Non-thermal emission from early-type stars

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Abstract. Massive, early-type stars deposit energy and momentum in the interstellar medium through dense, supersonic winds. These objects are one of the most important sources of ionising radiation and chemical enrichment in the Galaxy. The physical conditions in the winds give rise to thermal and non-thermal emission, detectable from radio to gamma rays. In this report the relevant radiation processes will be described and studies on particular systems will be presented, discussing the information provided by multifrequency observations. Future steps aiming at understanding the stellar wind phenomenon as a whole will be outlined.

Resumen. Las estrellas de gran masa entregan energía y momento al medio interestelar, no sólo en explosiones de supernova, sino a través de sus fuertes vientos; producen radiación ionizante y son una de las fuentes más importantes de enriquecimiento químico. En el plasma que forma los vientos tienen lugar procesos que generan tanto radiación térmica como no-térmica, detectable desde el rango de radio hasta rayos gamma. En este informe se describirán los procesos físicos generadores de la radiación, se presentarán y analizarán ejemplos de los objetos en estudio, se verá qué información proveen las investigaciones multifrecuencia hacia los mismos, y se discutirán los pasos a seguir en el futuro próximo, tendientes a completar el entendimiento del fenómeno de los vientos en su conjunto.

1. Introduction

Early-type stars are characterized by high masses ($\geq 8 \ M_\odot$), large luminosities ($> 10^{3} \ L_\odot$), and high superficial temperatures ($> 10^{4} \ K$). Although their life is shorter than the one of cooler stars, their influence on the surrounding interstellar medium (ISM) is enormous, not only because of the ionising power of their intense UV flux, but also through their strong winds. The winds, driven by radiation pressure, cause the stars to loose mass during all their life, and convey energy and momentum to the ISM. The winds also contribute to the Galactic chemical enrichment, by ejecting nuclear matter from the stellar surface. The stars described correspond to spectral types OB (O – B3), and Wolf-Rayet. Massive, early-type stars (METS) are detectable at radio continuum wavelengths, provided high angular resolution ($\sim 1''$), and sensitivity ($\sim$ mJy) is
attainable. The wind itself produces an excess in continuum radiation, from radio to IR ranges. This excess has already been measured for many METS (e.g., Bieging et al. 1989, Leitherer et al. 1995) (see Fig. 1-left). The electrons of the wind plasma emit free-free radiation while decelerate in the Coulomb field of the ions. This radiation is detectable as continuum (thermal) emission. The flux is fitted with a spectral index $\alpha \sim 0.6 - 0.8$ ($S \propto \nu^\alpha$), if an ionized, uniform, isothermal, and stationary gas flow (Wright & Barlow 1975) is considered. It can be demonstrated that the flux is related to the stellar mass loss rate $\dot{M}$: the detection of thermal radio flux offers a straightforward measurement of this stellar parameter.

However, the radio spectra of some stars present lower -even negative- spectral indices (e.g. Benaglia et al. 2001b, etc.) Fig. 1-right shows that non-thermal emission is also being radiated from the stellar winds. What can be learnt from METS non-thermal radio emission, mainly by means of radio observations, but complemented with higher energy studies, is the subject of this review.

2. Stars with non-thermal radio emission

Usually the non-thermal (NT) radio emission presents -at least- some of the following features: a spectral index value near zero or negative, radio variability, a radio-derived mass loss rate larger than the Hα-derived rate, and high brightness temperature.

Information of non-thermal WR, and OB stars can be found in Benaglia & Romero (2003) (see their Table 1), and van Loo (2005) (see his Table 1.1), respectively. As long as more radio detections of stellar winds are achieved with better instruments, the percentage of non-thermal to total emitters has been growing up to $\sim 40\%$. Most NT WR stars are not single stars. For OB stars, there are still a number of NT sources whose binarity status is unknown.
Under the physical conditions prevailing in the winds, the main process responsible of the non-thermal emission detected at radio waves is synchrotron radiation, i.e., produced by relativistic electrons that spiral around magnetic field lines. It is assumed that an electron is accelerated by the first order Fermi mechanism (Bell 1978) while traversing shocks in the wind. In single winds the shocks arise from instabilities, triggered, in turn, by perturbations in particle velocities, regions of co-rotating interaction, non-radial pulsations, etc. If the star has a companion having also a strong wind, and both winds interact with each other, there will be shocks at the wind collision region (WCR). Shocks can also be present at the zone where a stellar wind encounters the ISM (terminal shocks).

