Astronomy & Astrophysics manuscript no. HD93129 November 28, 2003
(DOI: will be inserted by hand later)

Radio observations of HD 93129A: The earliest O star with the highest mass loss ?

Paula Benaglia[1,2⋆], Bärbel Koribalski[3]

[1] Instituto Argentino de Radioastronomía, C.C.5, (1894) Villa Elisa, Argentina
[2] Facultad de Cs. Astronómicas y Geofísicas, UNLP, Paseo del Bosque S/N, 1900, La Plata, Argentina
[3] Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 1710, Australia

Received July 31; accepted November 6, 2003

Abstract. We present the results of radio continuum observations towards the open cluster Tr 14, where our main targets are the early-type O stars HD 93129A/B and HD 93128. The observations were carried out at 3 cm (8.64 GHz) and 6 cm (4.80 GHz) with the Australia Telescope Compact Array. Only HD 93129A (type O2 If*) was detected; we measure flux densities of $S_{3\mathrm{cm}} = 2.0 \pm 0.2$ mJy and $S_{6\mathrm{cm}} = 4.1 \pm 0.4$ mJy. The resulting spectral index of $\alpha = -1.2 \pm 0.3$ ($S_\nu \propto \nu^\alpha$) indicates predominantly non-thermal emission, suggesting HD 93129A may be a binary system. We propose that the observed 3 cm radio emission is mostly coming from the non-thermal wind collision region of a binary, and, to a lesser extent, from the thermal winds of the primary and secondary stars in HD 93129A. At a stellar distance of 2.8 kpc, we derive a mass-loss rate $\dot{M} = 5.1 \times 10^{-5}$ M$_\odot$ yr^{-1}, assuming the thermal fraction of the 3 cm emission is ∼0.5.

Key words. stars: early-type — stars: individual: HD 93129A, HD 93129B, HD 93128 — stars: mass loss — stars: winds, outflows — radio continuum: stars

1. Introduction

Massive, early-type O stars at the upper end of the stellar main sequence are known to have strong stellar winds, with velocities up to ∼3000 km s^{-1} (Prinja et al. 1990). Their evolution into Wolf-Rayet (WR) stars is marked by high mass loss rates of 10^{-7} to 10^{-5} M$_\odot$ yr^{-1} (e.g., Lamers & Leitherer 1993). The transition can be described by three Of phases (O – O((f)) – O(f) – Of – WR), where "f" stands for the presence of certain N III and He II spectral lines (see Maíz Apellániz & Walborn 2002 for details; also Table 1). Once the H-rich outer layers of the star are lost, the high temperature core is exposed, and the evolution from Of to WR star is complete. The action of the stellar wind on the ambient interstellar medium creates a cavity of hot, rarefied gas, surrounded by a slowly expanding envelope (Benaglia & Cappa 1999).

Wolf-Rayet stars have anomalously strong and broad emission lines, which are thought to come from the rapidly expanding stellar wind, but few absorption lines. With an average mass of 10 M$_\odot$, their mass loss rate can reach values up to 10^{-4} M$_\odot$ yr^{-1}. Van der Hucht et al. (2001, 2002) cataloged well over 200 WR stars in our Galaxy, more than half of which belong to the WN class, i.e. they show strong helium and nitrogen emission lines. A large fraction of the cataloged WR stars (∼40%) are known to be binaries.

According to Crowther et al. (1995), the most massive (> 60 M$_\odot$) O stars evolve from the Of stage directly into highly luminous late WN(+abs) and WN7 stars without passing through an intermediate Luminous Blue Variable or red supergiant phase. The slightly less massive O stars evolve through either of those intermediate phases into slightly less luminous WN8 stars (see also Langer et al. 1994). The quantitative spectroscopic properties show a smooth progression from Of stars to lower excitation or late WN stars (WNL) (Bohannan 1990). Walborn et al. (1992), Lamers & Leitherer (1993) among others, suggested that transition types Ofpe/WNL, and WNL stars, form a sequence of increasing wind density.

Examples of transition objects are Sk–67^0 22 (type O3If*/WN6-A, Walborn 1982), Sk–71^0 34 (type O4f/WN3, Conti & Garmany 1983), and, lately, the ones found in 30 Doradus (Massey & Hunter 1998). The mass loss rates of the transition objects are expected to lie between those for Of and WR stars.

Almost 400 Galactic O stars have recently been compiled in the new 'Galactic O Star Catalogue' (GOS) by Maíz-Apellániz & Walborn (2002). There are only about

Send offprint requests to: P. Benaglia
e-mail: paula@lilen.fcaglp.unlp.edu.ar
⋆ Member of Carrera del Investigador, CONICET

a dozen stars with spectral types O3.5 or earlier; five of these belong to the clusters Trumpler 14 and Trumpler 16, in the Carina region. Among them one star, HD 93129A, stands out as the earliest, most luminous, and most massive star known in our Galaxy. Walborn et al. (2002) re-analyzed spectra of HD 93129A, previously classified as O3, and find that it is the prototype of a new subcategory and the sole representative of type O2 If* (see Table 1). HD 93129A appears to have the most extreme stellar winds regarding ionization and terminal velocities (Walborn et al. 2002): $v_\infty = 3200 \pm 200$ km s^{-1}, an effective temperature $T_{\rm eff} = 52,000 \pm 1000$ K, and a stellar mass of 130 ± 15 $M_\odot$ (Taresch et al. 1997). Only 2.6" from HD 93129A, Walborn (1973) discovered a second star, HD 93129B, of type O3.5 V((f+)). Another star of the same type, HD 93128, is found at a projected distance of ∼ 20". The stellar parameters for all three stars are listed in Table 1.

