Wolf-Rayet Binaries and Their Stellar Wind Collision Activity [Postprint]

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Abstract

As massive stars in the late stages of evolution, Wolf-Rayet stars exhibit strong stellar wind mass loss. If a Wolf-Rayet star forms a binary system with another massive star, the stellar winds of the binary components collide to form a wind-collision binary system, producing non-thermal radiation in the wind collision region. Currently, multiple radio sources have been confirmed as Wolf-Rayet binaries, among which WR140, WR146, and WR147 have been observed in detail with radio interferometers, revealing wind-collision activity; additionally, a number of Wolf-Rayet binaries such as WR105 are potential candidates for wind-collision binary systems. Compared with typical interstellar medium environments, the wind collision region has higher material density, radiation flux, and magnetic field strength, making it easier for particles to be energized and produce non-thermal radiation, thus providing a more suitable environment for studying particle acceleration and radiation mechanisms. Furthermore, since the activity of the wind collision region is closely related to binary activity and evolution, studying wind collision regions can also aid in investigating the late-stage evolution of massive stars. However, current research on wind-collision binary systems remains scarce, with only WR140 having a relatively complete physical model established. This article briefly reviews the research progress on Wolf-Rayet binary systems and their wind collision regions, particularly highlighting the major contributions of recent radio interferometric observations to the study of wind-collision systems.

Full Text

Wolf-Rayet Binaries and Their Wind-Colliding Activities

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Abstract

As high-mass stars in the late stages of evolution, Wolf-Rayet (WR) stars exhibit intense stellar wind mass loss. When a WR star forms a binary system with another massive star, their winds collide to create a colliding-wind binary (CWB) system that produces non-thermal radiation in the wind-colliding region (WCR). Several WR binaries have been confirmed as radio sources, with systems such as WR140, WR146, and WR147 having been studied in detail through radio interferometric observations that have revealed wind-collision activity. Additional WR binaries, including WR105, are potential CWB candidates. Compared with typical interstellar medium environments, the WCR features higher matter density, radiation flux, and magnetic field strength, making it more conducive for particle acceleration and non-thermal radiation production—thus providing an ideal laboratory for studying particle energization and radiation mechanisms. Furthermore, because WCR activity is closely linked to binary activity and evolution, investigating these regions also aids in understanding the late-stage evolution of massive stars. However, research on CWB systems remains limited, with only WR140 having a relatively complete physical model established. This article briefly reviews the research progress on WR binary systems and their wind-collision regions, particularly highlighting the major contributions of recent radio interferometric observations of CWB systems.

Keywords: Wolf-Rayet binary; wind-colliding; non-thermal radio emission; radio interferometer observations

1 Introduction

Colliding-wind binaries (CWBs) are binary systems composed of early-type stars whose stellar winds collide to form a wind-colliding region (WCR) where particles can be accelerated to relativistic speeds and produce non-thermal radiation through interaction with magnetic fields in the WCR. In many cases, CWB systems can only be observed through non-thermal radiation from the WCR at radio wavelengths, making non-thermal radio emission a key diagnostic for identifying CWBs [1]. As a laboratory for particle acceleration mechanisms, the WCR provides higher matter density, radiation flux, and magnetic field strength than supernova remnants, facilitating studies of particle energization and radiation processes in interstellar space, while also contributing to investigations of late-stage stellar evolution [2].

CWBs typically form in binary systems with high wind mass-loss rates, such as those containing Wolf-Rayet (WR) stars. WR stars represent a class of massive stars in late evolutionary stages characterized by strong stellar wind mass loss and intense radiation fields. Their winds can transport large quantities of energetic charged particles into space [3]. When a WR star forms a binary with a massive O or B-type companion, wind collision readily occurs, creating a WCR near the contact surface between the winds where charged particles gain energy and produce non-thermal radiation [4], with synchrotron radiation from energized particles in magnetic fields being the most prominent signature [5]. Consequently, observing synchrotron radiation provides the best means for studying WCRs [6].

