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DEPARTMENT OF ASTROPHYSICS, GEOPHYSICS AND  
OCEANOGRAPHY

# Insight into the polarization and population of particle-accelerating colliding-wind binaries based on radio measurements

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# Declaration

I used ChatGPT (OpenAI) as a supporting tool to help me with some language-related aspects during the writing of this thesis, and to generate with close supervision the figures describing the Faraday rotation mechanism in the first chapter. All the scientific work presented in this thesis is my own, and is the result of the many fruitful discussions I have had with my supervisors, other colleagues, and my doctoral thesis committee.



# Abstract

Particle-accelerating colliding-wind binaries (PACWBs) are massive binary systems in which the powerful, supersonic winds of the stars collide, giving rise to a region of shocked plasma where particles can get accelerated to relativistic velocities. A population of relativistic particles, in the presence of a magnetic field, can produce non-thermal (NT) synchrotron radiation at radio wavelengths. Radio observations, therefore, provide a means of identifying and characterizing these systems. However, the detection and interpretation of NT synchrotron emission are sometimes hindered by the strong thermal emission and free-free absorption (FFA) associated with the dense winds of the system's massive stars.

This thesis investigates the radio properties of different PACWBs and PACWB candidates based on three different projects, intending to improve our understanding of their population, polarization properties, and observational signatures.

A first project focuses on the search for NT radio emission in a sample of Wolf-Rayet (WR) stars that had previously shown hints of binarity, but lacked a formal confirmation of binary nature to date. The goal was to investigate their low-frequency radio emission and, in the case of a synchrotron detection, provide further evidence for their nature as particle-accelerating binary systems (i.e., part of the PACWB class). Observations with the upgraded Giant Metrewave Radio Telescope (uGMRT) were obtained for five WR stars in two different observing bands at low radio frequencies. Only one source, WR 110, was detected in the range covered by our observations. Such a low detection rate exposes the observational challenges involved in identifying new PACWBs, particularly at low frequencies where FFA can severely suppress the synchrotron emission originating from the wind-collision region (WCR). These results also highlight the importance of accounting for observational biases when assessing the occurrence of particle acceleration in massive binary systems.

Beyond the detection of synchrotron emission, investigating its polarization can provide a probe of the magnetic-field conditions in PACWBs. The polarization properties of two established PACWBs (through their synchrotron radiation) were thus studied as our second project thanks to observations obtained with the Karl G. Jansky Very Large Array (VLA). No significant linear polarization was detected in the studied sources, despite the presence of established and bright NT synchrotron emission. This non-detection may result from the combined effects of turbulent magnetic fields, Faraday depolarization, and dilution by unpolarized thermal emission from the stellar winds. These results emphasize that the suitability of a PACWB as a target for radio polarimetry depends not only on the presence of synchrotron emission, but also on whether the polarized signal can survive the different observational,

emission, and propagation effects within and around the system.

The third project was conducted using observations obtained through a dedicated Australia Telescope Compact Array (ATCA) observing proposal, targeting a sample of WR stars and candidate PACWBs. In a similar approach to the first project, these observations aimed to investigate the radio properties of PACWB candidates, but provided a different, broader frequency coverage and targeted a different sample of stars. This broad frequency coverage allows the radio spectra to be characterized in greater detail than is possible from measurements at only a few narrow frequencies. In particular, the spectrum of the target WR 48a shows a more complex behavior than what would be expected for a purely thermal stellar wind. Its relatively flat spectral behavior at centimeter radio wavelengths and the overall shape of the spectrum observed are compatible with a contribution from a free-free absorbed NT emission component in addition to the thermal wind emission, although the available data do not allow the individual components to be properly separated. The preliminary result obtained on this target demonstrates the value of broadband radio observations but also exposes the limitations of single-epoch observations for studying PACWBs, whose emission and absorption properties can vary with orbital phase.

In a more general way, this thesis illustrates that the identification and characterization of PACWBs require a combination of broad frequency coverage, sensitive radio observations, and careful consideration of observational biases and propagation effects. The results show that a single-epoch non-detection, whether of radio emission, synchrotron emission, or polarization, cannot necessarily be interpreted as evidence for the absence of particle acceleration.

These findings motivate continued systematic radio surveys of massive binaries and multi-epoch observations, including high-angular resolution imaging, to build a more complete census of PACWBs and provide stronger constraints on particle acceleration and magnetic-field properties in colliding-wind systems.

# Résumé

Les binaires à collision de vents accélérant des particules (PACWB) sont des systèmes binaires massifs dans lesquels les vents stellaires puissants et supersoniques des étoiles entrent en collision, donnant naissance à une région de plasma choqué où les particules peuvent être accélérées jusqu'à des vitesses relativistes. Une population de particules relativistes, en présence d'un champ magnétique, peut produire un rayonnement synchrotron non thermique (NT) aux longueurs d'onde radio. Les observations radio constituent ainsi un moyen d'identifier et de caractériser ces systèmes. Cependant, la détection et l'interprétation de l'émission synchrotron NT peuvent être rendues difficiles par la forte émission thermique et l'absorption libre-libre (FFA) associées aux vents denses des étoiles massives du système.

Cette thèse étudie les propriétés radio de différents PACWBs, et candidats PACWB, à travers trois projets, dans le but d'améliorer notre compréhension de leur population, de leurs propriétés de polarisation et de leurs signatures observationnelles.

Le premier projet porte sur la recherche d'une émission radio NT dans un échantillon d'étoiles de Wolf-Rayet (WR) qui avaient précédemment montré des indices de binarité, mais dont la nature binaire n'avait pas encore été formellement confirmée. L'objectif était d'étudier leur émission radio à basse fréquence et, en cas de détection d'une émission synchrotron, d'apporter des éléments supplémentaires en faveur de leur nature de systèmes binaires accélérant des particules, c'est-à-dire de leur appartenance à la classe des PACWB. Des observations de cinq étoiles WR ont été obtenues avec le upgraded Giant Metrewave Radio Telescope (uGMRT), dans deux bandes d'observation à basse fréquence radio. Une seule source, WR 110, a été détectée dans la gamme couverte par nos observations. Ce faible taux de détection met en évidence les difficultés observationnelles liées à l'identification de nouveaux PACWB, en particulier aux basses fréquences, où l'absorption FFA peut fortement atténuer l'émission synchrotron provenant de la région de collision des vents (WCR). Ces résultats soulignent également l'importance de prendre en compte les biais observationnels lors de l'évaluation de la fréquence de l'accélération des particules dans les systèmes binaires massifs.

Au-delà de la détection de l'émission synchrotron, l'étude de sa polarisation peut fournir des informations sur les conditions du champ magnétique dans les PACWB. Les propriétés de polarisation de deux PACWB (établies grâce à leur émission synchrotron) ont ainsi été étudiées dans le cadre du deuxième projet, à partir d'observations obtenues avec le Karl G. Jansky Very Large Array (VLA). Aucune polarisation linéaire significative n'a été détectée dans les sources étudiées, malgré la présence d'une émission synchrotron NT établie et intense. Cette absence

de détection peut résulter des effets combinés de champs magnétiques turbulents, de la dépolarisation par effet Faraday et de la dilution due à l'émission thermique non polarisée des vents stellaires. Ces résultats montrent que la pertinence d'un PACWB comme cible pour des observations de polarimétrie radio ne dépend pas uniquement de la présence d'une émission synchrotron, mais également de la capacité du signal polarisé à subsister malgré les différents effets observationnels, d'émission et de propagation au sein et autour du système.

Le troisième projet a été réalisé à partir d'observations obtenues dans le cadre d'un programme d'observation dédié avec l'Australia Telescope Compact Array (ATCA), visant un échantillon d'étoiles WR et de candidats PACWB. Dans une approche similaire à celle du premier projet, ces observations avaient pour objectif d'étudier les propriétés radio de candidats PACWB, tout en offrant une couverture fréquentielle différente et plus étendue, et en ciblant un échantillon distinct d'étoiles. Cette large couverture fréquentielle permet de caractériser les spectres radio avec davantage de détails que ne le permettent des mesures effectuées à seulement quelques fréquences étroites. En particulier, le spectre de la cible WR 48a présente un comportement plus complexe que celui attendu pour un vent stellaire purement thermique. Son spectre relativement plat aux longueurs d'onde radio centimétriques, ainsi que la forme globale du spectre observé, sont compatibles avec une contribution d'une composante d'émission NT absorbée par absorption libre-libre, en plus de l'émission thermique du vent, bien que les données disponibles ne permettent pas de séparer correctement les différentes composantes. Ce résultat préliminaire met en évidence l'intérêt des observations radio à large bande, tout en soulignant les limites des observations à une seule époque pour l'étude des PACWB, dont les propriétés d'émission et d'absorption peuvent varier avec la phase orbitale.

De manière plus générale, cette thèse montre que l'identification et la caractérisation des PACWB nécessitent de combiner une large couverture fréquentielle, des observations radio sensibles et une prise en compte attentive des biais observationnels et des effets de propagation. Les résultats montrent qu'une non-détection à une seule époque, qu'il s'agisse d'une émission radio, d'une émission synchrotron ou d'une polarisation, ne peut pas nécessairement être interprétée comme une preuve de l'absence d'accélération des particules.

Ces résultats motivent la poursuite de campagnes radio systématiques sur les systèmes binaires massifs ainsi que des observations multi-époques, notamment par imagerie à haute résolution angulaire, afin d'établir un inventaire plus complet des PACWB et de mieux contraindre les processus d'accélération des particules et les propriétés des champs magnétiques dans les systèmes à collision de vents.



# Chapter 1

## Physical framework

This thesis focuses on the investigation of the non-thermal radio emission produced in binary systems made of high-mass stars. Throughout this chapter, we introduce the theoretical framework necessary to understand the production of radiation in these systems and lay the foundation for the questions that we plan to address.

### 1.1 Massive stars

#### 1.1.1 Definition and global properties

High-mass (or massive) stars are generally defined as stars with an initial mass greater than about eight solar masses ( $M_{\text{ZAMS}} \gtrsim 8 M_{\odot}$ ). The category of massive stars includes O-type and early B-type stars on the main sequence (MS), as well as evolved objects such as blue and red supergiants, luminous blue variables (LBVs), and Wolf-Rayet (WR) stars.

Owing to their larger masses, massive stars reach higher central temperatures and much higher luminosities than lower-mass stars. Since stellar luminosity increases steeply with mass ( $L \propto M^3$ ), massive stars radiate energy at a much higher rate and therefore must burn their nuclear fuel on much shorter timescales to sustain their high luminosities, leading to evolutionary timescales of only a few to a few tens of millions of years, and strongly influencing their subsequent evolution. They possess large convective cores that efficiently mix fresh Hydrogen (H) into the burning region, allowing sustained H fusion throughout the MS phase despite their high luminosities.

Regardless of their short lifetimes and their scarcity (less than  $10^5$  in the Milky Way), massive stars have a radical and irreversible impact on their surroundings. Their high luminosities, intense ultraviolet (UV) radiation, powerful radiatively driven winds, and eventual core-collapse supernova explosions inject substantial mechanical energy and nucleosynthetic products into the interstellar medium (ISM). In doing so, they chemically and dynamically modify their environments, leading to radiative feedback effects such as the formation of HII regions and, in some cases, triggering episodes of star formation through the compression of nearby dense molecular clouds. The expulsion of mass through winds and, in some cases, eruptive episodes affects not only their surroundings but also their evolution. In sufficiently massive stars, for example, the substantial mass loss may prevent evolution towards the red

supergiant phase and instead lead directly to a WR phase, in which the products of nuclear reactions in the inner layers become exposed at the surface as a consequence of envelope stripping. These advanced evolutionary stages are short-lived compared to the MS lifetime and, therefore, intrinsically rare. Because massive stars spend the majority of their lifetimes burning H in their cores, most O-type stars observed at any given time are still on the MS.

The stellar cores of massive stars reach sufficiently high temperatures and densities to ignite successive advanced nuclear burning stages beyond H burning, allowing nucleosynthesis to proceed through progressively heavier elements up to the formation of an iron-rich core, for which further exothermic fusion is no longer possible, ultimately leading to core collapse.

Thus, massive stars end their short lives with a core-collapse supernova (SN) explosion. The observed SN type depends on the degree of envelope stripping prior to collapse: stars that maintain their H-rich envelopes result in Type II supernovae, whereas heavily stripped progenitors, which have lost most or all of their H envelopes before explosion, result in Type Ib or Ic - if they additionally lack Helium (He) features in their spectra - supernovae. The explosion leaves behind a compact remnant such as a neutron star (NS) or black hole (BH), depending on the initial core mass (Eldridge and Tout, 2004; Jerkstrand et al., 2026).

### 1.1.2 Radiatively driven winds

Massive stars exhibit extremely high luminosities (typically in the  $10^5$ – $10^6$   $L_\odot$  range) and very high effective temperatures, typically  $T_{\text{eff}} \sim 20000$ – $50000$  K, or even higher values. Their spectral energy distributions (SEDs) therefore peak in the UV range, leading to copious emission of ionizing photons with energies  $h\nu > 13.6$  eV.

Their high luminosity and intense radiation field imply a strong radiative flux, which carries substantial photon momentum. In the outer layers of the star, the radiation pressure<sup>1</sup> can become comparable to, or even exceed, the inward pull of gravity. In hot, massive stars, this acceleration is primarily mediated by line opacity from metals: UV photons are absorbed and scattered by metal ions in the stellar atmosphere, transferring momentum to the gas and driving an outflow of material from the outer envelopes. This process, referred to as the line-driving mechanism, results in powerful, radiatively driven stellar winds (Lucy and Solomon, 1970; Castor et al., 1975; Puls et al., 2008).

These winds are characterized by high mass-loss rates, typically in the range  $\dot{M} \sim 10^{-7} - 10^{-5} M_\odot \text{ yr}^{-1}$ , and terminal velocities<sup>2</sup> of  $v_\infty \sim 1000 - 3000 \text{ km s}^{-1}$ , depending on the spectral type and evolutionary stage (Muijres et al., 2012; Hamann et al., 2019; Sander et al., 2019). This combination of high mass-loss rates and high velocities entails a substantial injection of wind kinetic energy and momentum into the surrounding medium. The sound speed in a fully ionized plasma (a stellar wind,

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<sup>1</sup>The radiation pressure,  $P_{\text{rad}}$ , is defined as the mechanical force per unit area applied on a given surface by the transfer of momentum from electromagnetic radiation.

<sup>2</sup>The terminal velocity,  $v_\infty$ , of a stellar wind is the constant, maximum speed reached by the outflowing gas when the outward acceleration caused by the radiative pressure is balanced by the inward pull of gravity, and the net force is zero.

in this case) is given by  $c_s = \sqrt{\gamma_{\text{ad}} k_B T / \mu m_p}$ , where  $\gamma_{\text{ad}}$  is the adiabatic index,  $k_B$  the Boltzmann constant,  $\mu$  the mean molecular weight, and  $m_p$  the proton mass<sup>3</sup>. For typical wind temperatures of  $T \sim 10^4$  K, this yields  $c_s \sim 10 \text{ km s}^{-1}$ . Since terminal wind velocities are on the order of  $10^3 \text{ km s}^{-1}$ , massive star winds are thus highly supersonic flows (sonic Mach number  $\sim 100$ ).

As stated above, radiatively driven winds can expel a notable fraction of the stellar mass over their lifetimes, and strongly influence both stellar evolution (Vink, 2008; Meynet et al., 2015; Josiek et al., 2024) and the circumstellar environment (Garcia-Segura et al., 1996b,a; Oey et al., 2001; Krause et al., 2013; Mackey et al., 2021). In multiple systems composed of two or more massive stars, the interaction of such powerful winds gives rise to shock structures where a percentage of the wind kinetic energy can be converted into thermal and non-thermal (NT) radiation.

### 1.1.3 Massive stars in binary systems

Apart from their strong winds, one characteristic of massive stars is that they are frequently found in binary or higher-order multiple systems. For O-type stars in young clusters, the multiplicity fraction (defined as the fraction of primaries with at least one companion) has been observed to be  $> 90 \%$  (Offner et al., 2023). Furthermore, observations and simulations have shown that massive stars in binary systems tend to have another massive star as a companion, both with comparable birth masses (Krumholz et al., 2009), which likely reflects correlated formation processes from the fragmentation of the natal accretion disk. Thus, most O-type stars are expected to undergo binary interactions during their evolution (Sana et al., 2012). In particular, in these systems where both components possess powerful radiatively driven winds, the form of interaction of interest to this thesis is the collision of their stellar winds. A multiple system of massive stars in which their winds collide is known as a colliding-wind binary (CWB). We will refer to the region between the two stars where the winds interact, and the collision occurs, as the wind-collision region (WCR).

## 1.2 Colliding-wind binaries

### 1.2.1 Shock physics in stellar winds

As stated in Sect. 1.1.2, massive star winds are highly supersonic. In terms of the sonic Mach number  $M$  (defined as the ratio of the flow velocity to the local sound speed), this corresponds to  $M \gg 1$ . When two of these winds collide, a set of two magnetohydrodynamic (MHD) shocks forms. The general geometry of the wind–wind interaction region is illustrated in Fig. 1.1.

Each stellar wind produces its own shock upon interaction, resulting in two shocks separated by a contact discontinuity. A shock, being a discontinuity in the flow of the wind or a jump, creates two separated regions (the pre-shock and the

---

<sup>3</sup> $\gamma_{\text{ad}} = 5/3$  for an ideal monoatomic gas and  $\mu = 0.6$  for a fully ionized plasma with solar-like composition (mostly H fully ionized and some He mostly ionized).

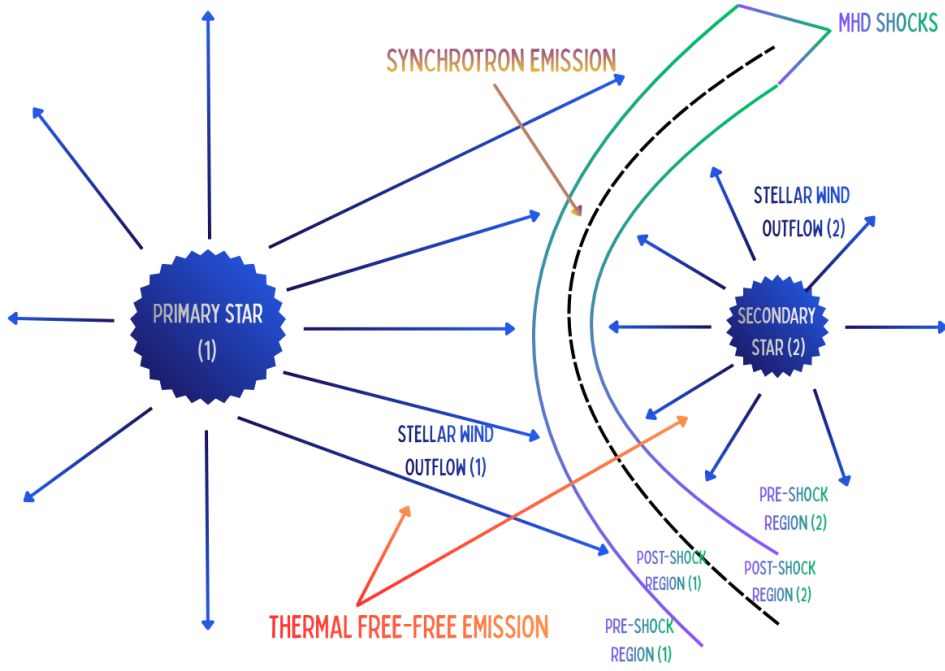


Figure 1.1: Schematic representation of a colliding-wind binary. The blue arrows illustrate the wind flow lines from both stars. The supersonic stellar winds collide, producing two MHD shocks separated by a contact discontinuity (dotted black line). The resulting wind-collision region (WCR) is shaped by the balance of ram pressures and is typically curved toward the star with the weaker wind. By convention, the primary and secondary stars are the stars with the higher and lower mass at formation, respectively. As a result, the star with the strongest wind may be a WR star (primary) with a current mass that may be lower than that of its O-type companion (secondary) due to severe mass loss. The thermal and synchrotron emission features mentioned in the figure refer to the radio spectrum that will be detailed in Sect. 1.3.

post-shock regions) where the physical properties of the plasma change abruptly on both sides.

In the case of strong ( $M \gg 1$ ) adiabatic shocks, which are frequently encountered in the context of highly supersonic winds colliding in massive binary systems, the equations that describe the jump conditions provide simple relations between upstream (pre-shock) and downstream (post-shock) physical quantities. In particular, the compression ratio  $\chi$ , defined as the ratio of downstream to upstream densities, depends on the adiabatic index  $\gamma_{\text{ad}}$  as

$$\chi = \frac{\rho_d}{\rho_u} = \frac{\gamma_{\text{ad}} + 1}{\gamma_{\text{ad}} - 1} \quad (1.1)$$

in the strong shock limit. Assuming a monoatomic gas ( $\gamma_{\text{ad}} = 5/3$ ), we thus obtain a compression ratio of

$$\chi = 4 \quad (1.2)$$

for strong (high Mach number) adiabatic shocks, showing how the density increases after the shock. In this same regime, the post-shock temperature can be approximated as

$$T_d = \frac{3}{16} \frac{m}{k_B} v_u^2, \quad (1.3)$$

where  $v_u$  is the pre-shock velocity,  $m$  is the mean mass per particle. This relation reflects the efficient conversion of kinetic energy of the pre-shock gas (the supersonic wind) into thermal energy in the post-shock region or shocked gas, and how a strong shock leads to a significant increase in the post-shock temperature. Consequently, fast stellar winds with velocities of order  $10^3 \text{ km s}^{-1}$  can produce very hot shocked plasma, reaching temperatures of  $10^7$ – $10^8 \text{ K}$ , as typically observed in CWBs through their thermal X-ray emission (see e.g. [Stevens et al., 1992](#); [Pittard and Parkin, 2010](#); [De Becker, 2015](#); [Arora et al., 2024](#)).

The expressions presented above were derived for an adiabatic shock, i.e., assuming that the total energy of the flow, including both mechanical and internal components, is conserved across the shock. However, in some cases, the heated post-shock gas may lose a significant fraction of its energy through radiation. When energy losses become important, the shock becomes radiative.

The distinction between these regimes is determined by the relative importance of the cooling and flow timescales. If the cooling time is longer than the flow timescale (that is, the time required for the gas to advect away from the shock), radiative losses are negligible, and the shock can be treated as adiabatic, with the shocked gas remaining hot. By contrast, if the cooling times are short, the shocked gas cools efficiently, losing its thermal energy quickly, and the shock becomes radiative.

The precise location and geometry of the wind-wind interaction region are determined by the balance of ram pressures of the two stellar winds. The resulting interaction region consists of two shocks separated by a contact discontinuity and forms a curved structure closer to, and opening around, the star with the weaker wind. The orbital motion of the system further modifies this geometry. As the stars revolve around their common center of mass, the WCR is distorted and can be wrapped into a spiral structure and even show dust pinwheel tails ([Williams, 2008](#),

for example). Furthermore, the eccentricity of the orbit causes the stellar separation to vary with the orbital phase, leading to significant changes in the physical conditions within the WCR. Variations in the wind density and magnetic field strength (both quantities dependent on the distance to the stellar surface), for instance, can produce phase-dependent changes in the WCR and, thus, in the radiation produced and the absorption properties over a whole orbital period.

Only a fraction of the stellar wind mechanical energy heading to the WCR effectively participates in the interaction, since only the velocity component normal to the shock contributes to the energy injection that feeds the emission processes in the WCR. As a result, shock obliquity plays a key role in determining the amount of wind kinetic energy injected at the shock and thus the energy available for particle acceleration (Sect. 1.2.2) and emission processes (Sects. 1.3.3 and 1.5) in the WCR. As illustrated in Fig. 1.1, the WCR is bent around the weaker wind in asymmetric systems. This means that a larger fraction of the weaker wind impacts the shock surface nearly perpendicularly, whereas the flow lines of the stronger wind encounter the shock at progressively larger obliquity angles away from the line of centers (also known as the apex). This effect is particularly pronounced in systems with highly asymmetric winds. In contrast, for systems with comparable winds, the WCR is more symmetric, and the contribution of each wind to the shock energy budget is more evenly distributed.

## 1.2.2 Particle acceleration in CWBs

As established above, the collision between the two supersonic stellar winds in massive binary systems produces strong shocks in the WCR. In addition to heating the plasma, such shocks can also serve as efficient sites for accelerating charged particles to velocities close to the speed of light. As a result, one can expect a population of relativistic particles to be associated with CWBs.

The mechanism through which particles are accelerated in these systems is diffusive shock acceleration (DSA), also known as first-order Fermi acceleration (Drury, 1983). In this process, charged particles gain energy through repeated deflections by magnetic irregularities (scattering centers) present on both sides of the shock. These act as moving mirrors, causing the particles to scatter and diffuse back and forth across the discontinuity. Particles experience a systematic energy gain as they are scattered by converging flows upstream and downstream, always bouncing head-on between approaching scattering centers on either side of the shock (see Fig. 1.2). This process leads to a net energy increase over successive shock crossings, with a fractional energy gain per cycle given by

$$\frac{\Delta E}{E} \propto \frac{V_{\text{sh}}}{c}, \quad (1.4)$$

where  $V_{\text{sh}}$  denotes the shock velocity.

While the fractional energy gain is warranted with repeated shock crossings, we have to account for the probability that accelerated particles escape the acceleration region at each iteration (thereby not increasing their velocity further). The competition between iterative crossings of the shock (and the resulting systematic

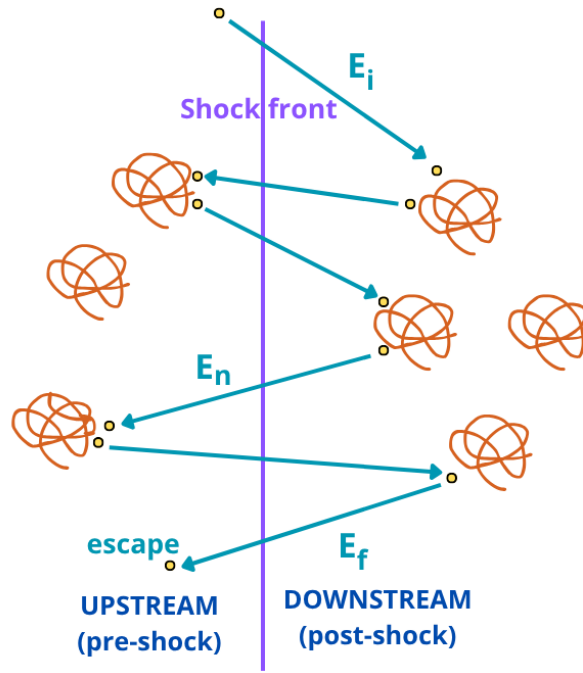


Figure 1.2: Schematic illustration of the diffusive shock acceleration (DSA) mechanism. The vertical line marks the shock front, separating the upstream (pre-shock) and downstream (post-shock) regions. Magnetic irregularities (orange clouds) act as scattering centers that repeatedly deflect charged particles back and forth across the shock front. Through successive scatterings and shock crossings, particles gain energy progressively. A particle enters the acceleration region with energy  $E_i$ , reaches an intermediate energy  $E_n$  after several crossings, and may eventually escape with a final energy  $E_f$ , where  $E_i < E_n < E_f$ .

energy gain), and the finite probability of being advected away from the shock (and thus escaping the acceleration region), leads to a power-law energy distribution of accelerated particles

$$N(E) \propto E^{-p}, \quad (1.5)$$

where  $N(E)$  is the number of particles per unit energy interval,  $E$  is the particle energy, and  $p$  is the power-law index of the energy distribution of relativistic particles. In the framework of DSA, this index is determined by the properties of the shock and is directly related to the compression ratio  $\chi$  (see Eq. 1.1 and Eq. 1.2). For a non-relativistic strong shock, this relation can be written as

$$p = \frac{\chi + 2}{\chi - 1}. \quad (1.6)$$

Thus, in the case of a strong adiabatic shock in a monoatomic gas, this yields  $p = 2$ , which corresponds to the canonical energy spectrum expected from first-order Fermi acceleration. The negative slope of the distribution in Eq. 1.5 reflects the fact that lower-energy relativistic particles are more numerous than higher-energy ones. This behavior makes sense considering the acceleration process: while particles gain energy through iterative interactions in the acceleration region, they also have a probability of escaping at each cycle. As a result, only a small fraction of particles remains in the acceleration region long enough to reach the highest energies in the relativistic population, which leads to the characteristic power-law distribution given in Eq. 1.5.

For the DSA mechanism to take place, inhomogeneities in the magnetic field are a necessary condition. Hence, magnetic fields play a crucial role in the efficiency of the acceleration process. Although the magnetic properties of massive stars are not yet fully understood, observational evidence suggests that massive stars can host either large-scale stable fossil fields, thought to be remnants of the star formation phase, or weaker, more complex field structures likely associated with sub-surface convection or localized instabilities in their largely radiative envelopes (in contrast to the sustained dynamo-generated fields found in lower-mass stars). While surface magnetic fields in massive stars can be probed through high-resolution spectropolarimetric observations based on the Zeeman effect, direct detections are challenging and generally limited to specific field configurations. Thus, indirect tracers such as the detection of NT emission in CWBs provide important complementary evidence for the presence of magnetic fields in massive stars (Walder et al., 2012).

The magnetic field present in the WCR originates from the stars and is geometrically diluted to the position of the WCR, where values of the order of a few mG up to a few tens of mG are expected (Eichler and Usov, 1993; Dougherty et al., 2003). The local magnetic field thus significantly exceeds the typical ambient interstellar field (on the order of a few  $\mu\text{G}$ ). In the WCR, the presence of strong shocks can compress and distort the magnetic field, enhancing magnetic inhomogeneities and turbulence. These turbulent magnetic fluctuations then scatter charged particles and allow them to diffuse across the shock front, enabling the repeated interactions required for DSA to operate, thus favoring particle acceleration.



This particle acceleration process is expected to act on any kind of charged particles present in the stellar winds, i.e., an ionized plasma dominated by protons and electrons, along with some heavier ions such as He. As a result, both leptons and hadrons may, in principle, be accelerated at the shocks.

The maximum energy that particles can reach depends on the competition between the acceleration rate through DSA and several energy-loss mechanisms acting in the WCR. For relativistic electrons, the most important losses typically arise from inverse Compton (IC) scattering in the intense UV radiation field of the massive stars, and synchrotron radiation in the magnetic field (see [Blumenthal and Gould, 1970](#), for a fundamental reference on these processes). The production of synchrotron radiation when spiraling around magnetic field lines in the shocked region makes relativistic electrons of particular importance in the framework of this thesis, because this synchrotron emission is responsible for the non-thermal radio component that can be observed in CWBs (see Sect. 1.3.3). Relativistic protons and heavier ions can also be accelerated by the shocks. Since they are less affected by radiative losses, hadronic particles may potentially reach higher energies than electrons. However, their observational signatures are generally more elusive, as they occur in the  $\gamma$ -ray regime, where current observational facilities often lack the sensitivity required for their detection (see Sect. 1.5).

While the emission resulting from hadronic processes is beyond the scope of this thesis, a brief review of how it concerns CWBs can be found in Sect. 1.5. Although both leptonic and hadronic acceleration are theoretically possible, most observational evidence for particle acceleration in CWBs currently relies on the detection of synchrotron radio emission produced by relativistic electrons. When we can account for the presence of a population of relativistic particles in a CWB, evidenced by the detection of NT emission (whether in the radio or the high-energy domains), we refer to this as a particle-accelerating colliding-wind binary (PACWBs, [De Becker and Raucq 2013](#); [De Becker et al. 2017](#)). To date, there are a few more than 60 CWBs that show clear observational evidence of particle acceleration, compiled in the catalogue of PACWBs<sup>4</sup>.

## 1.3 Observed radio spectrum in massive binaries

In the context of this thesis, we are interested in the emission from massive binary systems in the radio domain. Two main radiative processes account for the radio spectrum observed in PACWBs: Free-free emission (or *Bremsstrahlung*), which is a thermal emission process, and synchrotron emission, which is NT. In thermal emission processes, the population of particles responsible for the emission of radiation presents an energy distribution that follows a Maxwell-Boltzmann law, characterized by a given temperature. In NT processes, the particles responsible for the radiation mechanism are relativistic, and their energies are distributed following a power-law (see Eq. 1.5). The radiation produced by a population of relativistic particles is what we refer to as NT radiation.

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<sup>4</sup>A continuously updated version of the catalogue is available at <https://www.astro.uliege.be/~debecker/pacwb/>.

### 1.3.1 Free-free emission

As mentioned above, the thermal process behind the observed radio spectrum for PACWBs is free-free emission. This is the radiation resulting from the acceleration/deceleration that free electrons undergo when deflected by the Coulomb field of ions, as illustrated in Fig. 1.3. Since the electrons had a continuous distribution of their initial velocities, this process produces a continuous spectrum whose intensity depends on the density distribution and temperature of the plasma.

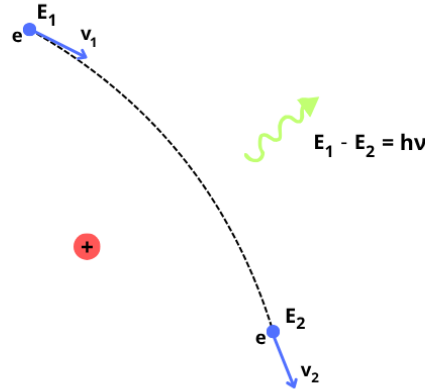


Figure 1.3: Schematic depiction of free-free (or bremsstrahlung) emission. A free electron (e) with initial kinetic energy  $E_1$  and velocity  $v_1$  passes near an ion (in red), interacting with its electric field. The resulting Coulomb force deflects the electron's trajectory and changes its velocity to  $v_2$ , corresponding to a lower kinetic energy  $E_2$ . The electron remains free after the interaction, while its lost kinetic energy is emitted as a photon (in green) with energy  $h\nu$ , where  $h$  is the Planck constant and  $\nu$  is the photon frequency, such that  $E_1 - E_2 = h\nu$ .

In the case of massive stars, thermal free-free emission is produced in their ionized stellar winds. For a spherically symmetric, steady, and isothermal stellar wind, the free-free emission produces the canonical optically thick thermal radio spectrum derived by [Wright and Barlow \(1975\)](#), characterized by a positive spectral index, in which the flux density follows a power-law dependence on frequency of the form

$$S_\nu \propto \nu^{0.6}, \quad (1.7)$$

where  $S_\nu$  is the flux density at frequency  $\nu$ .

However, while assuming a canonical spectral index  $\alpha = 0.6$  works well enough for O-type stars, the case of WR stars deserves some caution. Several studies have shown that the slope of the thermal spectrum for WR winds is usually steeper than expected from the canonical law, with reported spectral indices of up to 0.7–0.8. This behavior is likely related to intrinsic differences between WR and O-star winds, particularly the strong clumping that causes WR winds to depart significantly from the smooth-wind model, as well as changes in the ionization structure of the outflow ([Leitherer and Robert, 1991](#); [Nugis et al., 1998](#); [Montes et al., 2015](#)).

### 1.3.2 Free-free absorption

The same process responsible for free-free emission also produces absorption. Free-free absorption (FFA) occurs when a free electron absorbs a photon while under the Coulomb field of an ion. The electron remains unbound (free) both before and after the interaction, but its kinetic energy is increased to conserve energy and momentum. Details on this process can be found, for instance, in [Condon and Ransom \(2016\)](#) and [Rohlf and Wilson \(2000\)](#). Because stellar winds from massive stars are ionized plasmas, this effect plays a key role in CWBs and the resulting spectrum, especially at lower frequencies.

Radio photons propagating through an ionized plasma (the stellar wind) obey the radiative transfer equation

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu, \quad (1.8)$$

where  $I_\nu$  is the specific intensity at frequency  $\nu$ ,  $s$  is the path length along the line of sight,  $j_\nu$  is the emission coefficient, and  $\alpha_\nu$  is the absorption coefficient.

