Collision of stellar winds in the WR 146 and WR 147 binary systems

Author: Sara Villá Miró
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Dr. Josep Maria Paredes i Poy

Abstract: Binary systems of early-type massive stars, O and Wolf-Rayet type, which emit strong winds, present a colliding-wind region. In this area, charged particles are accelerated to relativistic velocities and, due to the fact that they are in the presence of a magnetic field, there is non-thermal radio emission. The flux density measured from these systems also includes the thermal emission coming from the individual winds. The two systems studied in this paper are WR 146 and WR 147, both of them located in the Cygnus constellation. We fit a model for the observed spectrum that takes into account thermal and nonthermal emission, as well as an expected thermal absorption due to the ionized attenuating medium, ignoring other processes like synchrotron self-absorption (SSA) or the Razin-Tsytovich effect (RTe). We study from the results whether these three processes explain the spectrum of WR 146 and WR 147 or not. Finally, we conclude that it is not necessary to include SSA or RTe to explain the flux density.

I. INTRODUCTION

The object of study is the flux density measured from the stellar wind collisions in binary systems, with diverse contributions in order to explain the observations. In particular, we are going to focus in analyzing the measures from the systems WR 146 and WR 147.

The binary systems that are going to be studied consist of early-type massive stars, O and Wolf-Rayet type, which present strong winds that bring energy and mass around the stars. As explained by Reimer et al. (2006), their temperatures are $T_{eff} > 10,000$K and their masses are above 20 $M_{\odot}$. The velocities of these stellar winds can be, as previously compiled for some WR systems by Williams et al. (1997), $v > 1000 - 5000$ km s^{-1}. Specifically for WR 146 is $v \sim 2900$ km s^{-1} and for WR 147 is $v \sim 1000$ km s^{-1}. In systems composed of two or more of these types of stars, there is collision of the emitted stellar winds in certain regions, called colliding-wind regions (CWR), where radiation is emitted.

The measured radiation mainly involves thermal and non-thermal emissions, which can be interpreted as contributions of free-free radiation from the individual stellar winds and synchrotron radiation from the colliding winds, respectively. The latest one can be explained because the non-thermal radiation (the synchrotron radiation) emerges from relativistic electrons accelerated in a magnetic field, which is the case of electrons in colliding-wind regions. We will also take into account the free-free absorption that can take place all over the spectrum, but especially at high frequencies.

There are two other effects: Razin-Tsytovich effect (RTe) and synchrotron self-absorption (SSA), which can also modulate the spectrum at low frequencies. The first one depends on the electron density and the magnitude of the magnetic field, and the second one on the relativistic electrons density and the magnetic field. On the one hand, we will evaluate in which regions RTe is important in the spectrums of the two systems of study. On the other hand, we can say that SSA will not be important, because the relativistic electron density needed is much higher than the one in the colliding-wind regions of the binary systems. This argument will be discussed again for WR 146 and WR 147 individually.

Benaglia et al. (2020) carried out observations of part of the Cygnus region, where these two binary systems are located. They conducted a study of the radio flux densities of several detections, including previous measurments at higher frequencies, to determine which stellar processes take place. Following this study, we are going to explain the observed spectra of these sources taking into account the first three mentioned contributions: thermal emission, non-thermal (NT) emission and free-free absorption.

In Section II we will explain the contributions to the emitted radiation and the final expression that will be used in the spectrums of the systems. In Section III we will describe the observations that are used and we will proceed to fit the spectrum model and analyse the results in each system. We conclude the article in Section IV.

II. CONTRIBUTIONS TO THE EMITTED RADIATION

The outgoing radiation of the collisional wind regions has two main contributions: thermal emission and non-thermal emission.

On the one hand, the thermal emission corresponds to the free-free radiation, which is the outflow emitted in the process of deacceleration of charged particles, when they are deflected by other charged particles. In this interaction, the deaccelerated particles experiment a loss of kinetic energy. Since there is energy conservation, the difference of energies between the initial state and the final state is invested in producing radiation, the free-free radiation, also called Bremsstrahlung radiation. The flux density S_ν relation of thermal emission can be expressed as

$$S_\nu \propto a\nu^{\alpha_{ff}}, \quad (1)$$

where a is a constant, ν is the frequency and α_{ff} is the free-free spectral index. Due to the fact that the spectral index in thermal emission is positive, as shown by Rybicki and Lightman (1979) in chapter 1, thermal emission will be smaller at low frequencies.

