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Radio Behavior of 4 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 ATCA, towards the four southern Of 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. 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 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} $M_{\odot}\,yr^{-1}$ at velocities of thousands of km s^{-1}. The winds are optically thick in the radio, radiate through the free-free mechanism, and produce an excess of flux density from radio to infrared. 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 that most of these stars are not single, this emission is probably produced in the 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 towards early-type stars, using the Australia Telescope Compact Array (ATCA) at maximum angular resolution, we have detected 4 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 towards these sources, at 1.4 and 2.4 GHz.

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 ($52,000 \pm 1000$ K), and luminosity ($\log(L/L_{\odot}) = 6.4 \pm 0.1$) (Taresch et al. 1997, and references therein).

HD 93129A has been detected in the radio at 3 and 6 cm (Benaglia & Koribalski 2004), with flux densities of $S_{3\rm cm} = 2.0 \pm 0.2$ mJy and $S_{6\rm cm} = 4.1 \pm 0.4$ mJy. The corresponding spectral index of 1.2 ± 0.3 implies the presence of non-thermal emission which, in principle, is produced in the 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 IIIn(f) star has been reported as an SB2 spectroscopic binary by Arnal et al. (1988), with an O6 star as a close companion, in a 2.7-day orbit. Mason et al. (1998) listed a third component for 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 $S_{3\rm cm} = 2.61 \pm 0.03$ mJy, and $S_{6\rm cm} = 5.57 \pm 0.03$ mJy (Benaglia, Cappa, & Koribalski 2001).

CD-47 4551. This field star is classified as an O4 III(f) by Maíz-Apellániz et al. (2004). Its spectro-photometric distance was derived as 1.7 kpc (see Benaglia, Cappa, & Koribalski 2001). There is no information of its binary status in the literature. It was detected at 3 and 6 cm with ATCA, showing $S_{3\rm cm} = 1.77 \pm 0.05$ mJy, and $S_{6\rm cm} = 2.98 \pm 0.05$ 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 over 13 channels. 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 bandwith was 128 MHz over 32 channels. The flux densities were calibrated against Mars.

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

4. Results

We detected the 4 targets at 1.4 and 2.4 GHz, and HD 93129A also at 17.8 and 24.5 GHz. Gaussian fits 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: $S_{17.8\mathrm{GHz}} = 1.8 \pm 0.2$ mJy, and $S_{24.5\mathrm{GHz}} = 1.5 \pm 0.2$ 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. (Maíz-Apel. et al. 2004)	$S_{13\mathrm{cm}}$ [mJy]	$S_{20\mathrm{cm}}$ [mJy]	α_{13-20}
CD-47 4551	O4 III(f)	3.82 ± 0.20	3.80 ± 0.25	$+0.01 \pm 0.2$
HD 93129A	O2 If*	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	$+0.50 \pm 0.2$
HD 150136	O5 IIIn(f)	3.05 ± 0.20	2.28 ± 0.40	$+0.54 \pm 0.2$

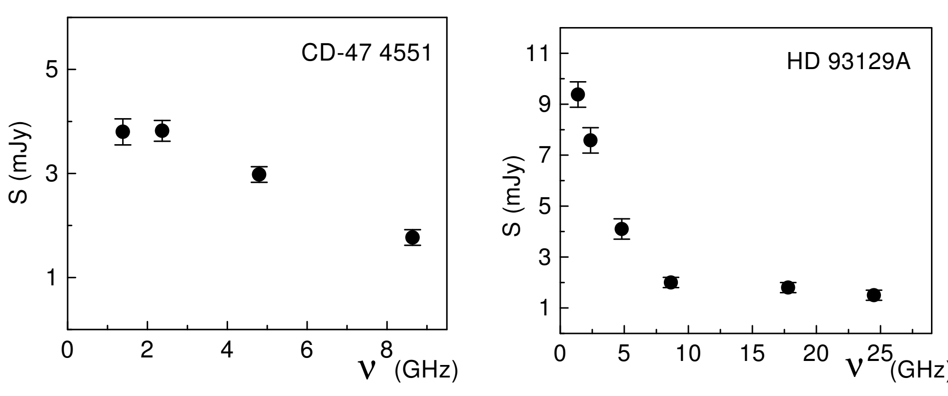

Figure 1. Radio spectra of the stars CD-47 4551 and HD 93129A

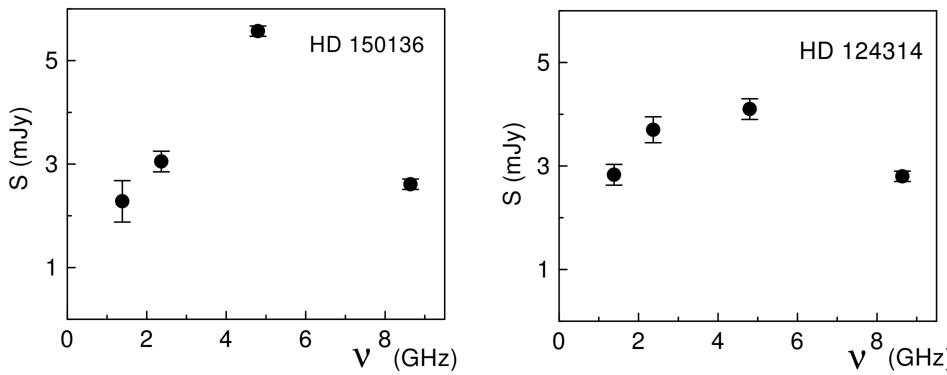

Figure 2. Radio spectra of the stars HD 150136 and HD 124314

5. The HD 93129A Radio Spectrum

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

In contrast, the component separation at the HD 93129A system grants a period larger than 50 yrs. The observations reported here can be considered as quasi-simultaneous, and they extend from 1.4 up to $\sim$ 25 GHz. At shorter frequencies we searched for 843 MHz-MOST emission, but contamination from background sources prevented us to isolate a reliable flux density value.