For a medium in thermodynamic equilibrium and with a source function (defined as the ratio of the emission to absorption coefficients,  $j_\nu/\alpha_\nu$ ) that is constant along the line of sight, the solution of this equation can be written as

$$I_\nu = I_{\nu,0}e^{-\tau_\nu} + B_\nu(1 - e^{-\tau_\nu}), \quad (1.9)$$

where  $I_{\nu,0}$  is the incident intensity at the boundary of the medium,  $B_\nu$  is the Planck function (which is equal to the source function,  $j_\nu/\alpha_\nu$ , in thermodynamic equilibrium), and  $\tau_\nu$  is the optical depth defined as

$$\tau_\nu = \int \alpha_\nu ds. \quad (1.10)$$

The variable  $\tau_\nu$  governs the attenuation of radiation. When  $\tau_\nu \ll 1$ , the medium is optically thin, and radiation escapes with little attenuation. On the contrary, when  $\tau_\nu \gg 1$ , the medium becomes optically thick and opaque, and the observed intensity  $I_\nu$  approaches the Planck function (or its Rayleigh-Jeans approximation at radio wavelengths).

The FFA coefficient in a thermal plasma can be approximated as

$$\alpha_\nu \propto n_e^2 T^{-3/2} \nu^{-2}, \quad (1.11)$$

where  $n_e$  is the electron density,  $T$  the plasma temperature, and  $\nu$  the observing frequency. This relation shows that the absorption decreases rapidly with increasing frequency. This strong frequency dependence implies that FFA primarily affects radiation in the radio regime, particularly at its lower-frequency end. As a result, ionized stellar winds are typically optically thick at sufficiently low radio frequencies and become progressively transparent - or optically thin - toward higher frequencies.

The transition between optically thick and thin regimes produces a turnover in the observed radio spectrum, commonly referred to as the free-free turnover. The turnover frequency  $\nu_t$  at which this transition between spectral regimes occurs can be defined by  $\tau_{\nu_t} \sim 1$ .

Below the turnover frequency, the plasma is optically thick, and radiation is strongly absorbed, while above it the medium becomes optically thin. This regime transition can be equivalently described in terms of the spatial variation of the optical depth within the wind along the line of sight. Radiation produced deep inside the wind may be absorbed before escaping, and the observed radio emission originates only from regions where the optical depth becomes sufficiently small. The radius at which the optical depth reaches unity,

$$\tau_\nu(r) = 1, \quad (1.12)$$

defines the radio photosphere of the stellar wind.

The size of the photosphere depends on the observing frequency, increasing toward lower frequencies (or longer wavelengths) where the free-free opacity is higher. Consequently, radio emission observed at a given frequency arises predominantly from regions located outside the corresponding radio photosphere. Emission produced at smaller radii, closer to the star, within the region where  $\tau_\nu > 1$ , will be significantly attenuated by FFA before escaping the stellar wind. For typical O-type stars, the radio photosphere may extend to several tens or even hundreds of stellar radii at centimeter wavelengths. In the case of WR stars, the situation can be even more extreme. Due to their higher mass-loss rates and thicker, dense winds, WR stars generally present much larger radio photospheres, which can extend to several hundreds or even thousands of stellar radii depending on the wind parameters and observing frequency. Several studies reported on the determination of the size of the radio photosphere for massive stars of various types, including [Abbott et al. \(1986\)](#), [Mahy et al. \(2012\)](#), [Benaglia et al. \(2019\)](#), and [De Becker et al. \(2019\)](#).

### 1.3.3 Synchrotron radiation

In addition to the thermal free-free emission produced in the individual stellar winds, the radio spectrum of PACWBs has the contribution of non-thermal synchrotron radiation generated by the population of relativistic particles accelerated in the WCR. Details on the physics of this radiative process can be found in [Blumenthal and Gould \(1970\)](#), along with textbooks such as [Rybicki and Lightman \(1979\)](#), [Condon and Ransom \(2016\)](#), and [Rohlf and Wilson \(2000\)](#).

Synchrotron radiation is produced when relativistic charged particles propagate in the presence of a magnetic field. A particle of charge  $q$  and mass  $m$  moving with velocity  $\mathbf{v}$  in a magnetic field  $\mathbf{B}$  is subjected to the Lorentz force (expressed below in cgs units),

$$\mathbf{F} = \frac{q}{c} \mathbf{v} \times \mathbf{B}. \quad (1.13)$$

Since this force is perpendicular to the particle velocity, it does not change the magnitude of the velocity but continuously alters its direction. Therefore, the particle follows a helical trajectory around the magnetic field lines. Because the (charged) particle is accelerated, it emits electromagnetic radiation known as synchrotron radiation. This emission process is shown in [Fig. 1.4](#).

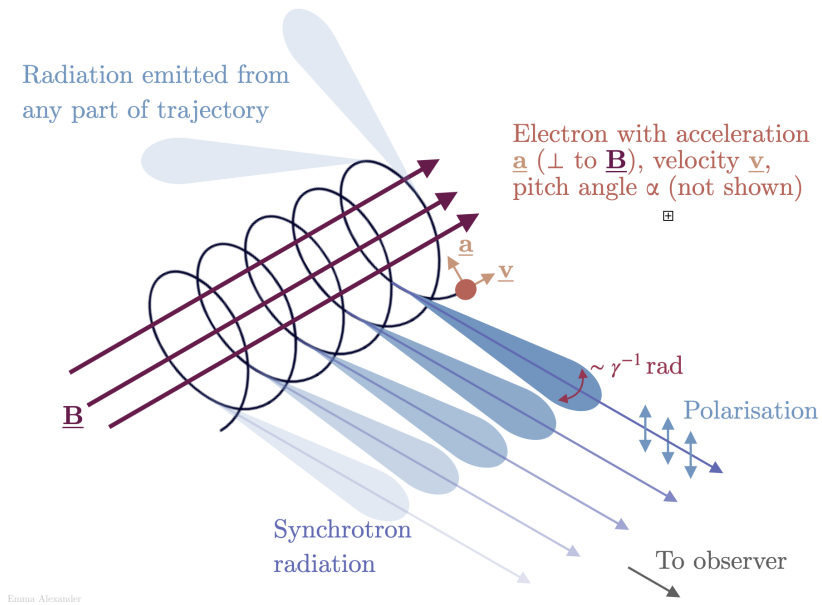


Figure 1.4: Diagram of the emission of synchrotron radiation, arising from an electron moving along a helical path around the lines of an ordered magnetic field. For illustration purposes, the elongated beam due to relativistic beaming, with a half-opening angle of the order of the inverse of the Lorentz factor of emitting electrons, is shown, particularly towards the direction of the observer. The linear polarization of the synchrotron radiation illustrated in the figure will be specifically addressed in Sect. 1.4. Reproduced under CC-BY from [Alexander \(2022\)](#).

For relativistic particles, the emitted radiation is strongly beamed along the direction of motion and is mostly concentrated around a characteristic frequency  $\nu_c$  given by

$$\nu_c = \frac{3}{2} \gamma^2 \frac{eB_\perp}{2\pi m_e c}, \quad (1.14)$$

where  $\gamma$  is the Lorentz factor of the radiating particle (defined as  $\gamma = E/(m_e c^2)$ ),  $e$  and  $m_e$  are the electron charge and mass, and  $c$  is the speed of light. In particular, as can be seen, the characteristic synchrotron frequency increases with increasing particle energy and with the component of the magnetic field perpendicular to the particle velocity,  $B_\perp$ .

In addition, the radiative losses through synchrotron emission scale as

$$P_{\text{syn}} \propto \frac{B^2 \gamma^2}{m^2}, \quad (1.15)$$

where  $B$  is the magnetic field strength and  $m$  is the particle mass. It can be seen that the emitted power is inversely proportional to the square of the particle mass, making synchrotron emission far more efficient for relativistic electrons than for protons.

As detailed in Sect. 1.2.2, in the WCR of PACWBs, there is not a single particle but a population of relativistic electrons, whose energy distribution is typically described by a power-law (see Eq. 1.5). For such a distribution, the resulting synchrotron spectrum is also a power-law,

$$S_\nu \propto \nu^\alpha, \quad (1.16)$$

where the spectral index  $\alpha$  is related to the index of the energy distribution of relativistic electrons  $p$  through

$$\alpha = -\frac{p-1}{2}. \quad (1.17)$$

Hence, measurements of the observed synchrotron spectral index provide direct information about the energy distribution of the relativistic electrons. Remembering that  $p$  is directly dependent on the compression ratio of the shock (see Sect. 1.2.2 and Eq. 1.6), the measurement of  $\alpha$  tells us about the fundamental properties of the shock responsible for the acceleration of relativistic electrons through DSA.

Although synchrotron emission is mainly observed at radio wavelengths, in some astrophysical environments (for instance, young supernova remnants: [van der Swaluw and Achterberg 2004](#); [Vink 2012](#)), it may also extend to optical and X-ray ranges, depending on the relativistic electron energy and magnetic field strength.

### 1.3.4 Observational consequences for PACWBs

While the thermal free-free emission from stellar winds produces a radio spectrum with a positive spectral index (typically  $\alpha \approx +0.6$ , or steeper for WR winds), NT synchrotron emission is characterized by a negative spectral index. Consequently, synchrotron radiation dominates the radio spectrum of PACWBs toward lower radio frequencies, whereas thermal wind emission becomes relatively more important

at higher frequencies. However, the dense stellar winds are not only emitters but also absorbers of low-frequency radiation through FFA, which may partially or completely attenuate the otherwise intrinsically stronger synchrotron emission at low frequencies.

The qualitative behavior described above is illustrated in Fig. 1.5, which shows a schematic radio spectrum that combines thermal and NT contributions and illustrates how FFA attenuates the synchrotron emission at low frequencies, thereby modifying the observed spectrum.

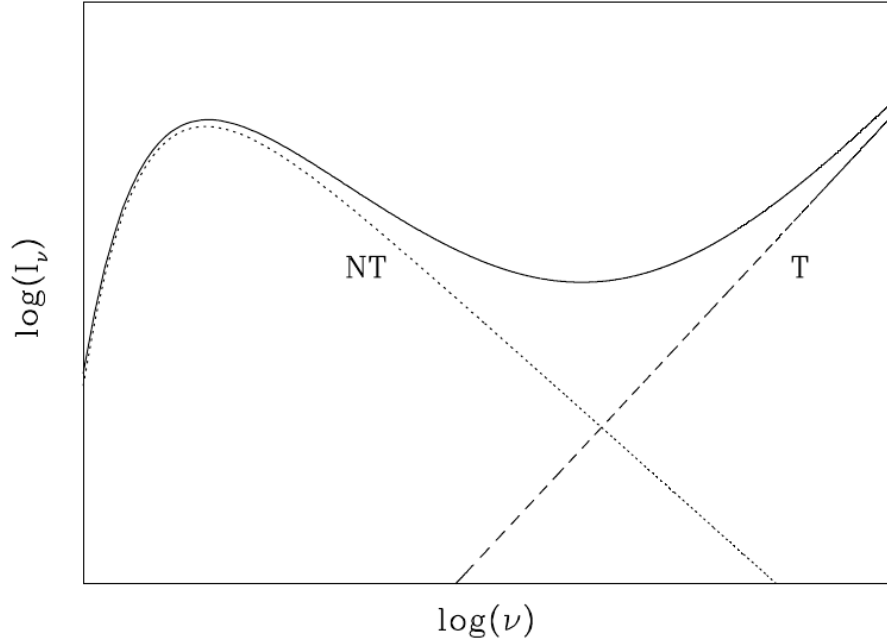


Figure 1.5: Schematic illustration of the radio spectrum expected for a particle-accelerating colliding-wind binary (PACWB). The horizontal axis represents the observing frequency, while the vertical axis shows the radio spectral intensity on a logarithmic scale. The dashed line (T) corresponds to thermal free-free emission from the stellar winds, the dotted line (NT) to non-thermal synchrotron emission, and the solid line to the resulting composite spectrum. At low frequencies, synchrotron emission dominates but may be significantly attenuated by free-free absorption (FFA), while at higher frequencies the thermal wind emission becomes the dominant contribution.

Given the typical angular scales of PACWBs, most current observations do not spatially resolve the individual stars from the WCR. As a result, although the thermal and NT components originate from different physical processes and in different regions of the system, they are generally observed as a composite radio spectrum (Fig. 1.5) reflecting the interplay between synchrotron emission produced in the WCR and thermal emission and absorption processes occurring in the surrounding stellar winds (see Fig. 1.1 for a schematic representation).

The detection of synchrotron radiation in a CWB is a clear indicator of the presence of a population of relativistic electrons, which in turn points to particle acceleration, thereby classifying the system as a PACWB. However, because several



physical processes contribute to the observed unresolved spectrum, detecting synchrotron emission in massive binaries is not always straightforward. In particular, FFA in the stellar winds can strongly affect the observed emission.

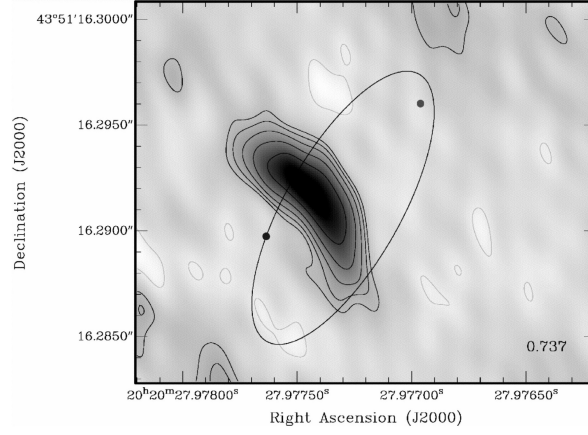
Since the column density of absorbing material along the line of sight varies with orbital phase, the impact of FFA changes throughout the orbit. This can lead to phase-dependent radio variability, and in some cases, the synchrotron emission may be almost completely absorbed at certain orbital phases. FFA, therefore, plays a crucial role in shaping the observed spectral properties and variability of radio emission in massive binary systems.

As a consequence, the detectability of synchrotron emission depends strongly on the observing frequency, the wind densities, and the orbital configuration of the system. In many systems, particularly those with short orbital separations, the WCR where the NT emission is produced may lie deep within the radio photosphere of one or both stellar winds, leading to the synchrotron radiation being undetectable due to FFA. This is very likely the case for WR 11, which is known to be a PACWB thanks to its  $\gamma$ -ray emission without displaying any radio synchrotron signature. Its orbital period of about 80 days makes it too compact to allow NT radio photons to escape from the dense WR wind (Benaglia et al., 2019). Synchrotron radiation may therefore only be detectable in systems with favorable orbital configurations or sufficiently wide separations between the stars, or during specific orbital phases when the line-of-sight absorption is reduced.

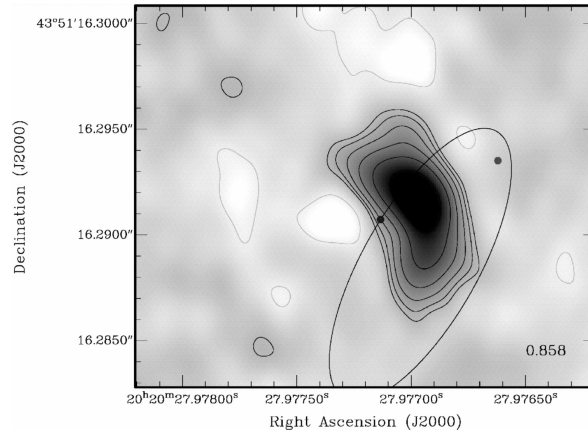
This significantly complicates the identification and characterization of new members of the PACWB class. However, in practice, radio observations remain the primary tool for discovering particle acceleration in CWBs. Radio measurements at two or more frequencies provide a diagnostic of NT emission through the determination of the spectral index. A significant deviation from the behavior expected for purely thermal winds, or the even more direct measurement of a negative spectral index, is commonly interpreted as evidence for a synchrotron component in the radio spectrum (see, e.g., Dougherty and Williams, 2000; De Becker and Raucq, 2013). Additional evidence supporting the PACWB nature of a system may come from mapping the extension and changes of the synchrotron-emitting region between the two stellar winds through high-resolution radio interferometry, providing spatial resolution of the different emission regions. To illustrate this, the PACWB WR 140 provides one of the best-studied examples in which the synchrotron-emitting region has been spatially resolved across different orbital phases using very long baseline interferometry (VLBI) (Dougherty et al., 2005), as shown in Fig. 1.6.

Additionally, in most PACWBs, the observed radio flux density varies with orbital phase as the FFA along the line-of-sight changes throughout the orbit. The observation of phase-dependent radio variability associated with orbital modulation of emission and absorption processes constitutes another piece of information towards unveiling the nature of massive-star emission. For these reasons, multi-band and phase-resolved radio observations are essential for disentangling the various emission and absorption processes operating in PACWBs.

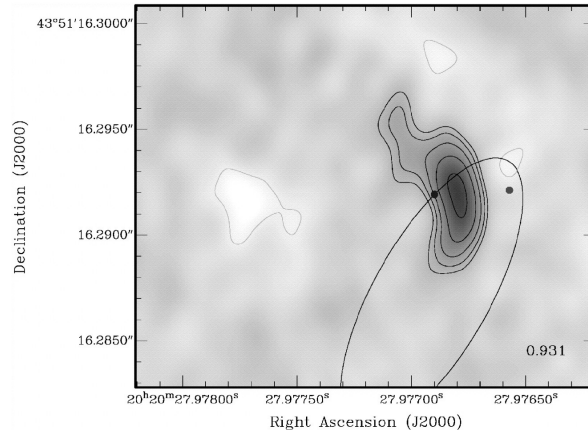




(a) Orbital phase 0.737



(b) Orbital phase 0.858



(c) Orbital phase 0.931

Figure 1.6: Orbit of the system WR 140 projected onto the plane of the sky at three different orbital phases. This binary system is formed by a WC7 star and an O4–5 star in a high-eccentricity orbit. The VLBA 8.4 GHz images show the rotation of the synchrotron emission region as the binary progresses through its orbit (the WR star is always to the right of the WCR in these images). Taken from [Dougherty et al. \(2005\)](#).

## 1.4 Polarization of synchrotron radiation

The synchrotron emission produced by relativistic electrons (described in Sect. 1.3.3) is intrinsically linearly polarized. This property comes from the motion of the particles having a preferential direction: around the magnetic field lines. The emitted radiation, as a result of the Lorentz acceleration, has an electric field vector with a preferred orientation, resulting in polarized emission.

The polarization state of electromagnetic radiation can be described using the Stokes parameters  $I$ ,  $Q$ ,  $U$ , and  $V$ . The total intensity of the radiation is given by  $I$ , while  $Q$  and  $U$  characterize the linear polarization, and  $V$  describes the circular polarization component.

The linear polarization state can be represented by the linear polarization vector

$$\mathbf{P} = Q + iU, \quad (1.18)$$

whose magnitude corresponds to the linearly polarized intensity

$$|\mathbf{P}| = P = \sqrt{Q^2 + U^2} \quad (1.19)$$

and whose orientation is related to the polarization angle

$$\psi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right). \quad (1.20)$$

Figure 1.7 illustrates the relation between the Stokes parameters, the linear polarization vector, and the polarization angle.

The degree of linear polarization is then defined as

$$\Pi = \frac{P}{I} \quad (1.21)$$

and represents the fraction of the total intensity that is linearly polarized.

For a power-law distribution of relativistic electrons (as seen in Eq. 1.5), the degree of linear polarization depends on the spectral index  $p$  of the particle distribution. In the case of a homogeneous, perfectly ordered magnetic field, the maximum (intrinsic) linear polarization degree expected for synchrotron emission is given by the following equation (Rybicki and Lightman, 1979),

$$\Pi_{max}(p) = \frac{p+1}{p+\frac{7}{3}}. \quad (1.22)$$

This yields values as high as  $\sim 70\%$  for  $p = 2-3$ . However, in realistic astrophysical environments, the magnetic field is not perfectly ordered. Magnetic field inhomogeneities and turbulence in the medium (a condition required for the DSA mechanism to take place) significantly reduce the observed degree of polarization. If  $B_r$  represents the random component of the magnetic field and  $B_0$  the ordered component, the resulting degree of polarization can be written as

$$\Pi_{obs} = \Pi_{max}(p) \frac{B_0^2}{B_0^2 + B_r^2}. \quad (1.23)$$

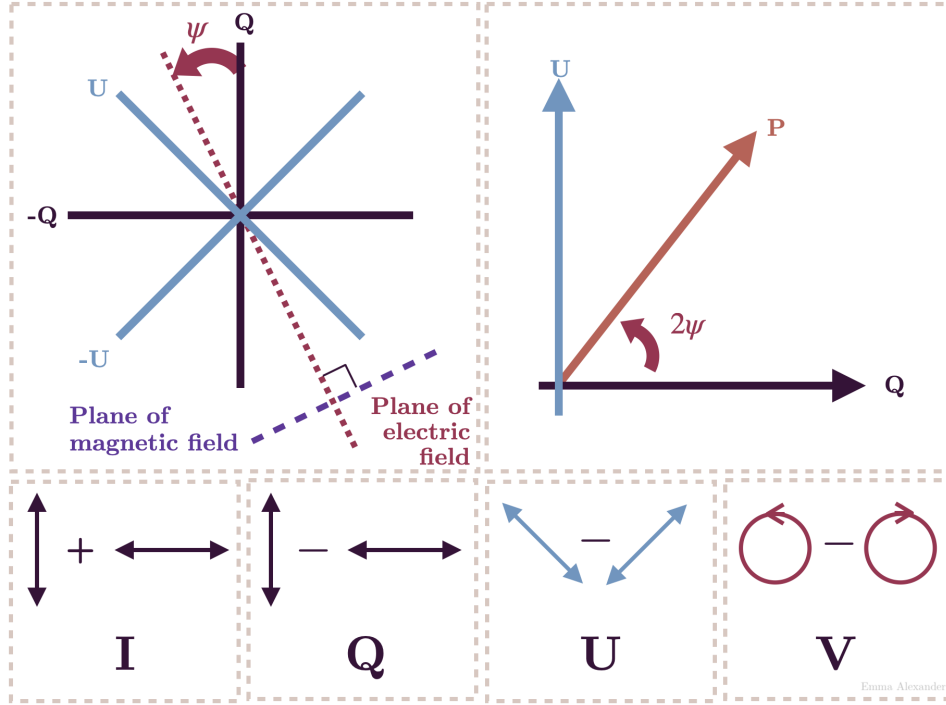


Figure 1.7: Representations of the Stokes parameters in relation to polarization angle  $\psi$ , polarization vector  $\mathbf{P}$ , and the planes of the electric and magnetic fields. Reproduced under CC-BY from [Alexander \(2022\)](#).

In addition to the intrinsic properties of the emitting region, propagation effects can further modify the observed polarization. In particular, when linearly polarized radiation propagates through a magnetized ionized medium, its polarization angle is rotated due to Faraday rotation ([Burn, 1966](#)). The observed polarization angle  $\psi$  is related to the intrinsic angle  $\psi_0$  as

$$\psi = \psi_0 + \text{RM} \lambda^2, \quad (1.24)$$

where  $\lambda$  is the observing wavelength, RM is the rotation measure (in  $\text{rad m}^{-2}$ ), and the term  $\theta = \text{RM} \lambda^2$  represents the Faraday rotation angle. The RM scales as

$$\text{RM} \propto \int n_e B_{\parallel} dl, \quad (1.25)$$

with  $n_e$  the free electron density,  $B_{\parallel}$  the component of the magnetic field along the line of sight, and  $dl$  the differential path length along the line of sight. Figure 1.8 illustrates the effect of Faraday rotation on a linearly polarized wave propagating through a magnetized plasma of length  $L$  between the source and the observer.

In astrophysical environments, Faraday rotation can be responsible for various depolarization mechanisms that reduce the observed polarization degree. These are the result of the amount of Faraday rotation varying either along the line of sight or across the observing beam. These variations in polarization angle can lead to a partial cancellation of the linearly polarized signal (the Stokes  $Q$  and  $U$  parameters)

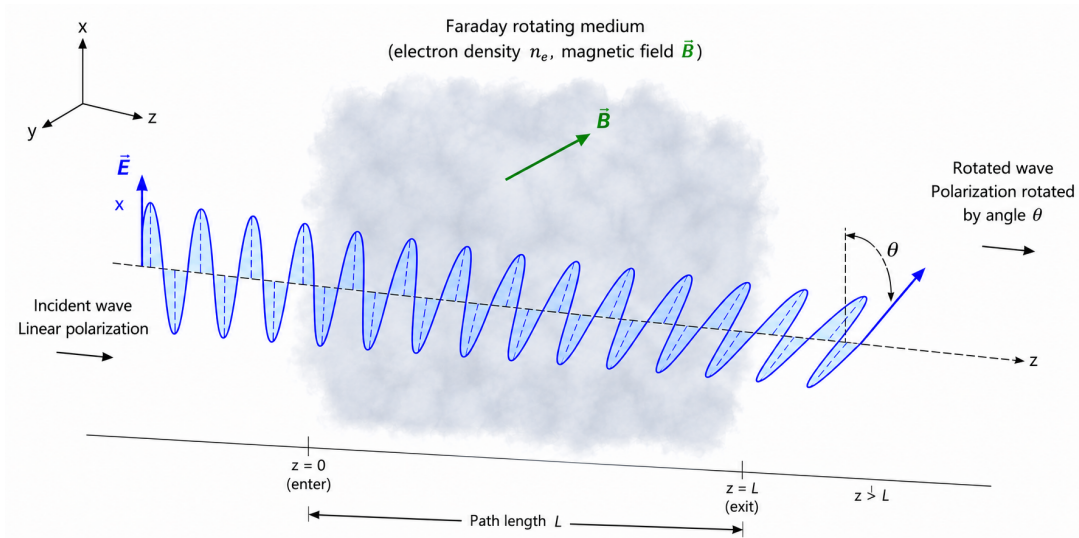


Figure 1.8: Schematic representation of Faraday rotation. A linearly polarized wave propagates through a magnetized ionized medium, which causes the rotation of the plane of polarization. Although the direction of the magnetic field illustrated in the cloud is randomly chosen, only its projection onto the direction of propagation of the radio waves (along the  $z$ -axis) participates in the Faraday rotation process.

when contributions with different polarization angles are averaged together, thereby reducing the observed degree of polarization.

The depolarization mechanisms include external Faraday depolarization, which occurs when the rotation takes place in a foreground magnetized plasma (see Fig. 1.8), and internal Faraday depolarization, which occurs when the emitting and rotating media coexist, so that radiation originating at different depths within the source experiences different amounts of rotation (because of the difference in path length, see Fig. 1.9).

In addition to these physical effects, observational limitations can also reduce the measured polarization. Bandwidth depolarization can occur when the polarization angle varies significantly across the observing bandwidth due to the  $\lambda^2$  dependence of Faraday rotation. This implies that different frequencies within the band experience different amounts of Faraday rotation. Averaging the signal over the entire bandwidth then leads to a partial cancellation of the polarization signature, reducing the observed degree of polarization, particularly at longer wavelengths or in regions with large RM. Similarly, beam depolarization occurs when regions in the sky with different polarization angles are unresolved within the observing beam, further enhancing the cancellation of the polarized emission. These depolarization mechanisms (illustrated in Fig. 1.10) are the result of different effects, but they all share the same consequence: intrinsically polarized signals with different polarization angles are averaged together, causing a reduction in the observed degree of polarization.

A more comprehensive review of the measurement of polarization in synchrotron radiation across different astrophysical sources will be presented in Chapter 4. In particular, in the context of PACWBs, the depolarization effects described are espe-

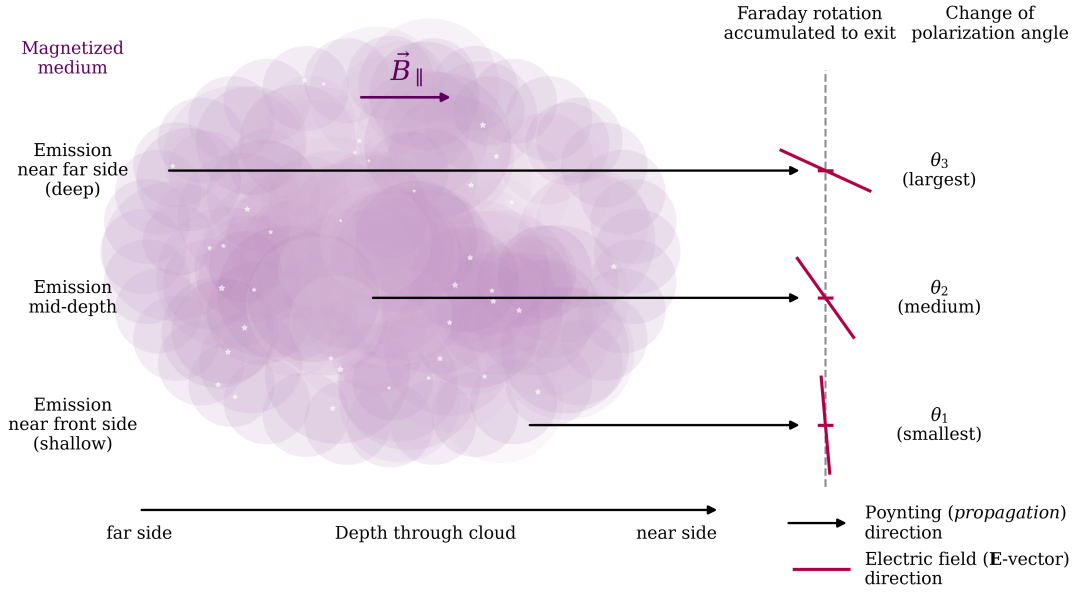


Figure 1.9: Schematic representation of the internal Faraday rotation depolarization mechanism. The purple medium both produces polarized synchrotron emission and Faraday-rotates its polarization angle. As the radiation propagates through the magnetized plasma, the polarization angle rotates progressively due to the component of the magnetic field parallel to the propagation direction (i.e., along the Poynting vector). Since emission originating at different depths travels through different path lengths within the rotating medium, the accumulated Faraday rotation differs, resulting in different polarization angles when the radiation emerges. The vector sum of these differently oriented polarization components has a reduced net polarized intensity, producing depolarization.

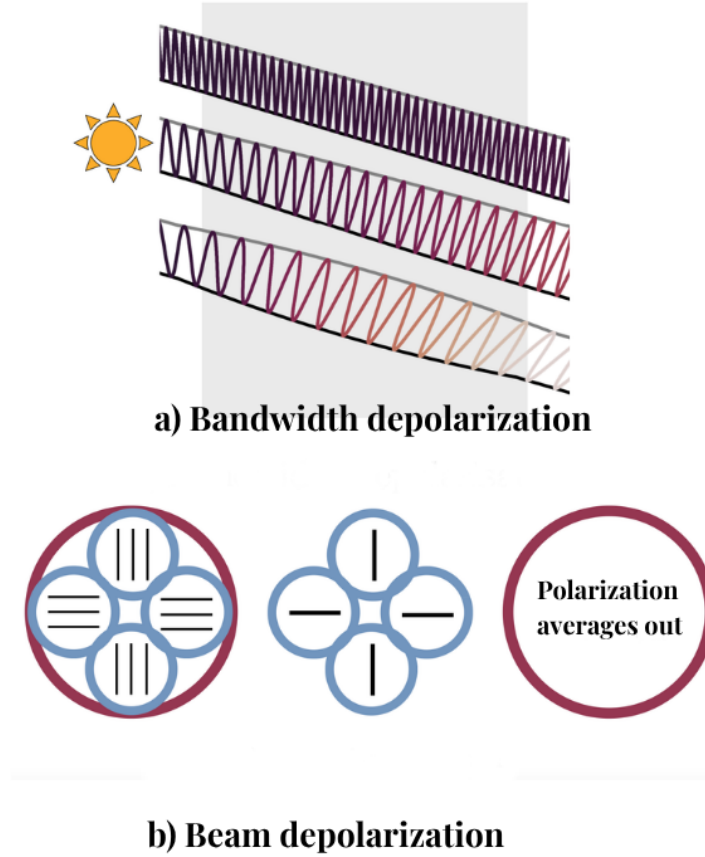


Figure 1.10: Schematic representation of common observational depolarization mechanisms affecting polarized radio emission. (a) Bandwidth depolarization: this is the result of the polarization angle changing significantly across a finite observing bandwidth due to the  $\lambda^2$  dependence of Faraday rotation. As a result, if the frequency resolution is not enough to sample this dependence, signals at different frequencies will contribute with different polarization angles, and averaging over the entire bandwidth will reduce the net observed polarization. (b) Beam depolarization: it arises from the limited spatial sampling, and averaging over unresolved spatial regions with different polarization orientations (indicated within the small circles) within the beam (red circle). Different polarization angles from the individual contributions cancel out, and the net effect is a reduction in the observed polarization degree. Figure adapted from [Alexander \(2022\)](#).

cially important. The shocked gas where synchrotron emission is produced, and the dense and highly ionized stellar winds that said emission has to go through on its way to the observer, provide a magnetized environment that can induce strong Faraday rotation and its resulting depolarization, especially at longer radio wavelengths (see Eq. 1.24). While polarization measurements, if available, could provide valuable constraints on both the magnetic field structure and the properties of the circumstellar environment in PACWBs, the detection of polarized synchrotron emission in these systems is especially challenging, and the measured polarization fraction could be significantly lower than the expected intrinsic value.

## 1.5 High-energy counterparts

In addition to synchrotron and free-free emission in the radio domain, PACWBs are expected to emit across a broad range of the electromagnetic spectrum as a result of both thermal and NT processes.

On the one hand, thermal X-ray emission is produced in CWBs. Although individual stellar winds contribute to some soft X-ray emission, the high Mach number shocks due to colliding winds in massive binaries often constitute a much brighter source of thermal X-rays. The shocked, heated plasma in the WCR can reach temperatures of the order of  $10^7$ – $10^8$  K, leading to thermal X-ray emission modulated by the orbital movement (Stevens et al., 1992; Pittard, 2010).

On the other hand, on top of thermal processes, NT mechanisms can also contribute to the high-energy emission in PACWBs. Relativistic electrons accelerated in the WCR can interact with ambient photon fields, primarily stellar radiation, through IC scattering (Blumenthal and Gould, 1970). In this process, lower-energy photons gain energy from the electrons and are scattered up to the X-ray and  $\gamma$ -ray domains. Relativistic electrons can also produce high-energy emission via relativistic bremsstrahlung through interactions with ions in the stellar winds, yielding  $\gamma$ -ray photons. Given the intense radiation fields produced by massive stars and the typical ambient densities, IC cooling is often the dominant energy loss mechanism for relativistic electrons in these systems. In the X-ray domain, thermal emission from the WCR likely dominates up to photon energies of 10 to 20 keV, masking any NT component at soft X-ray energies. This means that unveiling NT X-ray emission from CWBs requires investigating higher energies, namely the hard X-ray regime ( $\gtrsim 10$  keV) (De Becker, 2007).

Besides leptonic processes, hadronic interactions may contribute to the high-energy emission. Protons and other ions are accelerated through DSA in the WCR too, and can interact with nuclei from the wind through proton-proton ( $pp$ ) collisions, producing secondary particles including neutral pions ( $\pi^0$ ). These pions are unstable and decay rapidly into pairs of  $\gamma$ -ray photons ( $\pi^0 \rightarrow \gamma + \gamma$ ), providing a direct channel for  $\gamma$ -ray emission. This mechanism becomes more efficient in environments with high particle densities, such as in the wind interaction region of winds colliding at sufficiently high densities (Reitberger et al., 2014, 2017).

Despite these mechanisms taking place in PACWBs, the detection of NT high-energy emission from these systems remains challenging. In most cases, the expected



fluxes fall below the sensitivity limits of current X-ray and  $\gamma$ -ray instruments. To date, only a few PACWBs have been detected at high energies. The source  $\eta$  Carinae is the only confirmed system to radiate both  $\gamma$ -rays and hard NT X-rays (Tavani et al., 2009; Abdo et al., 2010; Hamaguchi et al., 2018). Another system, WR 11 ( $\gamma^2$  Velorum), has been associated with  $\gamma$ -ray emission detected by the Fermi Gamma-ray Space Telescope (Martí-Devesa et al., 2020), likely of hadronic origin.

