Radio behavior of four southern non-thermal O-type stars

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Abstract. We have conducted high resolution continuum observations at 1.4 and 2.4 GHz with the Australia Telescope Compact Array, towards the four southern O-type stars: CD-47 4551, HD 93129A, HD 124314, and HD 150136. All stars have been detected at the two frequencies. HD 93129A – the only O2 I star catalogued so far, and in a double system –, has also been observed at 17.8 and 24.5 GHz. Its radio spectrum, complemented with previous observations at higher frequencies, is analyzed here. The interpretation yields the estimate of its mass loss rate, and a non-thermal spectral index of radiation coming from a putative colliding wind region. The synchrotron and corresponding inverse Compton luminosities are derived.

1. Introduction

Early-type stars (O to ~B2) develop strong stellar winds that strengthen while they are leaving the main sequence towards the Wolf-Rayet phase. The mass loss can be as high as $10^{-5} M_{\odot} \text{ yr}^{-1}$ at velocities of thousands of km s$^{-1}$. The winds are optically thick, radiate through the free-free mechanism, and produce an excess of flux density from the radio to the infrared range. The thermal nature of the radiation can be confirmed computing a spectral index of about 0.6 – 0.8 (Wright & Barlow 1975). Once this radiation regime is established, the detection of the wind region, and consecutive measurement of the flux density allow a straightforward determination of the mass loss rate (Lamers & Leitherer 1993). However, emission characterized by a non-thermal spectral index has been reported repeatedly from early-type stars (e.g. Bieging, Abbott, & Churchwell 1989; Benaglia, Cappa, & Koribalski 2001). Given the fact that the majority of these stars are not single, this emission is probably produced at a colliding wind region (CWR) of a system formed by at least two early-type stars with winds.

The particles accelerated at the CWR can be also involved in high energy processes. Many of these stars have been detected in X-rays (e.g. Pollock 1987), and are proposed as counterparts of unidentified gamma-ray sources (Romero, Benaglia, & Torres 1999). Multifrequency studies -from radio to gamma rays- are fundamental to completely describe the emitting regions, and help in a comprehensive picture of the whole stellar wind phenomenon.
In the frame of a southern radio survey on early-type stars, using the Australia Telescope Compact Array (ATCA) at maximum angular resolution, we have detected four non-thermal emitters at 3 and 6 cm (Benaglia, Cappa, & Koribalski 2001; Benaglia & Koribalski 2004): CD-47 4551, HD 93129A, HD 124314, and HD 150136. In order to better define the radio spectrum, we have performed ATCA observations of these sources, at 1.4 and 2.4 GHz, and here the results are presented.

2. The target stars

HD 93129A. This star belongs to the Trumpler 14 cluster, in the Carina region. The field is very rich in early-type stars, gathering 5 of the 10 earliest catalogued stars in the Galaxy. Following Tapia et al. (2003) we adopt a distance to Tr 14 of 2.8 kpc. HD 93129A is the unique representative of spectral type O2 If*. Very recently it was discovered to be a binary with another early-type star (Walborn 2002; Nelan et al. 2004), 55 mas away (or 154 AU at 2.8 kpc). The star shows extreme values of terminal velocity (3200 ± 200 km s⁻¹), effective temperature (52,000 ± 1000 K), and luminosity (log(L/L☉) = 6.4 ± 0.1) (Taresch et al. 1997, and references therein).

HD 93129A has been detected in the radio band at 3 and 6 cm (Benaglia & Koribalski 2004), with flux densities of S₃cm = 2.0 ± 0.2 mJy, S₆cm = 4.1 ± 0.4 mJy. The corresponding spectral index of 1.2 ± 0.3 implies the presence of non-thermal emission which, in principle, is produced at a colliding wind region between the components of the binary system.

HD 124314. This is an O6 V(n)((f)) field star, at a spectro-photometric distance of 1 kpc. It has been observed three times at 3 and 6 cm with ATCA: on February 1998, on March 2002, and on April 2002, and presented flux density variations (see Benaglia, Cappa, & Koribalski 2001 for the details). It is catalogued as a possible SB1 by Gies (1987), due to excursions in radial velocity in excess of 35 km s⁻¹ that can be indicative of binarity. New spectroscopic observations are needed to confirm this result. Besides, the Washington Double Star Catalogue lists a visual companion at an angular distance of 2.8 arcsec (Worley & Douglass 1997).

