FF full-frame mode; or SW small-window mode.
[b] EPIC filter: T Thick filter; or M Medium filter.
[c] PI: Corcoran.
[k] PI: Kaastra.
[g] Slightly affected by a MOS chip gap.
[x] Badly affected by a MOS chip gap.

of these observations were designed with η Carinae in mind, with most of the EPIC-pn observations in small-window mode in which WR 25 was not visible. While nearly all the MOS1 and MOS2 observations provided high-quality data on WR 25, despite occasional bad columns and the proximity of chip gaps, in ObsIDs 0160160901 and 0160160901 the star fell squarely on chip gaps, in some exposures more seriously than others. With care these data are still useful, particularly for studying the spectrum given the energy independence of the PSF. Data were reduced using SASv6.0.0, using standard event selection criteria, and spectra extracted from a circle of radius 600 detector pixels centred on the star with the background estimated from a concentric annulus of inner and outer radii 1200 and 1800 pixels, respectively, using the SAS task `especget`, which also delivers the appropriate response and ancilliary response files.

3. X-ray flux and absorption variations in WR 25

It is obvious from the count rates alone reported in Table 1 that WR 25 showed considerable variability during the summer of 2003. Inspection of the raw spectra shows that this involved variations in both the intensity and the spectral shape, especially at low energies. By contrast, the spectrum did not change significantly over the few days covered by each observing season.

There are many possible ways to model the background-subtracted MOS spectra. We found good fits to the data between 0.3 and 10.0 keV with XSPEC (Arnaud 1996) using a single reference model subject to two extra degrees of freedom of luminosity and absorption. For the reference model, the most successful approach followed that of Raassen et al. (2003), who used a semi-empirical model consisting of two constant-temperature `vmekal` plasmas, each subject to independent `wabs` absorption. The best-fit reference model parameters, which are close to those reported by Raassen et al. (2003), are shown in Table 2 and describe the spectrum of WR 25 at its minimum luminosity and optical depth, defined most closely by Raassen et al. (2003)'s high statistical weight spectra taken over 5 days in June 2001. A large fraction of the observed absorption is due to the interstellar medium. Although Crowther et al. (1995) found that the extinction towards WR 25 is anomalous, their value of $E_{B-V} = 0.66 \pm 0.03$ implies an interstellar column density of roughly $N_{\rm H} \sim 4 \times 10^{21}$ cm^{-2} which would account for most of the soft X-ray absorption in the reference spectrum. The apparently high nitrogen abundance, which is required by the model to account for a few counts at very low energy, is subject to large error and makes no difference to the results presented below.

Figure 1 shows a comparison of the MOS reference spectrum with the two spectra in which the luminosity and absorption reached their highest respective values. The systematic
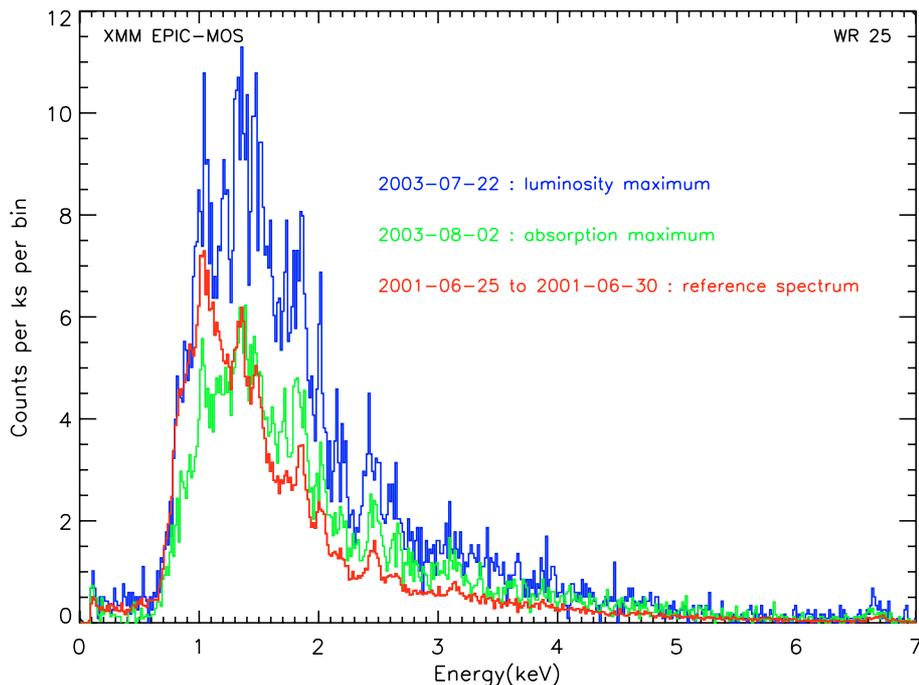
Fig. 1. Sum of *XMM-Newton* background-subtracted EPIC-MOS1 and EPIC-MOS2 spectra of WR 25 at 3 epochs: the low-luminosity, low-absorption reference spectrum of 2001 June in red; the maximum-luminosity spectrum on 2003-07-22 in blue; the maximum-absorption spectrum on 2003-08-02 in green.