NT X-ray emission has been identified in only a small number of PACWBs. In addition to  $\eta$  Carinae, the system Apep has been reported as an NT X-ray emitter (del Palacio et al., 2023). Notably, Apep is currently the only PACWB known to exhibit both NT radio and NT X-ray emission. Fig. 1.11 shows an example of a modeled broadband NT SED for Apep, illustrating different predicted synchrotron, IC, and hadronic contributions across the entire electromagnetic spectrum, from radio to  $\gamma$ -rays. Nevertheless, tentative evidence of an NT X-ray component has also been reported in the PACWB HD 93129A (del Palacio et al., 2020), whose NT radio emission has been well documented (see, e.g., Benaglia and Koribalski, 2004; Benaglia et al., 2006, 2025).

Interestingly, not all systems detected at high energies show clear evidence of synchrotron emission at radio wavelengths. In the case of  $\eta$  Carinae, this is generally attributed to strong FFA within its dense stellar winds, which likely suppresses any intrinsic synchrotron emission. Similarly, in the case of WR 11, the observed radio spectrum is consistent with pure thermal emission, with any NT component likely hidden below the turnover frequency (Benaglia et al., 2019). Such a diversity highlights the difficulty of linking high-energy emission with observable synchrotron radiation in PACWBs.

Overall, while multi-wavelength observations can provide insights into the population of relativistic particles in the WCR and the different energy loss mechanisms in PACWBs, radio interferometric observations remain the most sensitive and suitable probe of NT processes in these systems. In particular, synchrotron emission offers a direct tracer of relativistic electrons and magnetic fields in the WCR, making it the key tool for studying particle acceleration in CWBs.

## 1.6 Cosmic rays

Cosmic rays (CRs) are highly energetic charged particles that diffuse through the Universe, spanning a wide range of energies from  $\sim 1$  MeV up to beyond  $10^{20}$  eV. They are composed predominantly of hadrons, mainly protons, along with some He and heavier nuclei, with only a small leptonic (electrons and positrons) component.

The observed CR energy spectrum follows a power-law distribution over many orders of magnitude, with notable features such as the ‘Knee’ at  $\sim 10^{15}$  eV and the ‘Ankle’ at  $\sim 10^{18}$  eV. These spectral breaks, characterized by changes in the power-law index, are commonly interpreted as signatures of different acceleration mechanisms and/or source populations. At the highest energies, an extragalactic origin is widely accepted, while at lower energies (up to at least the Knee), CRs are believed to be predominantly Galactic.



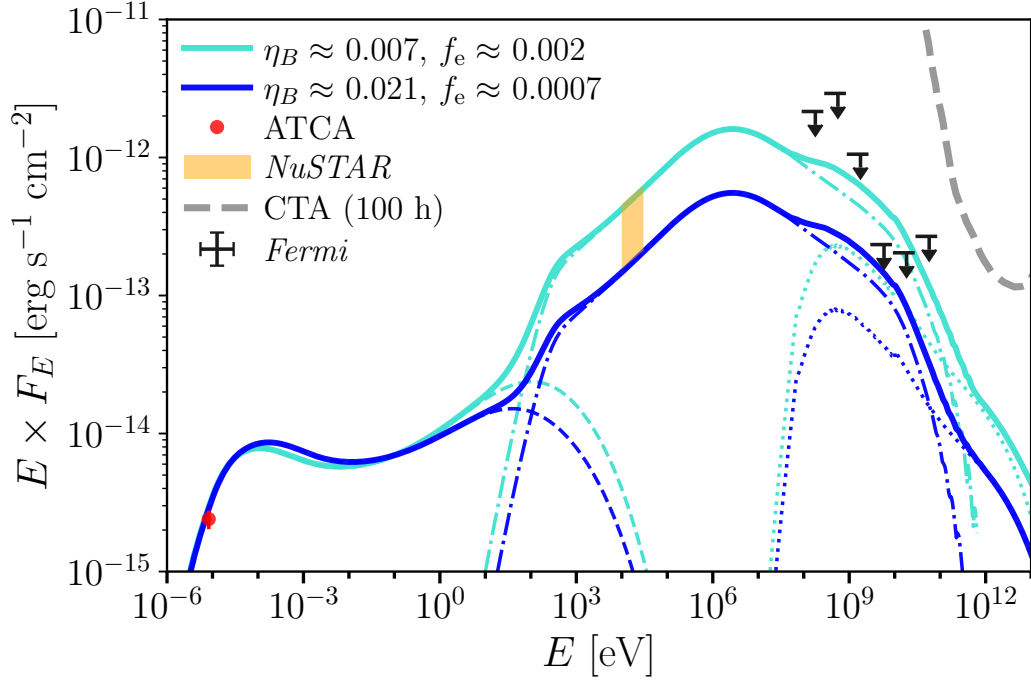


Figure 1.11: Example of a modeled broadband NT SED for the PACWB Apep, taken from [del Palacio et al. \(2023\)](#) and references therein. The different curves represent the synchrotron, IC, and  $pp$  contributions to the NT emission, together with the total predicted SED, for two different models (cyan and blue), with different values of  $\eta_B$  (the magnetic to thermal pressure ratio) and  $f_e$  (the fraction of energy injected into shocks transferred to relativistic electrons), that are compatible with the detected NT X-ray (*NuSTAR*) and radio (ATCA) observations. Dashed lines show the synchrotron component, dot-dashed lines the IC component, dotted lines the  $pp$  component, and solid lines the total SED. The Fermi-LAT upper limits and the sensitivity curve of the Cherenkov Telescope Array Observatory (CTA) are also shown. The figure illustrates how particle acceleration in the WCR can produce radiation across a broad range of the electromagnetic spectrum, from radio wavelengths to high-energy  $\gamma$  rays, with different radiation mechanisms dominating at different energies.

Due to their charged nature, CRs are subject to magnetic forces and get deflected by fields in the Galactic environment, which alters their trajectories and prevents a direct identification of their sources. Because of this, their origin must be inferred in other ways.

Within the Milky Way, several classes of astrophysical objects have been proposed as potential sources of Galactic CRs (GCRs). Supernova remnants (SNRs) are considered the primary contributors, as they can efficiently accelerate particles via DSA at their expanding shock fronts (especially young remnants, for which shock velocities are highest) while also providing an energy budget sufficient to sustain (to some extent) the observed GCR population (e.g. [Vink, 2020](#)). Other secondary candidate sources include pulsars, X-ray and  $\gamma$ -ray binaries, and strong stellar winds of massive stars. In this context, PACWBs represent an additional class of GCR accelerators, through the mechanism described in Sect. 1.2.2. While PACWBs are not expected to compete with SNRs in terms of their global contribution to the GCR population, they may still play a non-negligible role at lower energies and in specific environments that remain to be quantified ([De Becker et al., 2024a](#)). In particular, their continuous injection of energetic particles, combined with their relatively long lifetimes compared to transient events (such as SN explosions), makes them valuable laboratories for studying particle acceleration under steady-state conditions. Assessing their contribution could therefore provide a more complete picture of high-energy processes in the Galaxy.

## 1.7 Open questions and thesis goals

As discussed in the previous sections, PACWBs represent a subcategory of massive binaries capable of accelerating particles to relativistic energies. These systems provide unique laboratories for studying particle acceleration under conditions that differ significantly from those encountered in other Galactic sources, such as supernova remnants. In particular, PACWBs offer the opportunity to investigate particle acceleration in steady or periodically modulated shock environments, as well as the production and propagation of NT radiation in dense stellar surroundings.

Despite the progress achieved over the past decades, several key questions remain open. One of the main challenges lies in determining whether particle acceleration is a common property of CWBs or rather a phenomenon restricted to a subset of systems, in only a certain parameter space. The current census of PACWBs is likely affected by significant observational biases, as synchrotron emission can be partially or even completely absorbed by the surrounding stellar winds or diluted by the thermal contribution of free-free emission, particularly in systems containing a WR component. As a result, the known sample might be incomplete and not fully representative of the underlying population. A more systematic identification of PACWBs is therefore required to better constrain their true occurrence rate and to assess whether all massive binaries can host particle acceleration under suitable conditions.

Another major open question concerns the magnetic field properties in the WCR. While synchrotron emission provides indirect evidence for the presence of magnetic

fields, their geometry and degree of ordering remain largely unconstrained. In this context, radio polarimetry offers a powerful probing tool, since synchrotron radiation is intrinsically linearly polarized and can, in principle, trace the magnetic field structure. However, polarization studies of PACWBs remain extremely unexplored. To date, there has been only a single dedicated attempt (Hales et al., 2017), which did not lead to a clear detection, possibly due to a combination of depolarization effects (e.g., Faraday rotation and beam depolarization) and intrinsically complex or turbulent magnetic field configurations within the WCR, rather than an absence of polarized emission itself. In any case, most PACWBs have never been targeted with sensitive polarimetric observations, and the parameter space explored so far is limited.

Radio observations play a central role in addressing these questions. While multi-wavelength studies can provide valuable insight into the population of relativistic particles and the associated emission processes, their applicability is often limited by sensitivity thresholds and absorption effects, particularly at high energies. In contrast, radio observations offer a more direct and sensitive probe of NT processes in PACWBs through the detection of synchrotron emission, which directly traces the presence of relativistic electrons. This is why PACWBs are primarily identified through the detection of NT radio emission (De Becker and Raucq, 2013). Key diagnostics include the behavior of the spectral index of the emission, variability with orbital phase (not expected for steady thermal wind emission), and, in some cases, spatially resolved emission from the WCR using high-resolution interferometry (see, e.g., De Becker et al., 2024b).

In this context, the primary objectives of this thesis are twofold:

- (i) To investigate how radio observations can participate in improving the census of PACWBs and to identify what are the main challenges preventing us from identifying them
- (ii) To investigate whether, as synchrotron sources, PACWBs are valid targets for polarimetric studies and what to expect from such measurements

By addressing these questions, this work aims to advance our understanding of particle acceleration in stellar environments and to situate the role of PACWBs within the broader context of Galactic high-energy sources. Furthermore, this thesis involves the development and application of advanced radio interferometric data reduction and analysis techniques, applied to observations obtained with different facilities, providing the methodological framework required to extract and interpret the observational signatures of NT processes in massive binary systems.

The structure of this thesis is as follows. In Chapter 1, we introduce the theoretical framework of massive stars, binary interactions, and the associated radiative processes relevant to this work. Chapter 2 presents the fundamentals of radio astronomy, with a particular focus on radio interferometry, and describes the calibration and data reduction techniques used throughout the thesis. In Chapter 3, we present a search for synchrotron emission in a sample of WR stars with hints of binarity

using Giant Metrewave Radio Telescope (GMRT) observations, to identify new candidate PACWBs and explore the synchrotron–binarity correlation. In Chapter 4, we use Very Large Array (VLA) observations to investigate the polarimetric properties of two well-known PACWBs, aiming to assess the presence or absence of detectable polarized synchrotron emission. In Chapter 5, we present Australia Telescope Compact Array (ATCA) observations and associated data analysis, including proposal preparation, observational setup, and data processing, with the goal of expanding the studied sample and exploring additional candidate systems. Finally, in Chapter 6, we summarize the main conclusions of this work and outline some future perspectives.

# Chapter 2

## Radio data and observational techniques

Radio astronomy studies the Universe through the detection of electromagnetic radiation at wavelengths ranging from sub-millimeter to kilometer scales. Unlike in other parts of the electromagnetic spectrum, where the observable is the incoming photon flux, in the radio regime the measured quantity is the time-varying voltage induced in a receiver by incident electromagnetic waves. Through appropriate signal processing, we can recover information about the intensity and physical properties of the emitting source from the incoming signal.

Since this thesis focuses on astrophysical processes traced at radio wavelengths and relies on interferometric observations, it is helpful to first introduce some basic concepts underlying radio astronomical data. This chapter provides a brief overview of observational and data analysis techniques commonly used in radio astronomy, starting from the fundamental principles of signal detection in single antennas, progressing toward radio interferometry, and including a description of data reduction, calibration, and imaging techniques. This chapter is primarily based on standard references in radio astronomy and interferometry, particularly *Synthesis Imaging in Radio Astronomy* (Perley et al., 1989), *Essential Radio Astronomy* (Condon and Ransom, 2016), the NRAO Continuum calibration tutorial (NRAO CASA Team, 2024), and lecture notes from the European Radio Interferometry School (ERIS).

### 2.1 Basics of radio astronomy instrumentation

#### 2.1.1 Radio signal and instrumental response

Contrary to optical observations, radio measurements rely on the detection of the electric field of incoming electromagnetic waves.

In radio astronomy, a radio telescope is an instrument that collects and converts incident electromagnetic radiation into electrical signals. This resulting voltage signal is then processed by the receiving system to extract amplitude and phase information. A common design used in radio telescopes is the parabolic reflector antenna, in which a metallic reflecting surface shaped as a paraboloid redirects incident plane waves toward a focal point where the receiver is located. The defining

property of the paraboloid is that all rays from an incoming plane wave are reflected along paths of equal length and therefore arrive at the focus in phase. As a result, the electromagnetic signal is coherently combined at the receiver, maximizing the detected power. Once concentrated at the focus, the incident radiation is detected by the receiving system and converted into a measurable voltage signal.

The response of the antenna to incoming radiation is not isotropic, but instead characterized by a directional sensitivity function known as the antenna beam pattern (or radiation pattern), which describes the antenna's sensitivity as a function of direction in the sky. This pattern typically has a dominant central region, the main lobe, where the response reaches its maximum, and most of the received power is concentrated. In addition, the pattern includes side lobes, corresponding to directions where the antenna retains non-negligible sensitivity, as well as nulls where the response is suppressed. Although their amplitude is lower than that of the main lobe, side lobes are generally undesirable, as they allow radiation from off-axis sources to contribute to the measured signal, potentially introducing contamination from regions outside the target field.

The angular region around the main lobe over which the antenna maintains significant sensitivity is commonly referred to as the primary beam. This region defines the field of view (FoV) of the instrument, which is often characterized by the angular width of the main lobe, approximated by its full width at half maximum (FWHM). The same quantity also sets the angular resolution of the telescope, as it determines the response to a point source in the sky. The angular resolution of a radio telescope is limited by diffraction (given the finite size of the antenna aperture). For an antenna of diameter  $D$ , the characteristic angular width of the main lobe scales approximately as

$$\theta \sim \frac{\lambda}{D}, \quad (2.1)$$

where  $\theta$  is the angular size of the beam (typically identified with the FWHM of the main lobe) and  $\lambda$  is the observing wavelength. This relation indicates that, at the same wavelength, larger antennas produce narrower beams, improving the angular resolution. For instance, the 100-m Effelsberg radio telescope observing at  $\lambda \sim 21$  cm achieves an angular resolution (or beam width) of approximately  $9'$ . Smaller dishes or observations at longer wavelengths yield broader beams and can result in angular scales of the order of degrees.

Another important parameter is the effective collecting area,  $A_{\text{eff}}$ , which quantifies how much power from an incoming electromagnetic wave is captured by the antenna. A larger collecting area results in a stronger detected signal for a given source, and therefore improves the sensitivity of the instrument.

### 2.1.2 System temperature and antenna sensitivity

The sensitivity of a radio telescope can be understood as its ability to detect faint signals in the presence of noise. It is therefore fundamentally limited by the noise level of the system, which sets the minimum detectable signal for a given observation. In radio astronomy, noise is commonly expressed in terms of an equivalent

temperature. This convention comes from the fact that both the intrinsic noise of the instrument (generated by the random thermal motion of electrons) and the radiation entering the antenna can be described in terms of their associated power, which is proportional to temperature. Thus, different contributions to the observed signal (whether instrumental or environmental) can be expressed using a temperature scale.

In practice, several sources of noise contribute to the observed signal, arising both within the instrument and from the surrounding environment, each of which can be expressed in terms of an equivalent noise temperature. The total system temperature is given by the sum of these contributions,

$$T_{\text{sys}} = T_{\text{rec}} + T_{\text{spill}} + T_{\text{atm}} + T_{\text{sky}}, \quad (2.2)$$

where  $T_{\text{rec}}$  is a measure of the receiver noise, typically of the order of a few tens of Kelvin for cooled systems,  $T_{\text{spill}}$  accounts for ground emission entering through the side lobes,  $T_{\text{atm}}$  represents atmospheric emission, and  $T_{\text{sky}}$  corresponds to the background sky radiation. The relative importance of these terms depends on the observing conditions and frequency. Atmospheric emission becomes increasingly significant at higher frequencies, while  $T_{\text{sky}}$  depends strongly on both the observing direction and frequency, being dominated at low frequencies by Galactic synchrotron emission, particularly along the Galactic plane, in addition to a nearly isotropic contribution of approximately 3 K from the cosmic microwave background.

The sensitivity of an observation depends not only on the system temperature but also on observational parameters. Increasing the observing bandwidth  $\Delta\nu$  or the integration time  $t$  reduces the noise level, thereby improving the detectability of faint signals with wider bandwidths and longer integration times. This dependence is quantified by the radiometer equation

$$\sigma_T \propto \frac{T_{\text{sys}}}{\sqrt{n_p \Delta\nu t}}, \quad (2.3)$$

where  $\sigma_T$  is the root-mean-square (rms) noise in temperature units,  $T_{\text{sys}}$  is the system temperature and  $n_p$  is the number of independent polarization channels (typically  $n_p = 2$  when two orthogonal polarizations are combined). This equation indicates that the relevant quantity for signal detection is the rms noise level rather than the system temperature itself. In addition, the sensitivity of an antenna depends on its  $A_{\text{eff}}$ , scaling approximately with the ratio  $A_{\text{eff}}/T_{\text{sys}}$ , which indicates that high sensitivity requires both a large effective collecting area and a low system temperature.

The antenna temperature,  $T_A$ , is the power received by the antenna from the sky, expressed in units of temperature, and can be directly related to the flux density  $S_\nu$  of the observed source. The radiation collected by the antenna over its effective area,  $A_{\text{eff}}$ , produces a power that can be expressed either in terms of flux density or temperature. This leads to a proportionality between the two quantities,  $S \propto T_A/A_{\text{eff}}$ , indicating that a given source flux density corresponds to a higher antenna temperature for larger collecting areas. This relation provides the link between the physical properties of the source, typically expressed in units of flux density (Jy<sup>1</sup>),

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<sup>1</sup>The Jansky (Jy) is a unit of spectral flux density equal to  $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ , or  $10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$ .

and the sensitivity and measured signal in the receiver.

Finally, the quality of an observation is often characterized by its signal-to-noise ratio, defined as the ratio between the detected signal and the noise level, as well as by the dynamic range of the resulting image, i.e., the ratio between the brightest and faintest signals that can be detected simultaneously. Higher values of both quantities reflect better data quality, allowing for the detection of fainter features and a more accurate characterization of emission across a wide range of intensities.

### 2.1.3 Signal sampling and observational parameters

Radio observations are performed over finite frequency ranges, defined by the bandwidth of the receiver,  $\Delta\nu$ , which corresponds to the difference between the maximum and minimum observable frequencies within a given band. Depending on the instrument and scientific goals, bandwidths can range from tens of MHz to several GHz.

In practice, in many cases, the total observing bandwidth is often divided into several smaller sub-bands, or spectral windows (SPWs), each of which is processed independently. Each SPW is further subdivided into frequency channels of equal width, which provide the spectral sampling of the signal. Each channel corresponds to a narrow frequency range and is treated as an independent measurement.

The width of these channels determines the spectral resolution of the observation. Narrow channels allow for the resolution of fine spectral features and enable the study of velocity structures through Doppler shifts, while wider channels increase the signal-to-noise ratio by averaging over a larger frequency range. In particular, the separation into narrow sub-bands helps the identification and removal of narrow-band radio-frequency interference (RFI, see Sect. 2.3.1), as well as the analysis of frequency-dependent properties of the observed emission. The division of the signal into frequency channels also enables the measurement of flux density across different SPWs within the same total bandwidth, rather than as a single value averaged over the entire band.

## 2.2 Fundamentals of radio interferometry

So far, we have discussed the basic principles of single-dish radio astronomy, where the observable is the total received power collected by a single antenna. As we have seen, the angular resolution is fundamentally limited by Eq. 2.1, meaning that finer resolution can only be achieved by increasing the dish diameter. In optical astronomy, for example, this is less restrictive because short wavelengths (hundreds of nanometers) allow even meter-sized telescopes to reach sub-arcsecond resolution. In radio astronomy, however, the situation is very different.

The much longer wavelengths involved make high angular resolution difficult to achieve with a single dish, since it would require impractically large apertures. For example, achieving a resolution of  $\approx 1$  arcsecond at 21 cm would require a single dish with a diameter of roughly 50 km. This key limitation motivates radio interferometry: instead of building a single enormous telescope, multiple smaller antennas are distributed over large distances and used together simultaneously. By correlating the signals from each antenna pair, the array achieves the angular resolution



of one telescope with a diameter comparable to the largest antenna separation (the maximum baseline  $B_{\max}$ ), while still using much smaller collecting elements. The sensitivity, however, is still determined by the total collecting area (the total area of the individual antennas).

In this way, the achievable angular resolution is set approximately by  $\theta \sim \lambda/B_{\max}$  rather than  $\lambda/D$ , enabling orders-of-magnitude improvement in imaging detail at a given radio wavelength. This technique, known as aperture synthesis, forms the basis of interferometric observations.

However, rather than forming an image directly (or measuring the sky brightness distribution), an interferometer samples the spatial coherence of the incoming radiation by correlating the voltages measured at pairs of antennas, which are related to the incident electric field at each antenna.

For a baseline formed by antennas  $i$  and  $j$  as illustrated in Fig. 2.1, the fundamental observable is known as the visibility, and is defined as

$$V_{ij} = \langle v_i(t) v_j^*(t) \rangle, \quad (2.4)$$

where  $v_i$  and  $v_j$  are the complex voltages measured at each antenna after the received electromagnetic signal has been converted by the receiving system, and  $\langle \rangle$  denotes a time average.

Because the antennas are separated by a finite distance, the same wavefront reaches each antenna at slightly different times. This geometric delay introduces a relative phase difference between the signals (see Fig. 2.1). The resulting correlation between the signals, i.e., the visibility, is therefore a complex quantity, and can be written as

$$V = |V| e^{i\phi}, \quad (2.5)$$

where the amplitude  $|V|$  reflects the strength of the correlated signal, which is related to the flux density of the source, while the phase  $\phi$  encodes information about the source position.

The relationship between the measured visibilities and the sky brightness distribution is described by the Van Cittert–Zernike theorem. Before introducing this relation, it is useful to define the coordinate systems commonly used in radio interferometry. These coordinate systems are represented in Fig. 2.2.

The geometry of an interferometer is described by the projected baseline vector between two antennas, expressed in units of the observing wavelength  $\lambda$ . This vector is represented by the coordinates  $(u, v, w)$ , where  $u$  and  $v$  are the baseline components projected onto the plane perpendicular to the source direction (in the east–west and north–south directions, respectively, in the sky plane), while  $w$  is the component along the line of sight. The  $(u, v)$  plane is commonly referred to as the Fourier plane. Similarly, positions on the celestial sphere are described using the direction cosines  $(l, m, n)$  with respect to the  $w$ -axis. The coordinates  $l$  and  $m$  are the angular offsets in the east–west and north–south directions, respectively, while  $n = \sqrt{1 - l^2 - m^2}$  warrants the unitary length of the vector  $(l, m, n)$ .

For radio interferometric observations covering a sufficiently small field of view, the curvature of the celestial sphere can be neglected. Under this small-field approximation, the effects associated with the  $w$ -term are negligible. This approximation

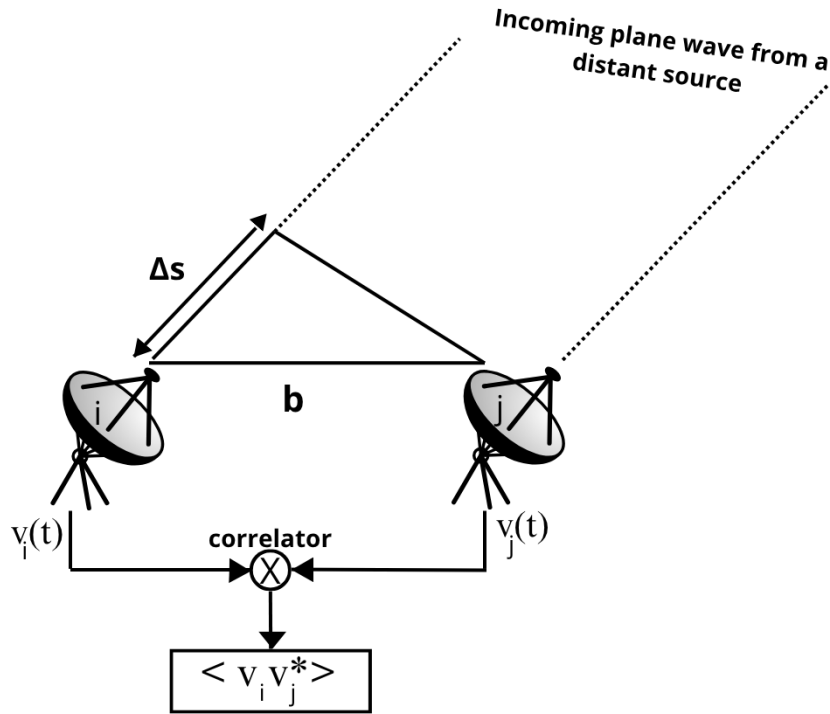


Figure 2.1: Schematic diagram of a two-element radiointerferometer. An incoming plane wave reaches antennas  $i$  and  $j$  at slightly different times due to their finite separation (baseline  $\mathbf{b}$ ). The corresponding path difference  $\Delta s$  represents the difference in distance traveled by the wavefront and leads to a geometric delay between the two received signals. In practice, this delay is later accounted for during the correlation and calibration processes, where the relative phase offsets introduced by the different signal propagation paths are corrected (see Sect. 2.3.2). The signal received at antenna  $i$  produces an output voltage  $v_i(t)$ , and antenna  $j$  produces an identical voltage  $v_j(t)$  except that  $v_i(t)$  is delayed by a geometric time lag. These voltages, which are proportional to the electric fields  $E_i(t), E_j(t)$  measured at each antenna, are then fed into a correlator where they are amplified, multiplied, and time-averaged to produce the final output response: the measured complex visibility  $V_{ij}$ .

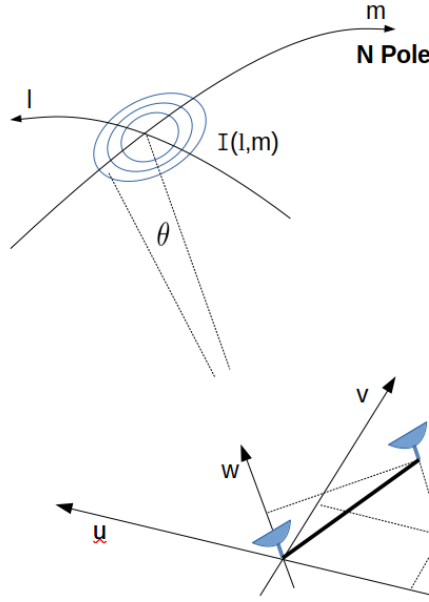


Figure 2.2: Coordinate systems commonly used to relate interferometer measurements to the true sky distribution. The thick black segment connecting the two antennas represents the baseline vector  $\mathbf{b}$  between the antenna pair. When expressed in the  $(u, v, w)$  coordinate system, its projected components define the interferometric coordinates, where  $u$  and  $v$  lie in the plane perpendicular to the direction to the source and  $w$  points along the line of sight. The sky coordinates are represented using the direction cosines  $(l, m)$  shown, with the coordinate  $n$  directed along the  $w$ -axis.

is valid for the observations presented in this thesis, allowing the visibility to be treated as a function of the projected baseline coordinates  $(u, v)$ :

$$V(u, v) = |V(u, v)| e^{i\phi(u, v)}. \quad (2.6)$$

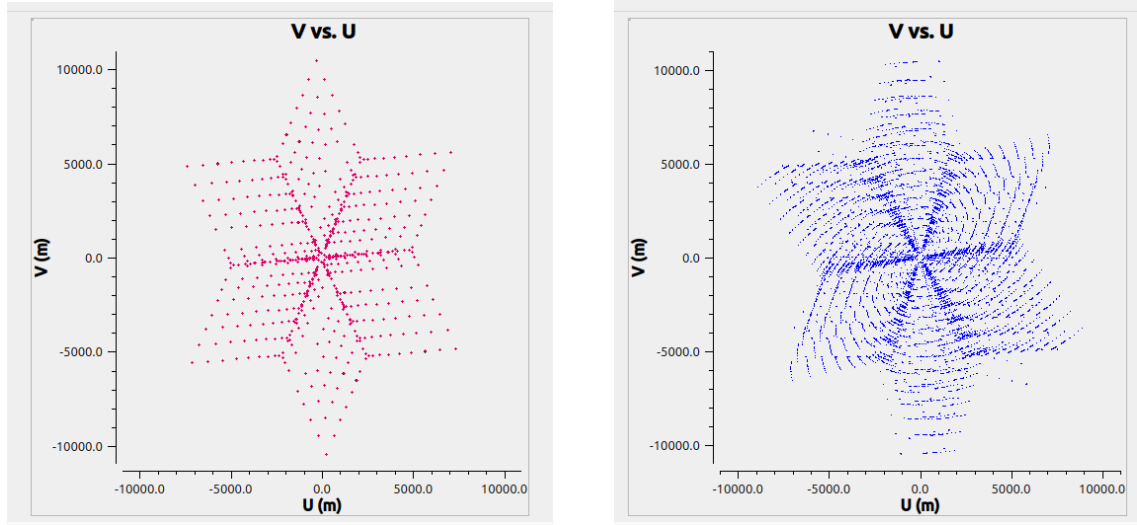
Using the coordinate systems described above, the Van Cittert–Zernike theorem relates the visibility  $V(u, v)$  to the sky brightness distribution  $I(l, m)$  through

$$V(u, v) = \iint I(l, m) e^{-2\pi i(ul+vm)} dl dm, \quad (2.7)$$

basically establishing that the complex visibilities correspond to the Fourier transform of the sky brightness distribution.

At a given observing frequency and instant in time, each antenna pair (each baseline) provides one visibility measurement, corresponding to a single point in the Fourier  $(u, v)$  plane. As the Earth rotates, the projected baselines change orientation and length, causing each baseline to trace a trajectory across the  $(u, v)$  plane. This process, known as Earth-rotation aperture synthesis, progressively improves the sampling of the  $(u, v)$  plane. The effect of Earth-rotation synthesis on the  $(u, v)$  plane sampling can be seen in Fig. 2.3.

Thus, in practice, since an interferometer contains only a finite number of baselines, it does not measure the continuous visibility function  $V(u, v)$ . Instead, the

(a)  $(u, v)$  coverage over a 5 s interval.

(b) Coverage after a full observation.

Figure 2.3: Effect of Earth-rotation synthesis on the sampling of the  $(u, v)$  plane. This sampling can be improved by taking advantage of the Earth's rotation, which changes the projected baselines as the source moves across the sky over time. As a result, each baseline traces a trajectory across the  $(u, v)$  plane, progressively improving its sampling. The panel on the left shows a snapshot of the coverage obtained over a few seconds. The right panel shows the coverage after the complete observation. The plots correspond to a Very Large Array dataset.

$(u, v)$  plane is sampled incompletely, only at discrete points determined by the projected baselines between a finite number of antenna pairs. This is described by the expression

$$V_{\text{obs}}(u, v) = SF(u, v) V(u, v), \quad (2.8)$$

where  $SF(u, v)$  is the sampling function of the interferometer, which encodes the locations in the  $(u, v)$  plane corresponding to the measured baselines, and  $V_{\text{obs}}$  are the sampled visibilities. This means that a specific array, in a given configuration, probes only a limited range of spatial frequencies, i.e., is sensitive to only certain angular scales on the sky. The inverse Fourier transform of the measured visibilities does not directly recover the true sky brightness distribution then, but instead produces a dirty image, corresponding to the true sky convolved with the point spread function (PSF), or dirty beam, of the array. This will be discussed in more detail in Sect. 2.4.

As mentioned earlier in this section, the effective angular resolution of the interferometer is mainly determined by the maximum baseline length  $B_{\text{max}}$ , and can be approximated as  $\theta \sim \lambda/B_{\text{max}}$ . In this sense, an interferometric array achieves the resolving power of a single antenna with diameter  $B_{\text{max}}$ . However, this increase is not linearly extrapolated to the sensitivity, which is instead set by the total collecting area of the individual antennas. The shortest baseline,  $B_{\text{min}}$ , determines the largest angular scale that can be recovered, so the range of spatial scales accessible to the interferometer depends on the distribution of baselines within the array. Additional improvements to the  $(u, v)$  sampling can be achieved by observing in array config-

urations that combine both short and long baselines, providing access to a broader range of spatial scales.

The sensitivity of an interferometric observation depends on the system temperature, total bandwidth, integration time, and the number of antennas. For an array of  $N$  antennas, the rms noise decreases approximately as  $\propto (N(N-1)\Delta\nu t)^{-1/2}$ , reflecting the number of independent baselines contributing to the measurement. Increasing the number of antennas, therefore, improves both sensitivity (through the total collecting area) and sampling of the  $(u, v)$  plane, leading to higher image fidelity.

## 2.3 Data processing

Interferometric observations produce raw visibilities that are affected by a variety of external and instrumental effects, including RFI, atmospheric distortions, and instrumental imperfections. As a result, the measured visibilities deviate from the true sky signal. The relation between the observed and true visibilities is described by the Radio Interferometer Measurement Equation. In its general form, this can be written as

$$\mathbf{V}_{ij}^{\text{obs}}(\nu, t) = \mathbf{J}_i(\nu, t) \mathbf{V}_{ij}^{\text{true}}(\nu, t) \mathbf{J}_j^\dagger(\nu, t) + \mathbf{N}_{ij}(\nu, t), \quad (2.9)$$

where  $\mathbf{V}_{ij}$  is a  $2 \times 2$  visibility matrix,  $\mathbf{J}_i$  and  $\mathbf{J}_j$  are the Jones matrices describing the instrumental and propagation effects affecting antennas  $i$  and  $j$ , and  $\mathbf{N}_{ij}$  represents additive noise contributions. This formulation makes explicit that the observed visibilities are a corrupted version of the true sky signal through a combination of multiplicative effects, encoded in the Jones matrices, and additive noise.

In the absence of polarization effects, the measurement equation reduces to a scalar form,

$$V_{ij}^{\text{obs}} = G_i G_j^* V_{ij}^{\text{true}} + N_{ij}, \quad (2.10)$$

where  $G_i$  and  $G_j$  are the complex antenna gains of antennas  $i$  and  $j$ .

The identification and removal of bad or corrupted data, and the subsequent calibration of the remaining data, are crucial steps in the data reduction workflow, allowing these corruption effects to be mitigated through a combination of data selection and model-based corrections. The general procedure described here follows standard processes implemented through tasks in software packages such as **CASA** (Common Astronomy Software Applications; McMullin et al., 2007), and is consistent with calibration guides such as the VLA Continuum Calibration Guide (NRAO CASA Team, 2024).

### 2.3.1 Corruptions in interferometric data

The corruptions affecting interferometric data can be broadly divided into additive and multiplicative contributions. Additive effects are primarily associated with noise and external contamination, whereas multiplicative effects arise from the array's instrumental and propagation responses.

Additive contributions include thermal noise and RFI spikes. RFI refers to unwanted signals, typically of artificial origin, such as communication systems, satellites, or radar transmissions<sup>2</sup>. These signals are often characterized by high intensity and narrow frequency or time localization, and are a major source of contamination in radio observations. Because such contamination does not follow the sky-based measurement equation that describes the sky signal, it cannot be corrected with calibration solutions and must instead be mitigated as much as possible before calibration.