Current observational research on CWBs remains in its early stages. Among 43 identified CWB candidates, only a small fraction have shown definitive non-thermal radiation from WCRs [6]. Confirmed CWB systems with detected non-thermal radio emission include only a handful such as WR89, WR140, WR146, and WR147, with WR140 being the only system having a complete model analysis [7]. This paper provides a brief overview of the formation mechanisms of WR binary CWBs and recent research progress on CWB systems. Section 2 introduces WR binary stars, Section 3 describes WCR formation mechanisms, Section 4 discusses methods for searching for WCRs, Section 5 presents observational studies of CWB systems and their wind-collision activities using typical systems WR140, WR146, WR147, and the potential CWB system WR105 as examples, and the final section offers concluding remarks.

2 Wolf-Rayet (WR) Stars

WR stars are massive stars in late evolutionary stages that have lost their hydrogen-rich envelopes, first discovered by French astronomers Wolf and Rayet through stellar spectroscopy studies [8]. Massive stars with initial masses greater than 25 $M_{\odot}$ (typically O-type or early B-type stars at solar metallicity during the main sequence [9]) develop strong stellar winds (approximately 10^3 km $\cdot$ s^{-1}) and extremely high mass-loss rates (10^{-6} to 10^{-5} $M_{\odot} \cdot \mathrm{yr}^{-1}$) in their late evolutionary stages. Before supernova explosion, these stars lose their gaseous envelopes through intense winds, exposing He, C, N, O-rich inner layers, at which point they evolve into WR stars [10]. The hallmark of WR stars is broad emission lines of C and N elements in their spectra. These strong, broad emission lines originate from their powerful stellar winds, which create optically thick continuum near the star while emission lines form in the more tenuous wind material farther out [10].

WR stars are spectroscopically classified into two types: carbon-rich WC stars and nitrogen-rich WN stars, with each type further divided into subtypes based on spectral details. Generally, WN2-5 and WC4-6 are considered early-type WR stars, WN7-9 and WC7-9 are late-type, while WN6 can be either early or late type [10]. Spectra of various WR types are shown in Figure 1 [Figure 1: see original paper], displaying from top to bottom: WN and WC type spectra, Smith-ubv narrow-band photometry (1984) [11, 12] r-band narrow-band system (gray dashed line), and Johnson-UBV broad-band system (red solid line) [10].

The typical formation pathway for WR stars is as follows: massive stars with initial masses $M > 60\ M_\odot$ evolve to the giant branch and become luminous blue variables (LBVs) after core helium ignition; stars with 25-60 $M_\odot$ first become red supergiants (RSGs) after the main sequence, then transition to LBVs after losing mass. The LBV phase features intense stellar winds, and through strong wind activity or other eruptive events, the stars lose their gaseous shells and evolve into WR stars. The WR phase follows a WN → WC evolutionary sequence lasting approximately 5 million years, eventually ending as Type Ib or Ic supernovae [13]. The role of the LBV phase remains uncertain, as massive star evolution may skip this stage in some cases, LBVs may follow the RSG phase, or may dominate mass loss before the WR phase [14, 15].

Approximately 50-70% of observed WR stars in the Milky Way belong to binary systems [16], allowing mass estimation through Kepler' s third law using orbital motion. Latest measurements show WC star masses range from 13-22 $M_\odot$ [18], while WN stars can reach 20-60 $M_\odot$ [19]. In close binary systems, when one member' s envelope expands beyond the Roche lobe, material transfers to the companion, accelerating the primary' s evolution into a WR star [20]; if the companion is a neutron star or black hole, the system may evolve into a WR X-ray binary like Cyg X-3 [21]. In wide WR binaries with sufficient separation, no mass exchange occurs, limiting the binary interaction' s influence on WR evolution and making wind collision the dominant interaction.

