学位論文要旨（博士（理学））

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論文題名：　X-ray studies of emission lines from wind collision shocks
in the massive star binary WR 140 with high resolution spectroscopy
（邦題）：高分解能 X 線分光観測で探る大質量連星系 WR 140 の星風衝突衝撃波の研究
（英文）

Classical Wolf-Rayet (WR) stars are evolved massive stars with initial masses $\geqq 25$ $M_\odot$, exhibiting high luminosities ($>10^5$ $L_\odot$) and powerful stellar winds (terminal velocity $\gtrsim 2000$ km s^{-1}, mass-loss rates $>10^{-5}$ $M_\odot$ yr^{-1}). In massive stellar binaries, particularly colliding wind binaries (CWBs), the collision of these fast winds generates intense X-ray emission with luminosities ranging from 10^{33} to 10^{35} erg s^{-1}. The gas in the shock region is heated to 10^7 - 10^8 K (K). X-ray variability is observed in highly eccentric systems due to changes in orbital separation and line-of-sight (LoS) absorption.

WR 140, the target of this study, is a highly eccentric ($e = 0.90$) WC7pd+O5.5fc binary with an orbital period of 8 years. Its X-ray emission originates from the shock cone formed by the collision of the WR wind ($\dot{M}_{WR} = 2.2 \times 10^{-5}$ $M_\odot$ yr^{-1}) and the O star wind ($\dot{M}_O = 9 \times 10^{-7}$ $M_\odot$ yr^{-1}) (Sugawara et al. 2015). Previous observations with *Suzaku* and *Chandra* have interpreted the X-ray spectrum of WR 140 as consisting of a high-temperature (3.0–3.5 keV) thermal plasma component and low- and medium-temperature components. The high-temperature component originates near the stagnation point of the wind collision region, while the low- and medium-temperature components are attributed to cooled plasma.

Miyamoto et al. (2022) analyzed a series of *XMM-Newton* RGS data sampling a single entire orbit. They found that WR 140 is bright in X-rays below roughly 2 keV while the O star is closer to the observer than the WR star (phases 0.816–0.987). In this phase, they identified strong K-alpha emission lines of Neon (Ne) and Oxygen (O), and L-alpha lines from Iron (Fe). They theoretically calculated the shape of the shock cone, from which they derived the ratio between the LoS velocities and velocity dispersions of emission lines. By comparing these ratios with observations, they successfully identified the Ne and O emission regions on the shock cone for the first time in the world.

Miyamoto et al. (2024) calculated the plasma LoS velocity and its dispersion along the shock cone separately, considering mass and momentum conservation. By comparing these with observations, the centroid positions of Ne and O emission lines were identified with higher accuracy. Furthermore, from the cooling time of the plasma and the plasma

flow velocity, they successfully evaluated the spatial extent of the Ne line-emission region.

Based on these established results and methods, we analyze the observation data of WR 140 obtained by the X-Ray Imaging and Spectroscopic Mission (*XRISM*). Using the X-ray microcalorimeter "Resolve," which has an unprecedentedly high energy resolution of approximately 4.5 eV, we observed WR 140 at the orbital phase 0.983, where the X-ray luminosity of this system peaks. The Resolve spectrum clearly detects He-like and H-like K-alpha lines from Fe, Sulfur (S), and Argon (Ar). Note that these lines are impossible to observe with *XMM-Newton* RGS.

In order to identify the emission regions of these lines from this highly resolved data, we construct a new emission spectrum model based on the geometry of the shock cone and the plasma flow velocity profile. The model spectrum is an ensemble of spectra from the axisymmetric ring region of the shock cone, which is divided into 180 evenly spaced segments in azimuth, emitting spectra with different LoS velocities. In evaluating the spectrum, we first assume that the WR and O star winds completely mix immediately after the collision (single-fluid model).

By examining the results, we discovered that the lower ionization state lines (He-like ions) tend to be emitted closer to the apex of the shock cone (upstream side), while the higher ionization state lines (H-like ions) tend to be emitted downstream for all Fe, S, and Ar. This discovery is important because it indicates that the shock plasma of WR 140 is an ionizing plasma that has not reached ionization equilibrium, whereas it was previously believed that the plasma reaches its maximum temperature at the apex of the shock cone and then cools radiatively.