The first step in the data processing is therefore the so-called *flagging* of bad data, which consists of identifying and removing the most obvious corrupted visibilities, generally due to issues such as malfunctioning antennas, shadowing in close configurations (shorter baselines), and RFI. This can be performed either manually or through automated algorithms. Throughout this thesis, a manual approach was preferred, allowing precise control over the affected time and frequency ranges and ensuring full traceability of the applied data selection. All the data *flagged* is excluded from the calibration and subsequent steps. An example of the effect of flagging is shown in Fig. 2.4.

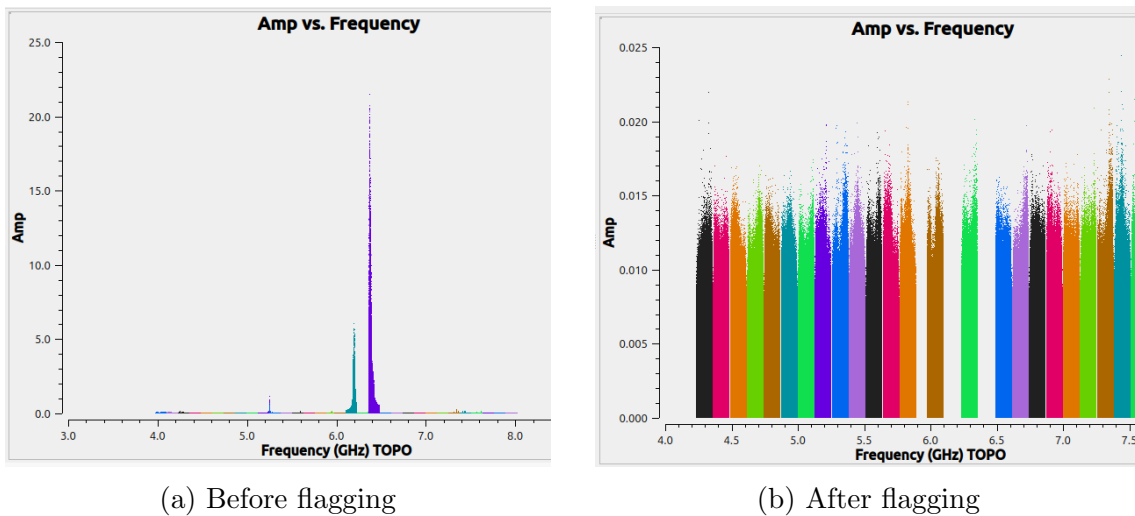


Figure 2.4: Impact of flagging on the visibility data. The panel on the left shows the dataset before flagging, while the right panel shows the same dataset after flagging, where contaminated visibilities were removed. The figures are from a Very Large Array dataset used during this thesis in the frequency range 4–8 GHz (see Chapter 4).

After flagging, the remaining visibilities are still affected by multiplicative effects, which are encoded in the Jones matrices. These effects distort both the amplitude and phase of the visibilities and must be modeled and corrected through calibration. These include:

- **Electronic and instrumental gains:** Every antenna modifies the incoming signal through its receiver and the subsequent signal processing electronics (including amplifiers, filters, cables, and digitization stages). The characteristic

<sup>2</sup>Examples of different RFI sources in the 1–2 GHz range can be found at <https://science.nrao.edu/facilities/vla/observing/RFI/L-Band>.

response of each antenna can be described by a complex gain, which acts as a multiplicative factor on the measured signal, affecting both its amplitude and phase. Variations in these components, for example, due to temperature changes or electronic instabilities, cause the gain to vary with time and frequency, introducing distortions in the visibilities that need to be accounted for during calibration.

- **Bandpass response:** The instrumental response is not uniform across the whole observing bandwidth, resulting in frequency-dependent structure on the visibilities that, if left uncorrected, can hide the intrinsic spectral properties of the target source.
- **Delay and clock errors:** Differences in signal path lengths or clock synchronization between different antennas introduce delays that translate into phase errors.
- **Atmospheric effects:** Signal propagation through the atmosphere introduces phase delays. The troposphere dominates at centimeter wavelengths, while the ionosphere produces dispersive effects at meter wavelengths.
- **Primary beam and pointing errors:** The antenna response pattern, or primary beam, introduces direction-dependent effects, and small pointing offsets can lead to additional errors.
- **Polarization leakage:** Imperfect separation of orthogonal polarizations in real antennas can lead to a mixing between polarization states (a leakage of one polarization into the other), affecting polarimetric measurements. This instrumental polarization, described by the so-called  $D$ -terms, affects mainly the cross-hand correlations, making Stokes  $Q$  and  $U$  particularly susceptible to errors if leakage is not properly corrected.

### 2.3.2 Calibration approach

Calibration consists of solving the measurement equation for the antenna-based response terms and applying their inverse to the observed data. This process relies on observations of calibrator sources with known or well-characterized properties, allowing the different components of the instrumental response to be constrained, as each calibrator is chosen optimized for a specific Jones term in the measurement equation.

The Jones matrices from Eq. 2.9 are factorized into contributions associated with different physical effects, which are typically solved for sequentially following a standard calibration strategy. While the specific order may vary depending on the software package used, the commonly adopted workflow consists of the following calibration steps:

- **Flux density calibration:** The first step consists of setting the absolute amplitude/flux density scale. This is done by referencing the observations to a standard candle calibrator, behaving as a stable, point-like bright source with



known flux densities. Each observatory usually has a list of possible sources to act as flux calibrators, observable from the location of the interferometer. These calibrators determine the reference level used to scale the target visibilities, thus setting the absolute amplitude of the antenna gains. In practice, the flux calibrator is observed a single time, either at the start or the end of the observing session.

- **Delay and Bandpass calibration:** In this step, we aim to correct for amplitude and phase variations due to the frequency dependence of the system response across the observing bandwidth. This is, solving for the instrumental delays (of each antenna, relative to a reference antenna) and for the bandpass term. Generally, the same calibrator used for flux density scaling is used to estimate these solutions too, since the bandpass and delay responses are mostly stable across an observing run.
- **Gain calibration:** Subsequently, we solve for time-dependent variations in both amplitude and phase of the antenna gains. These fluctuations are mainly driven by atmospheric and instrumental instabilities. Corrections for the complex gains are derived and then applied to the target data, using a secondary calibrator (sometimes referred to as phase or complex gain calibrator). Once relative gain amplitudes and phases are established from this calibrator, we relate them to the absolute flux density scale obtained in the first step through the primary calibrator. Because gain changes happen in short timescales, and since we intend to minimize the differences in atmospheric conditions between the lines of sight to the calibrator and to the target, this calibrator source must be located close to the target on the sky plane, and observed frequently, typically before and after each target scan, to measure similar conditions and derive solutions that can be reliably applied to the target data.
- **Polarization calibration:** Lastly, if a reconstruction of the Stokes parameters that depend on the cross-hand correlations is needed, there is an additional step to correct for the instrumental polarization response, including leakage terms and polarization angle. The absolute polarization angle is determined using a strongly polarized source with a well-characterized full-Stokes model. In addition, instrumental polarization leakage (or *D*-terms) can be estimated either from an unpolarized calibrator, where any detected cross-hand signal is attributed to feed leakage (i.e., instrumental) effects, or from a polarized calibrator with a known model. The specific steps will be described in more detail in Sect. [4.4.2](#).

## 2.4 Imaging and deconvolution

In the previous section, we described the steps through which raw interferometric data are calibrated to obtain corrected visibilities that are consistent with the measurement equation. Once calibration is completed, these visibilities can be used to reconstruct the sky brightness distribution. In this section, we move from the visibility domain to the image domain, describing how calibrated visibilities are



transformed into an initial image (the dirty image) and subsequently deconvolved to obtain a more faithful representation of the sky.

In Sect. 2.2, the van Cittert–Zernike theorem was introduced, describing how each measured visibility corresponds to a single Fourier component of the sky brightness distribution. It was also pointed out how, in practice, an interferometer measures a discrete and incomplete sampling of this Fourier space, because only a finite number of baselines are available and the  $(u, v)$  plane is only partially covered over time. To form an image, these calibrated visibilities are first weighted and gridded onto a  $(u, v)$  grid and then transformed back into the image domain using an inverse Fourier transform. The resulting image is known as the dirty image. However, because the Fourier plane is incompletely sampled, the dirty image does not directly represent the true sky brightness distribution. Instead, this dirty image corresponds to the true sky brightness convolved with the instrumental response imposed by incomplete  $uv$ -coverage, the so-called dirty beam or PSF, and can be expressed as

$$I_D(l, m) = I(l, m) * B_D(l, m), \quad (2.11)$$

where  $I(l, m)$  is the true sky brightness distribution,  $*$  denotes convolution, and  $B_D(l, m) = \mathcal{F}^{-1}\{SF(u, v)\}$  is the dirty beam (or PSF) of the interferometer. This PSF (or dirty beam)  $B_D(l, m)$  describes how a point source is represented in the reconstructed image due to the incomplete sampling of the Fourier plane, and it is given by the Fourier transform of the sampling function in the  $(u, v)$  plane,  $SF(u, v)$ . Eq. (2.11) is obtained by taking the inverse Fourier transform of Eq. (2.8) and applying the Fourier relationship between visibilities and sky brightness.

As a result of the gaps in  $(u, v)$  sampling, the PSF exhibits significant sidelobes. In practice, this means that bright sources in the dirty image produce extended artifact patterns that can distort them and obscure faint emission. To mitigate these effects and recover a more faithful representation of the sky brightness distribution, deconvolution techniques are required to deconvolve the dirty image from the PSF. The most widely used approach in radio interferometry is the CLEAN algorithm (Högbom, 1974; Clark, 1980). This algorithm models the radio sky as several point sources in an otherwise empty field, and proceeds iteratively. The general principle is illustrated in Fig. 2.5.

At each step, the brightest pixels (the peak) in the dirty image are identified, and the dirty beam is subtracted from those pixels' locations. The corresponding flux is stored as a CLEAN component (a model of the emission in those pixels). This is repeated several times until the remaining residual emission is consistent with the noise level of the image, indicating that the dominant emission has been modeled. In practice, the iterative procedure ends when a chosen stopping criterion is reached (e.g., noise level or iteration number limit). After convergence, the set of CLEAN components represents a discrete model of the sky brightness distribution, which is then convolved with the restoring beam (also referred to as the CLEAN beam), which results from fitting a Gaussian to the main lobe of the dirty beam, and defines the effective angular resolution of the final image.

Finally, the residual map (containing the remaining background emission and noise not captured by the model in the iterative steps) is added back to the convolved CLEAN components. This yields the resulting image, known as the CLEAN image,

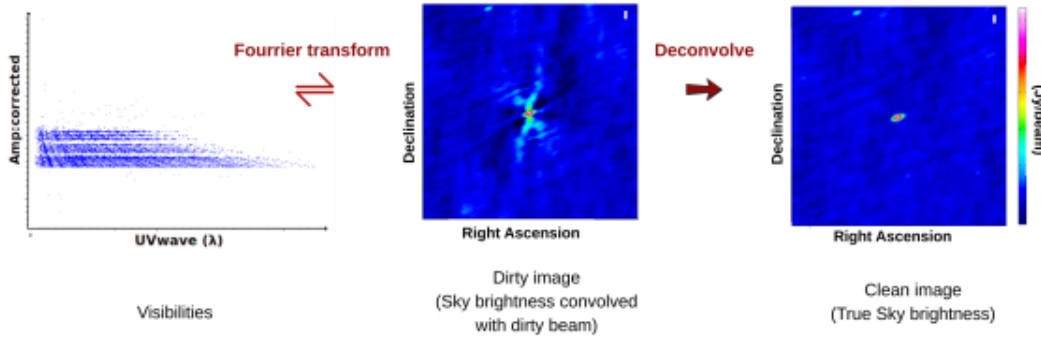


Figure 2.5: Representation of the radio interferometric imaging process. The observed visibilities,  $V_{\text{obs}}(u, v)$ , are inverse Fourier-transformed to produce a dirty image,  $I_D(l, m)$ , which is then deconvolved with the dirty beam,  $B_D(l, m)$ , using the CLEAN algorithm to obtain a clean estimate of the sky brightness distribution. Taken from [Kaur \(2026\)](#).

in which the sidelobe artifacts of the dirty beam have been largely removed. In this sense, the CLEAN algorithm can be understood as a procedure that reduces the “blurring” introduced by incomplete  $(u, v)$  sampling by iteratively modeling and subtracting the PSF response of bright sources in the field of view.

It is worth mentioning that the CLEAN reconstruction is not unique and depends on the adopted algorithm parameters and assumptions, including the number of iterations and stopping criterion, weighting scheme, and any scale choices used in the imaging process. In this context, imaging itself depends on the choice of weighting applied in the  $(u, v)$  plane prior to gridding and Fourier inversion. These choices directly affect the shape of the dirty beam and the noise properties of the resulting image. Thus, the quality of the final CLEAN image is determined both by the intrinsic  $(u, v)$  coverage of the array and by the adopted imaging parameters.

In this chapter, we have presented the general principles of radio interferometric data. In the following chapters, we turn to the specific characteristics of the datasets used throughout this thesis. In particular, radio interferometric observations from three different observatories are analyzed, and the technical and scientific details of each instrument, together with the corresponding observational setups and data reduction procedures, are introduced in the respective dedicated chapters (Chapters [3](#), [4](#), and [5](#)).

# Chapter 3

## Search for new PACWBs with the upgraded GMRT

### 3.1 Scientific motivation

For massive stars, it is not generally straightforward to detect a companion directly, particularly if the companion is fainter than the primary star or when the orbital period is long. Thus, the absence of observational evidence for binarity does not necessarily imply that the massive star in question is single. This caveat is especially important for WR stars, whose broad emission lines and thick, dense winds complicate the application of traditional spectroscopic techniques.

Because PACWBs are binary systems of massive stars in which a population of relativistic particles is produced and, thus, NT emission (particularly synchrotron) is radiated, there seems to be a correlation between synchrotron radio emission and binarity among massive stars. This is commonly referred to as the synchrotron-binarity correlation (De Becker et al., 2024b; De Becker and Arora, 2024). Physically, this correlation is expected: in CWBs, particle acceleration results from the head-on collision of two supersonic winds at the WCR, which produces a compact shock region well suited for efficient DSA. In contrast, an isolated massive star’s wind expands into the diffuse, steady ISM instead of colliding with a companion wind, so the resulting wind–ISM interaction is naturally weaker and far more extended, and is not expected to accelerate particles as efficiently as a WCR. Although NT radio emission has been reported to be associated with a small number of apparently single WR stars (see Prajapati et al., 2019; Saha et al., 2026), in both cases the emission originates from the extended stellar bubble produced by the large-scale interaction between the stellar wind and the ambient ISM, rather than from a compact WCR near the star. Notably, other isolated WR stars with comparably high wind kinetic power that are not associated with extended circumstellar structures have not shown synchrotron emission (Saha et al., 2023), suggesting that a powerful wind alone is not sufficient to produce detectable particle acceleration in single massive stars. Hence, the mentioned wind–ISM detections do not challenge the empirical association between compact synchrotron radio emission and particle acceleration in CWBs on which the synchrotron-binarity correlation is based.

The synchrotron–binarity correlation can thus be utilized in two complementary

directions. On the one hand, the detection of synchrotron emission in a system already known to be a massive binary allows it to be classified as a PACWB. On the other hand, in a massive star for which binarity has not yet been established, the detection of synchrotron emission - interpreted as tracing the presence of a WCR - can, together with other supporting evidence, provide indirect evidence of an unseen companion. This makes radio observations a valuable complementary tool for investigating the multiplicity of massive stars (Dougherty and Williams, 2000; De Becker et al., 2024b), particularly in regions of the parameter space that remain poorly explored by other traditional techniques.

The latter approach is especially relevant for WR stars. Their powerful winds are highly efficient at supplying energy to NT processes, making them promising candidates for particle acceleration. At the same time, their dense winds can strongly absorb synchrotron radiation through FFA. As a consequence, detectable synchrotron emission is expected primarily from systems with sufficiently large stellar separations. Thus, the detection of compact NT radio emission from a WR star usually implies the presence of a relatively wide binary companion (De Becker et al., 2019; De Becker and Arora, 2024).

Driven by these considerations, a dedicated radio observing campaign was proposed to search for synchrotron emission from a sample of WR stars lacking both evidence of NT radio emission and definitive confirmation of binarity (though they had previously shown hints pointing to a binary nature), with the intention of identifying new PACWBs and, in turn, improving the census of binary systems among evolved massive stars. This project, thus, contributes to the first objective described in Sect. 1.7.

## 3.2 The upgraded Giant Metrewave Radio Telescope

The observations presented in this chapter were obtained with the upgraded Giant Metrewave Radio Telescope (uGMRT), located in India. This telescope consists of 30 fully steerable parabolic antennas, each with a diameter of 45 m, distributed along baselines extending up to 25 km. The array has a hybrid configuration (see Fig. 3.1), with 12 dishes in a compact central square ( $1 \text{ km} \times 1 \text{ km}$ ), and the remaining 18 antennas distributed along three arms (West, East and South). As discussed in Sect. 2.2, this combined configuration provides sensitivity to both compact and extended radio emission.

In 2019, an upgrade of the facility, known as the upgraded GMRT (uGMRT), considerably improved its sensitivity and bandwidth, allowing it to now provide continuum frequency coverage between 130 and 1450 MHz through four broad observing bands: Band 2 (130–260 MHz), Band 3 (250–500 MHz), Band 4 (550–900 MHz), and Band 5 (1000–1450 MHz). A photograph of a handful of the uGMRT antennas is shown in Fig. 3.2.

For the present project, the uGMRT offered an ideal combination of sensitivity and frequency coverage. This was particularly important for distinguishing between thermal and NT radio emission from massive stars. Because synchrotron radiation

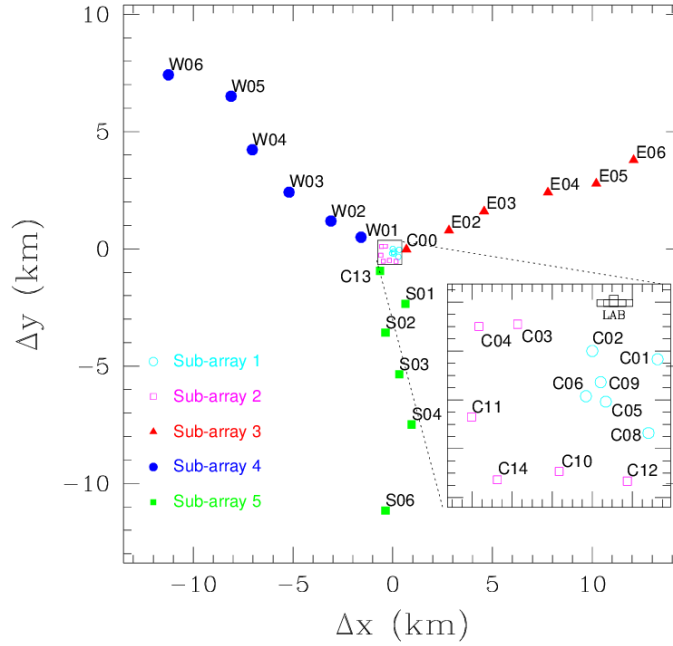


Figure 3.1: GMRT array configuration, showing the antenna locations across the arms and in the central square region. The axes are measured relative to the antenna C02, which is at (0, 0). Taken from [Bhat et al. \(2013\)](#).

is expected to exhibit a negative spectral index and becomes relatively stronger at lower radio frequencies, whereas thermal free-free emission from stellar winds follows the opposite trend (as described in Sect. 1.3.4), observations at meter wavelengths are especially well suited for tracing radio spectral indices and identifying a synchrotron component, if present, in the radio spectrum. In this work, observations were conducted in Bands 4 and 5, providing frequency coverage from 550 to 1450 MHz. The broad spectral coverage given by these bands ensures a wide characterization of the radio spectrum while remaining at frequencies where synchrotron emission is still expected to be detectable and less affected by absorption processes (at least at the higher end of that frequency coverage).

## 3.3 Observing proposal

### 3.3.1 Scientific justification

The telescope time proposal was led by M. De Becker as Principal Investigator (PI), with A. Tej, A. Blanco, and P. Benaglia as co-investigators. The primary incentive was to search for synchrotron radio emission from a sample of WR stars (that had previously shown hints of binarity) and identify new members of the PACWB population while, at the same time, shedding light on their multiplicity status.

The detection of synchrotron emission would imply the presence of a population of relativistic electrons, thus pointing to acceleration occurring in the shocks of



Figure 3.2: The upgraded Giant Metrewave Radio Telescope (uGMRT) located near Pune, India. Source: National Center for Radio Astrophysics (NCRA).

colliding winds, consequently providing strong support for the binary nature of the observed stars. Such detections would contribute to both the census of particle-accelerating massive binaries and the identification of binary systems with orbital periods that are difficult to probe using conventional spectroscopic techniques.

In a broader context, the project aimed to improve our understanding of the occurrence of particle acceleration among WR stars, a class of objects characterized by some of the most powerful stellar winds known (thus, some of the biggest reservoirs of energy to be injected into particle acceleration). Helping to establish the fraction of synchrotron-emitting WR stars, and their multiplicity status at the same time, are important steps towards understanding the relationship between stellar multiplicity, wind interactions, and NT processes in massive-star environments.

### 3.3.2 Technical justification

The observing strategy was designed to maximize the detectability of synchrotron emission by balancing two competing effects. On the one hand, observations at longer wavelengths probe the region of the radio spectrum where synchrotron emission is expected to be brighter, while the unresolved thermal contribution from the winds is usually negligible (due to its positive spectral index). On the other hand, frequencies that are too low have a greater chance of being strongly affected by low-frequency turnover processes, mainly FFA from the dense WR winds, with the risk of significantly attenuating or even suppressing the synchrotron component, potentially masking its presence. Very low frequencies, while reachable with the uGMRT, were thus avoided. The selected observing bands therefore represent a compromise



between these effects.

Based on these considerations, observations were requested in Bands 4 and 5, providing frequency coverage appropriate for measuring radio spectral indices in a sufficiently low-frequency region of the radio spectrum and potentially identifying synchrotron emission. To ensure high signal-to-noise detections, the observations were requested to reach rms levels of approximately  $30 \mu\text{Jy beam}^{-1}$  and  $20 \mu\text{Jy beam}^{-1}$  in Bands 4 and 5, respectively. Both observing setups employed the full 400 MHz bandwidth available in each band, with 4096 spectral channels and an integration time of 10.5 s in Total Intensity mode. Based on sensitivity estimates obtained with the online GMRT Exposure Time Calculator (ETC), total observing times (considering all five targets) of 14 h 11 min 30 s in Band 4 and 9 h 56 min 31 s in Band 5 were requested, including overheads.

Each target was observed once in each band, with the observations per target scheduled as closely in time as possible. This strategy minimizes the impact of intrinsic variability associated with orbital motion and warrants that the derived spectral indices accurately reflect the instantaneous radio spectrum of the source.

### 3.4 Observations and data reduction

The WR targets requested were observed with the uGMRT as part of cycle number 44, during June 2023.

The uGMRT data were reduced using the **CAPTURE** (CASA Pipeline-cum-Toolkit for Upgraded GMRT) pipeline<sup>1</sup> (Kale and Ishwara-Chandra, 2021). CAPTURE provides an automated framework for uGMRT data processing, performing tasks such as RFI flagging, calibration, imaging, and even iterative rounds of self-calibration. The package is specifically optimized for uGMRT observations, while still allowing the user to customize individual processing stages when required. Several reduction tests were carried out using different pipeline configurations, followed by additional manual flagging of residual RFI not identified by the automated processing. Final continuum images were produced for all targets in both Band 4 and Band 5 and used for the subsequent scientific analysis presented in this chapter.

### 3.5 Main findings

This project aimed to investigate the radio properties of a sample of five WR stars that had previously shown signs of multiplicity, but lacked definitive confirmation of binarity and, at the same time, evidence of NT radio emission (except for WR 98a, see below). By exploring the radio spectrum at frequencies lower than those explored in previous studies, the observations intended to detect synchrotron emission associated with particle acceleration in CWBs and, consequently, reveal new PACWB candidates.

Among the five targets observed with the uGMRT, radio emission was detected only from WR 110. Our measurements obtained in Bands 4 and 5, combined with

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<sup>1</sup>The pipeline is publicly available through its GitHub repository: <https://github.com/rutak/CAPTURE-CASA6>

previously published flux densities at higher frequencies, reveal a radio spectrum consistent with purely thermal emission. The derived spectral index,  $\alpha = 0.74 \pm 0.01$ , is somewhat steeper than the canonical value expected for a smooth stellar wind ( $\alpha = 0.6$ ), but remains compatible with the presence of a dense and clumped WR wind. Nothing in the analysis necessarily pointed to a NT component.

The remaining four targets (WR 87, WR 93, WR 98a, and WR 106) were not detected in either observing band. For these objects, upper limits to their flux densities were derived from the local rms noise levels of the images. These measurements provide new observational constraints on the radio properties of the targets and extend the explored frequency range below 1 GHz, a regime that had not previously been explored for any of the targets in the sample.

No observational evidence of synchrotron emission was found in any member of the sample. This result gives us valuable insight into the observational challenges associated with identifying particle accelerators among massive stars, even in the radio domain. In particular, the lack of a detection for all candidate systems suggests that FFA by the dense stellar winds plays a key role in strongly attenuating synchrotron radiation at low radio frequencies, probably preventing its detection even when particle acceleration is taking place. The case of WR 98a, previously identified as a particle-accelerating system on the basis of higher-frequency radio observations, serves as proof of this difficulty and highlights the importance of absorption effects when interpreting low-frequency radio measurements.

The main outcome of this study is therefore not the identification of new PACWBs - and hence not the confirmation of new binary systems hosting the observed WR targets - but rather a better understanding of the observational biases affecting their detection. We would like to emphasize that the absence of detectable synchrotron emission at low frequencies should not be interpreted as conclusive evidence against particle acceleration or binarity. Instead, the detectability of a NT component (assuming it is present) depends on a balance between synchrotron production and absorption processes, especially in systems hosting dense WR winds. This balance is also expected to vary with orbital phase, further complicating its observational detection.

We believe these findings can have important implications for future radio surveys of massive stars. While observations below 1 GHz remain useful for characterizing spectral turnovers and absorption effects, they should be complemented with measurements at frequencies of a few GHz, where FFA is less severe, and synchrotron emission may be more easily detectable. An approach combining several observations at different frequencies along the radio spectrum could be required to obtain a more complete census of particle accelerators among massive stars and to further investigate the synchrotron-binarity correlation.

The publication reporting on these results ([Blanco et al., 2024](#)) is included in Sect. 3.6.

### 3.6 Included publication



# Insight into the occurrence of particle acceleration through the investigation of Wolf–Rayet stars using uGMRT observations

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## ABSTRACT

**Context.** Massive stars produce strong stellar winds that consist of continuous outflows of material at speeds of thousands of km s<sup>−1</sup>. These winds convey large amounts of kinetic power, especially in the case of Wolf–Rayet (WR) stars. When these winds interact with nearby material, they will likely produce shocks. Among other processes, particle acceleration is expected to occur. This is particularly well established in the case of massive binary systems, where the stellar winds collide, allowing these systems to be identified thanks to the detection of synchrotron radio emission, produced by a population of relativistic particles accelerated in the shocks.

**Aims.** Our goal is to investigate the occurrence of particle acceleration among massive stars in their pre-supernova evolution phases.

**Methods.** We observed a subset of five WR stars in the radio domain using the upgraded Giant Metrewave Radio Telescope (uGMRT), located in India. The observations were carried out in bands 4 (550–950 MHz) and 5 (1050–1450 MHz) for all the targets.

**Results.** We detected radio emission for only WR 110 in bands 4 and 5. Its thermal spectrum displays a consistent index of +0.74 down to uGMRT bands. The four other targets were not detected and we derived 3 $\sigma$  upper limits on their flux density. Our upper limits in Band 4 are the first provided for these targets below 1 GHz. None of the targets was identified as a synchrotron radio emitter in these radio bands.

**Conclusions.** If some synchrotron emission is produced in these systems, the non-detection with the uGMRT can be most likely attributed to strong free-free absorption (FFA). This is especially relevant for WR98a which is catalogued as a particle accelerator based on previous measurements at higher radio frequencies. The prominence of FFA constitutes a severe obstacle to identifying particle accelerators in the radio domain.

**Key words.** acceleration of particles – radiation mechanisms: non-thermal – stars: Wolf-Rayet – radio continuum: stars

## 1. Introduction

High-mass stars ( $M \geq 8 M_{\odot}$ ), that include O-type, and early B-type stars, as well as their evolved counterparts, the Wolf–Rayet (WR) stars, present strong and dense, radiatively driven stellar winds (see e.g. Puls et al. 2008, for a review). These winds allow massive stars to continuously eject material from their outer layers, thus injecting chemically enriched matter and mechanical energy into the surrounding medium. This ejected material is accelerated to terminal velocities ( $v_{\infty}$ ) of a few 1000 km s<sup>−1</sup> with mass-loss rates ( $\dot{M}$ ) ranging typically between 10<sup>−7</sup> and 10<sup>−5</sup> M<sub>⊙</sub> yr<sup>−1</sup>, depending on the spectral type and luminosity class.

Furthermore, massive stars are mostly found to be part of binaries, or higher multiplicity systems. While the fraction of massive stars in binary systems has not been well determined yet, recent estimates point to a binary frequency of at least 90% for O-type stars in young clusters (Offner et al. 2023). In the case of a binary system made of high-mass stars, the powerful winds of both stars will collide somewhere in between the stars, giving rise to what we call a colliding-wind binary (CWB). Among the group of CWBs, there is a subcategory of binaries that are capable of accelerating particles up to relativistic velocities, and are called particle-accelerating colliding-wind binaries (PACWBs, De Becker & Rauq 2013; De Becker et al. 2017). To date, the

catalogue of PACWBs includes about 50 objects (De Becker & Rauq 2013)<sup>1</sup>.

The particle acceleration process that is active in PACWBs is believed to be diffusive shock acceleration (DSA; Drury 1983), occurring in the shocks produced in the colliding-wind region (CWR). This process can accelerate charged particles to relativistic velocities, including relativistic electrons at the origin of a series of non-thermal (NT) radiative processes.

Among these processes, it is worth emphasizing the importance of synchrotron emission. In the presence of a magnetic field, of likely stellar origin, relativistic electrons produce NT synchrotron radio emission, which is the main indicator of particle acceleration in PACWBs (e.g. De Becker & Rauq 2013). Focusing on that spectral domain is thus especially relevant to investigating the occurrence of particle acceleration in massive star systems. In this framework, two specific motivations at the core of the present study deserve to be clarified.

First, despite significant advances in our understanding of PACWBs, a notable gap exists in our knowledge of the fraction of particle accelerators among massive binaries. Achieving a better view of the full population of PACWBs is especially relevant for understanding the contribution of these objects to the acceleration of Galactic cosmic rays (De Becker et al. 2017). Second, since synchrotron radiation from massive stars is produced in

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<sup>1</sup> The updated version of the catalogue is available at <https://www.astro.uliege.be/~debecker/pacwb/>

**Table 1.** Selected sample of WR stars.

| Source | Spectral type | $\dot{M}$<br>( $10^{-5} M_{\odot} \text{ yr}^{-1}$ ) | $v_{\infty}$<br>( $\text{km s}^{-1}$ ) | $T_{\text{eff}}$<br>(kK) | $D$<br>(kpc)        | $P_{\text{kin}}$<br>( $10^{37} \text{ erg s}^{-1}$ ) |
|--------|---------------|------------------------------------------------------|----------------------------------------|--------------------------|---------------------|------------------------------------------------------|
| WR 87  | WN7h + ?      | 2.5 <sup>(a)</sup>                                   | 1400 <sup>(a)</sup>                    | 44.7 <sup>(b)</sup>      | 3.0 <sup>(c)</sup>  | 1.6                                                  |
| WR 93  | WC7 + O7 – 9? | 2.0 <sup>(d)</sup>                                   | 2200 <sup>(d)</sup>                    | 75 <sup>(d)</sup>        | 1.76 <sup>(e)</sup> | 3.1                                                  |
| WR 98a | WC8 – 9vd + ? | 1.6 <sup>(f)</sup>                                   | 1400 <sup>(f)</sup>                    | 60 <sup>(d)</sup>        | 1.9 <sup>(g)</sup>  | 1.0                                                  |
| WR 106 | WC9d + ?      | 1.6 <sup>(h)</sup>                                   | 1100 <sup>(h)</sup>                    | 45 <sup>(h)</sup>        | 2.32 <sup>(i)</sup> | 0.6                                                  |
| WR 110 | WN5 – 6b + ?  | 1.6 <sup>(j)</sup>                                   | 2300 <sup>(b)</sup>                    | 70.8 <sup>(b)</sup>      | 1.8 <sup>(c)</sup>  | 2.7                                                  |

**Notes.** <sup>(a)</sup>Hamann et al. (1995), <sup>(b)</sup>Hamann et al. (2006), <sup>(c)</sup>Crowther et al. (2023), <sup>(d)</sup>Crowther (2007), <sup>(e)</sup>Rate & Crowther (2020), <sup>(f)</sup>De Becker & Rauq (2013) <sup>(g)</sup>Monnier et al. (1999) <sup>(h)</sup>Sander et al. (2019), <sup>(i)</sup>van der Hucht (2001), <sup>(j)</sup>Chen et al. (2011). The spectral type was taken from the catalogue compiled by Rosslowe & Crowther (2015) in all cases. The values for the kinetic power of the winds were derived in this work.

the shocks taking place in the CWR, its detection in the radio domain points to a binary nature. As a result, binaries that are still unrevealed by classical multiplicity study methods (spectroscopic analysis, high angular resolution direct imaging...) may be evidenced by a particle acceleration signature. The connection between the NT radio emission from massive stars and their multiplicity is what we refer to as the synchrotron–binarity correlation. Keeping the aforementioned motivations in mind, we selected a sample of five WR stars for observation using the upgraded Giant Metrewave Radio Telescope (uGMRT).

This paper is structured as follows. We present the sample of targets observed and give a brief description of them in Sect. 2. The data acquisition and reduction procedure are described in Sect. 3. In Sect. 4, we present the main results of the data analysis. A detailed discussion of the results and their implications is carried out in Sect. 5, while the main conclusions are summarized in Sect. 6, along with potential suggestions for future research in this area.

## 2. Selected Wolf–Rayet stars

### 2.1. Sample description

We selected five WR stars from the Galactic Wolf Rayet Catalogue<sup>2</sup> (Rosslowe & Crowther 2015): WR 87, WR 93, WR 98a, WR 106, and WR 110. The motivation to select WR stars is two-fold. Firstly, WR stars are characterized by especially high values of the wind kinetic power (defined as the kinetic energy transferred per unit time in the wind outflow;  $P_{\text{kin}} = \frac{1}{2} \dot{M} v_{\infty}^2$ ), typically of the order of (or even above)  $10^{37} \text{ erg s}^{-1}$ . This represents a significant reservoir of mechanical energy available to drive physical processes associated with their winds, in particular processes related to shock physics in CWBs such as particle acceleration and emission of synchrotron radiation. Secondly, WR components are observed in nearly half of the identified PACWBs. This proportion is noteworthy, given that WR stars are expected to be remarkably less numerous than their O-type progenitors, considering the respective duration of their evolutionary phases. Additionally, the selected sample has shown potential indications of binarity, based on previous observational studies at different wavelengths. To mitigate the effects of brightness dilution associated with larger distances, we restricted our selection to stars within a maximum distance of 3 kpc. The selected sample of WR stars is presented in Table 1.

