Introduction to Colliding Winds in Massive Binaries

Massive stars are among the most energetic objects in galaxies. Most massive stars are associated with giant molecular clouds, where they are thought to be born. In the early stages after their birth, massive stars will heat the dust and excite the gas of the optically thick surrounding cloud and the cloud will radiate at the IR and radio wavelengths. Soon the strong radiation of the stars will blow the cocoons away. These strong stellar winds will dissociate the clouds and we will see HII regions at optical wavelengths. The O stars and their evolved descendants, the Wolf-Rayet (WR) stars, are the main contributors of ultraviolet radiation in galaxies, which heat the interstellar dust to radiate in the infrared. Their stellar winds are a powerful mechanism to enrich their surroundings, both with heavy elements and energy. This enrichment will reach its finale in the blast of a supernova (SN) explosion, which in turn will stimulate new star formation processes. In short, massive stars play a key role in the evolution of galaxies, and, therefore, it is very important to understand what is happening during the evolution of massive stars.

WR stars are evolved massive stars in their helium burning phase (e.g., Conti 1988). The intense heat of helium burning pushes the stellar envelope away and the radiation field produces a prodigious stellar wind. The mass-loss rates of WR stars are of the order of $10^{-5} \, M_\odot \, yr^{-1}$, with terminal velocities $v_\infty \approx 1000–3000 \, km \, s^{-1}$. WR stars show broad emission lines of He I and He II and other ionised ions. Based on the dominant ion lines, WR stars are grouped into three subclasses:

- WN, dominated by helium and nitrogen emission lines,
- WC, dominated by helium and carbon emission lines, and
- WO, dominated by oxygen emission lines.

Further decimal sub-classification is based on the line-widths, line-strengths and line-ratios. WN2-6 subtypes are also called WNE, WN7-11 WNL, WC4-6 WCE, and WC7-9 WCL, where E and L refer to ‘Early’ and ‘Late’, respectively.

The widely accepted evolutionary sequence of massive stars is as follows (Crowther et al. 1995a, Langer et al. 1994, Meynet & Maeder 1994):

Very massive stars, with $M_{\text{initial}} > 60 \, M_\odot$:

$O \rightarrow O\text{f} \rightarrow \text{WNL+absorption lines} \rightarrow \text{WN6-7} (\rightarrow \text{WNE}) \rightarrow \text{WC} \rightarrow \text{SN}$. 


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Stars with $25 \, M_\odot < M_{\text{initial}} < 60 \, M_\odot$:

$$O \rightarrow \text{LBV/RSG} \rightarrow \text{WN8} \rightarrow \text{WNE} \rightarrow \text{WC} \rightarrow \text{SN},$$

where the lower mass stars ($< 40 \, M_\odot$) undergo the red supergiant (RSG) phase and the higher ones ($> 40 \, M_\odot$) undergo the luminous blue variable (LBV) phase. The Wolf-Rayet phase lasts for about $5 \times 10^5$ years, and the resulting supernovae are of Type Ib and Ic.

Since the first detection by Wolf and Rayet in 1867, hundreds of stars and even galaxies are now observed to show WR phenomena in their spectra. Of the 227 Galactic WR stars discovered so far, 84 (37%) reside in binary systems (van der Hucht 2001). In 90% of the cases, the companion is a star of OB type, ~2% have a compact companion, and the rest are yet to be determined. When unexpectedly-bright radio emission was observed from a few Wolf-Rayet stars in the 70-80s, the exciting interpretation was that a compact, unseen companion was the origin, accreting matter from the WR star; that neutron stars or even black holes had been detected! Twenty years have passed, and the radio emission turns out to be of a different, equally exciting cause.

In the case that the companion to a WR star is a compact object, as in Cygnus X-3, the part of the dense wind from the WR component that eventually reaches the compact object is accreted by the compact star and an increased X-ray emission results. When the wind density is high, the luminosity will be so close to the Eddington limit that the accretion process becomes unstable. In this case, radio jets develop, presumably along the rotation axis of the disk around the compact object. The case is very different in WR+OB binaries.

Like WR stars, massive stars of O and B type have strong, dense winds. When a WR star resides in binary system with a massive star as companion, and their binary separation is great enough, their winds collide and the interaction shows profound effects. The wind matter, pushed from both sides of the interaction region, will heat up and the system may brighten up at all frequencies. The collision produces shock fronts. Upon passing this front, matter will be accelerated, and eventually flow out of the system along the interaction region. The interaction region can also act as a ‘wall’ shielding each binary component from the other’s influence during their evolution. Accordingly, we can expect that the binary components will evolve as if they were single stars. Therefore, colliding-wind binaries may give more insight in stellar evolution, due to the information they provide that single stars cannot give.

