Long-term X-ray variation of the colliding wind Wolf-Rayet binary WR 125

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ABSTRACT
WR 125 is considered as a Colliding Wind Wolf-rayet Binary (CWWB), from which the most recent infrared flux increase was reported between 1990 and 1993. We observed the object four times from November 2016 to May 2017 with Swift and XMM-Newton, and carried out a precise X-ray spectral study for the first time. There were hardly any changes of the fluxes and spectral shapes for half a year, and the absorption-corrected luminosity was $3.0 \times 10^{33} \text{ erg s}^{-1}$ in the 0.5–10.0 keV range at a distance of 4.1 kpc. The hydrogen column density was higher than that expected from the interstellar absorption, thus the X-ray spectra were probably absorbed by the WR wind. The energy spectrum was successfully modeled by a collisional equilibrium plasma emission, where both the plasma and the absorbing wind have unusual elemental abundances particular to the WR stars. In 1981, the Einstein satellite clearly detected X-rays from WR 125, whereas the ROSAT satellite hardly detected X-rays in 1991, when the binary was probably around the periastron passage. We discuss possible causes for the unexpectedly low soft X-ray flux near the periastron.

Key words: stars: Wolf-Rayet — X-rays: individual: WR 125 — binaries: spectroscopic

1 INTRODUCTION

Most of the Wolf-Rayet (WR) stars, massive stars with significant mass-loss, are known to be binaries (Rosslowe & Crowther 2015). In particular, those WR binaries which produce hot plasma from their stellar wind collision are called Colliding Wind Wolf-rayet Binaries (CWWBs). The shocked plasma has a temperature of $10^7$–$10^8$ K and high absorption columns of $10^{22}$–$10^{23}$ H cm$^{-2}$ (Schild et al. 2004). The X-ray luminosity is highly dependent on binary separations, mass-loss rates, and wind velocities (Stevens et al. 1992; Usov 1992). The X-ray energy spectra significantly vary with the binary orbital phase, which enable us to study orbital dependence of the plasma parameters and amount of the circumstellar absorption through spectral analysis. In this manner, we are able to constrain the wind acceleration and the mass-loss rate from the WR star. We have already applied this methodology to the CWWBs WR 140 (Sugawara et al. 2015) and WR 19 (Sugawara et al. 2017), which are relatively bright with known orbital parameters. We measured variations of the circumstellar absorptions on the orbital phases, and successfully constrained the mass-loss rates from these WR stars (Sugawara et al. 2015, 2017).

WR 125 is considered as a CWWB, consisting of a WC7 type WR star and an O9 III companion star (Williams et al. 1994). The orbital period is unknown, while it is reported that the infrared flux started to increase in 1990 July and reached the maximum during 1992 and 1993 (Williams et al. 1994). In general, infrared brightening in the long-period CWWBs is thought to be caused by dust formation near the periastron passage in their eccentric binary orbits (Williams et al. 1987, 2012).

In 1981, the X-ray observatory Einstein detected X-rays from WR 125 for the first time (Pollock 1987). The absorption-corrected luminosity was $(1.4 \pm 0.4) \times 10^{33} \text{ erg s}^{-1}$ in the 0.2–4.0 keV band at an assumed distance of 1.9 kpc. As discussed in Pollock et al. (1981), the log-likelihood detection statistic $\lambda$ gives a scale of the significant detection. In the case of Einstein IPC, $\lambda$ being greater than 3 is considered to be a significant detection. Since Pollock (1987) showed that $\lambda$ of WR 125 was 39.1, the detection was significant. Later, Pollock et al. (1995) claimed a marginal detection with ROSAT in 1991, where $\lambda$ was 5.8; this detection...
was not significant because $ROSAT$ usually takes $\lambda > 10$ as the detection threshold.

In this paper, we present new $Swift$ and $XMM-Newton$ monitoring observations of WR 125, and investigate the long-term X-ray variation. In section 2 we introduce the observation and data reduction, and in section 3 we present data analysis and results. We discuss long-term X-ray variation of WR 125 using all the available X-ray observational results in section 4.