WR 87 and WR 110 are both classified as nitrogen-rich WN spectral types. The former has shown both absorption lines of unknown origin and weak emission lines (Conti & Massey 1989;

Smith et al. 1996; van der Hucht 2001). WR 110 shows a thermal X-ray emission spectrum harder than expected for a single star's wind, which could be explained by colliding wind shocks. In contrast, its radio emission was observed to be consistent with free-free (FF) emission from the ionized wind (Skinner et al. 2002). WR 110 has also been studied by Shara et al. (2022) in the search for a close and faint companion. However, they found no indication of any companion that would fit the criteria of their analysis.

WR 93, WR 98a, and WR 106 belong to the carbon-rich WC spectral type. WR 93 is believed to be part of a binary system, with a possible late O-type companion revealed through spectroscopy studies showing double absorption lines, but without an orbital solution known to date (Lortet et al. 1984; van der Hucht 2001). WR 98a is an interesting target in the sample. It is confirmed as a PACWB (De Becker & Rauq 2013) with evidence of NT radio emission (a variable flux, and a value for the spectral index  $\alpha$  close to zero; Monnier et al. 2002; Cappa et al. 2004). This system is also observed to be associated with a dusty spiral pinwheel nebula revolving with a 1.4 yr periodicity (Monnier et al. 1999). The flux variation in the infrared (IR), believed to be due to the dust formation in the wind-wind interaction region, can be attributed to the orbital eccentricity of the system or to optical depth effects related to our viewing angle of the hot inner parts of the system (see e.g. Williams et al. 1995; Monnier et al. 2002). Hence, monitoring this system for NT radio emission is crucial to understanding the system in detail. WR 106 also belongs to the category of dust-makers, identified as such based on the detection of a significant IR excess, but not detected in X-rays (Cohen & Vogel 1978; De Becker 2015). While the non-detection of WR 106 in X-rays, plus the lack of Balmer absorption lines in its spectrum attributable to a hot companion (Williams & van der Hucht 2000), point to a single WC-type star scenario, the persistent production of dust is commonly explained in terms of the existence of enhanced density regions. These regions result from the collision of two winds, which would favour a binary system scenario. If WR 106 is not a CWB, a new explanation for the formation of its circumstellar dust should be found (Williams 2014).

### 2.2. Previous radio measurements

All the targets studied here had been previously observed in the radio domain and other wavelengths, and thus benefit from past radio measurements. For some of them, we also found prior observations at 1.4 GHz, which is the frequency range compatible with the uGMRT Band 5. In the cases of 1.4 GHz observations, no emission has been detected, with the previous

<sup>2</sup> <https://pacrowther.staff.shef.ac.uk/WRcat/>

**Table 2.** Previous radio measurements.

| Source | $S_\nu$ (1.4 GHz)<br>(mJy) | $S_\nu$ (4.9 GHz)<br>(mJy) | $S_\nu$ (8.4 GHz)<br>(mJy) | $S_\nu$ (15 GHz)<br>(mJy)  |
|--------|----------------------------|----------------------------|----------------------------|----------------------------|
| WR 87  | <1.26 <sup>(a)</sup>       | <0.40 <sup>(b)</sup>       | <0.24 <sup>(c)</sup>       |                            |
| WR 93  |                            | 0.9 ± 0.2 <sup>(b)</sup>   |                            |                            |
| WR 98a | <0.36 <sup>(d)</sup>       | 0.37 ± 0.07 <sup>(d)</sup> | 0.47 ± 0.05 <sup>(c)</sup> | 0.64 ± 0.11 <sup>(e)</sup> |
|        |                            | <0.39 <sup>(e)</sup>       | 0.55 ± 0.15 <sup>(d)</sup> |                            |
|        |                            |                            | 0.59 ± 0.06 <sup>(e)</sup> |                            |
|        |                            |                            | 0.62 ± 0.05 <sup>(d)</sup> |                            |
| WR 106 |                            |                            | <0.17 <sup>(c)</sup>       |                            |
| WR 110 |                            | 1.17 ± 0.04 <sup>(f)</sup> | 1.77 <sup>(f)</sup>        |                            |

**Notes.** <sup>(a)</sup>Chapman et al. (1999), <sup>(b)</sup>Abbott et al. (1986), <sup>(c)</sup>Cappa et al. (2004), <sup>(d)</sup>Monnier et al. (2002), <sup>(e)</sup>Montes et al. (2009), <sup>(f)</sup>Skinner et al. (2002). There are several values for the fluxes of WR 98a since it has been catalogued as a variable source.

works providing an upper limit. Radio measurements of the targets available in the literature are given in Table 2. We only show values up to 15 GHz since the emission is primarily thermal at higher frequencies. No measurements below 1 GHz have been reported for these targets. Hence, our data in Band 4 provide us with the first opportunity to measure the emission from these targets in this low-frequency range.

### 3. Observations and data reduction

The selected sample of WR stars was observed with the uGMRT situated in Pune, India. This Y-shaped array consists of 30 parabolic dishes with a diameter of 45 m each. Each of the three arms of the array contains six antennas, while the remaining 12 dishes are distributed in a central square kilometre region. The antennas are fully steerable and span over an extension of 25 km, with 100 m being the minimum baseline length, which allows the array to probe small and large spatial scales of radio emission. It operates at frequencies ranging from 50 MHz to 1450 MHz.

Single-epoch observations of the five targets were carried out from June 4 to 9, 2023, during cycle 44. Continuum observations were obtained in Band 4 (550–950 MHz) and Band 5 (1050–1450 MHz) using the GMRT Wideband Backend (GWB) correlator set to have a bandwidth of 400 MHz covering 4096 channels. The primary flux calibrators observed were radio sources 3C48 and 3C286, while sources 1822–096, 1626–298, and 1911–201 served as phase calibrators for determining the amplitude and phase gains necessary for flux and phase calibration.

All the steps of the data reduction process, namely flagging and removal of bad data and radio frequency interference (RFI) contaminated data, calibration, imaging of the target based on the calibrated visibility data, and self-calibration, were carried out using the CAPTURE<sup>3</sup> continuum imaging pipeline developed for uGMRT data (Kale & Ishwara-Chandra 2021). The pipeline makes use of tasks from the Common Astronomy Software Applications (CASA; McMullin et al. 2007) software. For some targets, additional manual flagging had to be carried out. Six iterations of phase-only self-calibration were performed before achieving the final image, to obtain maps with better rms noise. The maps were subsequently primary beam corrected, using the task `ugmrtpb`<sup>4</sup>.

<sup>3</sup> <https://github.com/ruta-k/CAPTURE-CASA6.git>

<sup>4</sup> <https://github.com/ruta-k/uGMRTprimarybeam-CASA6>

## 4. Results

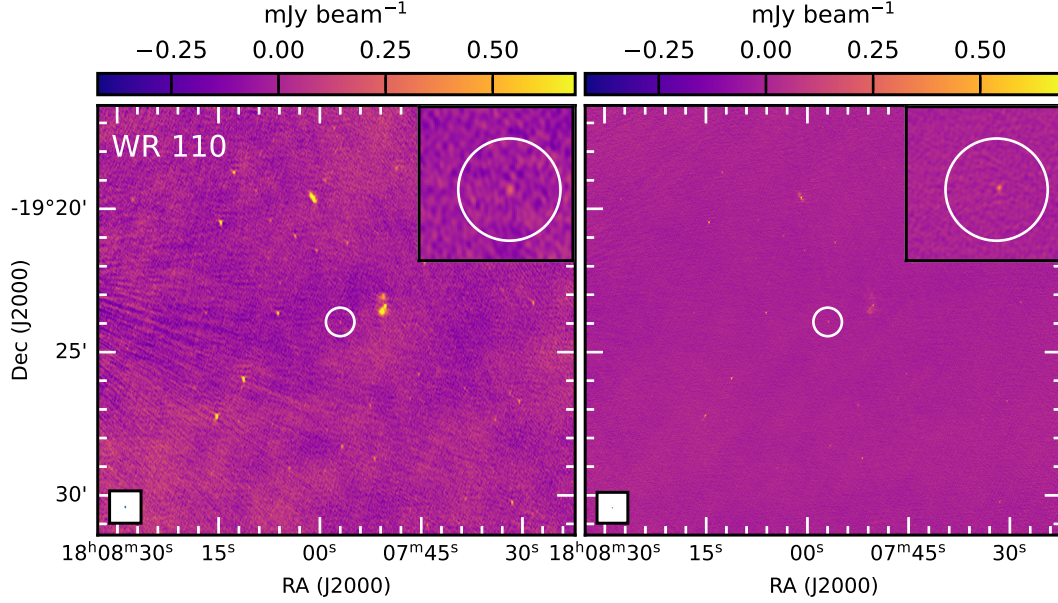
The synthesized beam size in both bands is of the order of a few arcseconds. At a distance of a few kiloparsecs, this angular size corresponds to projected linear distances on the plane of the sky of thousands of astronomical units. Only binary systems with orbital periods of several thousand years would reach such dimensions, which are significantly longer than the orbital periods of all known PACWBs. Our targets, if detected, should thus be unresolved and appear as point sources. The radio maps were therefore inspected to reveal the presence of point sources at the expected position of our targets, above a detection threshold set based on the rms sensitivity of the maps.

Radio emission was detected only for WR 110 in both bands. The field maps are shown in Fig. 1 with the location of the source encircled in white. No emission was detected for the other sources in both bands. The maps of these fields are presented in Fig. A.1. It is worth noting that we do not detect any radio emission from WR98a, which is reported as a PACWB from earlier work (De Becker & Raucq 2013). This is given a more specific discussion in Sect. 5.4.2. In the cases of non-detection, we derive  $3\sigma$  upper limits to the flux density of the WR stars from the rms levels at both frequencies. We use the CASA task `imfit` to estimate the flux density in both bands for WR 110. The faint detection in Band 4 is estimated to be just above the  $3\sigma$  level. The synthesized beam sizes, local rms values, and flux density values (and upper limits) of the clean Stokes  $I$  maps for all the targets in both bands are presented in Table 3.

## 5. Discussion

### 5.1. The radio emission from Wolf–Rayet stars

The thermal and NT radio emission associated with massive stars, and particularly with WR stars, in binary (or higher multiplicity) systems, has been extensively studied through the years (e.g. Dougherty & Williams 2000; Montes et al. 2009; De Becker & Raucq 2013; De Becker et al. 2019; Benaglia et al. 2020). The radio emission from PACWBs is a combination of two sources of emission: (1) the FF thermal emission from the individual stellar winds, and (2), the NT synchrotron radiation produced by the population of relativistic electrons accelerated in the CWR. The thermal emission is roughly steady, though in a binary system some enhancement is expected of the thermal emission, due to the wind compression in the CWR, especially for close binaries and/or systems with similar mass-loss rates (Stevens 1995). Variability of the thermal emission could in principle be observed for some binaries, with the variation associated with changes in the separation of the stars or orientation effects that result in a differential absorption through the circumstellar material (Pittard 2010). The most noticeable example of variable thermal emission from a massive binary is  $\eta$  Car, where the variability is explained by an orbital, phase-dependent alteration of the ionization of the wind material as it is exposed to the intense radiation field from the bright companion (Kashi & Soker 2007). For its part, NT emission produced in the CWR is intrinsically variable in eccentric orbits as a function of the orbital phase. It reaches its peak at periastron, due to a stronger local magnetic field acting at the CWR as a consequence of the smaller separation between the stars. In both cases, the emission spectra in radio follow a power-law dependence on the frequency and can be described by the expression  $S_\nu \propto \nu^\alpha$ . The power-law exponent,  $\alpha$ , is known as the spectral index and is typically below  $-0.1$ .



**Fig. 1.** Field around WR 110 in Band 4 (left) and Band 5 (right). The location of WR 110 is given by the white circle. A zoomed-in view of the source is shown in the top right corner.

**Table 3.** Parameters estimated from the radio maps.

| Source | Band 4 (550–950 MHz) |                                     |                  | Band 5 (1050–1450 MHz) |                                     |                  |
|--------|----------------------|-------------------------------------|------------------|------------------------|-------------------------------------|------------------|
|        | Angular resolution   | rms<br>( $\mu\text{Jy beam}^{-1}$ ) | $S_\nu$<br>(mJy) | Angular resolution     | rms<br>( $\mu\text{Jy beam}^{-1}$ ) | $S_\nu$<br>(mJy) |
| WR 87  | $7''.2 \times 3''$   | 156                                 | $<0.47$          | $3''.8 \times 1''.8$   | 29                                  | $<0.09$          |
| WR 93  | $8''.2 \times 3''.5$ | 478                                 | $<1.43$          | $3''.5 \times 1''.9$   | 224                                 | $<0.67$          |
| WR 98a | $5''.9 \times 3''.4$ | 108                                 | $<0.32$          | $4''.0 \times 1''.7$   | 34                                  | $<0.10$          |
| WR 106 | $5''.7 \times 3''.7$ | 106                                 | $<0.32$          | $2''.9 \times 2''.0$   | 29                                  | $<0.09$          |
| WR 110 | $5''.6 \times 3''.6$ | 57                                  | $0.18 \pm 0.08$  | $2''.6 \times 2''.1$   | 21                                  | $0.47 \pm 0.05$  |

for synchrotron radiation (e.g. [Kellermann 1964](#)), and canonically 0.6 ([Wright & Barlow 1975](#); [Panagia & Felli 1975](#)) for thermal FF radio emission assuming a spherically symmetric and homogeneous, single-star wind. This implies that the synchrotron radiation is stronger and dominates the radio spectrum at lower frequencies. At the same time, the thermal contribution from the winds increases with the frequency, and thus this emission dominates at higher frequencies. Consequently, a negative spectral index measured in the radio spectrum of a source and/or a bright emission in the low-frequency range indicates the emission's synchrotron nature.

However, synchrotron radio emission produced in the CWR is likely to be attenuated by free-free absorption (FFA). This absorption process is stronger at lower frequencies and depends on the column of ionized stellar wind along the line of sight. It is thus more pronounced in short-period binary systems, at times leading to a complete suppression of the synchrotron component, especially when the absorbing stellar winds are dense (e.g. [del Palacio et al. 2016](#); [De Becker et al. 2019](#)). In this context, WR winds are the most efficient absorbers. Thus, WR winds, with their high kinetic power, can feed NT processes efficiently and are, at the same time, the most likely to absorb the synchrotron emission through FFA if the stellar separation is

small enough. The FFA process is sensitive to orientation effects and the eccentricity of the orbit, as it depends on the column density of absorbing material along the line of sight. Consequently, FFA undergoes orbital modulation and intensifies as the system approaches periastron and the stellar separation decreases. This effect competes with the enhancement of synchrotron emission, also occurring at periastron.

Another phenomenon that can suppress the synchrotron radiation produced in a thermal plasma at low frequencies is the Razin effect (also known as the Razin–Tsytoich effect). This effect generates an exponential, sharp cutoff in the synchrotron radio spectrum, typically at frequencies lower than the Razin–Tsytoich cutoff frequency. According to [Pacholczyk \(1970\)](#), this frequency (in Hz) can be expressed as  $\nu_R = 20 n_e / B$ , where  $n_e$  is the number density of electrons in the plasma and  $B$  is the magnetic field intensity (both quantities expressed in cgs units). An in-depth exploration of the parameter space of every specific system is required to estimate which of these two processes (FFA or Razin effect) dominates the turnover. This was addressed for instance in the detailed modelling approach presented by [Dougherty et al. \(2003\)](#). Given the stronger sensitivity of FFA on the density, which is significantly high in WR systems (the absorption coefficient scales with the density squared) compared



to the Razin effect (cutoff frequency proportional to the density), we focus here on FFA only. Addressing more deeply the question of the nature of the dominant turnover process would require a much better knowledge of the parameters characterizing our targets.

### 5.2. The multiplicity of WR stars

Most WR binary stars are observed to have an OB star companion, some of them were found to have compact companions (e.g. Crowther et al. 2010), and only a few binary systems made of two WR stars are known so far, for example Apep, discovered by Callingham et al. (2020). The multiplicity fraction among WR stars was thought to be approximately 0.4, as reported by van der Hucht (2001). This value encompassed both spectroscopic and visual WR binaries but was strongly biased towards short-period systems. However, Dsilva et al. (2020) carried out a bias-corrected study of the multiplicity properties of Galactic WC-type WR stars obtaining an intrinsic multiplicity fraction for the Galactic WC population of at least 0.72. In a later study, they analysed the early-type, nitrogen-rich WR population (WNE, Dsilva et al. 2022) and the late-type, nitrogen-rich WR population (WNL, Dsilva et al. 2023) of the Galaxy. The combined study of both types of Galactic WN populations yields an intrinsic binary fraction for WN stars of 0.52, significantly lower than that obtained for WC stars.

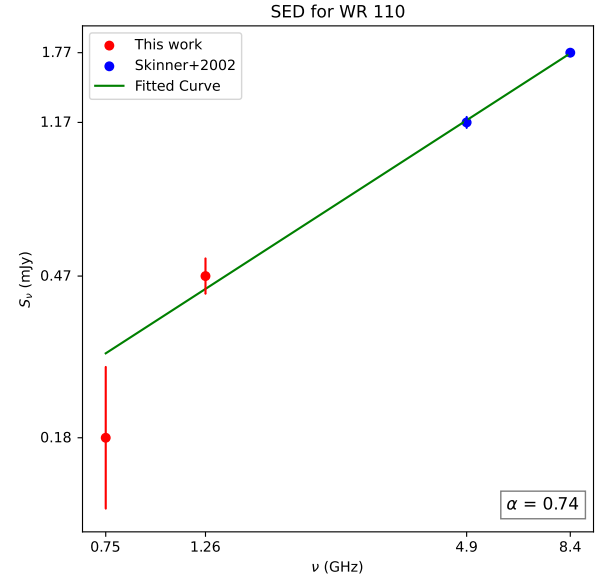
Generally, detecting potential companions of WR stars can be a challenging task due to the inherent characteristics of these stars (e.g. Shenar 2022; Shara et al. 2022). They emit intense radiation across a wide spectrum and this high intrinsic brightness makes them likely to overwhelm, by contrast, a putative, comparatively fainter emission from their companions in binary systems. The difficulty in detecting WR companions renders indirect methods, for example the synchrotron–binarity correlation, more valuable. Since FFA is more prominent in short-period binary systems, where stellar separation is small, detecting synchrotron radio emission from WR systems would reveal mostly systems with sufficiently long periods, typically spanning months, and often extending to years or even decades. This is particularly important considering that most studies and techniques focus on short-period systems (days, weeks, months).

The fact that synchrotron radiation from massive stars is thought to be produced almost exclusively in the context of a binary system (Dougherty & Williams 2000; De Becker & Rauq 2013) allows us to investigate the question of their multiplicity in a region of the orbital parameter space that is not so well explored and contributes to a better census of long-period binaries among WR stars.

### 5.3. Thermal emission

#### 5.3.1. Detection of WR 110

The detection of low-frequency radio emission in WR 110 is worth comparing with other measurements at higher frequencies (see Table 2). In particular, we expect higher frequency radio emission to be dominated by the thermal emission from the dense WR wind. The radio spectral energy distribution (SED) including our uGMRT measurements is shown in Fig. 2. The radio emission we detect in Band 5 is fully consistent with the trend displayed by previous flux density measurements at 4.9 and 8.4 GHz. This suggests that a unique radio emission process is at work across the SED. We used our measurements at bands 4 and 5 together with measurements at higher frequencies to estimate the spectral index  $\alpha$  in this frequency region and obtained



**Fig. 2.** Spectral energy distribution for WR 110 based on our observations and the ones from the literature. The fitted curve gives a spectral index  $\alpha = 0.74 \pm 0.01$ .

a value of  $0.74 \pm 0.01$ . The positive slope of the spectrum points to thermal emission from the wind, with a spectral index greater than the canonical value of 0.6 predicted by Wright & Barlow (1975). However, this is in agreement with other thermal indices determined for WR stars, and results from the influence of strong clumping in WR winds, as demonstrated by Nugis et al. (1998). We note that the flux measurement in Band 4 is lower than the linear trend displayed by higher frequency values. Given that the significance level in the Band 4 measurement is low, it would be purely speculative to provide a valid physical interpretation of this low-frequency deviation. We do not anticipate a change in slope at low frequencies, despite the limited investigation of WR stars in this range. A notable example is WR 11, which exhibits a consistent thermal spectrum down to 150 MHz (Benaglia et al. 2019).

#### 5.3.2. Non-detections

For WR 87, WR 93, and WR 106, the lack of detection at 1.4 GHz and higher frequencies by previous studies (Table 2) prevents us from estimating a spectral index. For WR 98a, its already established PACWB status does not allow us to determine a thermal index as we did for WR 110. As a consequence, it is not possible to investigate whether these WR stars also deviate from the canonical thermal emission law derived by Wright & Barlow (1975).

Even though we have good reasons to consider that our targets deviate from the canonical behaviour, as explained by Nugis et al. (1998), we predict the order of magnitude of the expected thermal flux density ( $S_v^{\text{ff}}$ ) in the wind of the stars using a slightly modified version of the equation given by Wright & Barlow (1975):

$$\left[ S_v^{\text{ff}} \right] = 23.2 \left( \left[ \frac{\dot{M}}{M_{\odot} \text{yr}^{-1}} \right] \left[ \frac{\text{km s}^{-1}}{v_{\infty}} \right] \frac{1}{\sqrt{f_w \mu}} \right)^{4/3} \times \left( \gamma g_{\text{ff}} Z^2 v \left[ \frac{\text{kpc}}{D} \right]^3 \right)^{2/3} \quad (1)$$

**Table 4.** Predicted values for the thermal flux density due to FF emission of the winds.

| Source | $S_v^{\text{ff}}$ (Band 4)<br>(mJy) | $S_v^{\text{ff}}$ (Band 5)<br>(mJy) |
|--------|-------------------------------------|-------------------------------------|
| WR 87  | 0.40                                | 0.54                                |
| WR 93  | 0.42                                | 0.58                                |
| WR 98a | 0.48                                | 0.66                                |
| WR 106 | 0.17                                | 0.23                                |

The values used for each target are listed in Table 1. The stellar wind clumping is considered in the volume filling factor  $f_w$ ; the parameters  $\mu$ ,  $Z$ , and  $\gamma$  are the mean molecular weight, the rms ionic charge, and the mean number of electrons per ion in the wind, respectively; and  $D$  is the distance to the source. For the calculations, we assumed the following set of values:  $f_w = 4$ ,  $\mu = 2$ ,  $Z = 1$ , and  $\gamma = 1$ . The free-free Gaunt factor,  $g_{\text{ff}}$ , was approximated, as done in [Leitherer & Robert \(1991\)](#),

$$g_{\text{ff}} = 9.77 \left( 1 + 0.13 \log \frac{T_e^{3/2}}{Z\nu} \right) \quad (2)$$

where the electron temperature of the wind was estimated as  $T_e \approx 0.3 T_{\text{eff}}$  for the outer layers of the wind where the radio emission is detectable ([Drew 1990](#)), and the values for the effective temperature are quoted in Table 1. The predicted flux density values for each non-detected target in both bands are listed in Table 4.

Comparing these theoretically estimated values with the  $3\sigma$  upper limits presented earlier in Table 3, we find the following:

- For the targets WR 87, WR 93, and WR 106 in Band 4, and WR 93 in Band 5, we obtain values for the estimated fluxes that fall below the measured  $3\sigma$  upper limit. In this sense, they are consistent with pure thermal emitters, and their expected emission is in agreement with a non-detection on our side;
- For WR 87 and WR 106 in Band 5, and WR 98a in both bands, the model predicts flux density values that are somewhat higher than our upper limits. However, these differences are not substantial when considering the inherent uncertainties of this approach. Given the uncertainties in the mass-loss rates and the influence of clumping, which is not properly accounted for in this method, some deviations are anticipated. Specifically, it is important to highlight that the actual thermal emission from these WR winds is likely steeper than predicted by the canonical law assumed in Eq. (1), leading to a lower flux at the low frequencies probed by our uGMRT data. We can thus conclude that our upper limits are not at odds with the expected behaviour of WR thermal winds.

#### 5.4. Non-detection of NT emission

##### 5.4.1. Interpretation framework

Although detecting synchrotron radio emission in our study would have provided strong evidence of particle acceleration processes near the star (indicating that the star is part of a multiple system), the absence of emission does not rule out this possibility either. A similar situation was encountered recently by [Saha et al. \(2023\)](#), and we adopt their approach to analyse the results.

The non-detection of radio emission in the lower frequency bands of the uGMRT, despite their relevance for probing the NT synchrotron emission, could be due to a few different reasons worth discussing.

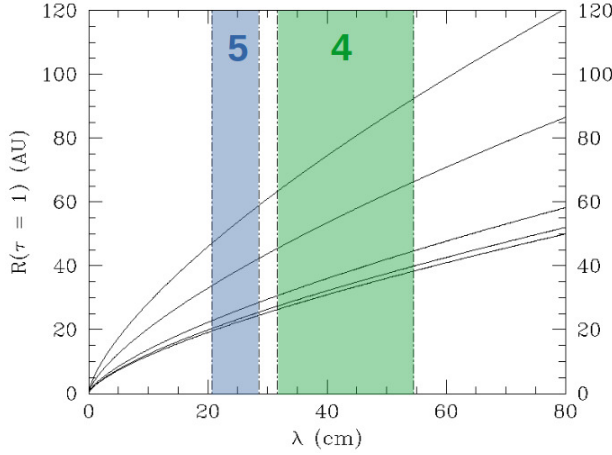
The stars in our sample might not be part of a binary system with a massive companion. If this were the case, there would not be wind shocks that provide the required conditions for accelerating particles, and thus no synchrotron emission. The possibility that the targets are isolated WR stars and not part of a CWB cannot be discarded. In this case, we would only expect the thermal FF emission from the ionized wind of a single star, which may not be strong enough to be detected in the low-frequency observational bands used here.

If we assume that they are part of massive binary systems, one plausible justification for the non-detection of synchrotron radiation could be due to a binary configuration characterized by a small separation, in a short-period system. If this were the case, the CWR would be deeply embedded within the radio-opaque stellar winds and the synchrotron emission would result significantly reduced due to FFA.

Considering a binary system, but with a significantly longer period than considered above, the lack of detection of synchrotron emission could arise in some parts of a highly eccentric orbit. It is acknowledged that the emission from the CWR depends on the stellar separation and that the synchrotron emission peaks towards the periastron, where the stellar separation is the smallest. In the case of a very long-period and highly eccentric orbit, two different configurations could lead to a lack of detection. In one case, if the stars of the system are close to apastron at the time of our observations, the large distance between them would cause the synchrotron emission to drop to its minimum. There are two reasons for this. The first is a drop in the local magnetic field (of stellar origin) in the CWR since it decreases as the separation between the stars increases ([Usov & Melrose 1992](#)) and the second is a drop in the injection rate of particles into the DSA process due to a lower density of the colliding flows in the case of a larger separation ([De Becker et al. 2024](#)). This could lead the synchrotron flux to fall below the detection threshold. Alternatively, close to periastron, the stellar separation can be small enough to substantially increase the impact of FFA, up to a level that may suppress any synchrotron radiation produced in the deeply embedded CWR, as described in the previous case. In this sense, the variable nature of the radio NT emission produced in the wind–wind interaction region draws attention to the temporal aspect of our observations, and it is worth noting that observations of the same target taken at a different epoch could lead to a very different result in terms of detection of NT emission.

As FFA could potentially explain the lack of synchrotron radio emission (provided it is produced in the system), it is worth looking at the constraints this provides in terms of the size of the putative binary system. We adopted the formalism proposed by [Wright & Barlow \(1975\)](#) making use of the wind parameters provided in Table 1 to estimate the radius equivalent to an optical depth ( $\tau$ ) equal to one for the WR winds. We adopted the same assumption for the temperature as in Sect. 5.3. Given the lack of information on putative companions, and the much weaker contribution to FFA coming from OB-type winds, we restrict the discussion to the WR winds.

Figure 3 shows the effective radii of the stellar wind photosphere as a function of the wavelength; uGMRT Band 5 gives a tighter constraint. The most conservative interpretation of these curves is to consider that a separation between the WR and the synchrotron emitting region shorter than  $R(\tau = 1)$  should lead

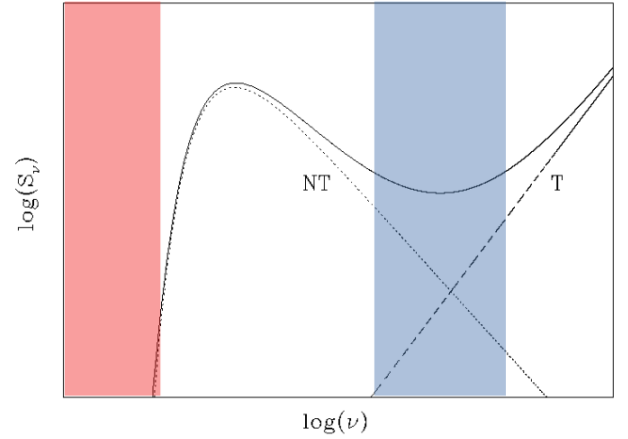


**Fig. 3.** Extension of the radio photosphere as a function of wavelength for the five targets. The uGMRT bands are highlighted in green (Band 4) and blue (Band 5). From top to bottom: WR 87, WR 106, WR 98a, WR 110, and WR 93.

to a significant level of FFA. Separations of a few tens of AU at a few kiloparsecs in principle convert to orbital periods of several years. However, various aspects have to be considered here. First, the synchrotron emission region is quite extended, opening the possibility for a fraction of the NT emission to escape the WR wind. The system's orientation is also expected to play a role: a WR wind located at the background of the NT emission region may allow some synchrotron emission to escape towards the observer. Finally, wind clumpiness is also likely to make the wind less opaque. All these factors may allow the synchrotron emission component to be detected even for smaller separations than plotted in Fig. 3.

#### 5.4.2. The case of WR 98a

As a bona fide PACWB, the non-detection of radio emission from WR 98a deserves further discussion. The synchrotron emitter status was established based on radio measurements at frequencies of several GHz (Montes et al. 2009). In particular, flux densities at 8.4 and 15 GHz (Table 2) indicate a flat spectrum (spectral index close to 0.0). This typically is evidence of a composite spectrum, where both thermal and NT emission components contribute to the radio measurement. This can be better appreciated in the generic spectrum illustrated in Fig. 4, which enables a qualitative discussion. The part of the composite spectrum that appears flat is highlighted in blue. The expectation for a brighter radio synchrotron emission at low frequencies (as discussed in Sect. 5.1) is valid when the optically thin unabsorbed part of the synchrotron spectrum is considered. However, turnover processes significantly suppress the radio emission in the lower part of the spectrum. The severe drop in the composite spectrum illustrates this. Our uGMRT measurements are possibly coincident with the spectral zone shown in red in Fig. 4. In the case of WR 98a, FFA is most likely the turnover process at work, given the density and composition of the WC wind (see also Fig. 3). According to Monnier et al. (1999), this may indicate an orbital period of 1.4 yr, which is short enough to make the synchrotron emission region severely affected by FFA over the majority of the orbit. Hendrix et al. (2016) estimated the orbital separation of the system to be  $\sim 4$  AU, based on the



**Fig. 4.** Schematic view of the radio composite spectrum (solid curve) of a PACWB presenting both a thermal component (T, dashed line) and a turned-over synchrotron component (NT, dotted curve). The blue highlighted part covers a spectral region with an almost flat spectrum, while the red part covers the region where NT emission is suppressed.

orbital period and the stellar masses. Comparing this result to our estimation in Fig. 3, we can expect WR 98a to be completely embedded in the radio photosphere of the WR star, which should be at least 20 AU. In the scenario proposed here to reconcile our non-detection with previous results, the FFA turnover frequency should be well above 1.4 GHz (frequency of the Band 5), but below frequencies closer to 8.4 GHz.

Finally, we note that the NT component's variability must be considered (see Sect. 5.1). The position of the FFA turnover is in particular very likely to change as a function of the orbital phase. This is certainly the reason why measurements at 4.9 GHz at some epochs point to lower flux density than those measured at higher frequencies (Table 2). This probably indicates that, at these epochs, the turnover occurred at a rather high frequency, potentially fully suppressing the synchrotron components and revealing only the thermal emission from the WR wind (dashed line in Fig. 4).

## 6. Conclusions

We conducted a radio continuum analysis of five WR stars (WR 87, WR 93, WR 98a, WR 106, and WR 110) that had previously displayed signs of being part of a multiple system. In the attempt to improve our comprehension of their possible role as particle accelerators, we performed low-frequency (735 and 1260 MHz) uGMRT observations in June 2023.

No radio emission was detected from WR 87, WR 93, WR 98a, and WR 106. For these cases, we give  $3\sigma$  upper limits to the radio flux densities in both bands of observation. We provide the first-ever observations in Band 4, a frequency range unexplored for these targets. For WR 93, WR 106, and WR 110, we offer the first observations in Band 5.

For WR 110, we detect Band 4 and Band 5 emissions consistent with pure thermal emission. Making use of our new measurements and of previously published flux density values at 4.9 and 8.4 GHz, we derived a thermal spectral index of  $0.74 \pm 0.01$ . This value, steeper than the usual canonical value, is compliant with expectations for dense and highly clumped WR winds. If WR 110 were indeed a binary system, and based on Fig. 3, we can see that its orbital separation should be greater

than  $\sim 20$  or even 30 AU, depending on the observing frequency, for us to detect some NT emission.

We found no observational evidence of synchrotron radiation, and therefore no indication of binarity, in any of the targets. Our uGMRT measurements at low-frequency bands are likely significantly affected by FFA, which would heavily suppress any potential synchrotron emission at these frequencies. This is particularly notable in the case of WR 98a; although it shows a composite spectrum (made of thermal and NT contributions) at higher frequencies, it was undetected in our data. This underscores the prominent role of FFA on observational biases affecting the census of PACWBs among CWBs. Detecting synchrotron emission at lower frequencies is thus highly dependent on the position of the FFA turnover. Therefore, we note the importance of including measurements at a few GHz as well, to investigate the nature of the radio emission from massive stars and to improve the census of particle accelerators among them. However, we note that lower frequency measurements remain necessary to characterize the turnover, especially in binary systems with sufficiently long periods that push the FFA turnover frequency below 1 GHz. These factors must be considered when addressing the observational biases that impact our census of particle accelerators among massive stars.

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<sup>5</sup> <https://www.astro.uliege.be/~debecker/pantera>



**Appendix A: Radio maps of the uGMRT fields**

Radio images without detection of the targets in Band 4 (left column) and Band 5 (right column) are shown in Fig. A.1. In all the cases, the expected position of our target is indicated by a white circle. The synthesized beam is shown in the bottom left corner.