On the other hand, non-thermal emission refers to synchrotron emission, which corresponds to the case where charged particles are accelerated by a magnetic field to relativistic velocities and therefore emit radiation. This radiation will be produced by the relativistic electrons that are obtained in the CWR. The energy distribution of particles can be modelled as a power law as

$$N(E)dE = kE^{-p}dE, \quad (2)$$

where $N(E)$ is the electronic density with energies between E and $E + dE$, k is a constant and p is the exponent of the energy spectrum. In order to have finite energy, the condition $p > 1$ must be fulfilled. To have an idea of the magnitude of this constant, for cosmic rays we have $p = 2.6$.

As explained by Romero and Paredes (2011) in chapter 6.3, the total radiated power per frequency and volume unit of an spectral distribution of particles can be obtained calculating the integral of the product between the radiated spectral power of an electron and the electronic density in Eq. (2). The result obtained is

$$P_{total}(\nu) \propto \nu^{\frac{1-p}{2}}, \quad (3)$$

where $\frac{1-p}{2} = \alpha_{NT}$ is the spectral index of the non-thermal radiation.

From this previous equation, the flux density (the energy per time, area and frequency unit) can be expressed as

$$S_\nu = b\nu^{\alpha_{NT}}. \quad (4)$$

b is a constant and α_{NT} corresponds to the non-thermal spectral index, defined in Eq. (3). NT radio emission can be used to track down relativistic particles, as well as particle-accelerating regions, due to the fact that these relativistic particles are the ones responsible for the emission of NT radiation.

There must be considered other effects, which are the free-free absorption (FFA), the synchrotron self-absorption (SSA) and the Razin-Tsytovich effect (RTe).

First of all, FFA takes place when free electrons gain energy absorbing photons and re-emitting them. This happens when the incident photon has an energy $h\nu \geq m_e c^2$, where $m_e c^2$ is the rest energy of an electron, and the electron is at rest in the reference system of the mass centre. This situation is more relevant for high frequencies and also in optically thick mediums, which present a higher probability of collision between photons and electrons, meaning a smaller mean free path of these particles.

To include this contribution to the flux expression, we will add a correction to the NT term corresponding to a contribution, as it is shown at the article by Benaglia et al. (2020) that we are following,

$$S_\nu \propto \nu^{\alpha_{NT}} \exp^{-\tau_0 \nu^{-2.1}}, \quad (5)$$

where τ_0 is the optical depth at 1 MHz.

Second, synchrotron self-absorption (SSA) occurs when the photons of the NT radiation are scattered by the relativistic electrons and lose energy; consequently, the flux observed is lower than if this scattering process did not take place. As explained by Romero and Paredes (2011) in chapter 6.3, SSA is not important at high frequencies, where emission dominates, in contrast to low frequencies, where SSA is more relevant. In the latest region, the medium is optically thick ($\tau >>1$); in other words, the free path of photons is small due to the fact that they scatters promptly. The flux density in these zones can be represented as

$$S_\nu \propto \nu^{5/2}. \quad (6)$$

As shown by Benaglia et al. (2020), considering that θ is the source size in arcsecs, B is the magnetic field in Gauss and $S_{\nu_{\rm SSA}}$ is, in mJy, the maximum flux density, the critical frequency below which SSA is relevant is

$$\nu_{\rm SSA} \approx 2.145 \left(\frac{S_{\nu_{\rm SSA}}}{\theta^2}\right)^{2/5} B^{1/5} \quad \text{MHz}. \quad (7)$$

This effect will not be taken into account for the study of CWRs because, as explained in the same article mentioned before, the number density in relativistic electrons needed in order to be a relevant effect is greater than the usual densities in colliding-wind binaries. In short, SSA is not important for our cases of study, as it will be corroborated later on with the WR 146 and WR 147 spectrums because we work at frequencies where the electron density is not high enough to consider it.

Lastly, the Razin-Tsytovich effect consists of the supression of the low-frequency synchrotron emission. As it is explained in Gunawan et al. (2000), using n_e as the electron density in $\rm cm^{-3}$ and B as the magnetic field in Gauss, RTe ceases synchrotron emission below the cut-off frequency

$$\nu_R \simeq 20\frac{n_e}{B} \quad \text{Hz}. \quad (8)$$

Therefore, RTe is expected to be an important absorption process at low frequencies, when there is high electron density. We will inspect in WR 146 and WR 147 if the observations made are at a high enough frequency to show this contribution to the measured radiation.