Table 2. Best-fit XSPEC reference model and abundances[a] of *XMM-Newton* observations of WR 25

$A(\texttt{wabs}(nH_1)\texttt{vmekal}(kT_1) + C_{12}\texttt{wabs}(nH_2)\texttt{vmekal}(kT_2))$			
A	=	3.445	$\pm$	0.001×10^{-3}
kT_1	=	0.609	$\pm$	0.005 keV
nH_1	=	7.17	$\pm$	0.12×10^{21} cm^{-2}
C_{12}	=	0.523	$\pm$	0.036
kT_2	=	2.774	$\pm$	0.041 keV
nH_2	=	5.07	$\pm$	0.35×10^{21} cm^{-2}
He	=	2.27[b]		
C	=	0.15[b]		
N	=	76.	$\pm$	17.
O	=	0.00	$\pm$	0.06
Ne	=	1.58	$\pm$	0.21
Na	=	7.5	$\pm$	1.9
Mg	=	1.41	$\pm$	0.17
Al	=	0.0	$\pm$	0.7
Si	=	1.46	$\pm$	0.16
S	=	2.00	$\pm$	0.21
Ar	=	2.03	$\pm$	0.33
Ca	=	2.36	$\pm$	0.42
Fe	=	0.81	$\pm$	0.09
Ni	=	1.12	$\pm$	0.44

[a] Relative to the default XSPEC solar abundances.
[b] Fixed value.

effects of changes are clear in luminosity at high energies and absorption at low energies. Despite this obvious overall variability, we found little evidence of any changes in the temperatures or luminosity ratio of the two components in any of the *XMM-Newton* observations, and so kept them and the minimum absorption fixed at the best-fit values to calculate the estimates of the history of WR 25's luminosity and additional absorption shown in Table 3 and plotted in Fig. 2 with details of the behaviour in 2003 shown in Fig. 3. MOS1 and MOS2 agree well although there is a tendency for MOS1 to yield values of N_H slightly larger by roughly 4×10^{20} cm^{-2}, due probably to remaining systematic uncertainties in the MOS calibration.

4. Origin of the X-ray variability of WR 25

The X-ray variability of WR 25 in the MOS spectra is similar to variations seen in other long-period, eccentric high-mass colliding-wind binaries in the following respects:

- a strong increase and subsequent decline in X-ray flux during a relatively brief interval;
- an accompanying increase in column density.

Given the optical spectrum and other circumstantial evidence about the duplicity of WR 25, the discovery of X-ray variability from the star almost conclusively identifies the star as a colliding-wind binary. The lack of radial velocity variations implies that WR 25 has a long period of some years. In eccentric systems of this type, X-ray variations can be produced by both changes in emission measure, expected to scale inversely with the binary separation, and changes in the amount of absorbing material along different lines-of-sight through the winds of the companion stars. Other long-period colliding-wind binaries, like WR 140, or suspected long-period CWBs, like η Carinae, show a gradual increase in X-ray flux to a maximum followed

Table 3. *XMM-Newton* EPIC-MOS X-ray history of WR 25.