3 Wind Collision and WCR

WR binaries with massive OB companions most readily form CWB systems due to the significant wind activity of OB stars. CWB radio emission consists of two components: thermal radiation from stellar winds and non-thermal radiation from the WCR. In massive stars, wind particles are ionized by intense UV photons, producing enhanced free-free transitions against the photospheric continuum, observable from infrared to radio wavelengths as an optically thick thermal envelope around the binary' s optical image [22]. CWB radio spectra exhibit distinct features: extremely high brightness temperatures of 10^6-10^7 K and spectral indices near zero or negative—both characteristic of non-thermal synchrotron radiation, indicating intense non-thermal emission from the WCR. Van der Hucht et al. [23] first proposed that non-thermal radiation originates in the WCR beyond the optically thick wind envelope. Similar to supernova remnant acceleration mechanisms, active winds supply abundant charged particles that gain energy at wind-collision shocks, accelerating to relativistic speeds. However, unlike supernova remnants, the WCR is closer to the stars and influenced by binary magnetic activity, causing high-energy particles to release more energy as synchrotron radiation within the WCR [24]. The non-thermal flux is variable [25, 26] because as the binary orbits, the WCR may be obscured by optically thick wind material, making non-thermal radiation difficult to detect beneath thermal wind emission.

Wind-collision activity also affects optical emission line profiles from WR winds, adding flux to the otherwise flat-topped profiles. Figure 2 [Figure 2: see original paper] illustrates this effect using the C III 5696 Å line of WR113, where the dashed line shows the flat-topped profile without wind collision and the solid line shows the actual profile with additional flux from wind-collision activity [27]. The line profile varies with orbital phase, demonstrating that collision-induced radiation is affected by binary motion [27].

Eichler and Usov [24] provided the first detailed CWB model description, with Figure 3 [Figure 3: see original paper] showing the schematic. Shock fronts S1 and S2 and contact surface C form near conical surfaces close to the stars. represents the angle between conical surface C and the line connecting the stars, with S1 and S2 within a Δ range centered on C. R_{WR} and R_{OB} denote the radio photospheric radii of the WR and OB stars. The binary orbits clockwise in the diagram. The lower panel shows an enlarged view of the collision region, where distances between S1, S2, and C are much smaller than the distances from the stars to the contact surface (r_{WR} and r_{OB}) [24].

Since WCR exhibits strong synchrotron radiation, magnetic fields must exist in the stellar winds and WCR, which also contains numerous accelerated relativistic electrons. The WCR can serve as a particle acceleration site through Fermi mechanisms, with free electrons accelerated to relativistic speeds at shock fronts between interacting winds. A key parameter describing the WCR is the wind momentum ratio [24]:

= (M_{OB} v_∞,OB) / (M_{WR} v_∞,WR)

where M_{WR} and M_{OB} are the mass-loss rates and v_∞,WR and v_∞,OB are the terminal wind velocities of the binary components. The distances r_{WR} and r_{OB} can be expressed as:

r_{WR} = D / (1 + ^{1/2}), r_{OB} = ^{1/2} D / (1 + ^{1/2})

where D is the binary separation. For the simplest case = 1, the WCR appears near the midpoint between the stars. When ≠ 1, the contact surface forms an approximate conical structure wrapped around the star with weaker wind momentum. In WR147 (WN8+B0), radio imaging resolves two components: thermal radiation from the WN8 wind and non-thermal radiation from the WCR region near the companion [28]. The WCR location matches the ram pressure balance surface, yielding = 0.011.

X-ray observations also detect WCR presence [29]. For early-type stars with terminal wind velocities reaching 10^3 $\mathrm{km \cdot s^{-1}}$, post-shock plasma temperatures exceed 10^7 K, with X-rays revealing the primary observational signatures of shock-heated plasma. CWB X-ray flux is substantially stronger than that of single WR stars, with γ Velorum reaching approximately 10^{24} $\mathrm{J \cdot s^{-1}}$. X-ray flux variations can be predicted due to changing wind opacity along the line of sight or varying binary separation perpendicular to the line of sight [30]. The archetypal X-ray CWB system is γ Velorum (WC8+O), where X-ray flux variations with orbital phase have been observed: when optically thick WR wind material lies in front of the O companion, X-rays from the WCR are absorbed;

when the line of sight is clear of WR wind, absorption decreases significantly [31].