In the radio regime, free-free thermal emission from the ionized wind of early-type OB and Wolf-Rayet stars can be modeled (Wright & Barlow 1975, Panagia & Felli 1975) yielding a spectral index (α) of typically $\sim 0.6-0.7$. Generally, the radio flux densities are of the order of mJy for stars at distances up to 2 kpc. About 80 WR stars (Abbott et al. 1986, Chapman et al. 1999) and ∼120 O stars (Bieging et al. 1989, Scuderi et al. 1998, Benaglia et al. 2001b, etc.) have been observed. Roughly half of them were detected at least at one frequency. When spectral indices could be measured, ∼40% showed non-thermal or composite indices.

In recent years the hypothesis was proposed (Chapman et al. 1999, Dougherty & Williams 2000) that non-thermal emission could be indicative of binarity. In that case, part of the emission comes from the colliding wind region (CWR) of two early massive stars. Chapman et al. (1999) observed 36 WR stars with the ATCA at 3, 6, 13 and 20 cm, obtaining an angular resolution of ∼ 1" at 3 cm. Dougherty & Williams (2000) discussed the spectral index behaviour of 25 WR stars, by taking into account observations carried out mainly with the VLA, ATCA, MERLIN and the WSRT. Benaglia & Romero (2003) presented a table with the characteristics of the non-thermal or composite WR emitters.

Unfortunately, in some particular cases where the non-thermal emission is strong, not enough spectroscopic data are currently available to investigate the binary status. For example, CD–47° 4551 (CPD–47° 2963), an O4 III(f) star (Walborn 1982), was observed with the ATCA (Benaglia et al. 2001b) and detected with flux densities of 1.77 ± 0.05 mJy at 3 cm and 2.98 ± 0.05 mJy at 6 cm ($\alpha = -0.89 \pm 0.06$). If the star is a binary with another WR or OB star, the non-thermal emission could be produced at the CWR of both stars.

Non-thermal radio emission can also be produced by the stellar wind of a single star, as described by White (1985). In his model, electrons are accelerated to relativistic energies by shocks in the wind near the star, and emit radio radiation. For strong shocks, the expected spectral index is +0.5. Though this is similar to the thermal index value, the non-thermal flux density coming from a single stellar wind will suffer a break at a frequency of a few GHz, and behave as $S(\nu) \propto \log(\nu)$ for larger frequencies, while the thermal flux will obey a $\alpha = 0.6 - 0.7$ law up to the infrared range.

Radio observations are very useful to derive the mass loss rates of early-type stars (Leitherer et al. 1995). The source HD 93129A represents one of the most interesting candidates because it is the only known example of the hottest supergiant class. With the help of high resolution radio data, properties of the wind can be unveiled. In detecting the stellar wind, we intend to identify its radio spectrum, look for a possible colliding wind region, and compare the mass loss rate with those derived from other methods. The observations will also allow us the study of other early-type stars in the region.

The paper is organized as follows: Section 2 summarizes the characteristics of the target sources relevant to this study. Section 3 describes the observations and data reduction. In Section 4 we present the results, followed by the discussion in Section 5. Section 6 contains our conclusions.

2. The target stars in Trumpler 14

The field of view of the present data (see Section 3) corresponds to the cluster Trumpler 14. Lists of the catalogued members can be found in Massey & Johnson (1993), and recently DeGioia-Eastwood et al. (2001). A wide range of spectroscopic or photometric distances can be found for Tr 14 in the literature. Humphreys & McElroy (1984) derived a distance of 3.47 kpc. Morrell et al. (1988) discussed two possible distances, 2.8 (variable R, from Tapia et al. 1988) and 3.45 kpc ($R = 3.2$), depending on the value taken for the ratio of total to selective absorption R. Massey & Johnson (1993) and Vázquez et al. (1996) found similar values of 3.2 and 3.1 kpc, respectively. Most recently, Tapia et al. (2003) computed spectroscopic parallaxes to derive a distance of 2.8 kpc. We adopt the latter value throughout this paper. At this distance, the projected cluster size of 140" (Tapia et al. 2003) corresponds to 1.9 pc. Chandra observations towards the η Carina region (Evans et al. 2003) revealed strong X-ray emission from the stars HD 93129A/B. Their combined X-ray luminosity is $L_{\rm X}(0.5 - 2.4{\rm keV}) = 2.9 \times 10^{33}$ erg s^{-1}, adjusted to a distance of 2.8 kpc.

Penny et al. (1993) presented radial velocity measurements for seven stars in Tr 14, with mean values of -4.4 ± 7.4 km s^{-1} for HD 93129A, 7.2 ± 2.4 km s^{-1} for HD 93129B and 7.3 ± 3.3 km s^{-1} for HD 93128. They concluded that none of them is a strong binary candidate (see also Conti et al. 1977, 1979). Based on the standard deviation in the mean stellar radial velocities, they estimated that the typical random motions in this cluster are 8.5 km s^{-1}. For HD 93129A Penny et al. placed an upper limit of ∼10 km s^{-1} on the semiamplitude of any short-period binary. To search for possible long-period bina-

Table 1. Stellar parameters adopted for the target stars

	HD 93129A	HD 93129B	HD 93128	
α, δ (J2000)	10 43 57.462[(a)]	10 43 57.638[(b)]	10 43 54.372[(c)]	h m s
	–59 32 51.27	–59 32 53.50	–59 32 57.37	° ′ ″
Spectral Class.	O2 If*[(d)]	O3.5 V((f+))[(d)]	O3.5 V((f+))[(d)]	
v_∞	3200 ± 200[(e)]	3070[(f)]	3070[(f)]	km s^{-1}
$T_{\rm eff}$	52000 ± 1000[(e)]	52000 ± 1500[(g)]	52000 ± 1500[(h)]	K
log $(L/{\rm L}_\odot)$	6.4 ± 0.1[(e)]	5.6[(g)]	5.7[(g)]	

References: (a): Hog et al. 2000; (b): Worley & Douglass 1997; (c): see Maíz Apellániz & Walborn 2002; (d): Walborn et al. 2002 (f* means the N IV 4058Å emission lines are stronger than the N III 4640Å emission lines, and HeII 4686Å is observed in emission, while ((f+)) means weak N III 4634-4640-4642Å emission lines, strong He II 4686Å absorption lines, plus Si IV 4089–4116Å emission lines); (e): Taresch et al. 1997; (f): interpolated from Prinja et al. 1990; (g): see text; (h): Vacca et al. 1996.

ries they obtained speckle observations, with negative results. Surprisingly, recent HST observations indicate that HD 93129A is a binary (Walborn 2002) with a separation of 55 mas (Walborn 2003, priv. comm.; Nelan et al., in prep.), which could have been detected by Penny et al. (1993).