Date	MJD	rev_ObsID	MOS1 F_X^a	MOS1 N_H (10^{21}cm^{-2})	MOS2 F_X^a	MOS2 N_H (10^{21}cm^{-2})
2000-07-26	51751	0115_0112580601	1.285 ± 0.018	0.41 ± 0.08	1.203 ± 0.017	0.03 ± 0.08
2000-07-27	51752	0116_0112580701	1.325 ± 0.032	0.69 ± 0.15	1.273 ± 0.033	0.16 ± 0.15
			1.294 ± 0.016	0.48 ± 0.07	1.218 ± 0.015	0.06 ± 0.07
2001-06-25	52085	0283_0112560101	1.017 ± 0.020	0.71 ± 0.12	0.974 ± 0.019	0.00 ± 0.22
2001-06-28	52088	0284_0112560201	0.985 ± 0.012	0.53 ± 0.07	1.003 ± 0.012	0.20 ± 0.07
2001-06-30	52090	0285_0112560301	1.013 ± 0.012	0.75 ± 0.07	1.009 ± 0.012	0.22 ± 0.07
			1.000 ± 0.008	0.64 ± 0.05	1.000 ± 0.008	0.17 ± 0.05
2003-01-25	52664	0573_0145740101	1.509 ± 0.047	2.01 ± 0.21	1.442 ± 0.046	1.65 ± 0.22
2003-01-27	52666	0574_0145740201	1.363 ± 0.043	1.37 ± 0.20	1.335 ± 0.043	1.10 ± 0.21
2003-01-27	52666	0574_0145740301	1.401 ± 0.044	1.59 ± 0.20	1.425 ± 0.046	1.35 ± 0.21
2003-01-29	52668	0575_0145740401	1.273 ± 0.037	1.11 ± 0.18	1.414 ± 0.041	1.48 ± 0.19
2003-01-29	52668	0575_0145740501	1.330 ± 0.041	1.09 ± 0.19	1.305 ± 0.043	1.13 ± 0.21
			1.368 ± 0.019	1.41 ± 0.09	1.384 ± 0.020	1.34 ± 0.09
2003-06-08	52798	0640_0160160101	1.385 ± 0.018^g	0.20 ± 0.08	1.341 ± 0.012^g	0.00 ± 0.04
2003-06-19	52809	0643_0160160901	0.914 ± 0.027^g	0.05 ± 0.17	1.026 ± 0.010^g	0.00 ± 0.03
2003-07-22	52842	0662_0145780101	2.912 ± 0.063	4.21 ± 0.17	2.453 ± 0.049	3.30 ± 0.15
2003-08-02	52853	0668_0160560101	1.779 ± 0.034	4.82 ± 0.16	1.696 ± 0.031	4.56 ± 0.15
2003-08-09	52860	0671_0160560201	1.673 ± 0.037	3.62 ± 0.17	1.682 ± 0.035	3.23 ± 0.16
2003-08-18	52869	0676_0160560301	1.406 ± 0.028	2.02 ± 0.14	1.345 ± 0.024	1.56 ± 0.11

[a] Ratio of the intersellar and circumstellar absorption-corrected 0.3-10. keV X-ray flux or luminosity to its 2001-06 minimum reference value.
[g] Affected by a MOS chip gap.
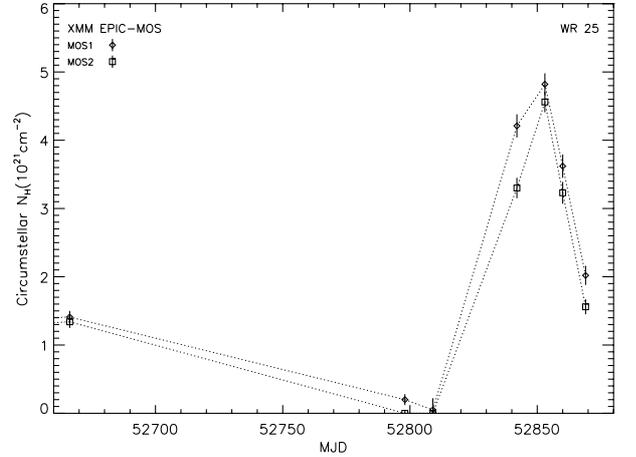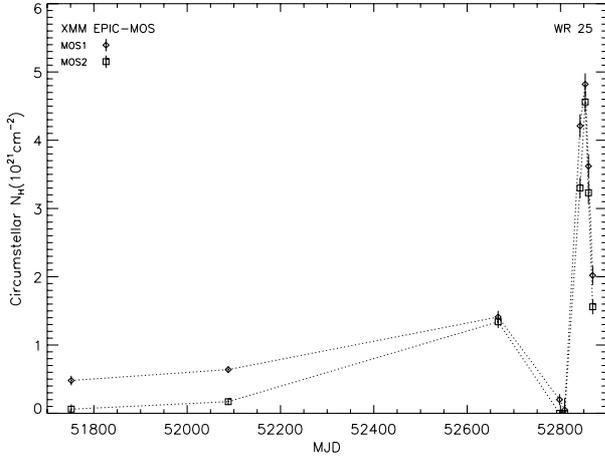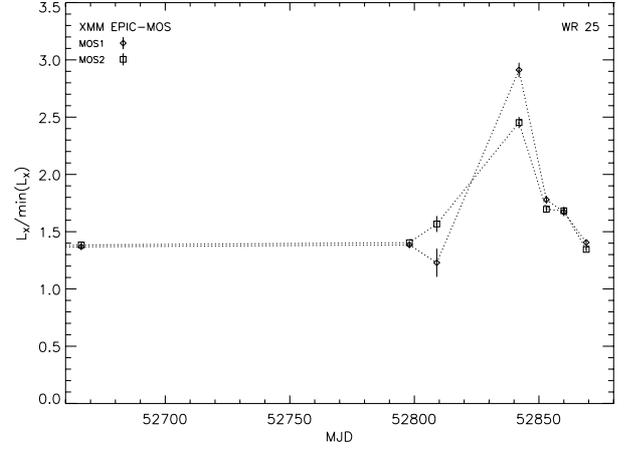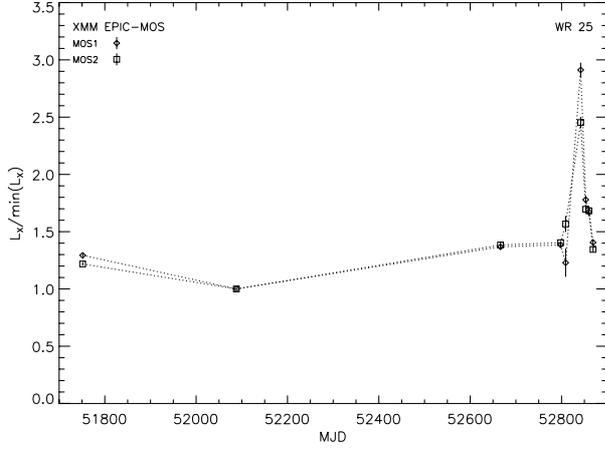
Fig. 2. The X-ray flux and absorption of WR 25 observed by *XMM-Newton* between 2000-07-26 and 2003-08-18.