Following Benaglia et al. (2020), the models used to describe the measured radio emissions from colliding-wind binaries (CWBs) consider free-free radiation and NT radiation modified by FFA. The total expression of the flux density that will be used is

$$S_\nu = a\nu^{\alpha_{ff}} + b\nu^{\alpha_{NT}} \exp^{-\tau_0 \nu^{-2.1}}. \quad (9)$$

These models assume that the relativistic electrons from the synchrotron emission are independent of the ionized attenuating medium, and they derive the flux density expression from the radiative transfer equation, as well as use hydrodynamical simulations, as said by Benaglia et al. (2020).

III. OBSERVATIONS AND ANALYSIS OF THE WR SYSTEMS

The binary systems which emissions are going to be studied with the model presented in Eq. (9) are WR 146 and WR 147. These two systems are located in the Cygnus constellation ($-65 \leq l \leq 95, -8 \leq b \leq +8$), which is a region with many star-forming activity and a high population of massive stellar objects. There are three different regions that have been examined in this area of the sky specifically by Benaglia et al. (2020), which are Cyg OB2, Cyg OB8 and Cyg OB9. The observations of the massive early-type stars of these regions have been carried out at low frequencies in order to determine the turnover of the spectrum of the CWRs.

As a way of establishing a detection in this region of the sky, Benaglia et al. (2020) considered an average rms (root mean square) as a measurement of the noise that is detected due to the instrumentation used and the intrinsic diffusive effect of the Cygnus region because of its structure. The rms that were considered are, as specified in the article mentioned before, 0.5 mJy per beam at 325 MHz and 0.2 mJy per beam at 610 MHz. The detections were accepted if the flux density of the observation was greater than three times the rms.

Earlier measures have been combined with more recent observations obtained between 2014 and 2017 using the Giant Metrewave Radio Telescope (GMRT). The most recent data collected corresponds to covering 15 square degrees of the sky and to detections around 325 and 610 MHz. Two of the observations made with GMRT by Benaglia et al. (2020) correspond to the WR 146 and WR 147 systems. The first one, as seen in Dougherty et al. (2000), is formed of a WR type star and an OB type star, probably a high-luminosity O8 star, and therefore also a CWR. Its expected spectral index is negative and its brightness temperature is $\sim 10^6$ K or higher, which is the same case for the system WR 147. These characteristics correspond to the properties of non-thermal emission. The period of WR 146 is of many years, with short-term and long-term variations, and it is located at 1.1 kpc from us. The WR 147 system is believed to have two components: a WN8 star and an early-type star, as said by Williams et al. (1997), also with the corresponding CWR. It is located at a distance of 1.79 kpc from us, according to Rate & Crowther (2020), not belonging to Cyg OB2, as it was believed.

In order to adjust the obtained data with the expression given in Eq. (9), we have utilised the fit command from gnuplot. It uses the nonlinear least-squares (NLLS) Marquardt-Levenberg algorithm to find the best possible parameters, given the errors in the input values. The data set used in this study is the one used by Benaglia et al. (2020) and is represented in Table I and Table II.

Table I: Frequency ν and measured flux density S_ν with the corresponding errors for the WR 146 system. The most recent measurements are those corresponding to frequencies 0.15GHz, 0.325 GHz, 0.610 GHz, 1.52 GHz and 6.00 GHz.

Frequency ν (GHz)	S_ν (mJy)
0.15	35 ± 10
0.325	111 ± 2
0.61	121 ± 4
1.465	78.4 ± 0.2
1.52	79.8 ± 1.6
4.885	37.6 ± 1.0
6.00	35.7 ± 0.7
8.435	29.8 ± 0.8
22.46	17.4 ± 1.5

Table II: Frequency ν and measured flux density S_ν with the corresponding errors for the WR 147 system. The most recent measurements correspond to the frequency 0.610 GHz.

Frequency ν (GHz)	S_ν (mJy)
0.325	16 ± 4
0.61	20.6 ± 0.3
1.4	25.5 ± 0.5
4.86	35.4 ± 0.4
8.44	40.3 ± 4
14.94	46.2 ± 3
22.46	52 ± 5
42.8	82.8 ± 2

A. WR 146

The data in Table I is represented in Figure 1, together with the fit of Eq. (9). As seen in Section II, the synchrotron emission term of the flux density has a spectral index $\alpha_{NT} = (1-p)/2$, where p is the exponent of the electron energy distribution. It is known that for strong adiabatic shocks in CWR, the usual value is $p = 2$, therefore $\alpha_{NT} = -0.5$. In this CWR, as Hales et al. (2017) characterised, it is better to establish $\alpha_{NT} \approx -0.6$.