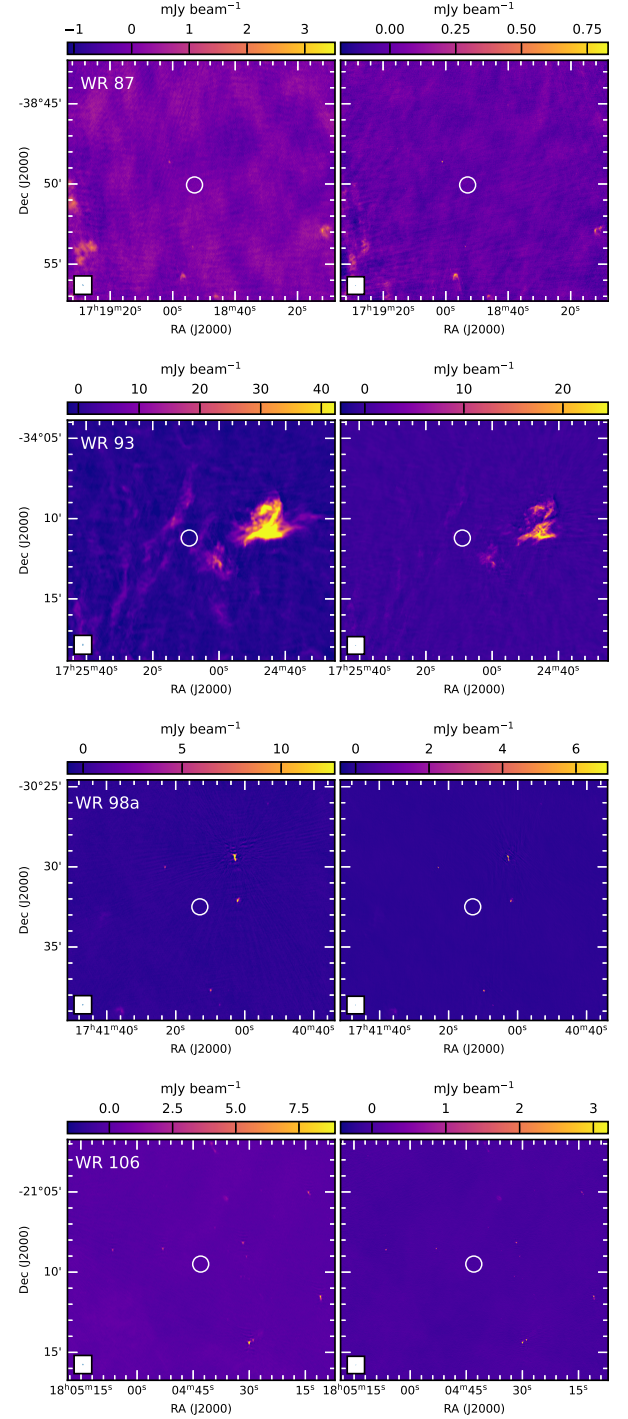


Fig. A.1: uGMRT fields around WR 87, WR 93, WR 98a, and WR 106 observed in Band 4 (left column) and Band 5 (right column).



# Chapter 4

## Search for polarization in known PACWBs with the VLA

### 4.1 Scientific motivation

As discussed in Sect. 1.4, synchrotron radiation is a physical emission mechanism that is intrinsically polarized. Because relativistic electrons gyrate around magnetic field lines, the emitted radiation exhibits a preferred orientation of its electric field vector, resulting in linearly polarized emission. Therefore, unlike total-intensity measurements alone, polarization measurements may provide direct information about the magnetic-field structure within the emitting region. For this reason, radio polarimetry is an important tool in the study of a variety of astrophysical sources of synchrotron radiation.

Despite its importance, polarization studies of PACWBs remain scarce. Although synchrotron emission has been identified in several PACWBs through their radio spectra, no polarization has yet been detected from any member of this class. The only previous dedicated attempt to search for radio polarization in a PACWB was carried out by [Hales et al. \(2017\)](#), who studied the system WR 146 but did not detect polarized emission.

The absence of observational detections is not necessarily unexpected. On the contrary, while synchrotron radiation is intrinsically polarized, the observed degree of polarization may be significantly reduced by several propagation and observational depolarization mechanisms operating both within the system and along the line of sight, as described in Sect. 1.4. In particular, PACWBs provide especially complicated environments for the preservation of the polarization signature in the synchrotron radio emission. Before reaching the observer, the synchrotron radiation must move through the dense, ionized, and magnetized winds of the massive stars, plus the WCR itself, where substantial Faraday rotation and the resulting depolarization may occur. Additional Faraday rotation may also occur due to any magnetized plasma located between the source and the observer. Furthermore, turbulent magnetic fields within the WCR lower the intrinsic degree of polarization, while observational effects such as bandwidth and beam depolarization can further suppress the measured polarized signal.

Consequently, the lack of detected polarization does not necessarily imply the

absence of intrinsically polarized synchrotron emission. Sensitive polarimetric observations can nevertheless provide meaningful constraints on the physical conditions within the WCR and on the processes affecting the propagation of the radiation. However, with only a single PACWB (WR 146) having previously been investigated from a polarimetric perspective, it remains unclear whether the absence of detected polarization is a specific characteristic of that individual system or a more general property of PACWBs. Expanding the sample of observed systems was therefore essential to place the polarization properties of PACWBs into a broader observational context and to assess whether common trends emerge across a more diverse population.

Motivated by these considerations, a dedicated full-polarization radio observing campaign was carried out with the Karl G. Jansky Very Large Array (VLA) to search for the signature of polarization in the synchrotron emission of a sample of well-established PACWBs. The selected targets are among the brightest synchrotron-emitting known PACWBs, safely ensuring the presence of strong synchrotron emission itself, to maximize the likelihood of detecting its polarized component. By extending the search beyond the single system previously investigated by [Hales et al. \(2017\)](#) and probing a broader region of the PACWB parameter space, we aimed to explore the polarization properties of PACWBs over a wider range of system characteristics and to establish a more representative observational picture of this class. Regardless of the detection outcome, the results would provide a stronger framework for constraining the polarization properties of PACWBs and for interpreting the role of depolarization processes than was previously possible. In this way, this project contributes to the second objective described in Sect. 1.7.

## 4.2 The Karl G. Jansky Very Large Array

The analysis presented in this chapter was carried out thanks to observations acquired with the VLA telescope. The Karl G. Jansky Very Large Array (VLA) is a radio interferometric array located in New Mexico, USA, and operated by the National Radio Astronomy Observatory (NRAO). The array is composed of 27 dishes, each 25 m in diameter, arranged along three arms in a Y-shaped configuration. The antennas are periodically repositioned along these arms, allowing the VLA to cycle through four standard configurations (A, B, C, and D), reaching maximum baselines that range from approximately 1 km in the most compact configuration (D) to 36 km in the most extended one (A). A view of several antennas in one of the rails is shown in Fig. 4.1.



Figure 4.1: One of the arms of the Jansky Very Large Array (VLA) telescope in New Mexico, USA. Source: Photo taken by Bettymaya Foott as part of an astrophotography project with the NRAO and the VLA.

The angular resolution of the VLA varies significantly with both configuration and observing frequency, ranging from several arcseconds in compact configurations at low frequencies to tens of milliarcseconds in the most extended configurations at high frequencies.

Following a major modernization completed in 2012, the VLA (now referred to as the Karl G. Jansky VLA) improved its sensitivity, instantaneous bandwidth, and spectral capabilities. The array now operates over a broad frequency range, from approximately 250 MHz (P band) up to 50 GHz (Q band), and additionally includes 4-band receivers covering the 54–86 MHz range.

For the project discussed in this chapter, the targets of interest were observed in L band (1–2 GHz) and C band (4–8 GHz), providing a combination of relatively-low-frequency coverage, where synchrotron emission is typically stronger, with higher-frequency data to help better characterize the spectral behavior.

### 4.3 Observing proposal

The observations used in this chapter were obtained through a VLA proposal led by Dr. Santiago del Palacio, from the PANTERA collaboration, as the PI.

The proposal was designed to investigate the polarization properties of synchrotron emission in a sample of known PACWBs through sensitive full-polarization radio observations. The scientific motivation behind the proposal follows the discussion presented in Sect. 4.1, namely to determine whether the lack of detected polarization previously reported for WR 146 is a common characteristic among PACWBs or the result of source-specific conditions.

From a technical perspective, the observations were carried out in the VLA B

configuration for both the L (1–2 GHz) and C (4–8 GHz) frequency bands. The combination of the L and C bands provided broad spectral coverage while allowing the investigation of potential frequency-dependent depolarization effects and the characterization of the emission properties within each observing band. Since the target systems were expected to remain unresolved, the B configuration offered sufficient angular resolution while minimizing contamination from extended Galactic emission. Full-polarization observing modes were employed in both bands, allowing the determination of all four Stokes parameters.

The requested observing time was optimized to achieve sensitivities capable of detecting a polarization degree of approximately 1–2% level in the target sources, while accounting for calibration overheads and the expected impact and subsequent loss of data due to RFI, particularly in the L band.

The proposal also included the observation of the calibrators required for full-polarization calibration. The standard calibrator source 3C286 (a strongly polarized source with a well-known model of polarization) was observed at the beginning of each observing run to establish the absolute flux density scale, determine the bandpass response, and calibrate the absolute polarization angle, while the weakly polarized source J2355+4950, whose polarization degree is below 0.25%, was observed at the end of the runs to determine the instrumental polarization leakage terms. The observations were carried out on 9 and 10 August 2016 in the L and C bands, respectively.

## 4.4 Observations and data reduction

The observations presented in this chapter were reduced using the **CASA** software, following the general procedure described in Sect. 2.3.2. This strategy is recommended by the NRAO for VLA full-polarization observations, and was based primarily on the **CASA VLA Continuum and Polarization Calibration Guides** ([NRAO CASA Team, 2024, 2026](#)).

The calibration procedure employed for this dataset can be divided into two stages. The first corresponds to the standard continuum calibration, in which instrumental and atmospheric effects that affect the measured visibilities are corrected. The second stage specifically addresses the instrumental response to polarized emission, and is required for a reliable reconstruction of the full polarization state of the incoming radiation.

### 4.4.1 Continuum calibration

The initial visibility calibration followed the standard VLA continuum-reduction procedure to obtain the correct amplitudes and phases. After an initial inspection of the data, RFI and corrupted visibilities were manually identified and flagged. The observer’s logs were consulted to identify periods affected by known problems (instrumental issues or antenna failures) during the observations. The standard calibrator 3C286 was then used to determine the absolute flux density scale and the frequency-dependent delay and bandpass response. Two different complex gain calibrators, one for each target field, were selected as secondary calibrators and

chosen to be close to their respective targets on the sky to properly track fast time-dependent atmospheric and instrumental phase variations. For this reason, they were observed before and after their corresponding target scans, and used to derive the time-dependent corrections (or gain solutions) that were then transferred to the target sources. These calibration steps allow us to obtain accurately calibrated Stokes  $I$  visibilities and constitute the starting point for the polarization calibration described below.

#### 4.4.2 Polarization calibration

Unlike total-intensity (Stokes  $I$ ) observations, full-polarization observations require additional calibration steps. The polarization calibration was required in this work to accurately recover the linear polarization properties of the target sources, encoded in the Stokes parameters  $Q$  and  $U$ .

Since the VLA employs circularly polarized feeds, each antenna records two voltage signals corresponding to the right-hand ( $R$ ) and left-hand ( $L$ ) circular polarization components of the incoming radiation. The measured visibilities are, thus, expressed in terms of right- and left-hand correlations: the parallel-hand products  $RR$  and  $LL$  (correlations between two right-hand and two left-hand circularly polarized signals, respectively), and the cross-hand products  $RL$  and  $LR$  (correlations between orthogonal circular polarizations). For a baseline formed by antennas  $i$  and  $j$ , the correlator computes the four visibility products

$$\begin{aligned} V_{RRij} &= RR_{ij} = \langle v_{R,i} v_{R,j}^* \rangle, \\ V_{LLij} &= LL_{ij} = \langle v_{L,i} v_{L,j}^* \rangle, \\ V_{RLij} &= RL_{ij} = \langle v_{R,i} v_{L,j}^* \rangle, \\ V_{LRij} &= LR_{ij} = \langle v_{L,i} v_{R,j}^* \rangle, \end{aligned} \tag{4.1}$$

where  $v_R$  and  $v_L$  denote the complex voltages measured by the right- and left-hand circularly polarized feeds, respectively, and  $\langle \rangle$  represents the time-averaged cross-correlation. The parallel-hand products are enough for total intensity analysis, whereas the cross-hand products are needed to analyze the linear polarization signal.

In the circular polarization basis, the Stokes parameters are related to these correlations by

$$I = \frac{RR + LL}{2}, \quad Q = \frac{RL + LR}{2}, \tag{4.2}$$

$$U = \frac{RL - LR}{2i}, \quad V = \frac{RR - LL}{2}. \tag{4.3}$$

Consequently, while the standard continuum calibration primarily relies on the parallel-hand correlations ( $RR$  and  $LL$ ), recovering the linear polarization components  $Q$  and  $U$  requires additional calibration of the cross-hand correlations ( $RL$  and  $LR$ ). Any residual cross-hand phase offsets or instrumental polarization (leakage) would otherwise introduce mixing between the Stokes parameters, contaminating the reconstructed linear polarization. For this reason, a full polarization calibration



was implemented in the analysis of the VLA dataset to properly calibrate the cross-hand visibility products, from which the linear polarization (Stokes  $Q$  and  $U$ ) is derived. The following paragraphs describe the additional calibration steps applied to specifically correct these instrumental effects.

Polarization calibration requires two additional calibrators beyond those used for total-intensity calibration: a polarization angle calibrator and a leakage calibrator. In this dataset, the source 3C286 was used to fix the absolute position angle of the polarized emission. Since its polarization properties are well known, a polarization model was first assigned to this source.

The leakage calibration was performed using the calibrator J2355+4950, a bright source with negligible intrinsic polarization at both  $L$  and  $C$  bands. Such sources are well suited for determining the instrumental polarization because any measured polarization can be attributed primarily to leakage between the two orthogonal polarization channels.

Before solving for the instrumental polarization, the residual instrumental cross-hand delay (i.e., between the two polarization channels,  $R$  and  $L$ ) was corrected. This step removes the timing difference that may remain between the two polarization signal paths after the standard calibration, eliminating the corresponding frequency-dependent phase difference between the right- and left-circular polarization channels before the following calibration steps.

The next stage in the polarization calibration was solving for the instrumental polarization (the leakage or  $D$ -terms) using J2355+4950. These terms estimate how much of the signal from one polarization channel is being detected by the other channel because of imperfections in the antenna feeds. Due to the calibrator source being effectively unpolarized ( $Q = U = 0$ ), any detected polarization can be interpreted as instrumental leakage and is thus used to calculate the corresponding corrections to the mixing between  $R$  and  $L$ . The derived leakage solutions were next applied to the target sources.

The final polarization calibration step is to solve for the cross-hand phases to match the polarization angle of the model and establish the absolute polarization position angle. This step is necessary because after the residual cross-hand delay has been corrected (during the first step), a constant phase offset between the two polarization channels may still remain. This offset rotates the measured polarization vectors by a constant angle on the sky, so this calibration references them to the correct orientation on the sky. Removing the constant offset is the final step to placing the polarization position angles on an absolute reference frame. The standard primary calibrator 3C286 was used for this purpose, since its polarization properties are known and routinely monitored by the NRAO. The expected frequency-dependent polarization model for 3C286 was obtained from the NRAO polarization calibration tables and supplied to CASA during the calibration process.

Thus far, we have derived all the polarization calibration tables needed. After applying the calibration solutions to the target data, we produced images in all four Stokes parameters. These images constitute the basis of the scientific analysis presented in this chapter.

## 4.5 Main findings

This study is about the search for linear polarization in the synchrotron radio emission of two well-known PACWBs, WR 147 and HD 167971, using full-polarization VLA observations at L and C bands. The choice of these bands represents a compromise between maximizing the synchrotron contribution while trying to limit the impact of FFA and Faraday-rotation effects that are also expected to be important at lower frequencies. The systems WR 147 and HD 167971 were selected due to being among the brightest synchrotron-emitting PACWBs known, and because of the differences in their stellar properties, which allow us to probe polarization in a diverse sample, under different physical conditions.

The main goal was to test whether the synchrotron emission produced in the WCR exhibits the expected linear polarization signature, and investigate what constraints on the physical properties of PACWBs could be inferred, whether polarization was detected or not.

Both systems were undoubtedly detected in total intensity at all observed frequencies, confirming the presence of bright, spatially unresolved radio emission resulting from a combination of thermal free-free emission from the stellar winds and NT synchrotron radiation from the WCR. However, no significant linear polarization signal was detected in either Stokes  $Q$  or  $U$  for any of the targets or frequency ranges. This non-detection remained robust even when restricting the analysis to narrower, high-frequency sub-bands designed to minimize bandwidth and Faraday depolarization effects. The resulting upper limits on the polarization degree are of order  $\lesssim 1\%$  for both sources across the different cases studied.

We contrasted these limits with the intrinsic polarization expected for synchrotron emission. The theoretical maximum polarization degree is of order  $\sim 0.7$  for a fully ordered magnetic field. Although some degree of magnetic turbulence is, in fact, required for DSA to efficiently accelerate the particles that will, in turn, emit synchrotron radiation, the observed upper limits show a severe suppression of the polarized signal, probably requiring a combination of physical and observational depolarization mechanisms to justify it.

We explain the non-detections as a combination of additional depolarization effects acting within the synchrotron-emitting region (the WCR) and while propagating along the line of sight. These include a local, highly turbulent magnetic field, as well as Faraday-rotation-driven effects such as differential rotation and bandwidth depolarization. Beam depolarization due to the limited angular resolution of the observations further contributes, as the complex structure of the synchrotron-emitting region remains unresolved. We suggest that thermal dilution likely plays a significant role as well, particularly for the system WR 147, where the strong stellar wind from the WR component contributes copiously to the observed flux. This unpolarized thermal emission may substantially reduce the effective maximum detectable polarization by diluting the synchrotron component.

Overall, we believe the results indicate that the absence of detectable polarization does not imply a lack of synchrotron emission or particle acceleration. Instead, it highlights the extreme efficiency of depolarization processes in PACWBs, where thermal emission contamination, magnetic turbulence, and propagation effects act

simultaneously. This combination appears to be sufficient to suppress the observable polarization.

These findings place PACWBs in contrast with other synchrotron-emitting systems where linear polarization has been detected. In PACWBs, the coexistence of strong thermal winds and compact, unresolved emission regions introduces additional challenges that seem to strongly hinder polarization measurements. High-sensitivity and high-angular-resolution observatories will be required to resolve and isolate the synchrotron component and further constrain the magnetic field structure in these systems.

The results of this study have been published ([Blanco et al., 2026](#)) and the paper is included for completeness in Sect. 4.6.

## 4.6 Included publication

## Search for radio polarization in the particle-accelerating colliding-wind binaries WR 147 and HD 167971

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### ABSTRACT

**Context.** Particle-accelerating colliding-wind binaries (PACWBs) are multiple systems of massive stars in which strong stellar winds collide, accelerating particles to relativistic energies. This population of relativistic particles emits NT radiation, including synchrotron radiation in the radio domain. This emission is expected to be linearly polarized, but the polarization signature has not yet been detected for a PACWB.

**Aims.** Our objective is to quantify the linear polarization of synchrotron radiation in two well-known PACWBs and to interpret our measurements within the framework of the physics of these specific NT emitters.

**Methods.** We observed the PACWBs WR 147 and HD 167971 with the Very Large Array (VLA) radio interferometer in the frequency bands *L* and *C* (1–2 and 4–8 GHz, respectively), where synchrotron emission is expected to be more prominent. We performed polarization calibration and analyzed the resulting Stokes maps.

**Results.** We did not detect any polarization signature for either of the two targets in either of the two bands, even when considering narrower bands to mitigate the effect of bandpass depolarization. The most conservative upper limit on the polarization degree is on the order of 1% for both targets.

**Conclusions.** The lack of linear polarization for the two targets is likely attributable to a combination of effects, including the turbulent nature of the magnetic field in the synchrotron-emitting region, and depolarization processes based on Faraday rotation that are certainly active in these sources. Their complex geometry, unresolved by the VLA at these frequencies, is most likely to lead to beam depolarization. We emphasize that, in contrast to other canonical synchrotron sources, PACWBs are also subject to thermal dilution. This is especially relevant for systems with stars whose winds are strong enough to contribute copiously to thermal emission, such as those harboring a Wolf-Rayet component.

**Key words.** polarization – radiation mechanisms: non-thermal – stars: individual: HD 167971 – stars: individual: WR 147 – radio continuum: stars

### 1. Introduction

High-mass stars ( $M \geq 8 M_{\odot}$ ) are a type of hot, luminous star commonly found gravitationally bound in binary or multiple systems, with a binary fraction of at least 90% for O-type stars in young clusters (Offner et al. 2023). They are characterized by strong, fast, and dense winds of ejected material that cause the environments of these stars to become irreversibly modified. The outflowing material that is expelled from the massive-star surface in the winds can reach terminal velocities ( $v_{\infty}$ ) of a few  $1000 \text{ km s}^{-1}$ , with mass-loss rates ( $\dot{M}$ ) that typically range between  $10^{-7}$  and  $10^{-5} M_{\odot} \text{ yr}^{-1}$ . These wind parameters are intimately dependent on the spectral type and luminosity class of the star. In particular, Wolf-Rayet (WR) stars, which are the evolved counterparts of O-type stars, are typically associated with significantly stronger winds.

When a multiple stellar system is made of two or more high-mass stars, their powerful winds collide, resulting in what is known as a colliding-wind binary (CWB). Within the category of CWBs, some systems show evidence of being capable of accelerating charged particles, such as electrons and protons,

to relativistic speeds. We refer to these systems as particle-accelerating colliding-wind binaries (PACWBs, De Becker & Rauq 2013; De Becker et al. 2017). Thus far, more than 50 objects have been catalogued as PACWBs (De Becker & Rauq 2013)<sup>1</sup>. The process responsible for particle acceleration in PACWBs is believed to be diffusive shock acceleration (DSA, Drury 1983). DSA occurs in the shocks produced by the collision of winds in the colliding-wind region (CWR) and allows particles to gain energy through iterative interactions. These relativistic particles will, in turn, emit nonthermal (NT) radiation through different radiative processes across the electromagnetic spectrum (Eichler & Usov 1993; Pittard & Dougherty 2006; Pittard et al. 2006; Reimer et al. 2006; De Becker 2007; Pittard et al. 2021). In particular, relativistic electrons in the presence of a magnetic field end up producing NT synchrotron radio emission. In PACWBs, the magnetic field present in the CWR, which is of stellar origin, interacts with the relativistic electrons accelerated in the shocks, and as a result, synchrotron radiation is produced.

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<sup>1</sup> The catalogue is regularly updated at <https://www.astro.uliege.be/~debecker/pacwb/>

**Table 1.** Parameters of the Stokes  $I$  maps for both targets.

| Source    | Observing band       |                                    |                  |                      |                                    |                  |                      |                                    |                  |                      |                                    |                  |
|-----------|----------------------|------------------------------------|------------------|----------------------|------------------------------------|------------------|----------------------|------------------------------------|------------------|----------------------|------------------------------------|------------------|
|           | L band (1–2 GHz)     |                                    |                  | C band (4–8 GHz)     |                                    |                  | C band (7–8 GHz)     |                                    |                  | C band (7.75–8 GHz)  |                                    |                  |
|           | Beam size<br>(" × ") | $rms$<br>( $\mu\text{Jy b}^{-1}$ ) | $S_\nu$<br>(mJy) | Beam size<br>(" × ") | $rms$<br>( $\mu\text{Jy b}^{-1}$ ) | $S_\nu$<br>(mJy) | Beam size<br>(" × ") | $rms$<br>( $\mu\text{Jy b}^{-1}$ ) | $S_\nu$<br>(mJy) | Beam size<br>(" × ") | $rms$<br>( $\mu\text{Jy b}^{-1}$ ) | $S_\nu$<br>(mJy) |
| WR 147    | $5.57 \times 3.28$   | 47.6                               | $25.5 \pm 0.3$   | $1.20 \times 0.95$   | 21.7                               | $38.1 \pm 0.7$   | $0.94 \times 0.76$   | 202.5                              | $39.2 \pm 2.3$   | $0.89 \times 0.74$   | 220.8                              | $39.1 \pm 2.4$   |
| HD 167971 | $4.61 \times 2.96$   | 86.1                               | $12.8 \pm 0.2$   | $1.45 \times 0.94$   | 62.7                               | $9.5 \pm 0.4$    | $1.12 \times 0.73$   | 42.3                               | $8.3 \pm 0.3$    | $1.07 \times 0.73$   | 68.2                               | $8.0 \pm 0.3$    |

**Notes.** Clean beam sizes are given in arcsec, rms noise levels off-source in  $\mu\text{Jy beam}^{-1}$ , and flux densities in mJy.

Synchrotron radio emission is believed to be highly linearly polarized. Theoretical values for the polarization degree,  $\Pi$ , defined as the fraction of the total intensity that is intrinsically linearly polarized, are expected to be at the level of about 70%. Polarized synchrotron radiation has, for example, been measured and well characterized in supernova remnants (SNRs), where particle acceleration and NT emission processes are known to be active (Dubner & Giacani 2015; Cotton et al. 2024). However, such a polarization signature has not yet been measured in the synchrotron emission of a PACWB, with only one attempt at detection reported in the literature thus far (Hales et al. 2017). Determining  $\Pi$  for a synchrotron source could help us infer the degree of turbulence and the characteristics of the magnetic field in the CWR. In this sense, our goal is to investigate the question of the polarization of the synchrotron radiation in PACWBs and to improve our knowledge of the NT emission in the environment of PACWBs. To this end, we started by selecting two well-known PACWBs known to be very bright at radio wavelengths, WR 147 and HD 167971. We observed them in the ranges of the radio domain where synchrotron emission is stronger (i.e., at GHz frequencies), where this emission is significantly produced and not too severely attenuated by free-free absorption (FFA).

We introduce the sample studied in Sect. 2. We describe the observations and data reduction process in Sect. 3. The results are presented in Sect. 4. In Sect. 5, we debate the physical interpretation of the results. A set of conclusions derived from the analysis is given in Sect. 6.

## 2. Selected targets

### 2.1. Sample description

In this work, we examine two massive star systems: one that includes a WR star and another harboring O-type stars only. Our approach aims at complementing the findings of Hales et al. (2017), while covering a wider region of the parameter space for this class of objects.

The massive system WR 147 is located in the Cygnus region and consists of a WN8 star and an early B-type or O8-9 V-III companion. These two stellar components are separated by a projected angular distance of approximately  $0''.6$ , as measured from VLA radio observations (Churchwell et al. 1992). For an adopted distance of 1.7 kpc (Crowther et al. 2023), this corresponds to a projected linear separation of about 1000 AU. Such a separation implies a very long orbital period, which has not yet been determined, but is thought to be on the order of a thousand years. Despite the large physical separation between the two stellar components, the system remains unresolved in our observations (see the angular resolutions achieved in Table 1, Sect. 4). WR 147 is known to be one of the most luminous synchrotron emitters among PACWBs, along with WR 146, which was the target of the study by Hales et al. (2017).

HD 167971 is a member of the NGC 6604 open cluster located at a distance of about 1.7 kpc (Reipurth 2008). It consists of a hierarchical triple system made of a close binary (O6-7 V + O6-7 V) with an orbital period of 3.3 days and an O8 supergiant that orbits the inner binary with a period of about 21 years (De Becker et al. 2012; Ibanoglu et al. 2013; Le Bouquin et al. 2017). The outer orbit of the system has been resolved using near-infrared (NIR) long-baseline interferometry at the VLTI, yielding a projected angular semi-major axis  $a$  of about 18 mas, with the separation varying along the orbit due to its significant eccentricity (Le Bouquin et al. 2017). At a distance of 1.7 kpc, this is correlated with a projected linear separation of roughly 30–45 AU. The combined winds of the inner binary collide with the wind of the supergiant, producing the population of relativistic particles that, in turn, are responsible for the synchrotron radiation emission. HD 167971 is also known as the brightest synchrotron radio emitter among O-type PACWBs.

### 2.2. Previous radio measurements

Both targets have been thoroughly studied in the radio domain in the past. However, no attempts have been reported to measure the polarization degree of their synchrotron radiation. The synchrotron emission region has been resolved due to high-angular resolution observations for both WR 147 (Churchwell et al. 1992; Williams et al. 1997) and HD 167971 (Sanchez-Bermudez et al. 2019; De Becker et al. 2024). In the range of frequencies of interest to this work, where synchrotron emission is stronger, and the thermal dilution caused by the winds is not too severe, both targets benefit from previous observations.

WR 147 has been observed in the MHz range with the Westerbork Synthesis Radio Telescope (WSRT) and the Giant Metrewave Radio Telescope (GMRT) by Setia Gunawan et al. (2003) and Benaglia et al. (2020), respectively, and flux measurements have been reported. The system has also been studied at centimeter wavelengths using Very Large Array (VLA) data (Skinner et al. 1999; Tasseroul et al. 2025). In particular, the study by Tasseroul et al. (2025) presented a detailed account of the radio spectral energy distribution of WR 147. This source is quite unique from the point of view of both the strength of the thermal emission from the WR wind and the brightness of its synchrotron component.

HD 167971 has also been studied extensively at centimetric wavelengths, mainly using VLA data. In addition to sporadic flux measurements obtained a few decades ago (Bieging et al. 1989; Phillips & Titus 1990; Contreras et al. 1996), Blomme et al. (2007) produced light curves at several wavelengths, allowing us to obtain an overview of the radio behavior of the system over its long orbit. The radio light curves clearly indicate significant variability correlated with the orbital phase, with a maximum that coincides with the system's periastron passage.

### 3. Observations and data reduction

The targets WR 147 and HD 167971 were observed as part of an observational campaign with the Karl G. Jansky Very Large Array (VLA) radio interferometer, located in New Mexico, USA. The observations took place in August 2016, while the array was in configuration B. According to the ephemeris published by [Le Bouquin et al. \(2017\)](#) for HD 167971, these dates correspond to an orbital phase that lies in the 0.34–0.39 range (taking into account the uncertainty on the period, i.e.,  $8706 \pm 540$  d). This corresponds to an orbital phase where the synchrotron emission is measured significantly away from periastron, thus preventing any substantial FFA from reducing the measured flux. For WR 147, the lack of published orbital elements prevents us from speculating on the orbital phase.

We performed full polarization observations in two frequency bands: the *L* band (20 cm, centered at 1.5 GHz) and *C* band (5 cm, centered at 6 GHz), spanning bandwidths of 1 GHz and 4 GHz, respectively. The correlator was configured to deliver 8 spectral windows in the 20 cm band, and 32 windows in the 5 cm band, with 64 channels in each window. With each channel spanning 2 MHz, the total bandwidth per spectral window was 128 MHz. The total observing time on-source was 36 min 36 s at the *L* band and 13 min 6 s at the *C* band for WR 147, and 37 min 57 s at the *L* band and 13 min 6 s at the *C* band for HD 167971. The calibrator 3C 286 was observed for flux density, bandpass, and polarization position angle calibration. QSO B2005+403 and QSO J1745-0753 were used for amplitude and phase calibration for WR 147 and HD 167971, respectively, and the unpolarized source J2355+4950 was observed for instrumental leakage calibration. Data reduction was performed using CASA (Common Astronomy Software Applications; [McMullin et al. 2007](#)). This included the flagging of bad data and data affected by radio frequency interference (RFI), followed by the standard gain and bandpass calibration. Polarization calibration was carried out using standard CASA polarization calibration routines, following the National Radio Astronomy Observatory (NRAO) guidelines. We solved for the cross-hand delays (with a multiband delay approach), followed by the determination of the instrumental polarization leakage terms (D-terms) and the absolute polarization position angle using the task `polcal`. The derived calibration solutions were then applied prior to imaging the targets in full Stokes parameters. The final products include Stokes *I*, *Q*, and *U* maps (see Table 1, Sect. 4, for the angular resolution and sensitivities achieved). Given that the targets were not expected to be spatially resolved at the angular resolutions reached by the VLA in these bands, for the imaging we adopted Briggs weighting (with `robust` = 0.5) to favor sensitivity without significantly degrading the angular resolution.

### 4. Results

We detected the systems WR 147 and HD 167971 in the intensity maps obtained in both bands, *L* and *C*, as unresolved point sources. However, we did not detect any emission in either band at the position of the target systems in the Stokes maps *Q* and *U*, where the signature of linear polarization (if present) should be located. The Stokes maps *I*, *Q*, and *U* for WR 147 and HD 167971 in both frequency bands are presented in Fig. 1.

To test whether bandwidth depolarization due to Faraday rotation could be affecting our results, we also produced additional Stokes *I*, *Q*, and *U* maps using narrower frequency ranges in the higher-frequency end of the *C* band for both WR 147 and HD 167971. As discussed in Sect. 5.3, given the dependence of

**Table 2.** Upper limit on the fractional polarization and the quantities used to derive it.

| Source                                 | $\sigma_Q$ | $\sigma_U$ | $\sigma$ | $I_{\text{peak}}$ | $\Pi_{\text{UL}}^{\%}$ |
|----------------------------------------|------------|------------|----------|-------------------|------------------------|
| WR 147 – <i>L</i> band                 | 26.6       | 26.3       | 26.6     | 22.3              | 0.36                   |
| WR 147 – <i>C</i> band                 | 9.7        | 6.5        | 9.7      | 24.7              | 0.12                   |
| WR 147 – <i>C</i> band (7–8 GHz)       | 26.9       | 15.8       | 26.9     | 24.3              | 0.33                   |
| WR 147 – <i>C</i> band (7.75–8 GHz)    | 85.4       | 111        | 111      | 24.0              | 1.38                   |
| HD 167971 – <i>L</i> band              | 28.3       | 29.8       | 29.8     | 12.4              | 0.72                   |
| HD 167971 – <i>C</i> band              | 10.3       | 11.7       | 11.7     | 9.0               | 0.39                   |
| HD 167971 – <i>C</i> band (7–8 GHz)    | 20.7       | 15.9       | 20.7     | 7.9               | 0.79                   |
| HD 167971 – <i>C</i> band (7.75–8 GHz) | 38.4       | 21.7       | 38.4     | 7.6               | 1.52                   |

**Notes.** *Rms* noise levels ( $\sigma_Q$ ,  $\sigma_U$ ,  $\sigma$ ) are given in  $\mu\text{Jy beam}^{-1}$  and peak Stokes *I* in  $\text{mJy beam}^{-1}$ .  $\Pi_{\text{UL}}^{\%}$  is expressed in %.

Faraday-rotation-driven depolarization processes on wavelength, we restricted this complementary analysis to the *C* band.

We generated a set of maps using the eight highest-frequency spectral windows of the *C*-band data (7–8 GHz) and another set using only the two highest-frequency spectral windows (7.75–8 GHz), corresponding to a total bandwidth of 250 MHz. The resulting images do not reveal any detectable polarized emission in either case.

We obtained flux density measurements for both targets in the *L* and *C* bands, together with the *rms* noise levels of the maps around the source. We present these values, with the synthesized beam of the cleaned Stokes *I* maps, in Table 1. Furthermore, in the same table, we report the values of angular resolution, *rms*, and flux density obtained for the narrow, higher-frequency-range images also produced.

The linearly polarized intensity is defined as  $P = \sqrt{Q^2 + U^2}$  and the polarization degree as  $\Pi = P/I$ . Given the absence of a significant polarization detection, we estimated upper limits on  $\Pi$  using the noise properties of the *Q* and *U* maps. The *rms* noise levels,  $\sigma_Q$  and  $\sigma_U$ , were measured over a region coincident with the spatial extent of the source in Stokes *I*. We adopted a conservative approach by using the larger of the two as a representative noise level  $\sigma$ . The noise in polarized intensity is therefore on the order of  $\sigma$ , and assuming a confidence level of  $3\sigma$ , we derive an upper limit on the polarized intensity of  $P_{\text{UL}} = 3\sigma$ . The corresponding upper limit on the polarization degree is then given by  $\Pi_{\text{UL}} = P_{\text{UL}}/I$ . To ensure consistency in units, the peak Stokes *I* intensity measured within the same region (in  $\text{Jy beam}^{-1}$ ) was used in the denominator. We report all quantities involved in these estimates, as well as the upper limit on the fractional polarization expressed in % ( $\Pi_{\text{UL}}^{\%}$ ), in Table 2.

The main result is the total absence of measurable linear polarization for both targets, regardless of the selected spectral band. Our most conservative upper limits on the polarization degree are on the order of 1 %.