Fig. 3. Details of the X-ray flux and absorption of WR 25 observed by *XMM-Newton* during 2003.

by a rapid decline associated, although not exactly coincident, with increasing column densities. Although the X-ray light curve of WR 25 has been sampled sparsely, several details support the proposal that the system is also an eccentric binary and give constraints on the orbital geometry:

- the maximum luminosity of 2003-07-22 marked the observation closest to periastron;
- the maximum luminosity ratio implies an eccentricity greater than about 0.5;
- the decrease of 20–30% in luminosity between 2000 July and 2001 June implies apastron occured in 2001, showing that the binary period is about 4 years;
- the maximum absorption observed 11 days after maximum luminosity marked superior conjunction of the more dense wind, presumably of the WR star;
- the low absorption of 2003 June a month or so before periastron marked quadrature;
- the intermediate absorption observed in 2003 January marked superior conjunction of the less dense wind, presumably of the O star;

The strongest X-ray variations of WR 25 have been confined to about 50 days of a supposed orbital period of perhaps 1500 days, giving a chance of only about 1 in 30 that a random observation falls sufficiently near periastron for variability to be detected. In retrospect, then, it is hardly surprising that none of previous observations made with a variety of X-ray instruments since WR 25's discovery in 1978 as a bright X-ray source have been successful in this respect. WR 25's X-ray spectrum shows obvious similarities to that of WR 140 described by Pollock et al. (2005), although it is a bit cooler. As pointed out by Raassen et al. (2003), lines are present in WR 25 from ionization stages of iron from Fe XVII at 15.015 Å to Fe XXV at 1.850 Å, and there may even be a weak feature in Fig. 1 of

Fe XXVI in the spectrum nearest periastron. In WR 140 the variety of lines testifies to a plasma that is out of equilibrium (Pollock et al. 2005). The same is likely to apply to WR 25.

It is an interesting coincidence that a periastron passage of WR 25 seems to have occurred at the height of the campaign to cover the deep X-ray minimum of η Carinae during its own periastron passage. This raises the possibility that some of the flux variability during η Carinae's 2003 minimum detected by *RXTE* (Corcoran 2005) might have been due to WR 25. However it is a possibility that, disappointingly, we have been able to exclude: folding the best-fit *XMM* models through the *RXTE* response shows that, even at its maximum, WR 25 was too weak to account for more than a few percent of the *RXTE* count rate.

On the basis of the arguments given above, the next periastron passage of WR 25 is expected in 2007, giving plenty of opportunity for the organization of a dedicated X-ray observing campaign.

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