## 2 OBSERVATIONS AND DATA REDUCTION

Table 1 gives the observation log and the observed count rates. We proposed a Target of Opportunity (ToO) observation of WR 125 with *Neil Gehrels Swift Observatory* (Gehrels et al. 2004), and three pointings were made from 2016 November 28 to 2017 March 16 for a total exposure of about 12 ksec. The X-ray Telescope (XRT; Burrows et al. 2005) was operated in the Photon-Counting mode. We processed the XRT data through the *Swift*-XRT data product generator 1 (Evans et al. 2007, 2009). We produced the XRT light curves, images and spectra by using the *Swift*-XRT data product generator (Evans et al. 2007, 2009).

Having confirmed significant detection by *Swift*, we proposed a more detailed observation with $XMM-Newton$ (Jansen et al. 2001), and the observation was carried out on 2017 May 11. The European Photon Imaging Camera (EPIC) is sensitive in the 0.2 to 12.0 keV energy range (Turner et al. 2001; Strüder et al. 2001). The data were reduced with SAS version 15.0.0 to obtain the filtered event files for EPIC-MOS1, 2 and pn in 0.3–10.0 keV.

Good time intervals were selected by removing the intervals dominated by flaring particle background when the single event (PATTERN = 0) count rate in the >10 keV band was larger than 0.35 counts s$^{-1}$ and that in the 10–12 keV band larger than 0.4 counts s$^{-1}$ for EPIC-MOS and EPIC-pn data, respectively. We used a circular regions of 22' radius from the same CCD for extracting source and background events. Following the SAS Data Analysis Threads 2, we obtained light curves and spectra. In the following analysis, we used HEASOFT version 6.22.1 and XSPEC version 12.9.1p.

## 3 DATA ANALYSIS & RESULTS

In the *Swift* of ToO observations, we detected a source at (19h 28m 15.6s, +19° 33' 20.9'') with a 90% radial error of 2.7''. The most precise coordinate of WR 125 is (19h 28m 15.61s, +19° 33' 21.53'') by Gaia Collaboration et al. (2018).

thus the detected object is certainly WR 125. Count rates of three *Swift* observations were almost the same (Table 1). We used XSPEC to analyze X-ray spectra. We made three energy spectra corresponding to three *Swift* observations. For $XMM-Newton$, we made MOS1, MOS2 and pn energy spectra, separately. We grouped three *Swift* spectra every 10 counts per bin and three $XMM-Newton$ spectra (MOS1, MOS2, pn) every 15 counts per bin.

We set the solar abundance by Wilms et al. (2000), and fitted the spectra using a simple model ($TBabs*apec$), where an emission spectrum from collisionally-ionized diffuse gas is affected by the interstellar absorption (Smith et al. 2001). First, we fitted the six spectra separately, and found that there were hardly spectral variations. Consequently, we fitted the six spectra simultaneously. The left-hand side of Table 2 shows the best-fit parameters using the simple model ($TBabs*apec$).

Now we estimate $N_H$ of the interstellar absorption from optical extinction. According to a catalogue of Galactic WR stars (van der Hucht 2001), $A_v$ is 6.68 mag for WR 125. Consequently, $N_H$ was estimated as $0.94 \times 10^{22}$ cm$^{-2}$ using the following equation (Vuong et al. 2003),

$$N_H = 1.41 \times A_v \times 10^{21} \text{ cm}^{-2}.$$

Meanwhile, our best-fit column density was $1.59 \times 10^{22}$ cm$^{-2}$. Therefore, we suppose that X-rays were further absorbed by the WR wind.

Next, we introduced another absorption model (varabs), in which elemental abundance is variable, in order to take the additional circumstellar absorption into account, fixing $N_H$ of $TBabs$ at the expected interstellar value ($0.94 \times 10^{22}$ cm$^{-2}$). We also changed apec to vvapec in order to specify abundances of the collisional equilibrium plasma and set $H$ abundance to zero. We took the C, O and Ne abundances of WR 90, which is another WC7-type WR single star and fixed other chemical abundances to the unknown $Fe$ abundance. Since hydrogen is depleted, we specified the C, O and Ne abundances relative to He, as (i.e. (C/He),/(C/He)$_0$ = 101.7, (O/He)/(O/He)$_0$ = 5.98 and (Ne/He)/(Ne/He)$_0$ = 3.81; Dessart et al. 2000). Abundances of H and N were set to zero, which is expected for WR 125 being a WC-type WR star, and the abundances of the emission ($vvapec$) and absorption (varabs) components were made equal. We fitted the six spectra simultaneously, allowing only the He abundance of varabs and the Fe abundance and $kT$ of vvapec to be free parameters.