The optical positions of the three earliest stars in the observed field were taken from the GOS catalog, and come from three different sources, varying in precision: the Tycho-2 catalog (Hog et al. 2000) lists a very accurate position ($\sigma \sim 5$ mas) for HD 93129A, whereas the position of HD 93129B originates from the Washington Double Star catalog (Worley & Douglass 1997) and that of HD 93128 was measured from NTT data, according to Maíz-Apellániz & Walborn (2002). For a summary of the stellar parameters see Table 1.

HD 93129A. The spectrum of this early O2 If* star is very similar to Wolf-Rayet stars of spectral type WN6 or WN7 (Walborn et al. 2002). Taresch et al. (1997) studied the spectrum from optical to FUV range, concluding that its strong wind is radiatively driven. By fitting an Hα profile they obtained a mass loss rate of 1.8×10^{-5} M$_\odot$ yr^{-1} compared to 2.2×10^{-5} M$_\odot$ yr^{-1} derived from Hα measurements by Puls et al. (1996; assuming $T_{\rm eff}$ = 50,500 K).

HD 93129B and HD 93128. The effective temperature of HD 93128 is 52000 ± 1500 K (Vacca et al. 1996). For HD 93129B, which has the same spectral type as HD 93128, we adopt the same value. The stellar luminosities were derived taking the absolute visual magnitudes from Walborn et al. (2002).

HD 93250. This star is a member of the Tr 16 cluster, located $\sim 10'$ East of HD 93129A/B (well outside our primary beam). Leitherer et al. (1995) reported a 3 cm flux density of 1.36 ± 0.17 mJy and a 3σ upper limit of 3.57 mJy at 6 cm. Assuming a purely thermal spectrum, a distance of 2.2 kpc, a wind velocity of $v_\infty = 3200$ km s^{-1} and an effective temperature of $T_{\rm eff}$ = 50,000 K ($T_{\rm e} = 0.4\ T_{\rm eff}$ = 20,000 K according to Drew 1989) Leitherer et al. derived a mass loss rate of 4.1×10^{-5} M$_\odot$ yr^{-1}. Considering a re-classified spectral type of O3.5 V((f+)) (Walborn et al. 2002) and a distance of 2.5 kpc to Tr 16 (Tapia et al. 2003) we revise the mass loss rate to 5×10^{-5} M$_\odot$ yr^{-1} (see Section 4.1).

3. Observations and Data Reduction

The observations presented here were obtained with the Australia Telescope Compact Array (ATCA) in January 2003 using the 6B configuration. The target field, which contains three massive Of stars, was observed simultaneously at two frequencies: 8.64 GHz (3 cm) and 4.80 GHz (6 cm), with a total bandwidth each of 128 MHz over 32 channels. The maximum baseline was 6 km, resulting in angular resolutions around 1" –2". The size of the primary beam is $10'$ at 6 cm and $5'$ at 3 cm. The pointing position was α, δ(J2000) = $10^{\rm h}\,43^{\rm m}\,56^{\rm s}$, $-59^\circ\,32'\,51''$, slightly offset from the three stars HD 93129A/B and HD 93128. The field was observed during intervals of 8 to 15 min, depending on the atmospheric phase stability, interleaved with short observations of the nearby phase calibrator 1045–62, and spanning an LST range of 12 h. The total time on the target field was nearly 300 minutes.

The data were reduced in MIRIAD using standard procedures. The flux density scale was calibrated with observations of the primary calibrator PKS B1934–638, assuming flux densities of 2.84 Jy at 3 cm and 5.83 Jy at 6 cm (Reynolds 1994). After data calibration the visibilities were Fourier-transformed using 'natural'- and 'uniform'-weighting. To overcome confusion due to diffuse emission from extended sources in or towards the observed fields, the shortest baselines were removed. For the same reason 'uniform'-weighting resulted in the lowest noise levels: 0.11 and 0.21 mJy beam^{-1} at 3 and 6 cm, respectively. The synthesized beam is 1.1" × 1.0" at 3 cm and 1.9" × 1.7" at 6 cm.

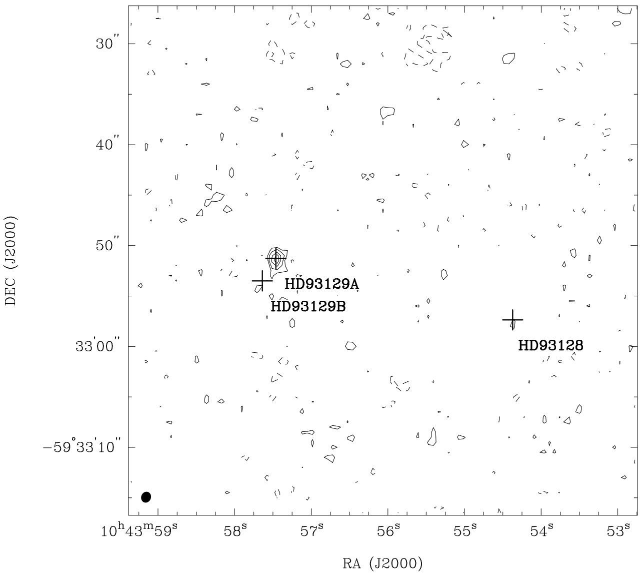

Fig. 1. ATCA 3 cm radio continuum image towards Tr 14. The optical positions of three stars (see Table 1) are marked. The contour levels are –0.22, 0.22 (2σ), 0.44, 0.66, 0.88, and 1.10 mJy beam^{-1}. The synthesized beam (1.1" × 1.0") is displayed at the bottom left.