**Single stars.** One of the first wind models for single stars was introduced by Lucy (1982). It is a phenomenological model, with outward shocks and adiabatic cooling. White (1985) proposed the non-thermal emission is synchrotron radiation by relativistic electrons accelerated in shocks embedded in the wind. The importance of inverse Compton cooling was recognized and included by Chen (1992), and Chen & White (1994). They could reproduce the negative radio spectral index, and concluded that the electrons must be accelerated in situ at the emitting region. The recent models by van Loo et al. (see van Loo 2005) consider shocks decreasing in intensity with stellar distance, narrow emitting layers, and strong shocks that dominate the emission. They use the latest 1D-hydrodynamical models to represent the gas flow. The models have trouble to reproduce some particular cases, for which a yet undetected binary companion is given as an alternative explanation.

**Stellar systems with interacting winds.** The interaction of two supersonic winds will create regions of shocked gas at high temperatures \(10^7 - 10^8\) K, from which both synchrotron and free-free emission (f-f) are expected. To detect the non-thermal radiation, the separation between binary components must be large enough (periods above some weeks) in order that thermal electrons from the wind do not bury, by absorption, the non-thermal emission. Eichler & Usov (1993) have physically described the scenario for wide systems. For radially-flowing winds, a contact discontinuity appears on the surface where ram pressure of both winds equalize. The position of this surface can be expressed in terms of the ratio of the components wind-momentum. The magnetic field in the presence of a stellar wind is assumed toroidal, and can be computed at the position of the WCR, if the stellar surface magnetic field values \(B_*\) are known. The authors derive expressions to estimate, among other quantities, the size of the WCR, the maximum energy the electrons can gain at the shock, the synchrotron luminosity, and discuss the production of high energy radiation. Values of \(B_*\) are very difficult to measure; it is possible to estimate an approximate magnetic field at the WCR by assuming energy equipartition (Miley 1980).

### 3. Current status of radio observations

From the observational point of view, the detection of radio fluxes from stellar winds implies a considerable amount of on-source integration time and the use
of interferometers. The first systematic detection experiment, carried out by Bieging et al. (1989) using the VLA, yielded 25 detections over 90 northern OB targets. The winds are seen as point sources for instruments having angular resolution lower than 1″. Nowadays the observed OB stars are ~150, and about one third of them have been detected. In the case of WR stars, circa 90 have been observed, from which more than 50 were detected at least at one frequency, and about 20 at more than one frequency (Abbott et al. 1986, Chapman et al. 1999, Cappa et al. 2004).

A major breakthrough was achieved in the last decade, when a few winds could be resolved through VLA, VLBA, and MERLIN data. The observations corresponded to colliding-wind binary (CWB) systems, and the very WCR could be imaged.

One of the first systems in which extended sources associated with stellar winds were detected was Cyg OB2 No. 5. This is a stellar system at 1.8 kpc, formed by a close pair (O7Iaf + Of/WN9) plus an early B (probable B0 V) (Contreras et al. 1997). The close pair and the B star are ~1700 AU apart. The period of the close pair is ~7 days. The system was observed with the VLA at 5 and 7 GHz (Contreras et al. 1997, Fig. 2, and references therein), and two sources were detected: an intense one coincident with the close pair, and a weaker one near the B star. The stronger source showed radio variability on periods of 7 yr, switching between a high state with non-thermal emission and a low-thermal state. The weakest radio source was non-thermal, and identified as the WCR of the system.