The right-hand side of Table 2 shows the best-fit parameters using the more sophisticated model ($TBabs*varabs*vvapec$). $\chi^2$/dof was 187/134(= 1.40), slightly better than that of the simple model. According to Gagné et al. (2012), absorption-corrected luminosities and temperatures of CWWBs range from $10^{31}$ to $10^{35}$ erg s$^{-1}$ and from 1 to 4 keV. The best-fit luminosity and plasma temperature of WR 125 were found within these ranges. The energy spectra and the best-fit models are shown in Figure 1.

## 4 DISCUSSION

We detected persistent X-ray emission from the Colliding Wind Wolf-rayet Binary WR 125 with *Swift* and $XMM$-

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1. http://www.swift.ac.uk/user_objects/
2. https://www.cosmos.esa.int/web/zmm-newton/sas-thread-pn-spectrum
3. https://www.cosmos.esa.int/web/zmm-newton/sas-thread-timing
https://www.cosmos.esa.int/web/zmm-newton/sas-thread-epic-filterbackground
https://www.cosmos.esa.int/web/zmm-newton/sas-thread-mos-spectrum
https://www.cosmos.esa.int/web/zmm-newton/sas-thread-pn-spectrum
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Table 1. Observation logs and the count rates with Swift and XMM-Newton

| Satellite/Detector | Obs. mode | Obs. ID | Start time [UT] | Exposure time (ks) | C 0.3–1.5keV$^a$ (10$^{-2}$ counts s$^{-1}$) | C 1.5–10.0keV$^a$ (10$^{-2}$ counts s$^{-1}$) |
|--------------------|-----------|---------|-----------------|--------------------|-------------------------|-------------------------|
| Swift/XRT          | Photon-Counting | 00034826001 | 2016-11-28T01:50 | 4.8 | 0.9±0.25 | 1.5±0.3 |
| Swift/XRT          | Photon-Counting | 00034826002 | 2016-12-17T13:27 | 4.7 | 0.6±0.20 | 1.7±0.3 |
| Swift/XRT          | Photon-Counting | 00034826003 | 2017-03-16T06:19 | 2.3 | 0.6±0.31 | 1.2±0.4 |
| XMM/EPIC           | Full frame | 0794581101 | 2017-05-11T09:06$^b$ | 21.5 | 5.2±0.5 | 15.5±0.8 |

$^a$ Observed count rates of each energy band. The rate of XMM-Newton is that by EPIC-pn detector.

$^b$ Starting time of EPIC-pn observation.

Figure 1. Spectra of WR 125 and the best-fitting models. The six spectra are fitted simultaneously. In the upper-panel, the solid lines show the best fitting models, which is $\text{TBabs*varabs*vvapec}$.

Neutron in a series of four observations carried out in 2016-2017, following a clear detection with Einstein in 1981 and a marginal detection with ROSAT in 1991. No significant flux/spectral changes were found throughout the first observation in 2016 November to the last one in 2017 May. We suppose that the orbital period may be longer than 24 years, considering that the last reported periastron passage (expected from the near infrared flux increase) was in 1993 (Williams et al. 1994), and there was no flux increase reported since then.

We carried out X-ray spectral analysis in 0.3–10 keV from WR 125 for the first time. From the spectra analysis, we found that the column density was probably increased by WR 125’s stellar wind component, and the plasma parameters (luminosity and temperature) were not so extreme values among WC-type WR binaries (Gagné et al. 2012).

