Redshifted emission lines and radiative recombination continuum from the Wolf-Rayet binary θ Muscae: evidence for a triplet system?

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ABSTRACT

We present XMM-Newton observations of the WC binary θ Muscae (WR 48), the second brightest Wolf-Rayet binary in optical wavelengths. The system consists of a short-period (19.1375 days) WC5/WC6 + O6/O7V binary and possibly has an additional O supergiant companion (O9.5/B0Iab) which is optically identified at a separation of ~46 mas. Strong emission lines from highly ionized ions of C, O, Ne, Mg, Si, S, Ar, Ca and Fe are detected. The spectra are fitted by a multi-temperature thin-thermal plasma model with an interstellar absorption \( N_H \approx 2-3 \times 10^{21} \text{ cm}^{-2} \). Lack of nitrogen line indicates that the abundance of carbon is at least an order of magnitude larger than that of nitrogen. A Doppler shift of ~630 km s\(^{-1}\) is detected for the O VIII line, while similar shifts are obtained from the other lines. The reddening strongly suggests that the emission lines originated from the wind-wind shock zone, where the average velocity is ~600 km s\(^{-1}\). The red-shift motion is inconsistent with a scenario in which the X-rays originate from the wind-wind collision zone in the short-period binary, and would be evidence supporting the widely separated O supergiant as a companion. This may make up the collision zone be lying behind the short-period binary. In addition to the emission lines, we also detected the RRC (radiative recombination continuum) structure from carbon around 0.49 keV. This implies the existence of additional cooler plasma.

Key words. X-rays: stars – stars: Wolf-Rayet – binaries: spectroscopic – stars: winds, outflows – stars: individual: HD113904

1. Introduction

Wolf-Rayet (WR) stars are the evolved descendants of massive O stars, whose optical spectra are characterized by strong helium, carbon, nitrogen and oxygen emission lines. These arise from hot stellar winds with typical terminal velocities of ~1000–3000 km s\(^{-1}\) and mass loss rates of the order of \( 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \). The visible spectra of WN stars and WC stars are dominated by nitrogen and carbon emission lines, respectively.

Pollock (1987) used the Einstein observatory, which covered the 0.2–4.0 keV energy band, to discover that several WR+O binary systems tend to be brighter in X-rays than single WR stars. This was confirmed by a ROSAT survey (Pollock 1995). The strong hard X-ray emission from WR binaries can be interpreted to arise from a collision of stellar winds from the WR star and that of the O star (e.g., Koyama et al. 1990). Recently, Schild et al. (2004) discovered the RRC (radiative recombination continuum) structure of carbon in the spectrum of the WC+O binary θ Velorum, which shows the existence of another cooler component.

θ Muscae (WR 48, HD 113904) is known to be a complex system. The history of observations and interpretations are summarized in Hill et al. (2002). Based on its spectrum, this system is known to be a binary or a line-of-sight double, and is the second brightest WR binary in optical wavelengths (Moffat & Seggewiss 1977). Moffat & Seggewiss (1977) showed that the WR star emission lines exhibited radial velocity variations with a period of 18.341 d but the absorption lines from the late O supergiant (O9.5/B0Iab; van der Hucht 2001) seemed to be stationary. This leads to two possible interpretations; one is an extremely large mass ratio, and the other is the hypothesis that the WR component shares its 18.341-d orbit with a third hidden star, and then the O supergiant star is either in a much wider, slower orbit with the other two or is a line-of-sight coincidence. The linear polarization data obtained by St.-Louis et al. (1987) confirmed that the O supergiant does not participate in the short-period orbit. Hartkopf et al. (1999) resolved the O supergiant to be 46 ± 9 mas away from the short-period binary using speckle interferometry.

Non-thermal emission is detected in radio wavelengths from this system (Leitherer et al. 1997; Chapman et al. 1999). Dougherty & Williams (2000) discussed, in their study of 23 WR stars, the possibility that the non-thermal emission arises not from a wind-wind collision zone in the short-period binary but from that between the supergiant and the short-period binary. The discussion is based on their obtained correlation between orbital period and radio spectral index in WR binaries. The data point for an orbital period of about 18 days and the spectral index of θ Mus (~−0.4) is offset from the correlation, while if the orbital period is that estimated for the wide binary (at least 130 yr), the data point lies on the correlation. The correlation would be reasonable if we think that detection of radio non-thermal emission is difficult in short-period systems because the wind-collision zone is deep inside the opaque region of the stellar wind from the WR star.