WR 147 is composed by a WN8(h) star plus an O5-7 star (Lépine et al. 2001). Its radio image, taken with MERLIN at GHz (Dougherty et al. 1997, Fig. 3, angular resolution: 70 mas) displayed two radio sources: the northern one has a non-thermal spectral index ($\alpha = -0.5$), and the southern one the characteristic +0.6 thermal index. The northern source has been identified with a WCR between the components. New MERLIN observations at three epochs (Watson et al. 2002) revealed that both the thermal and non-thermal sources vary on timescales of years.

The binary system of WR 146 (WC6 + O8) was observed very recently with the VLA plus one VLBA antenna, attaining an angular resolution of 30 mas, from 1.4 to 43 GHz. The data were combined with European VLBI Network (EVN, 9 mas) and 5-GHz MERLIN observations (O'Connor et al. 2005). Fig. 2-left shows two thermal radio sources on the stars, and a non-thermal one with a bow shock shape corresponding to the WCR.

Maybe the most striking observational radio results were obtained for WR 140 (WC7 + O4-5). The period of the system is 7.9 yr and the components are separated between 3 and 30 AU. Dougherty et al. (2005) presented VLBA-8.4 GHz data taken during two years, of a non-thermal ($T \geq 10^7$ K) source, moving along the orbit (Fig. 2-right). The flux depends on the phase. The radio source was identified with the WCR. The study was complemented with previous VLA data from 1.4 to 22 GHz. They derived new orbital parameters, and a new distance to the system of 1.85 kpc.
4. Radio continuum studies

Radio continuum observations at high angular resolution (\(\sim 1''\)) allow to derive spectral indices when data at more than one frequency are available. If the flux can be represented by a thermal spectral index, and the basic stellar parameters are known, the mass loss rate can be derived. In case the index is other than thermal, the study of the contributions to the radio spectra will give a hint on the radiation processes involved. An equipartition magnetic field at the WCR can be estimated, and a value for the stellar surface magnetic field, extrapolated. Non-thermal sources could show polarisation, too.

If both angular resolution and sensitivity are high enough, (< 1'' and 0.1 mJy, respectively), an \(x,y\) map of the emitting wind on the plane of the sky can be built.

Anyway, the observations can be used to compare different emission models, or to create new models in order to interpret the data. Studies on high-energy emission from the winds, optical searches for binary companions, low-resolution radio line observations over the circumstellar region allow a more complete description of the stellar winds.

4.1. Point source approach

When the stellar wind -or the WCR- is seen as a point source, a simple model that consist of a thermal source plus a non-thermal source attenuated by free-free absorption can be used (e.g. Chapman et al. 1999). The observed flux is expressed as \(S_{\text{obs}} = S_T + S_{\text{syn}} \tau\), where \(\tau\) is the f-f optical depth, at frequencies high enough to disregard synchrotron self-absorption and the Razin-Tsytovitch effects. The last equation can be solved by means of simultaneous measurements.
at different frequencies, and thermal from non-thermal contributions can be then

detached. This model does not take into account that synchrotron emission and opacity \( \tau \)

are probably time variable. Synchrotron emission will vary if the stellar separation varies as in an eccentric orbit. The opacity to the synchrotron emission will change as long as the line of sight moves around the system.

The simplification here is to consider a univalued opacity, determined through the unique line of sight, and a point synchrotron source. These models proved to reproduce the radiometry of various systems (Chapman et al. 1999, Skinner et al. 1998, Benaglia & Koribalski 2004, 2005).

4.2. Extended source approach

The wind collision regions are excellent places to study particle acceleration, because their mass, photon and energy densities are much higher than in the SN environment, and the fundamental parameters of the wind flow can be derived. A second approach in the physical description of stellar winds consists of assuming the WCR as an extended source, and is applicable to the cases where the spatial distribution of the radio flux can be imaged.