We carefully looked into the archival data of Einstein and ROSAT. Einstein data by Imaging Proportional Counter (IPC) instrument was sensitive in the 0.4 to 4.0 keV energy range. It was obtained in 1981 April 9 (sequence No. 8680), and the count rate was 0.0122(±0.0028) counts s$^{-1}$, which is considered as a significant detection (Pollock 1987; Harris et al. 1996). On 1991 October 28, ROSAT data was taken by Position Sensitive Proportional Counters (PSPC) instrument in 0.1-2.0 energy range for an exposure of 2105 seconds (sequence ID RP500042N00). As a result of scrutinizing the ROSAT data, we conclude that there was no meaningful X-ray detection from WR 125; the WR 125 count rate was less than that of the dimmest point source significantly detected in the field-of-view (5.0 × 10$^{-3}$ counts s$^{-1}$).

With WebPIMMS (ver. 4.9)$^4$, we converted the Einstein count rate into the flux in the 0.5–10.0 keV en-

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$^4$ https://heasarc.gsfc.nasa.gov/cgi-bin/toolsw3pimms/w3pimms.pl
In any case, even though the orbit of WR 125 has a high inclination, eclipse may not be expected in X-ray band. Actually, a total X-ray eclipse was never reported up to now in any CWWBs; for example, WR 20a does not show any eclipses (Nazé et al. 2008) and V444 Cyg shows only a partial one (e.g. Lomax et al. 2015) despite of their high inclination angles. Therefore, the first possibility may be low.

Second, soft X-ray from the colliding wind region may have been heavily absorbed by the WR star wind, while intrinsic X-ray luminosity of WR 125 is not significantly variable. While ROSAT/PSPC was sensitive to X-rays only between 0.1 and 2.0 keV, Swift and XMM-Newton are respectively sensitive in the 0.3 to 10.0 keV and 0.3 to 12.0 keV energy ranges. Therefore, it might be possible that ROSAT was not able to detect the soft X-rays if significantly absorbed by the WR star wind. When we increased $N_H$ from the best-fit $1.6 \times 10^{22}$ cm$^{-2}$ to $1.0 \times 10^{23}$ cm$^{-2}$ assuming the same intrinsic luminosity and the spectra determined by Swift/XMM, we found it impossible to detect WR 125 using ROSAT/PSPC. However, in fact, there are few observations that CWWB has such a high column density (Rauw et al. 2000; Schild et al. 2004; Sugawara et al. 2015). Then, we examined requirements that WR 125 column density would reach $1.0 \times 10^{23}$ cm$^{-2}$. According to Pollock et al. (2005), column density of a spherically symmetric WR wind at a distance $R$ from the WR star surface along the line of sight can be written as

$$N_H(R, \phi, i) \sim 4.3 \times 10^{23} M_{\odot}^{-1} \mu^{-1} v_8^{-1} (R/R_\odot)^{-1} \times (y/\sin y) \int_R^{\infty} x^{-2} (1 - 1/x)^{-2} dx \text{ cm}^{-2},$$

where $\cos \gamma = \cos \phi \sin i$, mass-loss rate $M_{\odot} = 10^{-6} M_{\odot}$ yr$^{-1}$, wind velocity $v_8 = 1000$ km s$^{-1}$, $\phi$ and $i$ are the orbital azimuthal and inclination angle, and $R_\odot$ is the WR stellar radius. In the case of WR 125, we used typical physical conditions in the WC type WR wind $M = 2 \times 10^{-5} M_{\odot}$ yr$^{-1}$, $v_\infty = 2000$ km s$^{-1}$ (Dessart et al. 2000), $R_\odot = 6.0 R_\odot$ (Koesterke & Hamann 1995), and mean atomic weight for nucleons $\mu = 6$, which was estimated by the G, C, O and Ne abundances. Since we cannot constrain other orbital parameters, we assumed $\phi = 180^\circ$, which gives the maximum column density. We examined two cases for different location of the X-ray emitting plasma, (1) $R = 0.5 R_\odot$ and (2) $R = 1.0 R_\odot$. As a result, we found that when only inclination $i$ is more than $78^\circ$ in situation (1) or $i$ is more than $84^\circ$ in situation (2), the column density reaches $1.0 \times 10^{23}$ cm$^{-2}$. Therefore, it is possible to attain $N_H = 1.0 \times 10^{23}$ cm$^{-2}$ only under the very limited circumstances with particular binary separation, orbital inclination angle and azimuthal angle.