HD 150136. HD 150136 belongs to the Ara OB1 association, at 1.4 kpc. This O5 III In(f) star has been reported as a spectroscopic binary SB2 by Arnal et al. (1988), with an O6 star as a close companion, in a 2.7 days orbit. Mason et al. (1998) listed a third component of the system, at 1.6" from the close pair. The ATCA 3 and 6-cm former observations detected emission from the system at a level of S₃cm = 2.61±0.03 mJy, and S₆cm = 5.57±0.03 mJy (Benaglia, Cappa, & Koribalski 2001).

CD-47 4551. This field star is classified as an O4 III(f) by Maíz-Apellániz et al. (2003). Its spectro-photometric distance was derived as 1.7 kpc (see Benaglia, Cappa, & Koribalski 2001). There is no information of its binarity status in the literature. It was detected at 3 and 6 cm with ATCA, showing S₃cm = 1.77 ± 0.05 mJy, and S₆cm = 2.98 ± 0.05 mJy.
3. Observations

The observations towards the four targets were carried out with the ATCA at 1.384, and 2.368 GHz (20 cm, and 13 cm respectively), at the array configuration 6A, in Dec 2003. The total bandwidth was 128 MHz. The calibration and analysis were performed with the Miriad routines. The flux density scale was calibrated using the primary calibrator PKS B1934-638. The resolutions achieved are about $\sim 5''$ at 13 cm, and $\sim 7''$ at 20 cm.

Additionally, HD 93129A was observed at 17.8 and 24.5 GHz in May 2004, with the ATCA 6C array. The total bandwidth was 128 MHz. The flux densities were calibrated against Mars. The angular resolutions achieved were $2.48'' \times 0.45''$ at 17.8 GHz, and $1.83'' \times 0.30''$ at 24.5 GHz.

In both cases, “robust” weighted images showed the best combination of signal-to-noise ratio and sidelobe suppression. The shortest baselines were excluded to get rid of the diffuse emission from nearby extended sources.

4. Results

We detected the four targets at 1.4 and 2.4 GHz, and HD 93129A also at 17.8 and 24.5 GHz. Gaussian fittings show all of them as point sources. The observed flux densities at 1.4 ad 2.4 GHz are listed in Table 1, together with the spectral indices. The flux densities detected towards HD 93129A, using the 3-mm ATCA receiver are: $S_{17.8\text{GHz}} = 1.8 \pm 0.2 \text{ mJy}$, and $S_{24.5\text{GHz}} = 1.5 \pm 0.2 \text{ mJy}$. The spectra are displayed in Figures 1 and 2, combined with the results of previous observations at 4.8 and 8.64 GHz. For all detections, the polarization factors remain below 2%.

Table 1. ATCA flux densities at 1.4 and 2.4 GHz

| Star      | Sp. class.† | $S_{13\text{cm}}$ [mJy] | $S_{20\text{cm}}$ [mJy] | $\alpha_{13-20}$ |
|-----------|-------------|--------------------------|--------------------------|------------------|
| CD-47 4551| O4 III(f)   | 3.82 ± 0.20              | 3.80 ± 0.25              | +0.01 ± 0.2      |
| HD 93129A | O2 II*      | 7.58 ± 0.50              | 9.38 ± 0.50              | −0.40 ± 0.4      |
| HD 124314 | O6 V(n)((f))| 3.70 ± 0.20              | 2.83 ± 0.25              | +0.50 ± 0.2      |
| HD 150136 | O5 III(n)   | 3.05 ± 0.20              | 2.28 ± 0.40              | +0.54 ± 0.2      |

†: Maíz-Apellániz et al. 2003

5. The HD 93129A radio spectrum

In close stellar systems, flux variability needs to be taken into account. An interpretation of the present multifrequency radio data from CD-47 4551, HD 124314 and HD 150136 can be envisaged only once the structure of the system is revealed. Optical observations are currently under way to investigate this issue (Niemela et al., in preparation).

We note that the component separation in the HD93129A system suggests a period larger than 50 yr. Here we report radio observations between 1.4 and
25 GHz. No flux density could be measured in the MOST 843 MHz maps due to source contamination.

The relatively low angular resolution of the radio data does not allow us to resolve the binary system. We detect the sum of the thermal emission from the winds of both stars as well as non-thermal emission from the colliding wind region (CWR).