While relativistic particles are generally thought to be accelerated in supernova remnants, many mechanisms can accelerate particles in the Galaxy, including binary wind-collision regions. In CWBs, wind collisions create strong shocks where diffusive shock acceleration (DSA) can produce relativistic particles. Although other mechanisms like magnetic reconnection may exist, DSA is considered the best explanation for relativistic particle energization [6]. CWB activity is significant for cosmic ray production. Unlike supernovae, these binary systems can generate high-energy particles throughout their evolution, potentially making them more important contributors to cosmic rays. For example, with an energy injection rate of 0.01%-1% into charged particles [4], binaries provide 10^{25}-10^{27} $\mathrm{J \cdot s^{-1}}$ to relativistic particles. If the Galaxy contains 10^5 such massive late-stage binary systems, they would produce 10^{30}-10^{32} $\mathrm{J \cdot s^{-1}}$ of cosmic ray energy, representing a substantial fraction of the total cosmic ray energy (10^{33} $\mathrm{J \cdot s^{-1}}$). Thus, studying particle acceleration in wind collisions is crucial for understanding cosmic ray formation.

4 Searching for CWB Systems

Forty-three potential CWB candidates have been identified (see Table 1), but only a small fraction show direct detection of non-thermal radiation from wind collisions. It remains unclear whether this reflects observational limitations or unknown particle acceleration mechanisms. If unknown mechanisms are responsible, current research may be missing key physical processes in particle energization. Therefore, particle acceleration and non-thermal radiation phenomena are crucial for CWB searches, with radio synchrotron radiation being the primary signature. However, single-dish observations lack the resolution to resolve WCRs, making radio interferometry the primary tool for finding CWB systems.

(1) Since CWB activity strongly depends on wind strength, binary systems with significant wind activity are the main search targets [6]. B-type stars have weaker winds and lower mass-loss rates. While stars with weaker winds can still accelerate particles, the associated radiation intensity is too low for detector sensitivity limits. Therefore, WR stars with extremely high mass-loss rates and O-type giants/supergiants are the most promising targets.

(2) Only a few systems have determined orbital periods, ranging from weeks to decades (some candidates have unconfirmed periods that may involve tertiary components). For larger systems like WR146, periods remain undetermined but certainly exceed 100 years. Thus, binaries of any separation can potentially form CWBs, except for extremely close systems where wind material may absorb WCR non-thermal radiation and wind turbulence may prevent adequate particle energization [4]. Therefore, searches

should focus on long-period (non-close) massive binary systems [6].

(3) Radio emission comprises thermal wind radiation and non-thermal synchrotron radiation from the WCR. While thermal flux remains constant, non-thermal flux varies with orbital phase. Variations occur because: (i) radiation intensity depends on magnetic field strength, brightening near periastron; and (ii) free-free absorption by wind material can weaken synchrotron radiation, making it difficult to observe at phases where radiation passes through thick wind material [6]. Other mechanisms including free-free absorption can significantly affect synchrotron radiation throughout the orbit, so flux maxima and minima need not coincide with periastron or apastron phases [2]. Multiple observations at different epochs are therefore required to confirm WCR presence and non-thermal radiation origin.

(4) WCR synchrotron radiation weakens with increasing frequency while free-free radiation strengthens, allowing spectral index determination of radiation origin through at least two-frequency measurements. Observations should focus on L to C bands where synchrotron radiation dominates [6]. Additionally, since WCR synchrotron radiation is linearly polarized, polarization detection can help identify it, though detecting polarization is more challenging than detecting non-thermal radiation itself due to WCR environmental complexity and flux limitations.

(5) Wind-collision activity also affects optical/infrared spectra, with extra radiation from colliding winds altering wind emission line profiles [27]. High-resolution spectroscopic observations of candidate binaries analyzing profile variations can serve as an auxiliary discovery method, though this approach depends on high-resolution spectroscopy and sophisticated line analysis theory, making it more difficult than other methods. For distant sources significantly affected by interstellar absorption, this technique' s feasibility remains to be verified.

5 Typical CWB Systems

High-resolution connected-element interferometer observations of WR147 first confirmed CWB models [33], while dramatic variations in WR140' s synchrotron flux further supported the model, showing clear orbital modulation of the WCR [7]. Among discovered WR stars, those showing strong non-thermal radiation are either binary systems or have nearby massive companions creating WCRs [34]. Below we introduce several typical CWB systems.