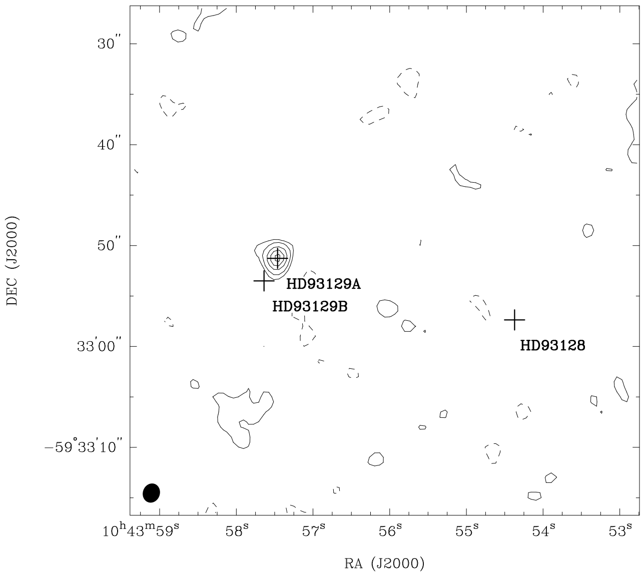

Fig. 2. ATCA 6 cm radio continuum image towards Tr 14. The optical positions of three stars (see Table 1) are marked. The contour levels are –0.42, 0.42 (2σ), 0.84, 1.26, 1.68, and 2.10 mJy beam^{-1}. The synthesized beam (1.9" × 1.7") is displayed at the bottom left.

Table 2. Flux densities (or 3σ upper limits) of the target stars.

Star	$S_{3\rm cm}$ (mJy)	$S_{6\rm cm}$ (mJy)
HD 93129A	2.0 ± 0.2	4.1 ± 0.4
HD 93129B	< 0.33	< 0.63
HD 93128	< 0.33	< 0.63

4. Results

Figs. 1 and 2 show the central part of the resulting 3 and 6 cm radio continuum images. The optical positions of the three target stars (see Table 1) are marked.

Only one radio source, HD 93129A, is detected. Using the MIRIAD task *imfit* we fit the position and flux density (of a point source) at both frequencies resulting in α, δ(J2000) = $10^{\rm h}\,43^{\rm m}\,57^{\rm s}.45$, $-59°\,32'\,51.36"$, 2.0 ± 0.2 mJy at 3 cm, and α, δ(J2000) = $10^{\rm h}\,43^{\rm m}\,57^{\rm s}.47$, $-59°\,32'\,51.23"$, 4.1 ± 0.4 mJy at 6 cm. From the 3 and 6 cm flux densities we derive a spectral index of $\alpha = -1.2 \pm 0.3$ ($S_\nu \propto \nu^\alpha$) indicating predominantly non-thermal emission. The measured flux densities for HD 93129A and the 3σ upper limits for HD 93129B and HD 93128 are listed in Table 2.

The separation between the fitted 3 and 6 cm radio continuum positions for HD 93129A is 0.2", slightly larger than the positional uncertainty (which is approximately the size of the synthesized beam divided by signal-to-noise ratio of the source). The radio and optical positions agree within the given uncertainties.

The Simbad database lists 250 Galactic objects within a radius of $2.5'$ around our pointing position (see Section 3), at least 11 of which are O-type stars, including the three target stars. Table 3 lists the eight additional stars, none of which was detected. The same 3σ upper limits apply.

4.1. Mass loss rates

According to Wright & Barlow (1975), the stellar mass loss rate, $\dot{M}$, of an optically thick ionized wind can be expressed in terms of the measured thermal flux density, S_ν, at a frequency ν, from radio to IR ranges, as:

$$\dot{M} = 5.32 \times 10^{-4}\, \frac{S_\nu^{3/4}\, d^{3/2}\, v_\infty\, \mu}{Z\,\sqrt{\gamma\, g_\nu\, \nu}} \quad {\rm M_\odot yr^{-1}}\ . \qquad (1)$$

Here d is the stellar distance in kpc, v_∞ the wind terminal velocity in km s^{-1}, S_ν the thermal flux density in mJy, and ν the frequency in Hz; μ stands for the mean molecular weight of the ions, γ is the mean number of electrons per ion and Z the r.m.s. ionic charge. For a fully ionized H-He gas, $\mu = 1.38$. In a first approximation, $Z \approx \gamma \sim 1$. We will take those values for all calculations throughout the text. The Gaunt factor g_ν can be approximated by:

$$g_\nu = 9.77\, \left(1 + 0.13 \log \frac{(0.4 \times T_{\rm eff})^{3/2}}{Z\nu}\right)\ . \qquad (2)$$

From the derived spectral index of $\alpha = -1.2 \pm 0.3$ we know that the observed radio continuum emission consists of thermal and non-thermal components. Their relative contributions (and locations) are unknown since the detected source is essentially unresolved. If $f_{\rm T}$ is the fraction of the thermal emission at 3 cm with $S^{\rm T}_{3\rm cm} = f_{\rm T} \times S_{3\rm cm}$, $f_{\rm T} = 0 - 1$, then the mass loss rate