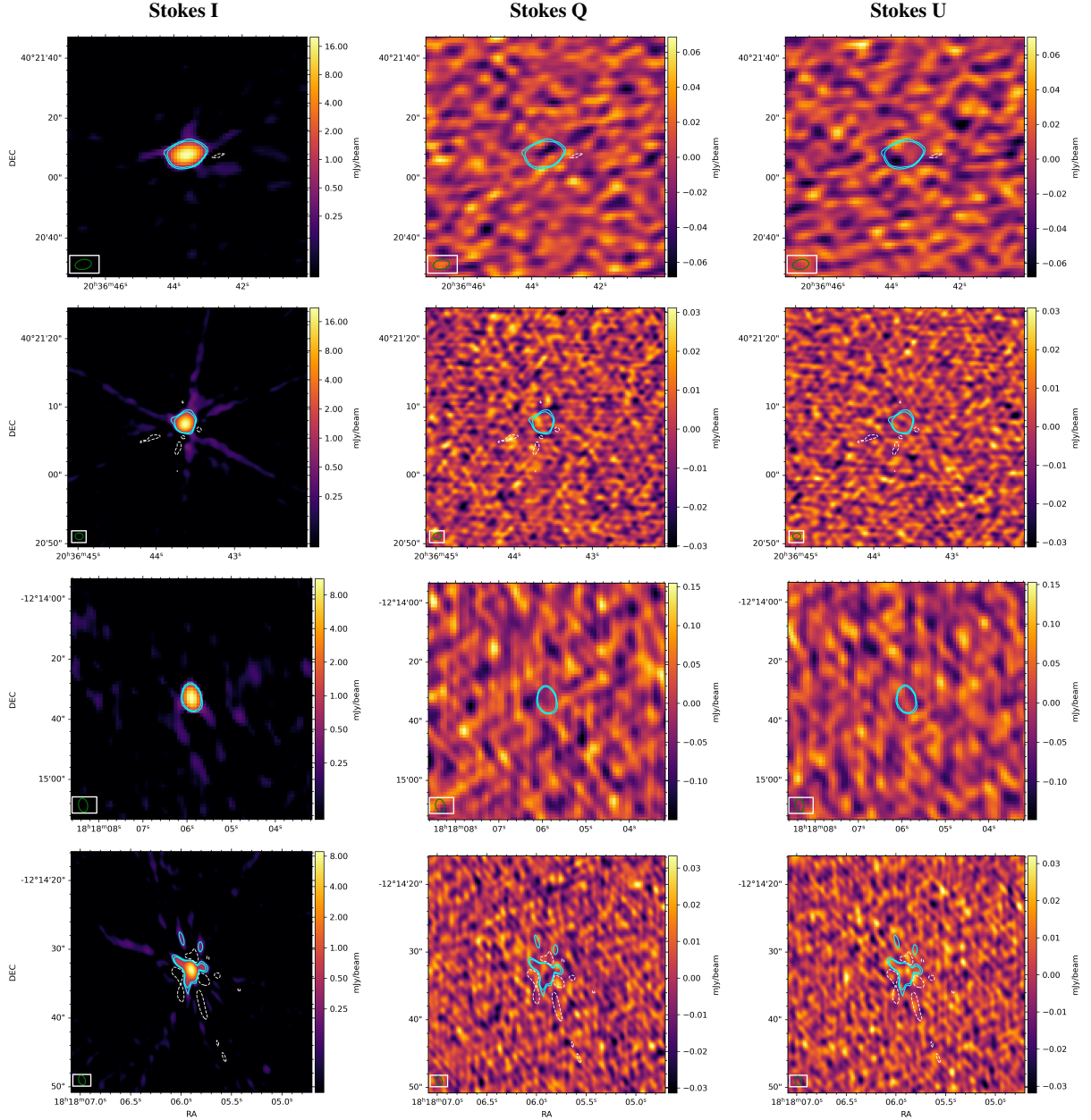
### 5. Discussion

The lack of significant linear polarization in the synchrotron sources studied deserves some discussion. Despite the a priori expectation of a polarization signature, the specific physical conditions that prevail in these objects have to be considered to relocate our results in their appropriate framework.

#### 5.1. Maximum polarization degree

Assuming a fully ordered magnetic field, the maximum intrinsic polarization degree ( $\Pi_{\text{max}}$ ) of a pure synchrotron source





**Fig. 1.** Stokes  $I$ ,  $Q$ , and  $U$  maps (from left to right) of WR 147 and HD 167971. From top to bottom: WR 147 in the  $L$  and  $C$  bands, followed by HD 167971 in the  $L$  and  $C$  bands. The Stokes  $I$  maps are shown with a logarithmic color scale.  $Q$  and  $U$  maps are displayed in a linear autoscale. In all panels, cyan contours at 5 and  $9\sigma$  indicate the target position, while white dashed contours show emission at  $-3\sigma$ . The synthesized beam is displayed in green in the bottom-left corner.

is determined based on the emissivities ( $j_{\perp}$  and  $j_{\parallel}$ ) for both polarization directions, namely the directions perpendicular and parallel to the projected direction of the magnetic field on the sky plane, respectively. It can be expressed as a function of the electron index ( $p$ ) of the relativistic electron population (Rybicki & Lightman 1979), namely,

$$\Pi_{\max} = \frac{j_{\perp} - j_{\parallel}}{j_{\perp} + j_{\parallel}} = \frac{p+1}{p+\frac{7}{3}}. \quad (1)$$

Expressing  $\Pi_{\max}$  as a function of the optically thin synchrotron spectral index ( $\alpha_{\text{NT}} = (p-1)/2$ ), we obtain

$$\Pi_{\max} = \frac{3(\alpha_{\text{NT}} + 1)}{3\alpha_{\text{NT}} + 5}. \quad (2)$$

For WR 147, Tasseroul et al. (2025) obtained  $\alpha_{\text{NT}} = 0.7$ . This leads to  $\Pi_{\max} = 0.72$ . In the case of HD 167971, our flux density measurements reported in Table 1 ( $L$  and 7.75–8 GHz bands) give a spectral index of about 0.3, leading to  $\Pi_{\max} = 0.66$ . These



numbers confirm the rather weak dependence of  $\Pi_{\max}$  on  $\alpha_{\text{NT}}$ , with values that are always on the order of 0.7.

We clarify that the synchrotron spectra of these sources are optically thin with respect to synchrotron self-absorption. The drop in  $\Pi$  expected for synchrotron self-absorbed sources is thus not applicable to our targets of interest. Because FFA is not sensitive to the polarization direction, there is no reason to consider that the alteration of the spectrum by FFA affects the polarization degree. The values derived above are considered as the maximum possible values for the degree of polarization, which would be valid for a fully ordered magnetic field, without considering thermal dilution and other depolarization processes that are addressed below.

### 5.2. Thermal dilution

When addressing the question of the polarization of a composite radio source (made of spatially unresolved thermal and NT components), it is relevant to estimate the fraction of the radio flux that is actually of synchrotron origin. The latter component is indeed the only one that has the potential to reveal a polarization signature.

For WR 147, an important insight comes from the detailed analysis of the radio spectral energy distribution performed by Tasseroul et al. (2025). In their Fig. 4, the best-fit composite model allows us to evaluate the contribution of synchrotron origin at any frequency. The synchrotron contribution, accounting for attenuation by internal FFA, is expressed as

$$S_{\nu}^{\text{NT}} = S_{\nu,0}^{\text{NT}} \nu^{-\alpha_{\text{NT}} + \beta} \left[ 1 - e^{-(\nu/\nu_{\text{i-FFA}})^{-\beta}} \right], \quad (3)$$

where  $S_{\nu,0}^{\text{NT}}$  is a normalization factor,  $\alpha_{\text{NT}}$  is the NT index of the optically thin synchrotron spectrum,  $\beta$  is the index of the internal-FFA absorption coefficient, and  $\nu_{\text{i-FFA}}$  is the internal-FFA turnover frequency. We refer to Tasseroul et al. (2025) for details. Using best-fit parameters ( $S_{\nu,0} = 18.90 \pm 0.24$  mJy GHz $^{-\alpha_{\text{NT}}}$ ;  $\beta = 0.89 \pm 0.03$ ;  $\nu_{\text{i-FFA}} = 5.20 \pm 0.70$  GHz) and a fixed value for  $\alpha_{\text{NT}} (= 0.7)$ , we estimated the NT contribution to the composite radio emission.

Let us define the thermal dilution factor ( $f_{\text{dil}}$ ) as the ratio of the synchrotron flux density to the total flux density, including the thermal contribution,

$$f_{\text{dil}} = \frac{S_{\nu}^{\text{NT}}}{S_{\nu}^{\text{NT}} + S_{\nu}^{\text{T}}}, \quad (4)$$

where  $S_{\nu}^{\text{T}} = S_{\nu,0}^{\text{T}} \nu^{\alpha_{\text{T}}}$ . In agreement with the formalism used by Tasseroul et al. (2025), the thermal contribution is defined by its normalization factor ( $S_{\nu,0}^{\text{T}}$ ) and a thermal spectral index ( $\alpha_{\text{T}}$ ). While the former was found to be equal to  $4.52 \pm 0.10$  mJy GHz $^{-\alpha_{\text{T}}}$ , the latter was fixed to a value of 0.75. This value is significantly steeper than the canonical index predicted by Wright & Barlow (1975) and is more typical of the thermal radio emission from WR stellar winds (Nugis et al. 1998).

At the central frequencies of the *L* and *C* bands (1.5 and 6.0 GHz, respectively), the best-fit model of the radio spectral energy distribution of WR 147 allows us to determine  $f_{\text{dil,L}} = 0.76 \pm 0.01$  and  $f_{\text{dil,C}} = 0.47 \pm 0.02$ . As a result, the maximum expected polarization degree is expected to be lowered by that factor. The thermal dilution effect is especially strong for WR 147 because of its unusual bright thermal emission component. Taking into account thermal dilution, the maximum expected polarization degree for WR 147 becomes  $\Pi_{\text{dil}} = f_{\text{dil}} \Pi_{\max} \approx 0.55$  and 0.34, respectively, for the *L* and *C* bands.

Alternatively, for HD 167971, the thermal emission is much weaker. At a distance on the order of 1.7 kpc, the thermal emission at these frequencies should be well below the 0.1 mJy level (De Becker 2018; De Becker et al. 2024). The thermal emission components of the O-type winds in the system are therefore very small compared to the synchrotron emission, resulting in  $f_{\text{dil}} \approx 1$  in both bands. Thus, the expected maximum value  $\Pi$  is not affected.

### 5.3. Bandpass depolarization

To consolidate the lack of polarization signature and discard the possible influence of Faraday rotation in our results, we replicated the analysis in two narrower, high-frequency sub-bands, as stated in Sect. 4.

When integrating over a broad bandwidth, Faraday rotation causes the linear polarization angle to vary across the band, as a result of its  $\lambda^2$ -dependence. This inevitably leads to a significant loss of polarization due to the averaging of differently rotated polarization vectors. This effect is expected to be reduced at higher frequencies (i.e., shorter wavelengths) and when using narrower frequency intervals (where there is less spread and/or scatter of the angle from the lower to the upper boundary of the sub-band). This is why we completed our analysis by producing Stokes maps in narrower bands, especially using the higher frequency spectral windows in the *C* band, as stated in Sect. 4.

The absence of polarization detection even in these cases consolidates the lack of a measurable polarization signature at a level greater than about 1%. As a result, the lack of linear polarization is not attributable to the sole bandpass depolarization effect. The same conclusion applies to the case of WR 146 investigated by Hales et al. (2017), where mitigating the effect of bandpass depolarization following the same approach did not lead to the detection of any linear polarization signature. Other depolarization effects appear to be active as addressed in Sect. 5.4.

### 5.4. Lack of synchrotron polarization in PACWBs

The effective polarization degree that is measured is not only dependent on the thermal dilution. The magnetic field in the synchrotron emission region is not perfectly ordered. According to Burn (1966), the reduction in the polarization degree due to the nonordered magnetic field is expressed by the ratio of energy densities in the ordered and total (i.e., ordered+turbulent) magnetic fields (the so-called turbulent dilution). In addition, wavelength-dependent depolarization effects (based on Faraday rotation) are known to further decrease the polarization degree. As a result, we may express the observed polarization degree as

$$\Pi_{\text{obs}} = \Pi_{\text{dil}} \frac{B_0^2}{B_0^2 + B_{\text{turb}}^2} D_{\lambda}, \quad (5)$$

where  $B_0$  and  $B_{\text{turb}}$  are ordered and turbulent magnetic field strengths, and  $D_{\lambda}$  is the depolarization factor (function of wavelength  $\lambda$ ) due to propagation effects. The latter consists typically of Faraday rotation with an amplitude that is dependent on the distribution of the rotation measure (RM) along the line of sight.

The amplitude of the impact of turbulent dilution is directly related to the turbulent-to-total ratio of magnetic energy densities. In the synchrotron emission region of PACWBs, we can only speculate on this ratio. In the very likely scenario where DSA is responsible for particle acceleration, a nonzero turbulent component is absolutely required. A purely uniform magnetic

field would compromise the iterative back-scattering on turbulent scattering centers required for significant energy gain of charged particles involved in the particle acceleration process. Thus, turbulent dilution is very likely to significantly reduce the effective polarization fraction.

The important role of depolarization processes in the lack of polarization signature measured for WR 146 has been well documented by [Hales et al. \(2017\)](#). Depolarization processes are reviewed by [Burn \(1966\)](#). These include differential Faraday rotation, where synchrotron photons produced at various depths are exposed to different levels of rotation measure. They lead  $D_\lambda$  (see Eq. (5)) to be significantly lower than 1. Given the  $\lambda^2$ -dependence of Faraday rotation that drives these depolarization processes, one anticipates that this effect is significantly more pronounced in the  $L$  band, compared to the  $C$  band. Adding to these physical processes, we also have to take into account beam depolarization, where various lines of sight characterized by different rotation measures are averaged in the instrumental beam, which also plays a role. This effect is highly dependent on the size of the synthesized beam. For instance, if a gradient in the magnetic field direction occurs or if there is a distribution of RM across the beam solid angle, the average polarization signature will be reduced. Therefore, this leads to an additional attenuation factor in addition to those accounted for in Eq. (5). In systems characterized by complex geometries such as PACWBs, low angular resolution polarimetry is very likely affected by beam depolarization.

### 5.5. Synchrotron polarization in a broader context

In the extragalactic context, radio jets of active galactic nuclei (AGNs) are also well-known synchrotron radio sources. Typical values for the polarization degree are in the range of a few %, with some cases reaching a few 10% ([Hovatta et al. 2012](#); [Blinov et al. 2021](#)). Here, again, a nonuniform magnetic field at the scale of the beam size and, to some extent, Faraday depolarization are the main causes for the drop in polarization degree ([Yushkov et al. 2024](#)).

In SNRs, which present similarities to some extent with PACWBs, polarization degrees as low as a few 10% are interpreted as a result of significant turbulent dilution ([Reynolds et al. 2012](#)). Several SNRs seem to show polarization degrees in the range of 20–30% ([Shimoda 2022](#)). However, higher values of the polarization degree have also been measured in some remnants ([Dubner & Giacani 2015](#)).

Protostellar jets are also known to be able to produce synchrotron radiation and are thus worth investigating from the point of view of their linear polarization. The inner lobes of the southern jet associated with the massive protostar IRAS 18162–2048 (specifically HH 80 and HH 81) are known to show a linear polarization degree of a few 10% ([Carrasco-González et al. \(2010\)](#); [Rodríguez-Kamenetzky et al. \(2025\)](#)). However, [Cheriyana et al. \(2026\)](#) reported on a lack of polarization signature in the knots of HH 80 and HH 81, with upper limits of 1–2%. This result is similar to the upper limits we derived for WR 147 and HD 167971. The absence of significant polarization was attributed by the authors to turbulence and beam depolarization. In addition, we might also expect some thermal dilution to contribute to the lack of measured polarization, given the nature of the jets that are mainly made of a thermal plasma.

A last example worth mentioning is that of bow shocks produced by runaway massive stars traveling at high peculiar velocities in the interstellar medium. A specific case of interest is EB 27. The study by [Benaglia et al. \(2021\)](#) provided

evidence for NT radio emission, although no linear polarization was detected. It is interesting to note that for all the examples mentioned above, significant detections of linear polarization arise from resolved sources, where at least the effect of beam depolarization is partly mitigated. However, the case of EB 27 shows that spatially resolved polarimetric measurements are not necessarily sufficient to warrant the detection of polarization in a synchrotron source.

When discussing the case of PACWBs in the broader astrophysical landscape, we can clearly see that the usual factors leading to a lowering of the polarization degree, namely, nonuniform magnetic field and Faraday depolarization, are valid for all synchrotron sources. However, PACWBs and, to some extent, jets associated with protostellar objects offer, moreover, ideal conditions for thermal dilution, leading in some cases to a stronger lowering of the maximum expected polarization degree. This effect is not really active for AGNs or SNRs, as such objects do not produce significant thermal radio emission in addition to their synchrotron radiation. In contrast, it becomes important in systems with strong stellar winds capable of generating substantial thermal emission within the spectral range used for the polarimetric analysis. When this thermal component is not spatially resolved from the synchrotron-emitting region, it leads to the thermal dilution of the polarized signal. In addition, because the thermal free-free emission of the winds increases with frequency, this dilution will be stronger at higher radio frequencies (and more so in the  $C$  band than in the  $L$  band). The typical case is that of PACWBs made up of at least one WR component, whose dense winds can produce a significant thermal contribution, as in the case of WR 146 ([Hales et al. 2017](#)) and WR 147 (this study). For O-type systems such as HD 167971, thermal dilution is not that important provided that the frequencies explored are not especially high. Thus, the other effects discussed above (i.e., turbulent magnetic field, Faraday-rotation-driven depolarization, beam depolarization) appear to be strong enough to lead to a drastic drop in the polarization signal.

## 6. Conclusions

We present a search for linear polarization in the synchrotron radio emission from two bright particle-accelerating colliding-wind binaries. No linear polarization was detected from either target in either of the observed bands, even after narrowing the bandwidth to attenuate band depolarization effects. These non-detections indicate that the signature of the expected polarization in these systems is heavily suppressed, despite the presence of synchrotron radiation. Our results suggest that no single mechanism is responsible for this; rather, several physical and observational effects act simultaneously to reduce the expected polarization degree to levels that remain below current detection limits.

The lack of a detection of polarization is most likely explained by a combination of a highly turbulent magnetic field in the synchrotron-emitting region (i.e., the colliding-wind region), significant Faraday depolarization, and beam depolarization due to unresolved structure.

In addition, thermal dilution plays an important role in PACWBs, particularly in systems hosting stars with strong thermal winds, such as WR components, where unpolarized free-free emission further contaminates the observable polarization degree. Together, these effects make the detection of linear polarization in such systems intrinsically challenging.

Future progress on this issue will likely require observations that combine a higher angular resolution and improved

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sensitivity, potentially at higher frequencies where Faraday depolarization is reduced. However, the decreasing synchrotron brightness at such frequencies makes these observations challenging. Next-generation facilities, such as the ngVLA and SKA-Mid, or VLBI observations at suitable frequencies, could provide the necessary capabilities to isolate the synchrotron-emitting regions from the thermal winds and potentially reveal polarized emission. Such observations would offer valuable constraints on magnetic field structure and particle acceleration processes in colliding-wind binaries, helping to disentangle intrinsic emission properties from depolarization effects.

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<sup>2</sup> <https://www.astro.uliege.be/~debecker/pantera>



# Chapter 5

## ATCA survey of candidate PACWBs

### 5.1 Scientific rationale

The scientific motivation of this project is closely related to that presented in Chapter 3. As discussed in Sect. 3.1, the association between synchrotron radio emission and binarity in massive stars offers an indirect method for identifying binary systems and, at the same time, new members of the PACWB class. This empirical association is known as the synchrotron-binarity correlation.

In the context of particle acceleration, WR stars constitute especially promising targets. Being the category of massive stars characterized by the highest wind kinetic powers, they provide a substantial reservoir of energy that can be channeled into NT processes, thus creating particularly favorable conditions for particle acceleration. The prevalence of WR stars in studies of particle acceleration is reflected in the current PACWB census. Although WR stars are significantly less numerous than their O-type progenitors, due to the much shorter duration of the WR evolutionary phase, more than 40 % of the systems included in the PACWB catalogue contain at least one WR component, as cataloged to date (De Becker and Raucq, 2013; De Becker et al., 2017)<sup>1</sup>. This highlights the relevance of WR stars as laboratories for studying NT processes in massive stars, and emphasizes their representation among the currently known PACWB population.

The importance of WR stars in the framework of this thesis extends beyond the identification of individual PACWBs. Despite their crucial role in the late stages of massive-star evolution, the binary fraction among WR stars remains poorly constrained, particularly at long orbital periods: spectroscopic multiplicity surveys are naturally biased towards close systems with short periods, whose orbital motion can be revealed through radial-velocity variations on relatively short timescales, whereas wider systems remain considerably more difficult to identify.

Therefore, the synchrotron-binarity correlation is particularly valuable in the case of WR stars. Moreover, their broad emission lines and large brightness contrast (in WR+O systems) can hinder the detection of companions through traditional

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<sup>1</sup>The updated version of the catalogue is available at <https://www.astro.uliege.be/~debecker/pacwb/>.

spectroscopic techniques. At the same time, their dense stellar winds can severely attenuate synchrotron radiation through FFA, particularly in close binaries, where the WCR remains deeply embedded within the winds, causing the NT radio emission to be heavily absorbed before escaping the system. As a consequence, the detection of synchrotron emission is generally favored only in systems with relatively wide separations. Radio observations can thus provide a complementary tool to probe this poorly explored region of the orbital-parameter space.

In this context, the identification of new synchrotron-emitting WR stars through the synchrotron-binarity correlation not only can help us improve the current census of PACWBs, but also contributes to our knowledge of the multiplicity properties of evolved massive stars.

Motivated by these considerations, a dedicated observing campaign was carried out with the Australia Telescope Compact Array (ATCA) to search for synchrotron emission from a complementary sample of candidate WR binaries. The target list was designed to complement that of the project described in Chapter 3 by including several southern WR stars displaying previous indications of binarity but lacking definitive confirmation. In line with the first objective presented in Sect. 1.7, the primary goal of this project is to characterize the nature of the radio emission of a sample of southern WR stars through the analysis of their SED and spectral indices. The detection of NT radio emission would allow the identification of new PACWB candidates and, consequently, through the synchrotron-binarity correlation, provide additional evidence supporting their binary nature.

## 5.2 The Australia Telescope Compact Array

This chapter focuses on observations obtained with the Australia Telescope Compact Array (ATCA), a radio interferometric array located near Narrabri, Australia, and operated by the Australia Telescope National Facility (ATNF).

The ATCA is formed by six 22-meter diameter dishes arranged along an east–west rail track. Five of the antennas can be repositioned along the track, while the sixth antenna is fixed, enabling several array configurations with baselines extending from 30 m up to 6 km. Hybrid array configurations can also make use of a north-south spur to improve the  $(u, v)$  coverage. A photograph of part of the array is shown in Fig. 5.1.

The array operates over a broad frequency range that spans from 1 to 105 GHz. For the purpose of this project, our observations were taken in the 16 cm continuum band (1.1–3.1 GHz) and in the C-band frequency range of the 4 cm continuum band (4–8 GHz)<sup>2</sup>. As was already described in the previous chapters (particularly, Chapter 3), this frequency coverage is well suited to characterize the radio spectral properties of the targets of interest. The combination of lower-frequency data, where synchrotron emission is typically stronger, with higher-frequency observations that are more sensitive to thermal free–free emission and less affected by FFA, allows for a SED analysis to separate thermal and NT components in the radio spectrum.

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<sup>2</sup>The full ATCA 4 cm continuum band allows for observations from 3.9 to 11.0 GHz, spanning the frequency ranges commonly referred to as the C and X bands.





Figure 5.1: The Australia Telescope Compact Array (ATCA), showing five antennas distributed along the east–west track. Taken from their official website (<https://www.narrabri.atnf.csiro.au/public/>).

This is especially valuable for determining spectral indices and identifying a possible synchrotron contribution that unmasks a population of relativistic particles.

### 5.3 Proposal strategy and observing campaign

The observations presented in this chapter originate from an ATCA telescope time proposal for which I (A. Blanco) was PI. The proposal was designed in collaboration with M. De Becker, P. Benaglia, and B. Marcote as co-investigators, and its goal was to target a sample of southern WR stars showing previous, but unconfirmed, hints of binarity, selected to complement the sample discussed in Chapter 3. Due to the limited time available within the scope of this thesis, preliminary results will be reported here for only one of the observed targets; the analysis of the remaining sample is left for forthcoming studies (see Section 6.2).

As it was already introduced in the previous section, the observing strategy for this project was designed to probe the radio spectrum of each target at two frequency bands: 1.1–3.1 GHz and 4–8 GHz. This dual-band strategy provides a direct diagnostic of the nature of the detected emission. Flux density measurements at shorter wavelengths trace a part of the radio spectrum that is less affected by FFA, whereas measurements at longer wavelengths are less contaminated by thermal photons and



are particularly sensitive to a possible NT contribution (since the synchrotron emission is expected to rise towards longer wavelengths, i.e. with a negative spectral index, while the thermal free-free spectrum instead declines towards longer wavelengths). Combining both bands thus could allow the thermal and NT contributions to be disentangled through the resulting SED and spectral index analysis.

At 4 cm, the band was split into two 2-GHz subbands, 4–6 GHz and 6–8 GHz, centered at 5 and 7 GHz respectively, while the 16 cm band is centered at 2.1 GHz. For each target, 60 minutes of on-source time were requested per band, corresponding to a total of 1.5 h per band once calibration overheads and antenna driving times were accounted for. The array was requested in the 6D configuration, which provides the best angular resolution available with the ATCA. A total of 24 h was awarded for the project, distributed over four sessions of 4.5, 4.5, 7.5, and 7.5 h, between 20 and 24 June 2024.

### 5.3.1 Remote observing

At the ATCA observatory, proposing teams are themselves responsible for the operation of their approved observations, either on-site or, subject to prior training, remotely. For the project of interest in this chapter, I was in charge of carrying out the observations remotely after having completed the required online training provided by the ATNF staff and preparing with the official ATCA Users Guide<sup>3</sup>.

Observations with the ATCA are controlled through schedule files that must be prepared by the user ahead of each observing session with the CABB<sup>4</sup> web scheduler. These files specify all the information required by the observing system to run, including source names and positions, frequency setups, and bandwidths.

They consist of a setup script defining the frequency setups and the primary calibrator scans needed to configure and calibrate the array. These primary calibrator observations are also used later to establish the absolute flux scale and calibrate the bandpass response. The schedule files also include an observing table specifying the cycle of phase (or secondary) calibrator and target-source scans to be performed throughout the observing run.

Each observing run follows a similar sequence: taking control of the array from the previous observer, setting up and calibrating the system (focus, delays, phases and gains) at both frequency bands, and then running the observing cycle between the phase calibrators and the target sources, including the necessary pointings to the primary flux calibrator. Throughout the session, the data were continuously monitored for technical issues (e.g., antenna dropouts) and, when the allocated time comes to an end, the last step consists of closing the schedule file and ending the session.

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<sup>3</sup>ATCA Users Guide: [https://www.narrabri.atnf.csiro.au/observing/users\\_guide/html/atug.html](https://www.narrabri.atnf.csiro.au/observing/users_guide/html/atug.html).

<sup>4</sup>Compact Array Broadband Backend, the ATCA correlator system.

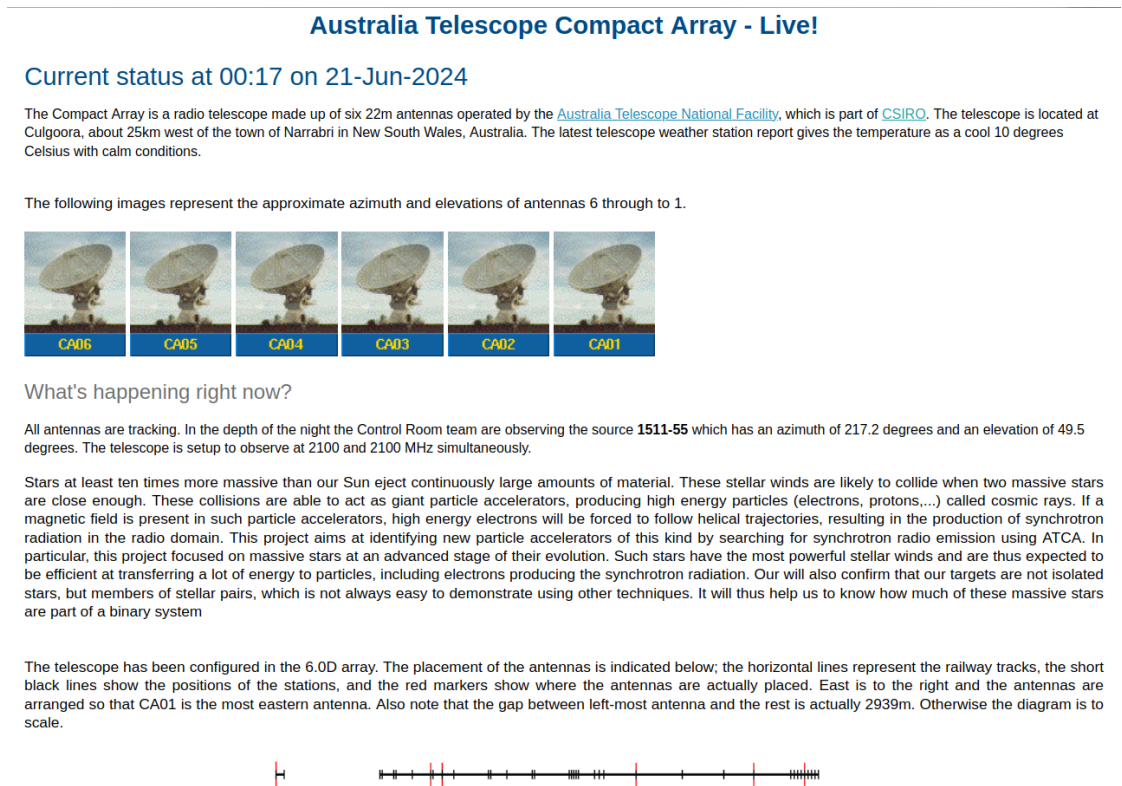


Figure 5.2: Screenshot of the ATCA webpage during one of the observing sessions presented in this chapter. The page provides real-time information on the array status and configuration, including the current target being observed, a brief description of the project for the general public, antenna positions, and local weather conditions.

## 5.4 Data reduction

The data presented in this chapter were reduced using the CASA software. Given the limited documentation available for ATCA data reduction with CASA, a dedicated reduction script was developed as part of this work, building on general guidance from an existing continuum-reduction tutorial<sup>5</sup> but adapted and extended to suit the specific needs of this project. This included, for instance, flagging RFI and bad data manually, scan by scan, rather than through automated routines.

The raw ATCA files are first converted into a Measurement Set (ms), CASA's native data format. The resulting datasets are then inspected in detail, examining the visibilities as a function of time, frequency, baseline, and antenna, in order to identify problematic data (e.g., RFI, antenna shadowing... ). Following this inspection, both automated and manual flagging are applied to remove corrupted visibilities. Particular attention should be paid to the 16 cm band, where RFI is typically more severe and almost half of the data can be expected to be lost to flagging. Afterwards, the flux, bandpass, and gain calibration solutions are derived from the primary and secondary calibrators, and subsequently applied to the target visibilities. Finally,

<sup>5</sup>[https://www.atnf.csiro.au/research/radio-school/2023/casa\\_basic\\_continuum\\_tutorial.pdf](https://www.atnf.csiro.au/research/radio-school/2023/casa_basic_continuum_tutorial.pdf)

the calibrated target data are imaged, producing, in our case, three continuum images: one centered at 2.1 GHz for the 16 cm band, and two centered at 5 and 7 GHz for the two 4 cm subbands.

The process of developing and validating this reduction script required a considerable, dedicated effort, and it has so far been applied in full to one of the observed targets, for which preliminary results are presented in the following section. This same pipeline can now be applied efficiently to the remaining targets of the observed sample, a task left for future work.

## 5.5 Preliminary results

The analysis of the full observed sample could not be completed due to the time constraints associated with the completion of this thesis. Therefore, the case of WR48a is presented here as a representative case study to illustrate the scientific potential of this ATCA survey through its whole scientific pipeline: from the original question that motivated this project, to the submission of an observing proposal and the subsequent telescope time granted, including the remote observing campaign, the learning of the data reduction procedure, all the way to obtaining preliminary results, and discussing them in an appropriate scientific framework. Hereafter, extending the same methodology to the rest of the dataset will enable a more comprehensive investigation of the synchrotron-binarity correlation in southern WR stars and will constitute the basis of a future publication.

### 5.5.1 WR 48a

The southern target WR 48a is a promising PACWB candidate. Located at  $\alpha_{J2000} = 13^{\text{h}}12^{\text{m}}39.61^{\text{s}}$ , and  $\delta_{J2000} = -62^{\circ}42'55.9''$ , at a distance of 2.27 kpc (Rate and Crowther, 2020), it is a carbon-rich WR star (WC8) that has exhibited strong IR emission associated with episodic dust formation and has been proposed as a CWB based on different observational traces.

The binary nature of WR 48a is supported by several studies. Recurrent dust-making episodes, long-term IR variability, and optical spectroscopic studies all point towards the presence of wind-wind interactions (Williams et al., 2012; Zhekov et al., 2014b). The properties of the companion star and the orbital parameters are mostly still uncertain, but it has been suggested that the companion may be a WN star (based on optical spectrum studies), with a long orbital period of  $\sim 32.5$  years in an eccentric orbit. Additional support for this scenario comes from X-ray observations. WR 48a is an exceptionally luminous X-ray source. Its X-ray emission seems to be of thermal origin, variable, with variable absorption as well. Such properties are generally interpreted as signatures of strong shocks generated in the WCR of a wide binary system (Zhekov et al., 2011, 2014a).

The radio properties of WR 48a are less well explored. Previous ATCA observations, obtained in 2000 and 2006 with a bandwidth of 128 MHz, detected variable radio emission at 4.8 and 8.6 GHz with spectral indices broadly compatible with thermal stellar-wind emission (Zhekov et al., 2014b). However, these measurements are sparse, were obtained at different epochs, and provide only limited constraints

on the overall shape of the radio spectrum. Moreover, the data available at lower frequencies were severely affected by RFI and could not be used, leaving the low-frequency behavior of the source poorly constrained. As a result, the existence of a NT synchrotron component has neither been firmly established nor ruled out.

These characteristics make WR 48a an interesting target to investigate the synchrotron-binarity correlation. The strong evidence for wind-wind interactions, its remarkably high X-ray emission, and its still uncertain radio properties motivated its selection as the first target analyzed within the ATCA survey presented in this chapter.

### 5.5.2 Observations and data reduction

The WR 48a observations presented in this chapter were obtained during June 2024 with the ATCA interferometer in the extended 6D configuration. The standard primary calibrator 1934–638 was observed to set the flux density scale and calibrate the bandpass for the whole dataset, while the nearby bright and unresolved source J1322–6532 was used as the phase calibrator. The source was observed simultaneously in three frequency ranges centered at 2.1, 5.0, and 7.0 GHz. The data were calibrated and imaged following the procedure described in Sect. 5.4. The resulting continuum images were used to measure the radio flux density of the source and characterize its spectral behavior across the observed frequency range.

### 5.5.3 Radio continuum results

Continuum images were produced for three 2-GHz-wide subbands centered at 2.1, 5.0, and 7.0 GHz. The resulting images are shown in Figure 5.3 and were obtained keeping only the longer baselines to ensure maximum angular resolution and to discard the extended emission which, with the array configuration used, was poorly probed and thus ill-imaged. In addition, the synthesized beams are significantly elongated as a consequence of the limited LST range available for these observations, which directly impacted the  $(u, v)$  coverage.

Our observations benefit from a substantially broader spectral coverage than the previous ATCA observations of WR 48a reported by Zhekov et al. (2014b), which were obtained with a significantly narrower bandwidth and a more limited number of frequency points. The present wide CABB bandwidth allows the radio spectrum to be sampled at multiple frequencies across the 4–8 GHz range, providing a more detailed characterization of the continuum emission over this frequency range.

At 5.0 and 7.0 GHz, WR 48a is clearly detected as a compact radio source. Taking advantage of the broad frequency coverage and the resulting spectral resolution, we further explored the spectral shape within the 4–8 GHz range through an intra-band analysis. To this end, each 2-GHz-wide band was divided into four 500-MHz-wide subbands. The flux densities were then measured in each subband image by fitting a Gaussian component using the CASA task `imfit`. The resulting measurements, with the uncertainties derived from the fitting routine and the local image noise, are summarized in Table 5.1.