Due to the spatial resolution of the radio data ($\sim 1''$), the flux density of the detected point source would sum up emission from the winds of both components, plus the non-thermal emission from the hypothetical CWR. In order to interpret the radio spectra we proceeded with a phenomenological approach, as it was done, for example, by Setia Gunawan et al. (2000) for WR 146.

5.1. Spectral Contributions

The thermal emission from the winds of both components can be approximated by 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's thermal ions. The contribution of synchrotron emission to the flux density, modified by thermal absorption, can be expressed as $S_\nu \propto \nu^{\alpha_{\rm NT}}\, e^{\tau_0 \nu^{-2.1}}$. 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 $S_\nu = \mathrm{A}\nu^{0.6} + \mathrm{B}\nu^{\alpha_{\rm NT}} e^{-\tau_0 \nu^{-2.1}}$ 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 last expression helps us to detach 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 ± 0.2 mJy (Benaglia & Koribalski 2004). Consequently, $S_{\rm T} = 0.6$ mJy, and $S_{\rm NT} = 1.4$ mJy, and the mass-loss rate for HD 93129A results in $\dot{M} = 3.6 \times 10^{-5}$ $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

If the secondary star is an O3.5 V, like the nearby stars HD 93128 and HD 93129B, the colliding-wind region would be ~ 120 AU from the primary, and ~ 34 AU form its companion, in an Eichler & Usov (1993) colliding-wind scenario. A synchrotron luminosity of 6×10^{33} erg s^{-1} is obtained up to 24.5 GHz.

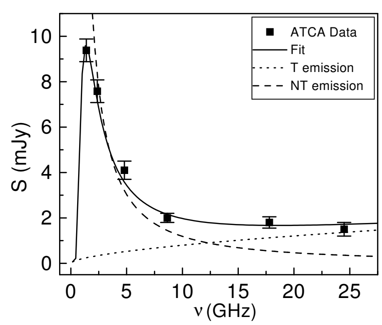

Figure 3. Spectral fitting for HD 93129A

6. Discussion

The system HD 93129A has a separation similar to that of WR 146 (210 AU, Setia Gunawan et al. 2000). This WR+O system 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 $\sim$ 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 $\gamma_{\rm max} = 1.8 \times 10^6$. 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 $\gamma_{\rm b} \sim$ 20,000. Finally, the inverse Compton luminosity results in $L_{\rm IC} = 1 \times 10^{33}$ 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* star HD 93129A enabled us to extract the thermal flux, and determine a value for the mass-loss rate of this peculiar system, of 3.6×10^{-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 ± 0.2, and a magnetic field of ~ 20 mGauss.

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Discussion

Sergey Marchenko: You have shown a table with the spectral indices. And there are a couple of sources with a positive value, 1.3, 1.7. Why are they so far away from the expected 0.6-0.8?

Paula Benaglia: I don't know yet, I have to study them.

Sergey Marchenko: Is it something about the change of the ionisation? What are the basic assumptions and why are they broken?

Paula Benaglia: Well, it could be something else. For HD93129A, we know that the period must be 60 years or more but for the other stars we don't know. And the observations are not simultaneous. Maybe the fluxes cannot be compared. We have to check first. The observations of HD93129A were separated by one year and in one year the system won't change but for the others we don't know; the observations are separated by two years, more than for the first star.

Hans Zinnecker: If you had not known that this star is a binary from Nolan's work, would you have predicted from your radio observations that it must be a binary?

Paula Benaglia: Well, my feeling is that they are all binaries if you have non-thermal emission. In that case, each time you try to determine if they are binaries or not you always have the result that they are binaries. But I cannot say definitely beforehand.

Hans Zinnecker: So, no?

Paul Crowther: So, yes?

Paula Benaglia: Yes, yes.

Paul Crowther: Non-thermal is a clear indication of a binary.

Hans Zinnecker: Could it be a triple?

Paula Benaglia: Yes, the system has a separation of 150 AU but then we don't know if the primary is a close pair.

Hans Zinnecker: Yes, that is what I was wondering about.

Julian Pittard: Actually, I have a quick comment. For HD93129A you had a non-thermal spectral index of -1.3 and you interpreted that as a different value for the shock compression ratio, other than 4, that you would typically expect. The simulations that Sean and I have been doing actually suggest that instead of Inverse Compton cooling giving you a very sharp break in the non-thermal spectrum, rather you get a general reduction in the slope, a steepening of the spectrum towards maybe -1.3. So it seems to me that probably the shocks are still very strong; you still have shock-compression ratios of 4. After all, these are very high Mach numbers. So most likely you don't need to adjust the shock compression ratio.

Nolan Walborn: Just to give some numbers on Hans' question. There are intensive radial-velocity studies of HD93129A and its RV is constant, so there is no companion within one AU. The limit of the FGS observations for a companion of comparable brightness is about 30 AU. So there is a gap between 1 and 30 AU that has not been covered observationally but there is nothing else outside of that gap.

Paula Benaglia taking the foreground