Table 3. Additional O-type stars within the observed 3 cm field

Name	α,δ (J2000) (h m s)	(° ′ ″)	Spectral type	$\dot{M}_{\rm exp}$ M$_\odot$ yr^{-1}	$S^{\rm T}_{\rm exp,3cm}$ mJy
Cl* Trumpler 14 MJ 165	10 43 55.43	–59 32 49.8	O8 V$^{(a)}$	8.5×10^{-7}	0.010
CPD-58 2620	10 43 59.92	–59 32 25.4	O6.5 V((f)) $^{(b)}$	1.7×10^{-6}	0.016
Cl* Trumpler 14 MJ 150	10 43 53.75	–59 33 29.0	O9: V$^{(a)}$	4.5×10^{-7}	0.005
Cl* Trumpler 14 MJ 127	10 43 48.82	–59 33 24.8	O9 V$^{(a)}$	4.5×10^{-7}	0.005
CPD-58 2611	10 43 46.69	–59 32 54.8	O6 V((f))$^{(b)}$	2.1×10^{-6}	0.021
HD 93160	10 44 07.27	–59 34 30.8	O6 III((f))$^{(b)}$	4.9×10^{-6}	0.064
HD 93161AB	10 44 08.90	–59 34 34.9	O6.5 V((f))$^{(b)}$	1.7×10^{-6}	0.016
LS 1832	10 44 06	–59 35 09.0	O6$^{(c)}$	2.1×10^{-6}	0.021

References: (a): Massey & Johnson 1993; (b): Maíz-Apellániz & Walborn 2002; (c): Reed & Beatty 1995.

of HD 93129A is $\dot{M} = (f_{\rm T})^{3/4} \times 8.6 \times 10^{-5}$ M$_\odot$ yr^{-1}. For $f_{\rm T} \lesssim 1$ this would be one of the highest mass loss rates ever derived for a massive, early-type star. For HD 93129B and HD 93128 we derive 3σ upper limits of $\dot{M} < (f_{\rm T})^{3/4} \times 2.13 \times 10^{-5}$ M$_\odot$ yr^{-1}.

Given a stellar mass, luminosity, effective temperature, and wind terminal velocity, the models of Vink et al. (2000) can be used to compute a theoretical — or expected — mass loss rate, $\dot{M}_{\rm exp}$. Using Vink's program (see astro.imperial.ac.uk/∼jvink/) and the values given in Table 1, we calculate $\dot{M}_{\rm exp} = 2.12 \times 10^{-5}$ M$_\odot$ yr^{-1} for HD 93129A. While this value is in good agreement with the Hα-derived mass loss rates (Puls et al. 1996, Taresch et al. 1997), it is a factor four smaller than that derived from the measured 3 cm radio continuum flux density, suggesting $f_{\rm T} = 0.15$. For HD 93129B and HD 93128 we calculate $\dot{M}_{\rm exp}$ of 0.3×10^{-5} M$_\odot$ yr^{-1}.

Table 3 lists the expected stellar mass loss rates for the other eight O stars in the field, estimated as for the earliest stars and assuming a distance of 2.8 kpc. The luminosities, masses, and effective temperatures were taken from Vacca et al. (1996). The terminal velocities were interpolated from Table 3 of Prinja et al. (1990) according to spectral type. The expected thermal flux density at 3 cm was computed inverting Eq. (1), and is listed in the last column.

5. Discussion

5.1. A CWR between HD 93129A and B ?

The distance of $D = 2.6" = 7300$ AU between coordinates of HD 93129A and B is a lower limit to their absolute separation. If a colliding wind region exists between the two stars, it would be located at projected distances $r_{\rm A}$, $r_{\rm B}$ (see Eichler & Usov, 1993):

$$r_{\rm A} = \frac{1}{1+\eta^{1/2}} D \ , \quad r_{\rm B} = \frac{\eta^{1/2}}{1+\eta^{1/2}} D \ . \tag{3}$$

The parameter η is defined in terms of the wind terminal velocities and the stellar mass loss rates $\dot{M}$:

$$\eta = \frac{\dot{M}_{\rm B} \times v_{\infty,{\rm B}}}{\dot{M}_{\rm A} \times v_{\infty,{\rm A}}} \ . \tag{4}$$

Using the derived theoretical values for $\dot{M}_{\rm A}$ and $\dot{M}_{\rm B}$, we find $\eta = 0.14$. Thus $r_{\rm A} = 1.9" \approx 5350$ AU, and $r_{\rm B} = 0.7" \approx 1950$ AU. The putative CWR would be centered around $\alpha,\delta({\rm J2000})_{\rm CWR} = 10^{\rm h}\,43^{\rm m}\,57.59^{\rm s}$, $-59°\,32'\,52.9"$, but no emission was detected with the ATCA. The same 3σ upper limits apply (see Table 2).

Assuming a spectral index of $\alpha = -0.5$ (Eichler & Usov 1993), we derive an upper limit to the non-thermal radio luminosity from a CWR between stars A and B of $L_{\rm obs} < 1.4 \times 10^{28}$ erg s^{-1}. The expected non-thermal luminosity from a possible A/B binary is difficult to estimate due to the poor knowledge of system parameters such as size of the CWR and the magnetic field. Moreover, according to Wright & Barlow (1975), the radii of the radio photospheres at 3 and 6 cm would be ∼30 and 60 AU, ($<< r_{\rm A}, r_{\rm B}$), respectively, if $\dot{M} = 5 \times 10^{-5}$ M$_\odot$ yr^{-1}. The existence of a CWR between HD 93129A and B is very unlikely (see Section 5.4).