In this approximation the wind region is divided in cells. A two-dimension hydrodynamical code is used to characterize the temperature and density of each cell, which are the input to compute the absorption and emission coefficients. The equation of transport for each line of sight is then solved numerically, supplying the flux on the plane of the source, for a given frequency (Dougherty et al. 2003, Pittard et al. 2005). This process was applied to WR 140 (Dougherty et al. 2003) and WR 146 (O’Connor et al. 2005) and the agreement between observations and predictions show the developments point in the right direction.

5. High energy non-thermal emission

Stellar winds have been recognized as places for particle acceleration; they are permeated by copious UV flux produced at the stars.

When relativistic electrons interact with UV stellar photons, these photons can be boosted to higher energies through inverse Compton (IC) scattering processes. By other hand, additional high energy emission is produced by the same relativistic electrons when they interact with the electrostatic field of the nuclei (relativistic Bremsstrahlung).

The same mechanism efficient to accelerate electrons to relativistic energies should act on the ions; the interaction between relativistic nuclei and cold wind nuclei (p-p interaction) yields to neutral pions that immediately decay generating gamma rays.

At the WCR, the same population of high energy electrons can give rise both to synchrotron and IC scattering, where \( \langle h\nu_{IC} \rangle = 4/3\gamma^2h\nu_\ast \). The temperatures present at the massive stars we are dealing with are consistent with seed photon energies of \( h\nu_\ast \sim \text{eV} \) which, combined with the electron Lorentz factors of \( 10^2 \) – \( 10^3 \) easily attained at the shocks will give IC photons from keV to MeV energies. If the electron energy distribution resulting from a first order acceleration process can be represented by a power law \( N_e(E) \propto E^{-\gamma} \), then the IC photon distribution
will also be a power law $dN_{ph}(E)/dE \propto E^{-\Gamma}$, where $\Gamma = (p + 1)/2$. In this scenario, the non-thermal spectral index $\alpha_{NT} = (p + 1)/2$.

The effect of the UV photons generated by the secondary star, closer to the WCR, will be more important than those from the primary star. Adiabatic, synchrotron, and IC losses are important particle energy losses. The latter two can produce a break at the electron distribution. The maximum energy gained by an electron at a certain WCR can be computed if parameters of the involved stars such as terminal velocities, luminosities, mass loss rates, and the local magnetic field are known.

The study of the gamma-ray production at stellar winds is valuable to find counterparts to unidentified gamma-ray sources, as the many detected by the EGRET experiment (Hartman et al. 1999, Romero et al. 1999).

6. Examples of multiwavelength studies

6.1. Cyg OB2 No. 5

This stellar system, described in Sect. 3, is positionally coincident with the probability contours of the unidentified EGRET source 3EG J2033+4118. If the gamma-ray source is located at the stellar distance, it will have a luminosity of $\sim 2.4 \times 10^{35}$ erg s$^{-1}$. The non-thermal radio emission detected from the putative wind collision region (Contreras et al. 1997) reveals the presence of relativistic electrons. The question to address is whether these electrons and heavier particles through different interactions could give rise to gamma-rays, and how much they contribute to the observed EGRET flux. We evaluated which processes are relevant in the different regions where shocks can be present in the stellar system (Benaglia et al. 2001a).

Firstly we needed to adopt stellar parameters such as mass loss rates, wind terminal velocities, and a stellar magnetic field. Three regions with shocks have been taken into account: the WCR between the close pair and the B star, the stellar winds themselves, and the terminal shock.

It can be demonstrated that the values for the synchrotron and IC luminosities are proportional ($L_{\text{syn}} = 840 L_{\text{IC}} B_{\text{WCR}r_2^2}/L_2$, “2” stands for the secondary; Chen & White 1994), when they are produced by the same population of particles. The gamma-ray flux corresponding to relativistic Bremsstrahlung by electrons involved in synchrotron processes can be expressed in terms of the synchrotron flux, as a function of the local electron density and magnetic field (Benaglia et al. 2001a). At the WCR the values obtained for the luminosities are $L_{\text{IC}} \sim 8 \times 10^{34}$ erg s$^{-1}$, and $L_{\gamma B} < 10^{31}$ erg s$^{-1}$.