1.1 Twinkle, twinkle binaries

The heat generated in the collision region will enhance radiation from near infrared up to ultraviolet wavelengths, both in continuum as well as in lines. In the continuum, due to temperature stratification, the optical and ultraviolet radiation are usually formed very close to the stellar surface, while the near-infrared radiation originates from further away. In the lines, there will be excitation/ionisation stratification. Therefore, by observing at different wavelengths, we can probe different parts of the collision region. We must exercise caution, however, as the excess emission in un-resolved systems can easily be confused with orbital effects. This confusion can even lead to wrong spectral classification if it occurs in classification lines.

We can expect the continuum levels and line-profiles to vary as a function of orbital phase. Excess emission in the lines can give more information about the geometry involved than the continuum, i.e., the kinematics can give information about the orbital parameters. Information extracted from emission lines due to colliding winds, is different from that of the absorption
lines. As the emission lines are usually optically thin, they will show only variation in the shape of the profiles, while the equivalent widths will remain the same. Therefore, we can obtain orbital parameters from these lines (Moffat 1999). However, absorption lines will be affected strongly by the geometry of the system with respect to the observer. This is due to the fact that absorption lines can only be formed between the observer and the illumination source. In using the absorption part of the P-Cygni profiles to determine the terminal velocities of the binary components, we have to be careful not to confuse the blue edge with any contamination from the colliding-wind absorption lines. Geometrically, the line-of-sight may coincide with the tail of the interaction region. When high velocity particles are flowing in this tail and moving toward the observer, the net velocity observed can be significantly higher than the actual terminal velocity of the wind.

Moffat (1999) made a compilation of all available optical studies of WR+OB binaries. He noted that the collision is stronger in WC+OB than in WN+OB binaries, which he suggested to be related to the higher metal abundance in WC stars, enhancing cooling. The colliding-wind effect seems to be stronger for binaries with intermediate periods (\(\sim 5\text{–}30\) days), as is also predicted by Eichler and Usov (1993), due to radiative braking.

### 1.2 Stardust

Dust is not expected to form in a hostile environment like that of hot massive star atmospheres. That no WR stars of the WN type show dust formation is in agreement with the expectation. However, some 30% of WC type stars do form dust, mostly those of WCL type. This phenomenon is observed in the form of infrared excess. While the process behind this dust formation is not yet fully understood, the clue to this process may lay in the fact that more than 60% of these dusty WR stars are binaries. Cherchneff & Tielens (1995) suggested that the process should take place in a very dense environment, \(\sim 10^{3\text{–}4}\) times higher than that of normal/uniform wind.

Some of the dusty WR stars show periodic infrared excess, indicating periodic dust formation. The best studied dust-forming WR star, WR 140 (WC7+O4-5, \(p=7.9\) yr, \(e=0.84\)), has been observed at three episodes of infrared excess, all occurring at similar orbital phase (Williams 1999). This is a hint to the required dense environment. The high orbital eccentricity of WR 140 provides two extreme conditions: at apastron (and for most of the time), the binary components are so far apart that the mass flux that enters the collision region is small, resulting in a lower density matter behind the shock. The opposite happens at periastron, when the density of matter before entering the colliding-wind region is about 40 times greater. Williams (1999) noted that there is a \(\sim 90\) days delay between periastron passage, which gives the maximum density and infrared (K-band) maximum. Taking the wind terminal velocity into account, he suggested that this 90 days is the time needed by the compressed matter to travel away from the star, so that it can cool-down and condense to form dust.

With this in mind, we can explain qualitatively episodic infrared excesses in other systems. It is also applicable to WR binaries which persistently show infrared excess. This can be seen beautifully in the infrared images of WR 104 (WC9+B0.5V) taken with an infrared interferometry technique, at two different epochs which coincide with different binary phases (Tuthill et al. 1999). They observed a spiralling feature (Fig. 1.1), suggesting synchronous rotation with orbital motion. As the binary components travel along their orbits, the interaction region will also travel, shedding compressed matter in its wake, which cools down and
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FIGURE 1.1 — The persistent dust-maker WR 104, WC9+B0.5V binary: the observation (taken from Tuthill (1999), with permission) and the model (with permission from Tuthill).
forms dust.