5.2. A CWR between the binary components of HD 93129A ?

Walborn (2002) recently reported that HD 93129A is a binary system. Using the HST Fine Guidance Sensor Interferometer, Nelan et al. (2003, in prep.) resolved it into a 55 mas binary with a magnitude difference of 0.9 mag (Walborn 2003, priv. comm.). In the binary system, we will call "a" the O2 primary, and "b", the secondary. The total V magnitude measured for HD 93129A is 7.2 mag (Hog et al. 1998). Given that $V_{\rm a} = 7.6$ mag, and $V_{\rm b} = 8.5$ mag (Walborn 2003, priv. comm.), the secondary has a magnitude similar to that of HD 93129B ($V = 8.9$ mag) and HD 93128 ($V = 8.8$ mag) (Walborn et al. 2002). The four stars are probable coeval, and their spectral types should be similar (E. Nelan et al., in preparation).

The binary separation (55 mas = 154 AU) implies that the stellar winds are likely to interact. In fact, there is a high probability that the system is an O+O colliding wind binary. Additional support to this idea can be found by studying the radio spectral index (see Section 5.3). Assuming that the companion is an O3.5 V star with the same terminal velocity, effective temperature, luminosity, and expected mass loss rate than HD 93129B (see Table 1), we find $\eta = 0.14$, $r_{\rm Aa} = 112$ AU, and $r_{\rm Ab} = 42$ AU. The binary separation of HD 93129A is similar to that of WR 146 (210 AU, Setia Gunawan et al. 2000), thus it is reasonable to assume a similar extent for the CWR, i.e. $\sim$50 AU. We estimate the equipartition magnetic field for the CWR according to Miley (1980) and find $B_{\rm CWR} \approx 4$ mG. Using the magnetic field structure given by Eichler & Usov (1993), the surface magnetic field of HD 93129Aa can be extrapolated to $B_* \sim 100$ G, if the stellar rotational velocity is $0.1 v_\infty$ (Conti & Ebbets 1997). This estimate is consistent with the few observational values available (Donati et al. 2001, 2002).

Substituting the parameters of HD 93129Aa and Ab into Eqs. (15) and (16) from Eichler & Usov (1993) we obtain:

$$L_{\rm rad} \approx\ 7.4 \times 10^{31}\, \beta\, \left(\frac{\epsilon}{10^{-2}}\right) \left(\frac{\xi}{10^{-3}}\right) {\rm erg\,s^{-1}} \qquad (5)$$

for the expected non-thermal radio luminosity of the CWR, and $\xi \approx 5 \times 10^{-5}$. Taking typical values of $\beta \sim 0.1$, $\epsilon \sim 10^{-2}$, we calculate $L_{\rm rad} \approx 4 \times 10^{29}$ erg s^{-1}.

From the observed flux densities we obtain a radio luminosity of $L_{\rm obs} = 1.12 \times 10^{29}$ erg s^{-1} for HD 93129A between 4.8 and 8.64 GHz, which is in good agreement with the total expected one.

In a colliding wind binary system like the one described here, a total X-ray luminosity due to Bremsstrahlung can be computed. Following Usov (1992) we obtain 2.2×10^{33} erg s^{-1}, very close to the observed X-ray luminosity by Evans et al. (2003).

5.3. Spectral index considerations

The spectral index of -1.2 ± 0.3 derived from the observations presented here is much steeper than that estimated by White (1985), $\alpha = +0.5$, for synchrotron emission from a single star. Steeper indices can result in the CW scenario as the effect of the softening of the particle spectrum due to inverse Compton (IC) losses (Benaglia & Romero 2003). At a CWR the accelerated electrons follow a power-law spectrum $N(E) \propto E^p$, with $p = -2$. Both synchrotron and IC processes help electrons to lose energy. At high energies, the radiative cooling would be dominated by IC losses, due to the strong photon fields at the CWR. At the energy $E_{\rm b}$ at which the cooling and escape times are equal (e.g. Longair 1997, p. 281), IC losses produce a break in the spectrum, from an index p to $p' = p-1$. The same population of relativistic electrons is capable of losing energy via synchrotron emission, producing a flux $S(\nu) \propto \nu^\alpha$, where $\alpha = (p+1)/2$. Thus, for $E < E_{\rm b}$, $\alpha \approx -0.5$, and for $E > E_{\rm b}$, $\alpha \approx -1$. This last value seems to be consistent with the spectral index derived from the present observations. The break energy can be computed if the following set of parameters is known (see Benaglia & Romero 2003): the mass loss rates, wind terminal velocities, and luminosities of both components, and the magnetic field at the CWR, together with the size s of the non-thermal source. Replacing the values adopted or obtained above, the break frequency in the radio range will be a few GHz. ATCA observations at 1.4 and 2.4 GHz are necessary to test this scenario.

The relative importance of the processes already mentioned can be measured by estimating the time needed for an electron to lose all its energy, either in the form of synchrotron radiation ($t_{\rm syn}$) or IC scattering ($t_{\rm IC}$). The importance of synchrotron and inverse Compton radiation for electrons of the same energy can be measured computing the ratio between the corresponding lifetimes (Longair 1997, p.274):

$$\frac{t_{\rm syn}}{t_{\rm IC}} = \frac{U_{\rm rad}}{U_{\rm mag}}, \qquad (6)$$

where $U_{\rm rad}$ and $U_{\rm mag}$ are the energy densities of the radiation field and of the magnetic field respectively. Using the observed radio luminosity $L_{\rm obs}$, we get $U_{\rm rad} = 2.5 \times 10^{-9}$ eV m^{-3}. The variable $U_{\rm mag}$ is 6.4×10^{-15} eV m^{-3}. The corresponding time ratio is about $\sim 4 \times 10^5$, thus $t_{\rm syn} >> t_{\rm IC}$. Following this last estimate, and under the conditions mentioned above, IC losses should dominate over synchrotron ones.