For the thermal contribution, the used spectral index is $\alpha_{ff} = 0.6$, as specified by Benaglia et al. (2020), because the free-free emission corresponds to a measured value of 1 mJy at 5 GHz. The first contribution comes from the colliding winds, which emit strong non-thermal radiation, and the second contribution is from the individual winds of the binary system. The fit of Eq. (9) that has been performed with said spectral indexes gives

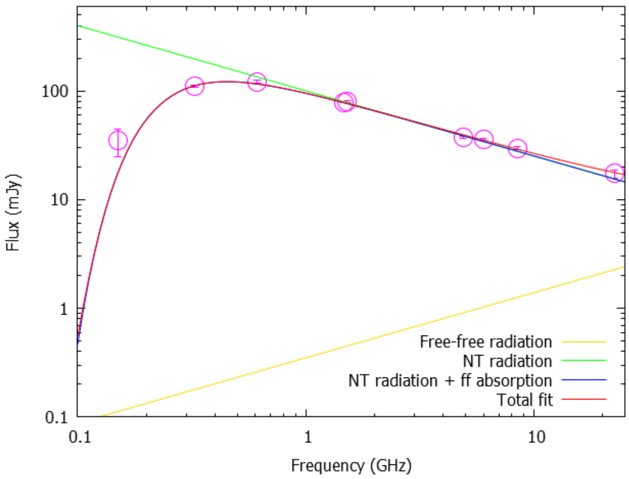

Figure 1: Measured spectrum of the WR 146 system (circle symbols) with the corresponding errors of the flux density values. The free-free contribution, $0.4\nu^{0.6}$, is represented in yellow, the NT emission part is represented in green as $100.5\nu^{-0.6}$, the NT emission fit term with the correction of FFA is represented in blue as $100.5\nu^{-0.6}\exp(0.054\nu^{-2.1})$ and the total fit is represented in red as the addition of the yellow and blue terms.

the parameters $a = 0.4 \pm 0.2$ mJy GHz^{-1}, $b = 100.5 \pm 0.6$ mJy GHz^{-1} and $\tau_0 = 0.054 \pm 0.003$.

The spectrum represented in Figure 1 with the obtained fit shows two regimes, a change of slope at frequency $\nu = 610$ MHz, which is consistent with the expected syncrothron radiation spectrum. Hence we can conclude that WR 146 has a strong synchrotron emission at the measured frequencies with small contribution of the free-free radiation, as it can be seen in the graphic. Observing Figure 1, the fit performed considering NT and FF emission, as well as FFA, is well adapted to the data. As it is studied by Setia Gunawan et al. (2000), RTe and SSA are not relevant effects in the spectrum of WR 146.

First of all, FFA is included because it is expected a suppression of the synchrotron emission by the plasma in the CWR. We observe that this contribution fits the model to the data correctly at low frequencies. Second, synchrotron self-absorption is not relevant for the absorption at low frequencies, as explained in Section II, because the relativistic electron density needed is higher than the one in the CWR. Using the expression for the brigthness temperature

$$T_b = 1.037 \times 10^{-2} \left(\frac{S_\nu}{\nu^2 sin^2\theta} \right) \quad \text{K}, \qquad (10)$$

where S_ν is the flux density in mJy, ν is the frequency and θ is the size of the source in arcsec, Setia Gunawan et al. (2000) calculated the brightness temperature necessary to have SSA, which is $T_b \simeq 8 \times 10^{10}$ K. However, the brightness temperature obtained for the non-thermal northern source of WR 146 is 1.37×10^6 K, which is 5 orders of magnitude lower than the needed T_b. Therefore, SSA is not the process that explains the absorption of synchrotron radiation. Also, the fact that we have not used SSA in the model applied to the observations and that we have obtained a good fitting supports these arguments.

Lastly, the Razin-Tsytovich effect is not dominant at the measured frequencies, also due to the fact that the fit adjusts well to the data without including it. In other words, if there is RTe, it will be significant below 150 MHz, which is the lowest frequency where there has been a detection, because it is needed a high electron density, which can be found at low frequency zones.

B. WR 147

The data in Table II is represented in Figure 2, together with the fit of Eq. (9).