1.3 Turn on that radio

For a smooth, spherically symmetric wind, flowing continuously, Wright & Barlow (1975) showed that the free-free flux-density, $S$, at infrared to radio frequencies can be expected to vary with frequency according to $S \propto \nu^{0.6}$. Observations have shown that this relation does hold for thermal objects. If we cannot resolve a binary system, the extra emission due to the colliding winds will increase the total flux-density observed and the spectral index will depart from the expected value of 0.6. The extra emission is thought to be due to synchrotron processes (see Sect. 1.5).

There are several processes that may influence the spectrum of the synchrotron emission. Synchrotron emission can become self-absorbed. The absorption coefficient of synchrotron radiation depends on frequency according to $\kappa_\nu \propto \nu^{-\alpha}$ and so the source may become optically thick at low frequencies. In normal circumstances we can ignore this absorption, since the collision region is not compact enough to be optically thick for synchrotron emission.

The beaming of pulses of radiation by relativistic particles in plasma can be shut off at frequencies lower than the plasma frequency times the Lorentz factor, i.e., a few 100–1000 times higher than the usual plasma cutoff. This is because the phase velocity of the radiation exceeds the velocity of light, so that the new pulses of radiation from the relativistic particles can no longer boost the synchrotron radiation. The plasma frequency depends on the density of the plasma, therefore this Razin-Tsytovich suppression will take place when the plasma is very dense. Strong magnetic fields will prevent this from happening, as these will strongly accelerate the electrons.

However, the dominant process is free-free absorption. In hot stars, the temperature stratification in the stellar atmosphere causes the absorption coefficient to vary with frequency. As a result, the stellar radius varies with frequency as well. In the radio regime, the free-free radiation originates from radiophotospheres with radii of $\sim 10^7$–$10^8$ $R_\odot$. The lower the frequency, the bigger the radiophotosphere. If the collision region is within the radiophotosphere of the binary components at a certain frequency, the collision-created emission at that frequency will be absorbed by free-free absorption. External screens may also add to free-free absorption.

1.4 Hop, skip and jump to the high energies

Different processes are involved in the high-energy emission from WR binaries. Colliding winds are expected to add extra high-energy emission through Bremsstrahlung. Then, when relativistic particles with Lorentz factor $\gamma_L$ are formed in the collision region, the stellar photons with energy $E_i$ can be Inverse Compton scattered to a final energy of $E_f = \gamma_L^2 E_i$. WR stars have high effective temperatures ($\sim 30–50$ kK) and the initial energy of the stellar photons is $\sim 1–20$ eV. These photons can be kicked to hard X-rays and even $\gamma$-rays, when the relativistic particles have high enough energies. Therefore, due to the common origin, we can expect a variable radio excess to be correlated with variability at high-energies.

1.5 The answer is blowing in the colliding-wind model

Colliding winds were first suggested to be responsible for the observed excess X-ray emission in the WR binaries EZ CMa and V444 Cyg by Moffat et al. (1982) and for all frequency
anomalies in HD 193793 (WR 140) by Williams et al. (1987b). A first analytic model of colliding winds was proposed by Usov (1992), where the interaction region is defined by equal wind ram-pressures. In this model he suggested that shocks are formed in the interacting region. Behind the shock, the gas will be heated to temperatures of \(10^7 - 10^8\) K, and X-ray emission will be generated through Bremsstrahlung. Further development of the model by Eichler & Usov (1993) showed that the shock will accelerate particles (electrons), to relativistic velocities. In the presence of a magnetic field, the relativistic particles will move in a helical motion along the magnetic field lines and produce synchrotron emission, giving rise to radio emission.

The shape of the colliding-wind region according to Eichler & Usov’s model is shown in Fig. 1.2, where the effect of orbital motion is also taken into account. Assuming a smooth, continuous, spherically symmetric wind, the distance from the WR star to the stagnation point depends only on the ratio of momenta of winds, i.e., on the mass-loss rate \(\dot{M}\) and \(v_\infty\) of each wind. As mass-loss rates of OB type stars are lower than those of WR stars, while the terminal velocities are of the same order of magnitude, the colliding-wind cone is closer to the OB star. Eichler and Usov (1993) successfully applied this model to WR 140 to explain the X-ray and radio variabilities observed in this system. Usov’s model has also been applied by various groups to other WR binaries, e.g., WR 11, WR 39, WR 146, and WR 147 (e.g., Dougherty et al. 1996, Williams et al. 1997).