5.4. Colliding wind emission from other binaries

There are only a few examples (WR 146, WR 147, Cyg OB2 No. 5) of early-type binary systems in the literature where radio emission from the CWR has been observed. WR 146 is a WC6+O8 binary (van der Hucht 2001). Dougherty et al. (2000) observed the stars with MERLIN at 5 GHz twice, and with the VLA at 1.4, 5, 8.5 and 22 GHz. The combination of their MERLIN data with the 22 GHz VLA data allowed them to detect two thermal sources, coincident with the WR and OB stars, plus a non-thermal one in-between, nearer to the OB star, and possibly coming from the CWR. At a distance of 1.25 kpc (van der Hucht et al. 2001), the separation of the stellar components is $\sim$210 AU, and the size of the non-thermal source is $\sim$50 AU (Setia Gunawan et al. 2000). The flux densities quoted in the literature are: 31.4 ± 0.4 mJy and 28.5 ± 0.3 mJy at 5 GHz for the source identified as the CWR, 7.0 ± 1.3 mJy at 22 GHz for the emission possibly related to the WR star, and 10.4 ± 1.0 mJy from the OB star. The ratios of the non-thermal to thermal flux densities are $\sim$3 for the O star, and $\sim$4 for the WR star.

Contreras & Rodríguez (1999) presented 8.5 GHz-VLA observations of the star WR 147, a binary system formed by WN8 (h)+B0.5 V components (van der Hucht et al. 2001), at a distance of 650 pc (van der Hucht 2001). They detected a southern, thermal radio source coincident with the WR component, and a northern, non-thermal source.

The latter is interpreted as originating at the intera zone between the winds of the WR and OB stars. averaged measured flux densities are 28.4 ± 0.5 mJy the thermal source, and 10.4 ± 0.5 mJy from the thermal source. The stellar separation is ~420 AU Gunawan et al. 2001). The non-thermal to therma density ratio is ~0.4.

Cyg OB2 No. 5 seems to be formed by three an O7 Ia+Ofpe/WN9 contact binary, and a B0 V s a larger orbit (Contreras et al. 1997, Rauw et al. 1 located at 1.8 kpc (e.g. Waldron et al. 1998). The se tion between the contact pair and the third compon about 1700 AU. Radio observations by Persi et al. (and Miralles et al. (1994) at 1.4, 5, 8.5 and 15 GHz, sh that the source coincident with the contact pair pres flux variations, defining a "high" emission state ($S_{8.5}$ 5 – 7 mJy, and $\alpha \sim 0$), and a "low" emission state (S_{8} = 1 –2 mJy, and $\alpha \sim 0.6$). Contreras et al. (1996, performed VLA observations at 5 and 8.5 GHz, dete a non-thermal source ($\alpha = -2.4 \pm 0.6$) near the B0 V and proposed it was a CWR in the system. They mea a flux density at 8.5 GHz of 0.31 ± 0.02 mJy. The ra the emission from the weaker non-thermal source t emission of the contact pair at the lower state, is 0.2.

The system HD 93129A presents a binary sepa similar to that of WR 146. The ratio of non-therm thermal emission is unknown. If the magnetic field a CWR is equal to the equipartition field derived abov mG, then it is similar to those derived for WR 147 (5 and WR 146 (25 mG); see Benaglia & Romero (2003 scarcity of the examples and the huge differences i ratios of CWR-non-thermal to stellar-thermal flux ties measured for the three cases from the literature, the results of the comparison inconclusive.

5.5. The radio spectrum of HD 93129A

To separate the thermal and non-thermal contribu to the spectrum of HD 93129A, further radio observa are needed at lower and, particularly, at higher radio fre-quencies. These can be obtained with the ATCA at 1.4, 2.3, 16–25, and 85–91 GHz. The system can be resolved with the Long Baseline Array, but the flux densities of the thermal winds are likely too low for a detection, and an absolute position for the CWR would be difficult to obtain.

If the actual mass loss rate of HD 93129A is $\dot{M} = 2.1 \times 10^{-5}$ M$_\odot$ yr^{-1}, i.e. $f_{\rm T} = 0.15$ (see Section 4.1), the thermal and non-thermal contributions to the 3 cm radio flux density are ~0.3 and ~1.7 mJy, respectively. Assuming a spectral index of $\alpha_{\rm T} = 0.6$ for the thermal component, we find the spectral index for the non-thermal component is $\alpha_{\rm NT} \sim -1.4 \pm 0.3$. The expected total flux densities (see Fig. 3a) are ~1.2, ~ 1, and ~1.3 mJy at 16, 25 and 90 GHz, respectively.