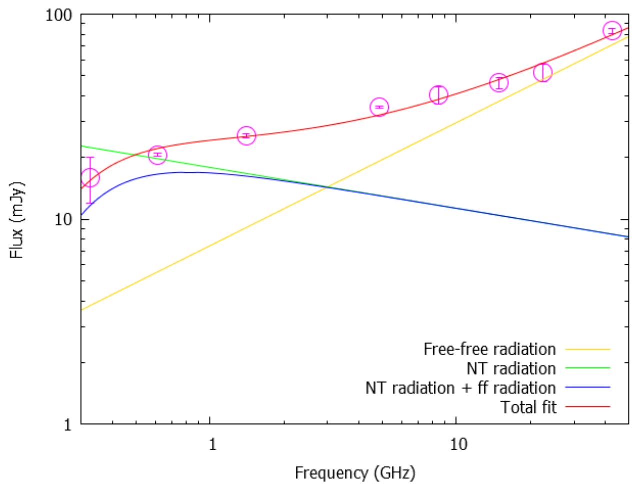

Figure 2: Measured spectrum of the WR 147 system (circle symbols) with the corresponding errors of the flux density values. The free-free emission term is represented in yellow as $7.4\nu^{0.6}$, the NT emission part is represented in green as $18\nu^{-0.2}$, the NT emission term with the correction of FFA is represented in blue as $18\nu^{-0.2}\exp(0.06\nu^{-2.1})$ and the total fit is represented in red as the addition of the yellow and blue terms.

As seen for the WR 146 system, the spectral index for the thermal contribution is $\alpha_{ff} = 0.6$. For this case, the spectral index of the term of NT radiation modified with FFA is left to be determined in the fit of Eq. (9), together with the other constants. The parameters obtained in the fit are $a = 7.4 \pm 1.0$ mJy GHz^{-1}, $b = 18 \pm 4$ mJy GHz^{-1}, $\alpha_{NT} = -0.2 \pm 0.2$ and $\tau_0 = 0.06 \pm 0.06$. Representing these curves at Figure 2, we observe that there is a good agreement between the data and the total fit.

Due to the fact that the flux density measurements are well adjusted to the curve, we can affirm that SSA and RTe are not relevant at the frequency range where the detections have been made, giving the same explanation as for the previous system. The Razin-Tsytovich effect, if present, may be relevant below 325 MHz, which is the lower frequency where there is a detection of this binary system. It is observed that at low frequencies the NT radiation dominates, even though the thermal contribution is not zero. Also in this range of frequencies, FFA makes it possible to adjust the fit to the data, lowering the NT emission. However, at high frequencies, the free-free emission is more relevant than the NT and the expected synchrotron spectrum is not obtained. This behaviour of the flux density is different from WR 146, where it is clear that the synchrotron emission is the most important contribution; thermal contribution cannot be disregarded for the WR 147 case.

Comparing both systems is a complex task and is out of this study because the NT emission depends on numerous variables, such as the wind velocity of the two colliding winds or the geometry of the CWR, which also depends on several parameters characteristics of each system.

IV. CONCLUSIONS

The objective of this paper was to study the radiation emitted from the collision of stellar winds. We have analysed the flux density measures of the binary systems WR 146 and WR 147, which are known to have a colliding-wind region. In the analysis, we have used a model that describes the observations with a thermal contribution coming from the individual winds of each component of the binary system, together with a non-thermal contribution coming from the CWR. This last term has been modified by the thermal absorption (free-free absorption), that is caused by the ionized medium of the system. Two other absorption processes, which are synchrotron self-absorption and the Razin-Tsytovich effect, are not taken into account in the model.

We have fitted the data of WR 146 and WR 147 of Benaglia et al. (2020) following the expression given by the mentioned model. The main conclusions that we can draw from the results are the following:

- Thermal and NT emission, together with FFA, can accurately describe the flux density spectrum of WR 146 and WR 147, two systems with colliding-wind regions.
- Synchrotron self-absorption is not a relevant contribution to the cases studied, due to the fact that the relativistic electron density needed for it to be important is higher than the density of the binary systems. We have also explained this argument as a much lower brightness temperature of WR 146 than the one expected for SSA, as well as that it has not been mandatory to include it in the model to fit the data correctly.
- Razin-Tsytovich effect is also not dominant for the range of frequencies studied because, as with SSA, it has not been included in the model and the results show that it is not necessary to do so in order to obtain a good fitting.

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