In the neighborhoods of Cyg OB2, various CO clouds have been detected (Dobashi et al. 1996), with masses $\sim 10^{3} M_\odot$. This observational fact allowed to conclude that the gamma-ray luminosity produced by $\pi^0$ decay by hadrons “illuminating” those clouds would sum up to $10^{33}$ erg s$^{-1}$ (see Aharonian & Atoyan 1996). The important contribution in gamma rays at the base of the wind is from $\pi_0$ decays, and has been computed by White & Chen (1992) as $L_{\pi^0} \sim 5 \times 10^{34}$ erg s$^{-1}$.

The sum of all luminosities mentioned above can explain about half of the detected gamma ray flux. We speculate that the remaining flux can be due to the action of other METS present in the field.
6.2. WR 140, WR 146, and WR 147

The (WR+O) binary systems of WR 140, WR 146, and WR 147 are among the most studied ones. All have been observed several times and at different angular resolutions with interferometers. WR 140 is a 8 yr-period binary, while the other two are in very wide orbits, with probable periods larger than 100 yr. From these stars not only non-thermal emission has been detected and monitored, but a map of the radio flux distribution could be built.

WR 140 is located onto an unidentified EGRET source (3EG J2022+4317). The estimated EGRET threshold at the positions of WR 146 and WR 147 is high, more than 50% of the 3EG J2022+4317 flux value. With the synchrotron flux and the size of the WCR it is possible to evaluate the contribution of IC scattering, relativistic Bremsstrahlung and $\pi^0$ decay processes producing gamma rays at the WCR, and compare it with the EGRET results (Benaglia & Romero 2003).

An improvement has been included in working out the problem, with respect to the case of Cyg OB2 No. 5, by taking into account the break in the energy distribution due to synchrotron and IC losses.

The local magnetic field was the main unknown: we have estimated an equipartition value for each system. Ultimately, the process served to calibrate the adopted parameters (see Benaglia & Romero 2003). It was shown that under reasonable assumptions, (i) the gamma-ray emission from 3EG J2022+4317 could be produced by the CWB system of WR 140 and (ii) the high energy emission from WR 146 and WR 147 remained below the EGRET detection limit.

As in the case of Cyg OB2 No. 5, new gamma-ray observations with better angular resolution and sensitivity are necessary to fine-tune the assumed physical parameters relevant in this kind of studies.

6.3. HD 92129A

This is the only O2 If* cataloged so far (Walborn et al. 2002), a member of Tr 14 in the Carina region ($\sim$ 2.5 kpc, Walborn 1995). HST observations have revealed the presence of an early-type companion, at 55 mas ($\sim$ 150 AU) (Nelan et al. 2004).

The system was detected at radio continuum from 1.4 to 25 GHz (Fig. 3-left) over a period of 1 yr (Benaglia & Koribalski 2005). The radio spectra displayed strong non-thermal emission, superposed to the thermal emission from the hot winds. In order to disentangle both contributions, we fitted the flux with the expression $S_{\nu} = S_{\nu}^T + S_{\nu}^{NT} = C_1 \nu^{0.6} + C_2 \nu^{\alpha_{NT}} e^{-\tau_0 \nu^{-2.1}}$, by assuming that f-f absorption is modifying the synchrotron emission. On this first approximation, the Razin-Tsytovitch effect and synchrotron self-absorption were disregarded.

The results allowed not only to characterize thermal emission and derive the mass loss rate of the system, but to find the non-thermal average spectral index which represents the synchrotron radiation. The assumption of a colliding wind region size leaded to the estimate of a local magnetic field value of $\sim$ 10 mG.

In the near future, long baseline radio observations will be envisaged, to map the strong NT source that represents the wind-collision region.
Figure 3. Left: ATCA 3-cm radio continuum image towards Tr 14. Optical positions of the earliest stars are marked. Contour levels of -0.22, 0.22 (2σ), 0.44, ..., and 1.1 mJy beam⁻¹. The synthesized beam (1.1′′ × 1.0′′) is displayed at the bottom left corner. Right: Radio flux density measured for HD 93129A (squares) and result of the fit (solid line).