The images of WR 104 (Fig. 1.1), together with the radio images of WR 146 and WR 147 obtained a few years before (Dougherty et al. 1996, Williams et al. 1997), give strong evidence in support of Usov’s colliding-wind model.

1.6 May I have this dance?
Motivation and outline of the thesis

At the start of this thesis work there were several open questions related to Wolf-Rayet stars:

- How real is the assumption of smooth, spherically symmetric winds?
- How does radio luminosity depend on the mass-loss rate, binary geometry?
- Do all WR stars reside in binary systems? If not, what is the binary frequency?

These questions motivated the work described in this thesis.

The spectral energy distribution of a selection of WR stars is discussed in Chapter 2. We combined the results of our observations at 1.3 mm and \(JHKLM\) bands of a group of WR stars with available optical to radio data, to form multi-epoch, multi-frequency energy distributions. There it can be seen that the WR binaries in the sample show different characteristics in their spectral energy distributions from that of single WR stars.

In Chapter 3, the ultraviolet variations of the WR binary WR 140 (WC7+O4.5V) are presented. This highly eccentric binary system (\(e=0.87\)) was monitored using the late International Ultraviolet Explorer (IUE) for about 15 years, spanning almost twice the binary period of 7.9 yr. The variation in the P-Cygni profiles in this system shows that there are selective line eclipses due to the orbital geometry.

In Chapter 4 we show the possibility that WR 146, a WC6+O9.5 binary with non-thermal radio emission, is actually a triple-star system. We monitored this system for 8.4 yr at 5 and 1.4 GHz with the Westerbork Synthesis Radio Telescope (WSRT). During that period, the non-thermal emission from this binary system was rising steadily, which we interpret as due to increasing colliding-wind effects as the WC and O components are getting closer in their
1.6 May I have this dance?

Figure 1.2—Interaction region in a colliding-wind WR+OB binary system (hatched). As the OB wind has lower momentum, the interaction region is closer towards the OB star. $S_1$ and $S_2$ are the shock fronts and $C$ is the stagnation surface. At intermediate distances the shock fronts and the stagnation surface are close to the conic surfaces $S_1$, $S_2$ and $C$, with angle $\theta$. At further distances, the orbital motion, clockwise, comes into effect. $R^\text{rad}_{WR}$ and $R^\text{rad}_{OB}$ are the radiophotosphere of the WR and OB stars. (From Eichler & Usov 1993, with permission).
thousand-year orbit. On top of this we also found a sinusoidal variation with a 3.4 yr period in its 8.4 yr 1400-MHz light-curve. We suggest that this variation is due to the presence of a third body in the system.

WR 147, another WR+OB binary system, was also monitored using the WSRT at 1.4 and 5 GHz, and is discussed in Chapter 5. This WN8+OB system shows a somewhat different variation than WR 146. During the 10-yr monitoring, the flux densities at both frequencies show no systematic variation. However, there are irregular, stochastic variations which we suggest to be caused by inhomogeneities or clumping in the winds.

Encouraged by the characteristics shown by WR binaries, namely the extra emission and variation at radio frequencies, we set forth to find more WR stars in an area that is very rich in massive stars, but has very high optical extinction: the Cygnus OB2 region. At radio frequencies this obscuration is almost absent, and therefore we expect to be able to see deep into the spiral arm and beyond. This task was carried out using a mosaic technique with the WSRT at 1400-MHz. Fortunately, we could also make use of an unpublished 350-MHz map of the area obtained by Vasisht and de Bruyn. These results are presented in Chapter 6. The source count of the area shows more objects compared with other source count studies, which mainly show counts of sources of extragalactic origin. This suggests that toward the Cyg OB2 region we see an excess of objects of galactic origin. We carried out identification with objects from various surveys from radio to optical, where the identification is quantified by the Likelihood Ratio (LR). A high LR means that the identification is highly likely. We show that some of the identified sources have colliding-wind characteristics, i.e., nearly flat or inverted spectral indices and variable flux densities, and some of the unidentified sources are probably also radio stars. We also found a new candidate non-thermal radio star, which has a high likelihood of being identified with an O7V star.

As is often the case, this study has raised as many questions as it has answered. These and some promising directions for future research are presented in Chapter 7, where we also show a recent result from peering into the colliding-wind region of WR 146, using Very Long Baseline Interferometry (VLBI) at 1660 MHz.

Some of the chapters above were already published in or submitted to refereed journals. These papers are presented in this thesis 'as they are'. However, as the chapters have many references in common, all the references were compiled in one list, presented toward the end of this dissertation.

And now, lets tango ...