At 2.1 GHz, no emission at the position of WR 48a is detected above the local noise level. We estimated a  $3\sigma$  upper limit on the flux density from the local image

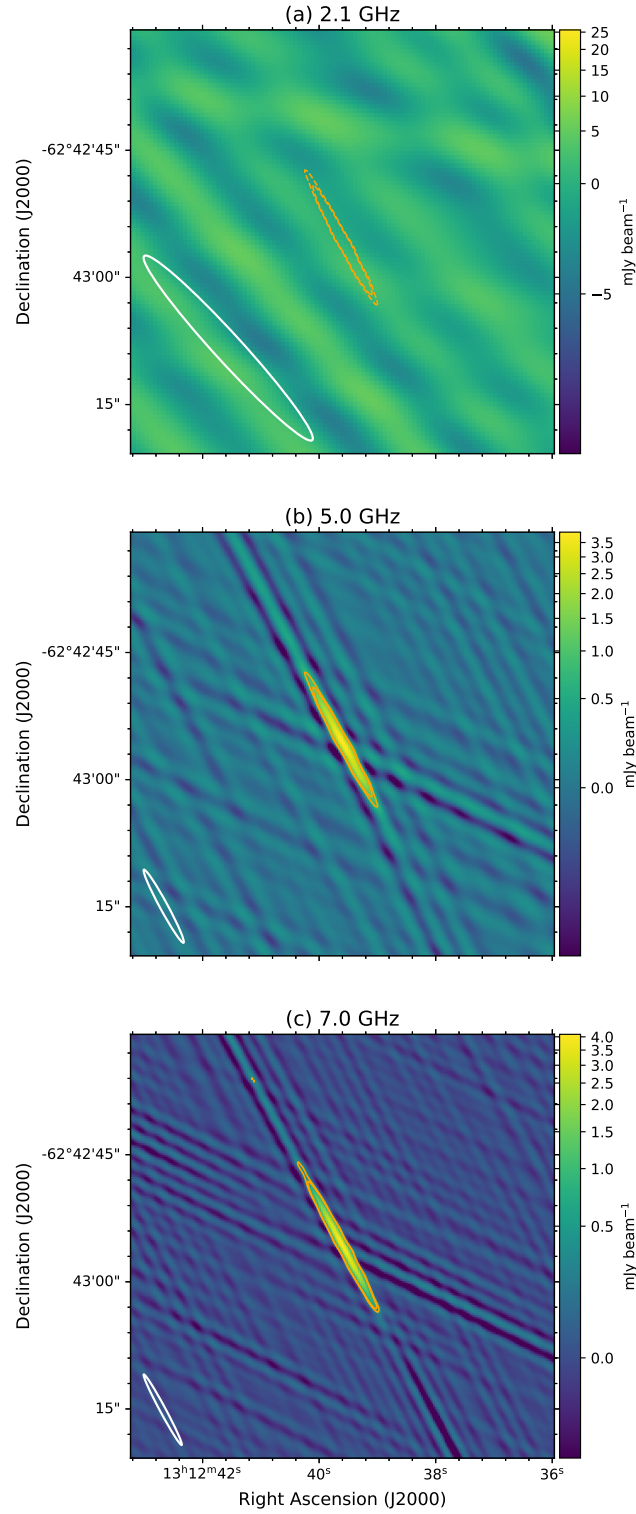


Figure 5.3: ATCA continuum images of WR 48a at 2.1, 5.0, and 7.0 GHz, obtained using a 2 GHz bandwidth. The source is detected as a compact radio component at 5.0 and 7.0 GHz. Orange contours correspond to the 6 and 9 $\sigma$  levels, where  $\sigma$  is the local rms noise of the corresponding image. No significant emission is detected at the position of WR 48a at 2.1 GHz. In this panel, the dashed orange contours are taken from the 5.0 GHz image to indicate the position of the source as detected at higher frequency. The synthesized beam is shown in white in the lower-left corner of each panel.

rms, which is also reported in Table 5.1.

Table 5.1: Radio continuum measurements of WR 48a from the ATCA observations. The frequencies listed in the first column correspond to the central frequencies of the respective band and subbands. For the 4–8 GHz range, flux densities are reported for each individual 500-MHz-wide subband image, together with the corresponding synthesized beam sizes and local image rms values. The  $3\sigma$  upper limit at 2.1 GHz corresponds to the full 1.1–3.1 GHz continuum image.

| Frequency<br>(GHz) | Clean beam size<br>(arcsec $\times$ arcsec) | rms<br>(mJy beam $^{-1}$ ) | Flux density<br>(mJy) |
|--------------------|---------------------------------------------|----------------------------|-----------------------|
| 2.10               | $29.4 \times 3.3$                           | 2.33                       | $< 7.0 (3\sigma)$     |
| 4.23               | $11.7 \times 1.2$                           | 0.28                       | $3.51 \pm 0.48$       |
| 4.75               | $11.8 \times 1.1$                           | 0.17                       | $3.73 \pm 0.31$       |
| 5.26               | $10.5 \times 1.0$                           | 0.16                       | $4.20 \pm 0.28$       |
| 5.77               | $10.1 \times 0.8$                           | 0.14                       | $4.42 \pm 0.28$       |
| 6.23               | $9.4 \times 0.8$                            | 0.12                       | $4.06 \pm 0.19$       |
| 6.75               | $9.5 \times 0.8$                            | 0.10                       | $4.04 \pm 0.30$       |
| 7.26               | $11.2 \times 0.7$                           | 0.09                       | $4.45 \pm 0.18$       |
| 7.77               | $11.3 \times 0.6$                           | 0.10                       | $4.59 \pm 0.19$       |

Using the flux density measurements from the eight 500-MHz-wide subbands between 4 and 8 GHz, we first characterized the overall spectral behavior by fitting a single power-law model of the form  $S_\nu \propto \nu^\alpha$ . This yielded  $\alpha = 0.34 \pm 0.12$ , a value considerably flatter than the canonical  $\alpha = 0.6$  expected for thermal free-free emission from a stellar wind, even within the uncertainty margins. Moreover, the thermal slope from WR stellar winds is frequently found to be even steeper than this canonical value (Nugis et al., 1998), making a purely thermal interpretation more difficult to reconcile with the observed spectrum.

While the single power-law fit gives us a useful phenomenological description of the observed spectral behavior, it does not separate between the different emission mechanisms expected to contribute to the radio emission of a PACWB. We therefore explored a composite model consisting of a thermal free-free component and a NT synchrotron component affected by FFA at low frequencies (Benaglia et al., 2020; Tasseroul et al., 2025). The model was expressed as

$$S_\nu = A\nu^{\alpha_{\text{Th}}} + B\nu^{-\alpha_{\text{NT}}} e^{-(\nu/\nu_{\text{FFA}})^{-2.1}}, \quad (5.1)$$

where  $A$  and  $B$  are the normalization parameters of the thermal and NT components, respectively, and  $\nu_{\text{FFA}}$  is the turnover frequency for FFA due to absorbing plasma distributed along the line of sight to the source (the so-called foreground FFA, Tasseroul et al. 2025). The exponent  $-2.1$  comes from the frequency dependence of the optical depth,  $\tau_\nu \propto \nu^{-2.1}$ , which follows from the frequency dependence of the FFA coefficient introduced in Section 1.3.2 (Eq. 1.11) with a slight additional frequency dependence coming from the Gaunt factor<sup>6</sup> ( $\propto \nu^{-0.1}$ ). Since the NT radiation is attenuated as  $e^{-\tau_\nu}$ , this results in the exponential FFA term used above.

<sup>6</sup>The free-free Gaunt factor is a dimensionless quantum-mechanical correction to the classi-



The spectral indices  $\alpha_{\text{Th}}$  and  $\alpha_{\text{NT}}$  were fixed during the fitting process, while  $A$ ,  $B$ , and  $\nu_{\text{FFA}}$  were left as free parameters. We explored nine combinations of spectral indices, with  $\alpha_{\text{Th}} = 0.70, 0.75$ , and  $0.80$ , and  $\alpha_{\text{NT}} = 0.50, 0.55$ , and  $0.60$ . These values cover plausible slopes for the thermal and synchrotron components (see, e.g., Benaglia et al., 2019; Blanco et al., 2024; Tasseroul et al., 2025) while allowing us to avoid an unnecessarily large number of free parameters, given our limited amount of available measurements to constrain the model.

For each of the nine combinations of fixed spectral indices, the three free parameters were determined through a weighted least-squares fit, with five degrees of freedom in each case. The formally best-fitting combination was obtained for  $\alpha_{\text{Th}} = 0.80$  and  $\alpha_{\text{NT}} = 0.60$ , with  $\chi^2_{\text{red}} = 0.739$ . However, the differences in  $\chi^2_{\text{red}}$  between the different combinations are very small, so the data do not clearly favor this particular pair of spectral indices over the others in a statistically significant way. For this model, the fitted turnover frequency of the FFA term is  $\nu_{\text{FFA}} = 2.74 \pm 2.35$  GHz. The large uncertainty is a reflection of the limited constraints on the low-frequency regime provided by the available data.

The resulting radio spectrum of WR 48a, including the eight measured flux densities between 4 and 8 GHz, the 2.1 GHz upper limit, and the best-fitting composite model together with its thermal and absorbed NT components, is shown in Figure 5.4. The figure also shows the  $1\sigma$  uncertainty of the composite model and the fitted turnover frequency of the FFA term.

### 5.5.4 Discussion of the physical interpretation

The new ATCA observations presented in this chapter provide the broadest simultaneous frequency coverage available for WR 48a to date and thus allow us to re-examine the nature of its radio emission in a new light. The source is clearly detected across the 4–8 GHz range, but no significant emission is detected at 2.1 GHz. The intra-band analysis performed over the 4–8 GHz range, where both thermal and NT components (if present) are expected to contribute, yielded a spectral index of  $\alpha = 0.34 \pm 0.12$  when assuming a single power-law behavior ( $S_\nu \propto \nu^\alpha$ ). This value is considerably flatter than what is expected for the optically thick thermal free-free emission from a WR wind. Motivated by this discrepancy, we proposed a composite spectral model to test whether the observed flat spectrum could be physically interpreted in terms of multiple emission components, as described in Sect. 1.3.4. In this model, the thermal component increases with frequency, while the NT synchrotron component decreases with frequency and is progressively suppressed towards lower frequencies by foreground FFA. Their superposition naturally produces a flatter overall spectrum, particularly over the frequency range of our observations (see the blue region in Fig. 5.5). We do find combinations of parameters that can satisfactorily reproduce the observed data, although our measurements do not uniquely constrain the relative contributions of the two emission components. The very similar goodness-of-fit values obtained for the different combinations of spectral indices, together with the large uncertainty on  $\nu_{\text{FFA}}$ , indicate that the com-

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cal bremsstrahlung emission and absorption coefficients, accounting for the detailed electron–ion Coulomb interaction.



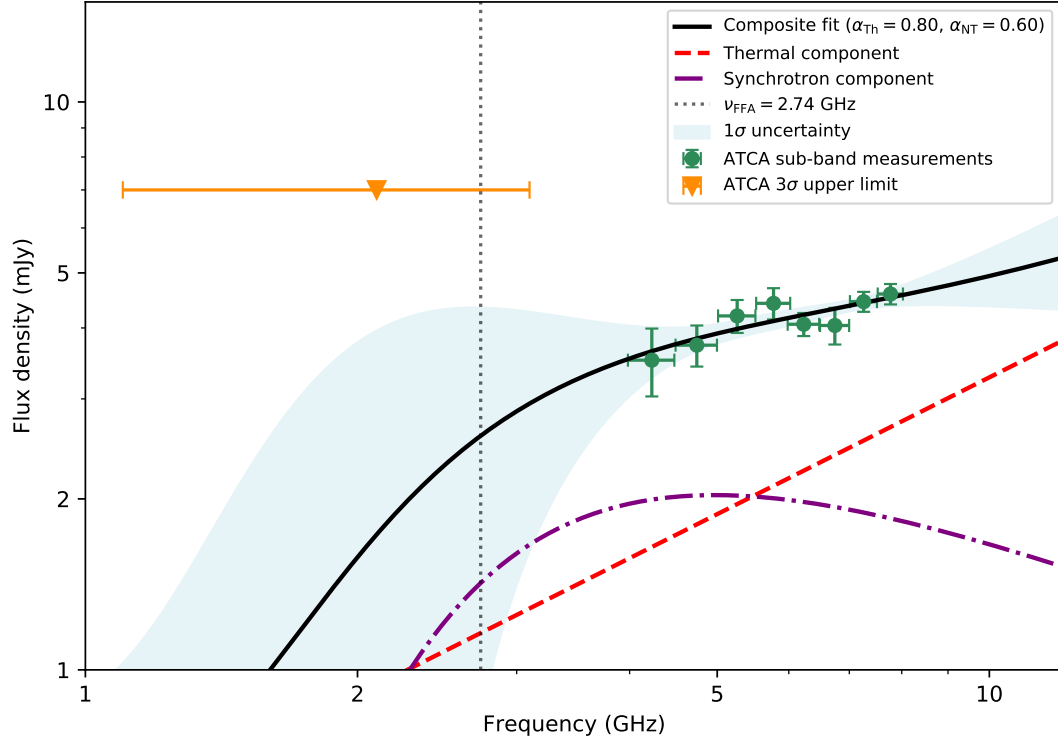


Figure 5.4: Radio spectrum of WR 48a based on the ATCA observations presented in this chapter. The green symbols show the flux densities measured from the eight 500-MHz-wide subbands between 4 and 8 GHz, while the downward orange arrow indicates the  $3\sigma$  upper limit derived from the 1.1–3.1 GHz continuum image. The solid black line shows the best-fitting composite model, consisting of thermal free-free emission plus a NT synchrotron component attenuated by FFA. The corresponding thermal and absorbed NT components are shown separately with red dashed and purple dotted lines, respectively. The shaded region indicates the  $1\sigma$  uncertainty of the composite model at each frequency. The vertical line marks the fitted turnover frequency of the FFA term.

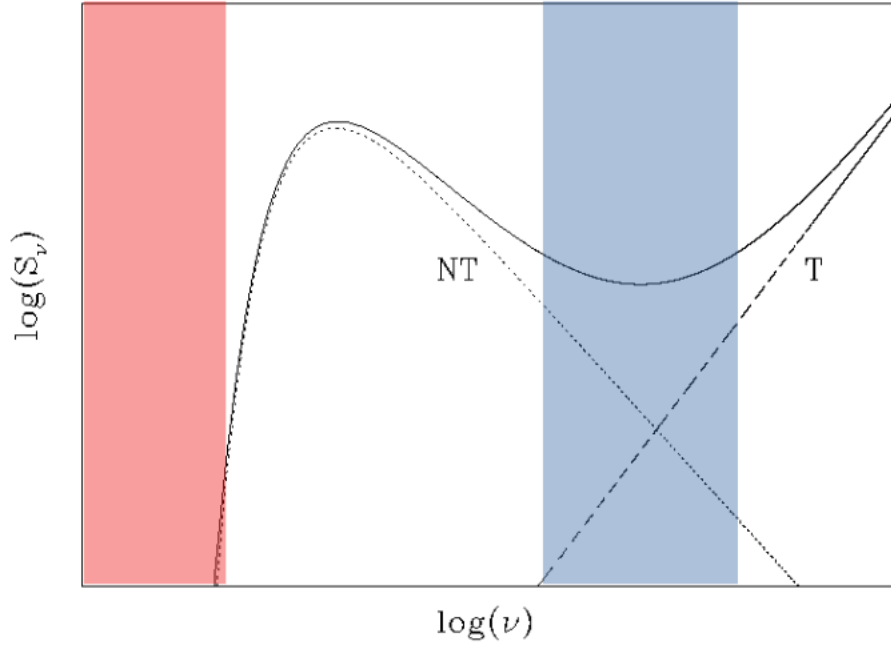


Figure 5.5: Schematic view of a generic PACWB radio composite spectrum (solid curve) showing both a thermal component (T, dashed line) and a turned-over synchrotron component (NT, dotted curve). The part highlighted in blue covers a spectral region with a near-flat spectrum. The part in red covers the region where NT emission is suppressed by FFA. Taken from [Blanco et al. \(2024\)](#).

posite model proposed should be considered as a physically motivated description of the observed spectrum rather than as a unique decomposition of the thermal and NT emission.

Previous radio observations of WR 48a, obtained with ATCA in 2000 and 2006 at 4.8 and 8.6 GHz ([Zhekov et al., 2014b](#)), allow for an interesting comparison with the present results. In 2000, flux densities of  $3.94 \pm 0.21$  and  $5.39 \pm 0.46$  mJy were measured at 4.8 and 8.6 GHz, respectively, while in 2006 the corresponding values decreased to  $1.90 \pm 0.27$  and  $3.64 \pm 0.18$  mJy. Thus, the radio emission decreased at both frequencies between the two epochs, and this decrease was substantially stronger at 4.8 GHz. The resulting spectral indices,  $0.53 \pm 0.17$  in 2000 and  $1.10 \pm 0.25$  in 2006, were interpreted by [Zhekov et al. \(2014b\)](#) as compatible with thermal emission. However, this thermal interpretation does not account for the flux variations between the two epochs, since thermal emission from massive-star winds is not expected to vary significantly on time scales of a few years. The frequency-dependent flux variation between the two epochs may then indicate a (varying) contribution from an absorbed NT component. In this interpretation, the stronger decrease at 4.8 GHz in 2006 could reflect a stronger suppression of the NT emission, which, due to its negative spectral index, contributes more strongly at the lower frequency, causing the total spectrum to become more dominated by thermal emission in 2006. However, this interpretation is only speculative, since the two-frequency measurements alone do not allow for the thermal and NT contributions to be properly disentangled.

The different radio properties observed in 2000 and 2006, together with our results, should also be considered in the context of possible orbital variability in WR 48a. If the system is indeed a long-period CWB, changes in its geometry through different orbital phases can modify both any intrinsic synchrotron emission and the degree of FFA along the line of sight. While recurrent dust-formation episodes suggest a periodicity of about 32.5 years (Williams et al., 2012), the orbital solution remains unknown. In a colliding-wind scenario interpretation, Zhekov et al. (2022) associated the maximum of the near-IR light curve with a presumed periastron passage around the end of 2011 or beginning of 2012. This would imply that the 2006 radio observations were obtained closer to the presumed periastron passage than the 2000 observations. If the radio emission includes a synchrotron component produced in the WCR, its observed contribution may then depend on the orbital configuration through changes in the amount of absorbing stellar wind material along the line of sight. In particular, as the stars approach each other, the changing wind geometry could lead to stronger FFA of the synchrotron emission. This provides a possible framework in which the stronger suppression of the lower-frequency radio emission observed in 2006 could be related to the orbital evolution of the system. However, testing this scenario would require a better-constrained orbital solution. The differences between the radio properties observed in 2000, in 2006, and those measured in 2024 (this work) may therefore reflect orbital variability, but a more quantitative interpretation is not yet possible.

The non-detection at 2.1 GHz is consistent with a scenario in which synchrotron emission is, although likely present, strongly attenuated at low frequencies by FFA within the dense stellar wind(s). For the best-fitting model, the predicted flux density at 2.1 GHz is  $\sim 1.7$  mJy, well below the  $3\sigma$  upper limit derived from our ATCA observations. The upper limit is therefore satisfied by the model, although it provided only a weak constraint. This is also consistent with the absence of a radio counterpart at the position of WR 48a at 1.3 GHz (Tasseroul et al., 2026) in the SRAO (South African Radio Astronomy Observatory) MeerKAT Galactic Plane Survey (SMGPS), whose observations were obtained between 2018 and 2020 and covered the frequency range 856–1712 MHz (Goedhart et al., 2024). Together, these results are all consistent with a turnover somewhere below the 4–8 GHz range that lowers the low-frequency emission below our detection thresholds.

Overall, these preliminary results strengthen the case for WR 48a as a promising PACWB candidate. We demonstrated that the observed radio spectrum is flatter than what is predicted for purely thermal stellar-wind emission (especially for a WR star), while a composite thermal+absorbed NT model yields a physically plausible interpretation, and seems compatible with the observed spectral shape. In particular, this model naturally accounts for the relatively flat 4–8 GHz spectrum and the lack of a detection at lower frequencies through the suppression of the synchrotron component by FFA. However, the current data do not allow the thermal and NT contributions, nor the FFA turnover frequency, to be uniquely constrained. Furthermore, if a low-frequency turnover is indeed present and governed by FFA in the stellar winds, its spectral position depends on the geometry of the system and may therefore vary with orbital phase. Thus, extending this analysis to multi-epoch broadband observations will be essential to test this scenario under different condi-

tions and to better characterize the variability of its radio spectrum (see Chapter 6, Sect. 6.2).

# Chapter 6

## Conclusions and future perspectives

PACWBs are a particular astrophysical laboratory that allows us to investigate particle acceleration and the resulting production and propagation of NT radiation in the specific context of long-term interactions between the dense winds of massive stars. While we currently know much more about PACWBs than we did just a couple of decades ago (De Becker, 2007; De Becker and Raucq, 2013; De Becker et al., 2017), many fundamental questions remain unanswered. Among them are the fraction of particle-accelerating systems among massive binaries (i.e., the true size of the PACWB population), the specific combination of conditions (if any) that need to be met for efficient particle acceleration to occur and become observable, and the role of magnetic fields and their degree of turbulence in determining the observed properties of NT emission.

As we have seen throughout this thesis, one of the main obstacles to answering these questions has to do with the observational challenges involved in detecting and characterizing NT radio emission. Addressing these questions, thus, requires not only sensitive observations, but also an understanding of the observational biases and the physical effects that can influence the production, transfer, detection, and interpretation of radio emission from massive binaries.

In this thesis, these questions have been explored through three complementary observational studies based on radio interferometric observations obtained with the uGMRT, the VLA, and the ATCA observatories. Together, these projects sought to address the main objectives presented in Section 1.7: improving our understanding of the PACWB population through radio observations, and assessing the potential of radio polarimetry as a probe of the physical conditions within the WCR. While the research developed in this thesis does not claim to provide definitive answers to the open questions motivating this work, it does collectively highlight both the complexity of detecting, identifying, and characterizing NT radio emission in massive binaries and the importance of current and future radio-observing facilities to continue expanding our knowledge about these objects.

The following sections summarize the main conclusions we draw from our work, discuss the observational challenges that limit progress in the field, and lay the groundwork for some promising directions for future studies of PACWBs.

## 6.1 Main conclusions

The observational studies that were presented in the previous chapters addressed two aspects of PACWBs: the characteristics and completeness of the known population census through the search for new synchrotron-emitting systems, and the potential of radio polarimetry to investigate their magnetic properties. The main conclusions derived from these two research lines are summarized below.

### 6.1.1 Population properties of PACWBs

Regarding the PACWB population, the results obtained in this thesis suggest that the current census is likely affected by important observational biases, and that the main challenges are related to the observational limitations involved in detecting and characterizing NT radio emission. Because the radio properties observed from a PACWB are a consequence of the physical and orbital properties of the system at a given epoch, systems with intrinsically different levels of radio emission may or may not become detectable depending on the observing frequency and system configuration, in a manner that is not straightforward to predict.

The uGMRT observations presented in Chapter 3 illustrate one aspect of this issue. None of the five WR stars investigated showed evidence of synchrotron emission, which highlights the limitations of low-frequency observations alone for identifying particle acceleration. In particular, FFA can severely impact synchrotron emission in PACWBs through the dense stellar winds. This makes such emission preferentially detectable in systems with large stellar separations, since in wide binaries, the WCR is located farther from the stars, allowing the synchrotron radiation to escape before being absorbed by the winds. This selection effect may bias the observed PACWB population towards systems with long orbital periods, and is expected to be particularly important for WR binaries, due to the high densities of WR winds.

The case of WR 98a is, notably, an example of this limitation. Despite having previously shown a composite thermal and NT spectrum at higher frequencies, the system was undetected in both uGMRT bands in our observations. This non-detection does not necessarily indicate the absence of synchrotron emission; on the contrary, it emphasizes how the emission can remain hidden at low frequencies. At the same time, low-frequency observations are valuable in themselves. Measurements at lower frequencies remain needed since they can constrain the FFA turnover and thereby the shape of the spectrum, but they need to be complemented by observations at higher frequencies, where FFA becomes less important, and a potential synchrotron component may become detectable, although it is expected to be intrinsically weaker. Hence, our findings point to the importance of broad spectral coverage for identifying and characterizing PACWBs from their radio emission.

The preliminary results described for WR 48a in Chapter 5 represent a complementary example of the challenges of correctly interpreting the observations, even when the radio emission is detected. In this case, the broad frequency coverage allowed us to reconstruct a more detailed characterization of the radio spectrum. We showed that it can be adequately described by a composite model including thermal and FFA-absorbed NT emission, although the frequency range covered by our ob-

servations does not allow the individual parameters of these emission components to be unambiguously constrained. In particular, different combinations of the thermal and NT spectral indices result in similarly good fits, demonstrating the degeneracy of the decomposition. This highlights the value of broadband observations for revealing spectral complexity that might have remained hidden if only a few frequency points were available. At the same time, the limited sensitivity at some frequencies, particularly around 2.1 GHz where only an upper limit could be obtained so far, illustrates how broad frequency coverage alone is not sufficient: adequate continuum sensitivity is also required to detect weaker (intrinsically or absorbed) NT components and thus to better constrain the spectral shape and disentangle the contributions of thermal and NT components.

Together, these results show that the absence or ambiguity of a detectable synchrotron component is not, in itself, proof against particle acceleration. Instead, the detectability of NT emission depends on the balance between its intrinsic production and the effects of absorption, dilution, sensitivity limitations, and orbital configuration at a given time of observation. A complete PACWB census will require systematic radio surveys of a larger and more diverse sample of massive binaries, combining broad spectral coverage with sufficient sensitivity to detect systems with weaker NT emission rather than only the brightest and nearest PACWBs.

A natural next step would be to focus such surveys on binaries whose binarity or multiplicity is already firmly established and whose orbital parameters are sufficiently well characterized. This would reduce some of the uncertainties associated with target selection. In addition, multi-epoch observations would provide information on the temporal dimension, enabling the variation of the detectability and spectral properties of NT emission with orbital phase to be investigated. Expanding the sample in this way, while combining broadband and multi-epoch observations, will be essential to determine how common particle acceleration is among massive binaries and to move towards a more complete census of PACWBs.

### 6.1.2 Polarization properties of PACWBs

The second aspect addressed in this thesis concerns the potential of radio polarimetry as a tool to investigate the magnetic properties of PACWBs, particularly those of their WCRs, given that it is the synchrotron radiation originated there that is expected to be polarized.

The VLA observations of WR 147 and HD 167971 introduced in Chapter 4 offered a valuable test since both systems are bright synchrotron-emitting PACWBs and were observed in full polarization at L and C bands (where synchrotron emission should still significantly contribute to the radio spectrum). Despite their strong total-intensity emission, no significant linear polarization was detected in either system. This remained consistent even when we restricted the analysis to narrower, higher-frequency sub-bands, indicating that bandwidth depolarization alone cannot explain the lack of polarization signature.

The non-detections seem, a priori, hard to reconcile with the high intrinsic polarization expected from synchrotron emission. In reality, we believe they indicate that the polarization signature in the radiation is strongly suppressed before it can



be detected. Rather than being fully explained by a single mechanism, the results are likely the consequence of the combination of several physical and observational effects. A highly turbulent magnetic field within the WCR is expected to reduce the degree of intrinsic polarization, while Faraday rotation and associated depolarization processes can further modify the signal as it propagates through the WCR and the surrounding stellar winds. Furthermore, the limited angular resolution of the observations can produce beam depolarization when the complex structure of the synchrotron-emitting region is unresolved. Finally, thermal free-free emission from the stellar winds is naturally unpolarized and can dilute the polarized synchrotron component, making the polarization degree of the total observed emission substantially lower than the intrinsic polarization of the synchrotron component on its own.

Therefore, the absence of detectable polarization is not evidence against synchrotron emission, especially considering that for both systems analyzed, the presence of this NT radio emission was firmly established in advance. More importantly, we highlight that selecting PACWBs as suitable targets for radio polarimetry requires more than the detection of synchrotron emission. The polarized signal must also survive the different depolarization and dilution mechanisms acting within the system and along the line of sight, and still be detectable with the available sensitivity and angular resolution.

We consider that our results, together with those found by [Hales et al. \(2017\)](#) for WR 146, suggest that PACWBs may be intrinsically more challenging polarimetric targets than other synchrotron-emitting systems. The coexistence of a compact, turbulent synchrotron-emitting WCR with dense, unpolarized stellar winds introduces extra sources of depolarization.

In this context, extending this analysis to similar unresolved polarimetric observations of a larger number of PACWBs may not necessarily provide additional information unless accompanied by improved angular resolution. Future observations will then need to combine high sensitivity with higher angular resolution, ideally at frequencies where Faraday depolarization is less severe while still having sufficient synchrotron brightness. Higher angular resolution would not, by itself, guarantee the detection of polarized emission, as several other depolarization mechanisms may still be in place. However, resolving the synchrotron-emitting region and separating its emission from that of the thermal winds would remove or reduce some of the effects that currently affect the detectability of polarization. This could offer more favorable conditions for future searches and potentially allow the first direct observational constraints on the magnetic-field structure and orientation in PACWBs.

*Finally, we would like to stress that the results presented in this thesis emphasize the complexity of PACWBs as synchrotron-emitting systems. Their radio emission does not behave as that of a textbook synchrotron source, since the observed measurements are the result of the interplay between particle acceleration, the orbital configuration of the system at a given epoch, dense thermal stellar winds, and the propagation of the radiation through this environment. The synchrotron component may be hidden by FFA, diluted by thermal free-free emission, or modified by other*

*effects that depend on the specific system and the observing epoch. As a result, even when synchrotron emission is present, PACWBs do not necessarily show the spectral or polarization signatures that would be expected from an idealized, isolated synchrotron source: their spectra can be strongly affected by the coexistence of thermal and NT emission and our limited angular resolution, while their polarization could be strongly suppressed because of several depolarization mechanisms. These effects make both the detection and the interpretation of synchrotron emission in PACWBs challenging, and provide a plausible explanation for the non-detections and ambiguous results encountered in this thesis. However, these complexities are not only challenges to overcome; they are also a reflection of the rich physics of PACWBs, making them particularly interesting systems in which to study particle acceleration and magnetic fields in the environment of massive stars.*

## 6.2 Future directions

The challenges identified in the conclusions of this thesis point towards several promising lines of future research. Some of these are directly connected to observations already obtained as part of the projects developed during this PhD, while others involve extending this work to new projects.

A first step will be completing the analysis of the ATCA observations presented in Chapter 5. Although the discussion in this thesis has focused on the target WR 48a, the observational campaign carried out included additional WR targets that could not be analyzed within the time available for this work. The corresponding observations and the reduction scripts, achieved as described in Section 5.4, are already available. Completing the reduction and analysis of the whole dataset will provide us with a larger, diverse sample observed with the same broad frequency coverage. This would allow the spectral properties of the different targets to be compared in a more homogeneous way and help assess whether the spectral behavior found for WR 48a is also present in other systems.

Another possible line of work is to investigate earlier ATCA observations of the same targets, obtained in 2019 by collaborators (PI: M. De Becker). These observations were designed for the same target sample and frequency coverage as the more recent observations. However, technical problems during the observations, including the loss of one antenna, affected the available baseline coverage. Firstly, we would have to evaluate whether the 2019 datasets are of sufficient quality to be used for scientific analysis. If they are, these observations could be reduced and combined with our more recent data to obtain a multi-epoch analysis for the same targets. This would add the temporal dimension to the study and could reveal changes in flux density or spectral properties that could not be identified from a single observing epoch.

There is a complementary direction that was already initiated during this PhD through another ATCA project targeting southern massive O-star binaries with known three-dimensional absolute orbits. The targets were selected among massive binaries with a well-determined orbital configuration that are not currently known to be particle accelerators, with the aim of searching for synchrotron emission. The

observing time requested in the proposal was awarded, and the observations were carried out remotely, in the same manner described in Section 5.3.1. The resulting datasets are already available, but their reduction and analysis were beyond the scope of this thesis.

Searching for a signature of NT emission in targets with confirmed binarity eliminates one source of ambiguity that was present in other population studies, where the binary status was not necessarily established. In addition, having absolute orbital solutions for these systems is particularly useful in this context. For these systems, we are able to determine the physical separation and orientation of the components at the time of the radio observations. As discussed throughout this thesis, the radio properties observed can depend strongly on this configuration, both through the location and properties of the WCR and through the amount of FFA along the line of sight. Our new observations could be used not only to search for NT emission, but also to investigate whether and how its detectability is related to the known stellar and orbital properties of the systems. In particular, the observing epoch and corresponding orbital phase can be taken explicitly into account. This would complement the population study presented in this thesis, allowing us to tackle some of the observational challenges encountered.

More generally, combining these datasets would allow the PACWB population to be studied from several complementary perspectives: increasing the number of systems observed, comparing different epochs, and focusing on established binaries for which the orbital configuration is known in detail. All of this could help distinguish between intrinsic differences in the radio emission and variations caused by absorption or orbital configuration, while also assessing how representative the currently known PACWBs are of the broader population of massive binaries and refining the criteria used to search for new members of the class.

A complementary future step concerns the use of polarization as a probe of the NT emission and magnetic-field structure in PACWBs. The polarimetric analysis presented in Chapter 4 shows that the presence of synchrotron emission does not necessarily translate into detectable polarization, likely due to several depolarization and dilution mechanisms that can act within these systems. Based on these results, simply increasing the number of studied targets may not necessarily lead to improved detection rates. A potentially promising direction worth exploring would instead be to investigate systems in which the WCR can be spatially resolved, for instance through VLBI observations. In such cases, the thermal emission from the stellar winds could be separated from the synchrotron-emitting region, enabling a cleaner investigation of the polarization properties of the NT emission. This would allow us to study the spatial distribution of the magnetic-field orientation with less contamination from the thermal winds, and infer properties such as its degree of order and overall structure. Future facilities with improved sensitivity and angular resolution could make such studies possible and offer an opportunity to revisit the polarization of the synchrotron emission in PACWBs.

Altogether, these future efforts would extend the work presented in this thesis towards a more systematic study of particle acceleration in massive binaries, from the conditions that allow it to occur and become observable to its broader consequences. Understanding these processes is relevant not only for characterizing the

radio emission of massive stars, but also for studying how high-energy particles and radiation are produced and how they interact with and affect their surrounding environments. The combination of larger samples, broader spectral coverage, multiple observing epochs, and better knowledge of the orbital configuration should help reduce the observational biases and provide a clearer picture of particle acceleration among massive stars.



# Publications

## Publications in peer-reviewed journals as first author

- *Insight into the occurrence of particle acceleration through the investigation of Wolf-Rayet stars using uGMRT observations*  
**Blanco A. B.**, De Becker M., Saha A., Tej A., Benaglia P., 2024, *Astronomy & Astrophysics*, 690, A78
- *Search for radio polarization in the particle-accelerating colliding-wind binaries WR 147 and HD 167971*  
**Blanco A. B.**, De Becker M., Benaglia P., del Palacio S., 2026, *Astronomy & Astrophysics*, 710, A157

## Publications in peer-reviewed journals as co-author

- *Foreground and internal free-free absorption in particle-accelerating colliding-wind binaries: Insights from the radio emission of WR147*  
Tasseroul M., De Becker M., **Blanco A. B.**, Benaglia P., 2025, *Astronomy & Astrophysics*, 701, A243
- *Radio study of the colliding-wind binary HD 93129A near periastron and its surroundings*  
Benaglia P., del Palacio S., Saponara J., **Blanco A. B.**, De Becker M., Marcote B., 2026, *Astronomy & Astrophysics*, 698, A23





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