5.1. Spectral contributions

The thermal emission from the winds of both components can be approximated with a radio flux density of $S_\nu \propto \nu^{0.6}$. At the CWR, strong shocks are capable of accelerating wind particles to relativistic energies giving rise to synchrotron emission in the presence of magnetic fields (Guinzburg & Syrovatskii 1964). However, part of the synchrotron photons can be absorbed by the wind thermal ions. The contribution of synchrotron emission to the flux density, modified by
thermal absorption, can be expressed as \( S_\nu \propto \nu^{\alpha_{NT}} e^{\tau_0 \nu^{-2.1}} \). The influence of synchrotron self-absorption (SSA) would cause the spectrum at short frequencies to be represented by \( S_\nu \propto \nu^{-2.5} \). We will disregard the consequences of the Razin-Tsytovitch effect, because according to the value of the magnetic fields involved, it would affect the emission up to some MHz.

### 5.2. Fitting results

We fitted the above contributions to the spectra of Fig. 1:right, and found the best fit was given by \( S_\nu = A \nu^{0.6} + B \nu^{\alpha_{NT}} e^{\tau_0 \nu^{-2.1}} \) mJy, if \( A = 0.17 \pm 0.05 \), \( B = 28.6 \pm 6.6 \), \( \alpha = -1.31 \pm 0.18 \), and \( \tau_0 = 1.41 \pm 0.37 \) (see Figure 3). The lack of data below 1.4 GHz precluded the search for a SSA signature.

The above expression helps us to separate thermal from non-thermal emission, and to compute a mass loss rate from the thermal radio flux. At 3 cm the total flux measured is 2.0\pm0.2 mJy \cite{Benaglia2004}. Consequently, \( S_T = 0.6 \) mJy, and \( S_{NT} = 1.4 \) mJy, and the mass loss rate for HD 93129A results in \( \dot{M} = 3.6 \times 10^{-5} M_\odot \text{yr}^{-1} \).

If the secondary star is an 03.5 V, like the nearby stars HD 93128 and HD 93129B, the colliding wind region would be \( \sim 120 \) AU from the primary, and \( \sim 34 \) AU from its companion, in an \cite{Eichler1993} colliding wind scenario. A synchrotron luminosity of \( 6 \times 10^{33} \) erg s\(^{-1} \) is obtained up to 24.5 GHz.

![Figure 3. Spectral fitting for HD 93129A](image-url)
6. Discussion

The system HD 93129A has a separation similar to that of WR 146 (210 AU, Setia Gunawan et al. [2000]). The latter is a WR+O system that has been resolved in the radio continuum with MERLIN, and the emission probably coming from a CWR could be mapped (Dougherty, Williams, & Pollaco 2000), as a 38 mas source (or ~ 50 AU at a distance of 1.25 kpc). It seems reasonable to assume that the size of a colliding wind region of HD 93129A should be alike, and thus we adopt for it a value of 40 AU. The equipartition magnetic field at the CWR will result in ~ 20 mGauss, (Miley 1980), and the stellar magnetic field, ~ 500 Gauss.

The same electrons involved in synchrotron processes can be scattered by the inverse Compton mechanism, producing gamma-ray continuum emission. The maximum Lorentz factor attained by the electrons at the CWR, computed as in Benaglia & Romero (2003), is $\gamma_{\text{max}} = 1.8 \times 10^6$. This corresponds to a maximum synchrotron frequency of $\nu = 2 \times 10^{15}$ Hz, and a cutoff energy for the IC photons of $E = 500$ GeV. The energy at which the electron distribution changes, due to synchrotron and inverse Compton losses, is defined by $\gamma_b \sim 20,000$. Finally, the inverse Compton luminosity results in $L_{\text{IC}} = 1 \times 10^{33}$ erg s$^{-1}$, well below the EGRET threshold at the location of this particular star.

Optical spectroscopy to define the spectral type of the HD 93129A companion, and very high resolution radio observations to resolve the system, are crucial to refine the figures given here. The gamma-ray predictions can be confronted against GLAST observations in the near future.

In the case of CD-47 4551, HD 124314, and HD 150136, the knowledge of the system structure is fundamental to allow the study of the radio data.

7. Conclusions

Non-thermal contribution to the radio emission has been detected for the stars CD-47 4551, HD 93129, HD 124314, and HD 150136. The spectral fitting for the radio emission from the O2 If* HD 93129A enabled to extract the thermal flux, and determine a value for the mass loss rate of this peculiar system, of $3.6 \times 10^{-5}$ M$_{\odot}$ yr$^{-1}$. The non-thermal radiation, coming probably from a colliding wind region between the stellar components, is characterized by a flux density spectral index of $-1.3 \pm 0.2$, and a magnetic field of ~ 20 mGauss.

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