In X-ray wavelengths, the Einstein observatory detected strong X-ray emission with an observed luminosity of...
2.0 \times 10^{33} \text{ erg s}^{-1} in the 0.2–4.0 keV band (Pollock 1987), and
the ROSAT observatory detected emission at 1.4 \times 10^{33} \text{ erg s}^{-1}
in the 0.2–2.4 keV band (Pollock et al. 1995). However, despite
the past observations, the origin of the X-ray emission is not
well understood. The large effective area and the excellent spec-
tral resolution over a broad band of XMM-Newton allows us to
measure the detailed structure of atomic lines. We present here
XMM-Newton observations of \theta Muscae.

We adopt the short orbital period of 19.1375 days derived most
recently (Hill et al. 2002) and assume the distance to be 2.27 kpc (van der Hucht 2001).

2. Observations and data reduction

XMM-Newton was launched in 1999 December from French
Guyana. The observatory consists of three X-ray telescopes and five X-ray instruments: three European Photon Imaging Cameras
(EPIC: PN and two identical MOS CCDs), which have high sen-
sitivity up to 10 keV, and two identical reflection grating spec-
trometers (RGS), which have excellent energy resolution in the
soft X-ray band (0.3–2.5 keV).

\theta Muscae was observed by XMM-Newton between 2004 July
20 11:21:43 UT and 2004 July 21 20:36:35 UT, giving 119 692 s
of observation time. For the orbital solution of the WC star, we
adopted that obtained in Hill et al. (2002):

\[ \text{HJD (at } \phi = 0) = 2 451 377.51 + 19.1375E \]  

where the eccentricity is zero and \( E \) is the number of orbits since
the passage on HJD 2 451 377.51. Phase 0.0 is defined as the
time when the WR star occults its companion. Our observations
cover the orbital phase from 0.596 to 0.668, during which the O
star was located in front of the WR star. Each phase has errors
\( \pm 0.024 \) and \( \pm 0.012 \). The former corresponds to the uncertainty
of the initial epoch, while the latter to the offset of the orbital
period.

All the data were analyzed with the 6.0.0 version of the
XMM Science Analysis System. The pipeline processing tasks
EMCHAIN, EPCHAIN and RGSPROC were executed using the
available calibration files, and data were filtered via EVSELECT
to select good event patterns. We use all valid event patterns
(PATTERN 0–12) for the MOS cameras but use valid PN events
with single and double events (PATTERN 0–4). In the energy
band below 1.8 keV, the emission-line peaks of the EPIC spec-
trum are not consistent with those of the high resolution RGS
band below 1.8 keV, the emission-line peaks of the EPIC spec-
trum. The solid line in Fig. 3 indicates the model for NEI.

3. Results

Figure 1 shows the X-ray image taken with MOS 1. \theta Muscae
is the dominant X-ray source in the MOS field of view. We
derived light curves in the soft band (0.3–2 keV) and hard
band (2–10 keV). The average count rates are 0.13 and 3.1 \times
10^{-2} counts s^{-1} respectively. We detected no significant variabil-
ity.

We obtained X-ray spectra from the RGS and EPIC (PN,
MOS 1 and 2) data. The broad band spectra are shown in Fig. 2
and the enlarged spectrum for the RGS data is shown on a linear
scale in Fig. 3. Emission lines from helium-like and hydrogen-
like ions of various elements (e.g. carbon, oxygen and neon)
were detected. Since a single temperature plasma cannot repro-
duce these emission lines simultaneously, we executed simul-
taneous fitting of the three datasets (RGS, MOS and PN) with
a multi-temperature plasma model with an absorption model
(wabs) using XSPEC ver. 12. The multi-temperature model we
adopted first is the simple collisional ionization equilibrium
(CIE) model (cvmkl), where the emission measures follow a
power-law in temperature, i.e., the emission measure from the
electron temperature \( kT \) is proportional to \( (kT/kT_{\text{max}})^\alpha \) with an
index \( \alpha \) (Singh et al. 1996). The secondary adopted model is
the two temperature plane-parallel shock model (2T vphshock),
which does account for non-equilibrium ionization (NEI).

In both fittings, line broadening and shifts were seen. Then
we fitted the high-intensity O VIII line around 0.65 keV with
a single Gaussian model to investigate the width. The obtained
broadening is \( 1.3^{+0.3}_{-0.2} \text{ eV in 1 } \sigma \), which corresponds to a velocity
of 1190–1720 km s^{-1} in FWHM. With this value, we adopted a
Gaussian smoothing (gssmooth) of the multi-temperature mod-
els, fixing the ratio \( \sigma / E \sim 1.3 \text{ eV / 0.65 keV and allowing the}
redshift to be a free parameter.