Third, size of the X-ray emitting (colliding wind) might be reduced near the periastron under some circumstantial conditions. For example, one possibility is lack of the enough acceleration in the O-star wind. In general, wind momentum of the WR star overwhelms that of the O-star, so that the colliding region almost reaches the O-star surface. Consequently, near the periastron, O-star wind may not have sufficient space to reach its terminal velocity before entering the shock region, and collides with the WR star wind before reaching the terminal velocity; this will lead to reduction in the wind momentum fluxes (e.g. Luo et al. 1990; Stevens et al. 1992; Myasnikov & Zhekov 1993). Other possi-

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### Table 2. The best-fitting parameter of spectral fitting

| Parameter             | TBabs+apec | TBabs+varabs+vapec |
|-----------------------|------------|--------------------|
| $N_H$ (10$^{22}$ cm$^{-2}$) | 1.59±0.10  | 0.94 (fixed)       |
| Circumstellar absorption | ---       | 0.16±0.06          |
| Thin thermal plasma   | ---        | 0.16±0.06          |
| $kT$ (keV)            | 2.33±0.16  | 2.1$^{+0.3}_{-0.2}$|
| (Fe/He)/(Fe/He)$_0$   | ---        | 0.29±0.33          |
| E.M. (10$^{58}$ cm$^{-3}$) | 2.7$^{+2.1}_{-1.0}$ | 1.3$^{+1.0}_{-0.2}$|
| $F_1$ (10$^{-13}$ erg cm$^{-2}$s$^{-1}$) | 7.9$^{+1.1}_{-0.3}$ | 7.3±0.2          |
| $L_\nu$ (10$^{24}$ erg s$^{-1}$ cm$^{-2}$) | 3.5$^{+1.2}_{-0.6}$ | 3.0$^{+0.6}_{-0.4}$|

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### Table 3. Observed flux with Einstein, ROSAT, Swift and XMM-Newton

| Obs. date | Satellite/Detector | Observed flux $a$ ($10^{31}$ erg s$^{-1}$ cm$^{-2}$) |
|-----------|--------------------|---------------------------------------------------|
| 1981.04   | Einstein/IPC      | 7.3±1.7                                           |
| 1991.10   | ROSAT/PSPC        | < 4.2                                             |
| 2016.11–2017.05 | Swift/XTK-XMM/EPIC | 7.9$^{+1.2}_{-1.0}$                                |

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$a$ We converted each count rate to the flux in the 0.5–10.0 keV range using model APEC with WebPIMMS.
abilities are radiative inhibition and radiative braking, which can be obstacles of wind-acceleration (e.g. Stevens & Pollock 1994, Gayley et al. 1997). The radiative inhibition is a process where the acceleration of each wind is reduced by the radiation from its companion star. The radiative braking describes a scenario in which the WR wind is slowed after reaching a large velocity. These mechanisms require small binary separations; for example, the smallest separation in V444 Cyg is 35.97 R⊙ (0.33AU) (Eri¸s & Ekmek¸ci 2011). If binary separation of WR 125 is sufficiently small, these processes can slow down the wind velocity significantly, and reduce size of the colliding wind region, decreasing the X-ray flux. With a hydrodynamical simulation, it is suggested that X-ray flux could even disappear due to a full disruption of the colliding wind region (e.g. Parkin & Gosset 2011). In conclusion, we suppose that the significant low soft X-ray flux in 1991 was likely to be a consequence of mixture of the second and third possibilities.

In summary, we have confirmed a long-term X-ray variation from WR 125 over 36 years for the first time using four X-ray satellites. Still, WR 125 has many unknown aspects, even its orbital period. If we can determine the orbital parameters precisely in future, we may understand reasons of the significantly low luminosity in 1991. According to Williams et al. (1992), extinction of the non-thermal radio emission is expected to increase by the dense WR wind material just before the dust formation. Thus, we suppose that significant change of the radio flux may become a sign of the periastron passage. We propose multi-band monitoring observations of WR 125 including radio, in order to determine the orbital parameters and clarify the wind parameters.

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