5.1 WR147

As the first discovered CWB, the WR147 (WN8+B0) system lies 650 pc from the Solar System [35] and was first confirmed to have wind-collision activity by Williams et al. [33]. Observations by Moran et al. [36] using MERLIN revealed two distinct radio components: thermal radiation near the WR star' s optical position and non-thermal radiation concentrated 0.6″ north of the WR star (see Figure 4 [Figure 4: see original paper]). Contours show 5 GHz MERLIN observations from 1992, while the grayscale shows a 1997 UKIRT 2.2 m infrared image. The arc-shaped non-thermal region appears significantly closer to the companion with weaker wind [33] (coordinates use B1950 reference frame). Moran et al. hypothesized a companion, but initial optical R-band observations found none. In 1997, Williams et al. [33] used UKIRT at 2.2 m with sufficient resolution to identify a B0 companion 3 mag fainter than the WR star at 2.2 m, located 60 mas north of the non-thermal region—consistent with the position predicted from wind momentum ratio. This confirmed WR147 as a CWB system. Chandra X-ray observations also detected WCR X-ray emission [37]. Recent VLA observations show spiral structure in radio emission around the WN component (see Figure 5 [Figure 5: see original paper]), possibly indicating an undiscovered third component [38].

5.2 WR140

WR140 is one of the earliest discovered CWB systems, consisting of a WC7 WR star and an O4-5 main-sequence companion in a highly eccentric orbit ($e \approx 0.88$) with a 7.9-year period at a distance of (1.81 ± 0.08) kpc [7]. Radio observations show dramatic non-thermal flux variations with orbital phase, increasing approximately 100-fold between phases 0.65–0.85 (see Figure 6 [Figure 6: see original paper]) [34, 39].

Many orbital parameters, particularly period P, epoch T_0, eccentricity e, and periastron longitude ω, are determined through radial velocity measurements using the Doppler effect [40]. However, inclination i, semi-major axis a, and longitude of ascending node Ω require resolving the binary and measuring relative position changes. With a separation of only 2–30 AU (1.1–16.7 mas at 1.8 kpc), conventional optical or radio observations cannot resolve WR140, making very-long-baseline interferometry (VLBI) the only viable technique. Assuming negligible free-free absorption along the line of sight, the WCR appears near the O companion as a bowl-shaped region pointing toward it. As the binary orbits, the bowl’ s orientation changes. If the WCR emission symmetry axis aligns with the binary centerline projection on the sky, the WCR direction variations can constrain orbital inclination and phase.

Dougherty et al. [7] used the VLBA for 21 epochs in 1999–2000 and 14 epochs in 2004–2008 at 8.4 GHz (orbital phases 0.43–0.97) to image WCR shape evolution. Figure 7 [Figure 7: see original paper] shows three epochs where the WCR arc orientation rotates from southeast to east, which is key for determining WR140’ s orbit. Assuming symmetry about the binary line, the O companion lies southeast of the WCR at phase 0.74 and east at phase 0.93. Orbital fitting yields $i = (120 \pm 4)^\circ$, $\Omega = (352 \pm 2)^\circ$, and $a = (16.28 \pm 0.81)$ AU, giving a refined distance of (1.85 ± 0.16) kpc.

High-precision spectroscopic observations also play a crucial role in determining orbital parameters through Doppler-derived radial velocities. Thomas et al. used

ESPaDOnS at CFHT from June 2008 to June 2018 for high-resolution spectroscopic imaging, analyzing WR140' s emission lines to calculate radial velocities and track temporal variations [41]. Combined with CHARA interferometer observations and Monnier et al.' s data [42], they measured component positions at different epochs to determine the orbit: $i = (119.07 \pm 0.88)^{\circ}$, $\omega = (353.87 \pm 0.67)^{\circ}$, $a = (13.55 \pm 0.21)$ AU, and distance $d = (1.518 \pm 0.021)$ kpc. These results agree well with Gaia DR3 and Dougherty et al.' s measurements, demonstrating the feasibility of using Doppler spectroscopy as an auxiliary method for determining CWB orbital parameters.