The above fittings reasonably reproduced the overall spec-
trum. The solid line in Fig. 3 indicates the model for NEI.
However, residuals around 0.49 keV were left (see Fig. 3) in
the RGS band. The excess is identified with the RRC structure of C
VI. We then added a recombination edge (edge) model to the
above models, and re-fitted the datasets. The results are shown in
Table 1. The better fit is obtained with the NEI model. The
solid lines in Fig. 2 show the best-fit NEI model.

The best-fit NEI model, and also the CIE model, showed that
carbon is overabundant by at least an order of magnitude com-
pared to nitrogen in \theta Muscae (see Table 1), indicating that the
plasma originates from Wolf-Rayet (WC) stellar winds. The best
fit model has an absorption-corrected X-ray luminosity \( L_X \) of
3.1 \times 10^{33} \text{ erg s}^{-1} (0.3–8.0 keV band) and \( \log L_X / L_{\text{bol}} \) of \(-5.56 \)
\( \log L_{\text{bol}} / L_{\odot} = 5.47 \) (Nugis & Lammers 2000), which is slightly
larger than the known correlation \( L_X = 10^{-7} L_{\text{bol}} \) for O+O and
WN+O binaries (Berghoefer et al. 1997; Oskinova 2005). The
absorption of 2.4 \times 10^{21} \text{ cm}^{-2} is consistent, within a factor of
1.5, to the interstellar absorption 1.6 \times 10^{21} \text{ cm}^{-2} derived from
\( N_H = 0.93 \text{ mag and the correlation in Predehl & Schmitt (1995).}
The red-shift is \( 2.2 \times 10^{-3} \), which corresponds to 650 km s^{-1}.
Independently, we further fitted each emission line with a single
Gaussian model, and obtained a similar red-shift \( \sim 2 \times 10^{-3} \) (see
Table 2).
The RRC structure of carbon we detected is the second example among WR massive binaries, with the first case being the spectrum of \( \gamma^2 \) Velorum (Schild et al. 2004). The fitting of the RRC structure in \( \theta \) Muscae needed a plasma temperature of 4.7 (3.3–6.2) eV, which is similar to but about 1.3 times higher than that of \( \gamma^2 \) Velorum. The cool plasma component which makes up the RRC structures may be common in WR binaries. Interestingly, the best-fit value of the RRC indicated a red-shift of \( 2.5 \times 10^{-3} \), which is similar to that obtained in lines, although the error is large.

We further analyzed the emission lines around 0.56 keV and 0.9 keV, which are the helium-like triplets of oxygen and neon, respectively. The intensity ratio of forbidden lines (HE6) to resonance lines (HE4) indicates that the lines originate from a thin-thermal plasma whose density is less than \( 10^{11} \) cm\(^{-3} \) (Porquet et al. 2001), which favors the NEI model.

### 4. Discussion

The X-ray spectra from the massive binaries WR140 (Pollock et al. 2005), \( \gamma^2 \) Velorum (Schild et al. 2004), WR25 (Raassen et al. 2003), V444 Cygnus (Maeda et al. 1999) are all strong in hard X-rays with high temperature components of several keV. The hot component of \( \theta \) Muscae also strongly suggests that X-rays originate from wind-wind collisions. The absorption-corrected X-ray luminosity of \( \theta \) Muscae is \( 3.1 \times 10^{33} \) erg s\(^{-1} \), which is similar to those of the other massive binaries (WR140, \( 2.0 \times 10^{34} \) erg s\(^{-1} \); \( \gamma^2 \) Velorum, \( 8.4 \times 10^{33} \) erg s\(^{-1} \); WR25, \( 1.3 \times 10^{34} \) erg s\(^{-1} \); V444 Cygnus, \( 1.4 \times 10^{33} \) erg s\(^{-1} \)).

High dispersion spectra of the massive binaries have been obtained for WR140 (Pollock et al. 2005), \( \gamma^2 \) Velorum (Henley et al. 2005), and \( \theta \) Muscae (this study). Significant Doppler shifts are only reported by Pollock et al. (2005) for WR140 at the pre-periastron phase when one side of the bow-shock zone approaches toward the line of sight. They detected a significant blue shift of 600 km s\(^{-1} \). No detection of the Doppler shift at post-periastron was interpreted to result from the bow-shock zone being aligned perpendicular to the line of sight. No detection from \( \gamma^2 \) Velorum is also attributed to a similar situation or to a wide open angle of the bow-shock zone.