6.4. WR 21a

The star WR 21a (or Wack 2134) constitutes perhaps the best example to show how the information obtained at different spectral windows aid in assembling a complete picture of the object under study (Benaglia et al. 2005).

WR 21a is a WN 6 star (van der Hucht 2001), ∼ 3 kpc from the Sun, and its spectra showed evidence of an early-type companion (Reig 1999). It is positionally coincident with a brilliant X-ray source (1E 1022.2-5730), and with an EGRET source (3EG J1027-5817).

Spectroscopic optical monitoring was carried out to look for a print of the putative companion, and Niemela et al. (2006) discovered its binary nature with a probable O companion, with a period of weeks. A complete set of archived X-ray data was analyzed, and strong variability was confirmed. The available data span over 11 yr, but the irregularly time spacing between observations with different instruments preclude a fit with the new period discovered.

High-angular resolution radio continuum observations were conducted to observe the wind emission. The system was followed with ATCA at 4.8 and 8.64 GHz. A radio source of 0.26 mJy was detected at 4.8 GHz at the stellar position, and not at 8.64 GHz over a r.m.s. of 0.1 mJy beam⁻¹. The derived spectral index of α < 0.3 suggests the presence of NT emission (Benaglia et al. 2005).

Low resolution HI-line radio observations were taken at IAR (HPBW = 30′), to study the interaction between the stellar wind and the ISM. A minimum over the position of the star was found in the HI distribution. Unfortunately, it represents not only lack of gas (a bubble formed by the WR+O system?), but mainly absorbed HI caused by the strong continuum HII region source RWC 49 that lies beyond WR 21a along the same line of sight. An HI concentration appeared on the position of the EGRET source probability contours, with a mass $M \geq 1500 M_\odot$. If this cloud is illuminated by relativistic protons accelerated at
the stellar winds, the gamma-rays produced might explain, in part, the emission from the EGRET source.

A thorough HI study, to allow the separation of emission and absorption and identify the neutral clouds that surround the stellar system, plus gamma-ray observations, capable of resolving the high energy stellar emission, are fundamental to complete the study towards this interesting system.

7. Summary and perspectives

Massive, early-type stars emit non-thermal radiation, identified as synchrotron radiation at low energies. This fact unveils the existence of relativistic particles and magnetic fields in the winds. The particles are accelerated in shocks present at the winds of single stars, at the regions where winds of early-type stars forming binary systems collide, and presumably at the terminal shock where a stellar wind encounters the ISM.

The non-thermal radio emission is detected at colliding wind regions; the picture is not so clear for single stars. The presence of synchrotron radiation and external photon fields suggest that high energy emission will be produced too, detectable by means of gamma ray satellites.

Comprehensive models to reproduce the spectral and spatial distributions are currently under development (Reimer et al. 2005, Pittard et al. 2005).

The number of cases in which the emission from wind regions could be resolved is still low: Cyg OB2 No. 5, WR 140, WR 146, WR 147.

From the theoretical point of view, the next steps will include the generation of 2- and 3-D hydrodynamical models up to a large wind extent, to describe stellar
winds; the application of such models as an input to develop, in turn, more realistic models to explain the non-thermal radio emission from single stars; the building of self-consistent models which take into account the anti-reaction of relativistic particles over the shock structure, etc.

Main challenges on the observational side are to use very long baseline interferometry (mas resolution) to scrutinize the regions of the stellar winds and map them, especially the ones of colliding winds. Going even further, in time and imagination, the settlement of an instrument of that kind to glaze at the southern stellar wind regions -yet obscure- will be welcome by the massive stars researchers community. These studies need to be complemented with optical ones to investigate the structure of the stellar systems, together with high-energy (X- and gamma-rays: Chandra, INTEGRAL, GLAST) in order to achieve a complete picture of the stellar winds phenomenon.

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