5.3 WR146

WR146 is another CWB archetype consisting of a WC6 WR star and O8 main-sequence companion at a distance of $1.2^{+1.0}_{-0.4}$ kpc with a separation of 182^{+156}_{-62} AU [32]. WR146 is one of the brightest WR stars at radio wavelengths [43] with sufficiently strong non-thermal emission for high-resolution studies [44]. However, its orbital period remains controversial: estimating from binary masses (20–30 $M_{\odot}$) and separation (~150 mas) suggests a ~500-year period, but Setia Gunawan et al. [45] found 3.38-year flux variations in WSRT L-band observations, hinting at a possible ~3-year period. This uncertainty prevents establishing a reliable orbital model, limiting our understanding of WR146.

HST optical imaging and photometry show WR146 as a highly reddened binary pair with similar luminosities, colors, and Q-factors [46]. The lower-than-typical Q-factor may result from WR emission lines affecting broadband photometry or lack of UBV calibration [47]. Spectroscopic imaging reveals the WR component's characteristic broad C emission lines and some interstellar absorption, indicating vigorous wind activity with a terminal velocity of ~2900 $\mathrm{km \cdot s^{-1}}$, while the companion shows H and He absorption lines consistent with an O8 spectral type.

VLA imaging resolves both components with a separation of (152 ± 2) mas, consistent with optical positions and thermal radio distribution. EVN observations reveal an arc-shaped WCR region pointing toward the O8 companion, with its symmetry axis aligned with the binary line, allowing analysis of relative motion through WCR orientation (see Figure 8 [Figure 8: see original paper]). Radio continuum observations (see Figure 9 [Figure 9: see original paper]) show both thermal and non-thermal components. Below 22 GHz, non-thermal synchrotron radiation dominates, while above 22 GHz, thermal wind emission becomes significant [48].

5.4 WR105

WR105 is another bright WR radio source and potential CWB candidate [4]. Located at ~1.82 kpc [32], it is classified as WN9h. VLA observations reveal unusual non-thermal radio emission, with flux at 3.6 cm 50% higher than typical WR stars [50]. Spectral index fitting yields α between −0.6 and −0.7, confirming strong non-thermal radiation [3, 50], leading De Becker and Raucq [4] to include it in their CWB candidate list. HST imaging shows an F or G-type star ~350 mas northwest of WR105 (see Figure 10 [Figure 10: see original paper]). If confirmed as a companion, wind collision would likely occur, making it a CWB system.

Additionally, Chapman et al. [51] noted WR105' s unusual X-ray emission compared to typical WR stars. XMM-Newton observations also reveal a strong X-ray source, suggesting particle acceleration in an active WCR producing X-ray emission.

6 Summary

CWB systems are important sources of high-energy particles in the universe, and detailed studies help us understand particle acceleration mechanisms. Since CWBs typically involve massive late-stage stars with strong winds (such as WR stars), they also serve as probes for massive star evolution. While such binaries are not rare in the Milky Way, only WR140, WR146, WR147, and a few others have been confirmed as CWBs, with candidates like WR105 awaiting confirmation. In typical systems such as WR140 and WR146, radio observations detect WCR regions between components, with radio emission comprising thermal bremsstrahlung from winds and non-thermal synchrotron radiation from the WCR. Measuring WCR orientation variations provides orbital parameter data.

To discover more CWB systems, searches must continue for massive binary candidates, primarily using radio interferometry. Targets should focus on WR or O-type binaries with strong winds but not too close separations. Multi-epoch, multi-frequency radio observations are needed to identify WCRs and confirm non-thermal synchrotron radiation, with polarization observations providing additional confirmation.

High-resolution radio interferometry remains essential for establishing CWB models and interpreting phenomena, particularly for imaging WCR structures. These capabilities will enable broader searches and studies of WR binary formation. With increasing observational data and new instruments like the Square Kilometre Array (SKA) providing higher sensitivity, future searches will enrich our understanding of CWB systems. ALMA' s high-sensitivity observations at millimeter/submillimeter wavelengths will also improve CWB data quality and enable studies of interstellar media behind these systems, further elucidating relationships between wind-collision activity, interstellar medium, and high-energy cosmic particles.

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Note: Figure translations are in progress. See original paper for figures.