Our detection of the Doppler-shift in the emission lines is the second example among the massive binaries. The red-shift in the emission lines strongly suggests that one side of the bow-shock zone is receding along the line of sight, indicating that the primary WR star is in front. However, this geometry is inconsistent with the orbital solution for the short-period binary in Hill et al. (2002) in which the O star is likely in front. Instead, if the O supergiant separated by 46 mas from the short-period binary is a companion of this system and located behind the primary WR star, as shown in Fig. 4, the wind-wind collision zone could be receding.
This idea that the wind-wind collision zone is between the short-period binary and the O supergiant is the same as that of Dougherty & Williams (2000). By assuming that the distance to θ Muscae is 2.27 kpc, the projection of 46 mas corresponds to \(~100\) AU. It is well known that X-rays from massive binaries suffer absorption from the WR wind if the WR star is in front (e.g., Maeda et al. 1999). An X-ray emitting region widely extended over 100 AU should avoid the absorption in the θ Muscae system. This interpretation strongly suggests that the astrometric O supergiant is a companion to the system. The wind from the spectroscopic O star companion should be much weaker than that from the optically identified O supergiant.

Another interesting possibility was obtained from the RRC structure. Table 2 shows that the RRC may be red-shifted with a similar velocity to the emission lines. If this is true, the RRC may originate from ions that escape from the bow-shock layer.
through diffusion or convection processes, and exchange electrons in the following less-ionized winds. Follow-up observations with much deeper exposure are necessary to test this idea since we need to restrict the Doppler shift of the RRC structure more tightly.

5. Summary

The XMM-Newton spectra of θ Muscae show He- and H-like emission lines from various elements as well as the RRCs from carbon. The results of our study are as follows:

A. The He-like and H-like emission can be reproduced by a multi-temperature plasma model. A better fit was obtained for the NEI case (vpshock) rather than the collisional equilibrium (cevmkl) model. The high temperature component of the NEI model is as high as $kT \sim 3$ keV. The high temperature component indicates the existence of plasma heating by a wind-wind collision shock.

B. We detected RRC structure which implies the existence of a wind-wind collision shock.

C. The abundance of carbon is at least one order of magnitude higher than that of nitrogen. The over-abundance indicates that the Wolf-Rayet (WC) stellar winds dominate the X-ray emission lines from carbon, oxygen, neon and silicon.

D. The emission lines from carbon, oxygen, neon and silicon and possibly the RRC from carbon show red-shifts of...
Table 2. Doppler shift of emission lines and RRC from the WR binary θ Muscae.

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<th>Ion</th>
<th>C VI</th>
<th>C VI</th>
<th>O VII</th>
<th>O VIII</th>
<th>Ne IX</th>
<th>Ne X</th>
<th>C RRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$(keV)$^a$</td>
<td>0.3675</td>
<td>0.4356</td>
<td>0.5739</td>
<td>0.6536</td>
<td>0.9050</td>
<td>1.0218</td>
<td>0.4900</td>
</tr>
<tr>
<td>$E_{\text{obs}}$(keV)$^a$</td>
<td>0.3668</td>
<td>0.4344</td>
<td>0.5725</td>
<td>0.6522</td>
<td>0.9022</td>
<td>1.0196</td>
<td>0.4892</td>
</tr>
<tr>
<td>Redshift$^d$ ($\times 10^{-3}$) &amp; $1.9^{+0.9}<em>{-0.9}$ &amp; $2.8 \pm 0.6$ &amp; $2.5 \pm 0.5$ &amp; $2.1 \pm 0.3$ &amp; $3.1^{+1.1}</em>{-1.3}$ &amp; $2.2^{+0.8}<em>{-0.9}$ &amp; $1.6^{+1.5}</em>{-2.0}$</td>
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<td>$v$ (km s$^{-1}$) &amp; $560^{+270}<em>{-280}$ &amp; $830^{+170}</em>{-180}$ &amp; $750^{+140}<em>{-150}$ &amp; $630^{+100}</em>{-120}$ &amp; $930^{+220}<em>{-240}$ &amp; $650^{+260}</em>{-280}$ &amp; $490^{+320}_{-410}$</td>
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$^a$ Doppler shifts of the emission lines were measured with a single Gaussian fitting. That of the RRC was picked from the best-fit parameter of the 2T vpshock model in Table 1.

$^b$ Theoretical energy of the line center.

$^c$ The center energy of the observed line.

$^d$ The redshift defined as $(E_0 - E_{\text{obs}})/E_{\text{obs}}.$

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van der Hucht, K. A. 2001, NewAR, 45, 135 (VIIIth WR Catalogue)

~600 km s$^{-1}$ with broadenings of ~1400 km s$^{-1}$ in FWHM. The red-shift would be evidence supporting the widely separated O supergiant as a companion with which the collision zone could be formed, lying behind the short-period binary. The wind from the O star in the short-period binary should be much weaker than that from the O supergiant in the wide binary.