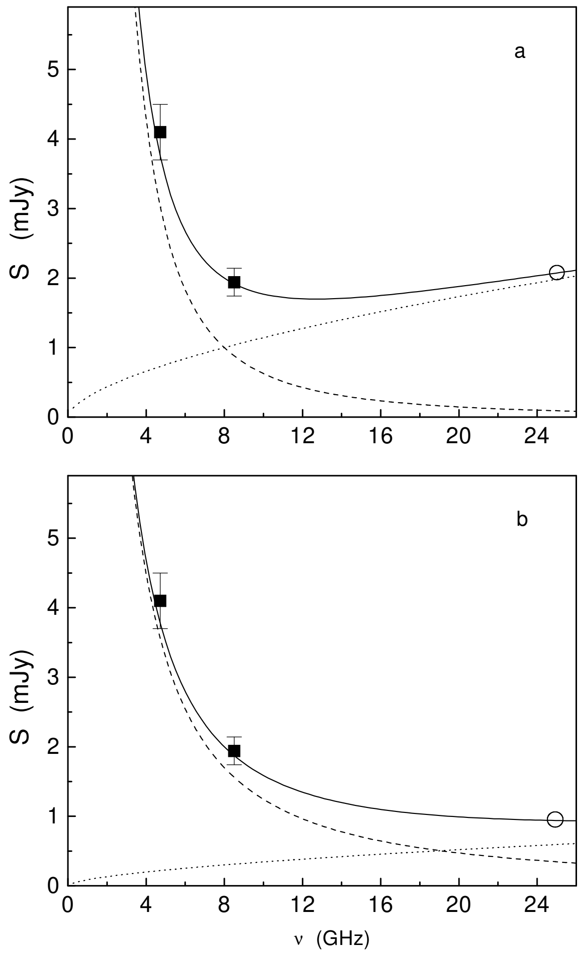

Fig. 3. a) Measured and predicted radio continuum flux densities for HD 93129A in the frequency range from ~1 to 25 GHz. The two measurements at 4.8 and 8.64 GHz are indicated by black squares. Assuming that the flux density measured at 8.64 GHz, $S_{3\rm cm}$, consists to equal parts of thermal and non-thermal emission ($f_{\rm T} = 0.5$), and that the thermal emission has a spectral index of $\alpha_{\rm T} = 0.6$, we can fit the observed flux densities by adding a non-thermal component with $\alpha_{\rm NT} = -2.1 \pm 0.3$. The dotted and dashed lines show the thermal and non-thermal radio emission, respectively. The solid line represents the combined thermal and non-thermal radio emission for this model. b) As Fig. 3a, but assuming $f_{\rm T} = 0.15$. In this case, we can fit the observed flux densities by adding a non-thermal component with $\alpha_{\rm NT} = -1.4 \pm 0.3$.

In contrast, for $f_{\rm T} = 0.5$ we find $\alpha_{\rm NT} \sim -2.1 \pm 0.3$, similar to that derived for other Of systems (e.g., Cyg OB2 No. 5, Contreras et al. 1996, 1997). At 16, 25 and 90 GHz we expect ~1.7, ~2, and ~4.1 mJy (see Fig. 3b). In this case, the radio derived mass loss rate of the system is 5.1×10^{-5} M$_\odot$ yr^{-1}. The two scenarios can be distinguished with high-frequency ATCA synthesis observations.

6. Conclusions

The field of view towards the Galactic cluster Tr 14 has been observed with the ATCA in the radio continuum at

4.80 GHz (3 cm) and 8.64 GHz (6 cm). Only one source, the O2 If* star HD 93129A, was detected with flux densities of 2.0 ± 0.2 mJy at 3 cm, and 4.1 ± 0.4 mJy at 6 cm, resulting in a very steep spectral index of $\alpha = -1.2 \pm 0.3$. This star, recently reported as binary, is the earliest known O-star and potentially the most massive system in the Galaxy, followed by η Carina. The observed radio emission is most likely coming from (a) the thermal winds of both binary components and (b) the non-thermal emission from the colliding wind region. The negative spectral index of HD 93129A suggests that the latter is the dominant emission mechanism.

We derive a mass loss rate of $(f_{\rm T})^{3/4} \times 8.6 \times 10^{-5}$ M$_\odot$ yr^{-1} for HD 93129A and 3σ upper limits of $(f_{\rm T})^{3/4} \times 2.13 \times 10^{-5}$ M$_\odot$ yr^{-1} for HD 93129B and HD 93128, where $f_{\rm T}$ is the thermal fraction of the 3 cm radio continuum emission.

Although the secondary star in the binary HD 93129A remains yet unclassified, the presence of intense non-thermal emission and high radio luminosity together suggest it is another massive, early-type star.

The lack of radio emission near HD 93129B, and the extremely large separation of HD 93129A/B (7300 AU at 2.8 kpc) conspires against the existence of a colliding wind region in-between the stars.

It is crucial to perform observations (i) at lower frequencies, where the thermal contributions should be negligible, and an accurate non-thermal index can be derived; this would help to investigate the processes responsible for the radiation detected; and (ii) at high frequencies, at which non-thermal emission decreases, and the estimation of the thermal flux will enable us to derive the value of the true mass loss rate of HD 93129A.

Acknowledgments

We would like to thank the anonymous referee for comments and suggestions that help to improve the presentation of our investigation. We are indebted to E. Nelan and N. A. Walborn for allowing us to share their HST results before publishing, and to N. A. Walborn and G. E. Romero for a critical reading of the manuscript. P.B. is grateful to the ATNF staff at Sydney and Narrabri. This research has been supported mainly by Fundación Antorchas (P.B.), and has made use of the SIMBAD database operated at CDS, Strasbourg, France.

References

Abbott, D.C., Bieging, J.H., & Churchwell, E. 1986, ApJ 303, 239
Benaglia, P., & Cappa, C.E. 1999, A&A 346, 979
Benaglia, P., Romero, G.E., Stevens, I.R., & Torres, D.F. 2001a, A&A 366, 605
Benaglia, P., Cappa, C.E., & Koribalski, B.S. 2001b, A&A 372, 952
Benaglia, P., & Romero, G.E. 2003, A&A 399, 1121
Bohannan, B. 1990, in "Properties of Hot Luminous Stars", ed. C.D. Garmany, Brigham Young Press, 39
Chapman, J.M., Leitherer, C., Koribalski, B.S., et al. 1999, ApJ 518, 890
Chlebowski, T., & Garmany, C.D. 1991, ApJ 368, 241
Conti, P.S., Leep, E.M., & Lorre, J.J. 1977, ApJ 214, 759
Conti, P.S., Niemela, V.S., & Walborn, N.R. 1979, ApJ 228, 206
Conti, P.S., & Garmany, C.D. 1983, PASP 95, 411
Conti, P.S., & Ebbets, D. 1997, ApJ 213, 438
Contreras, M.E., Rodríguez, L.F., Gómez, Y., et al. 1996, ApJ 469, 329
Contreras, M.E., Rodríguez, L.F., Tapia, M., et al. 1997, ApJ 488, L153
Contreras, M.E., & Rodríguez, L.F. 1999, ApJ 515, 762
Crowther, P.A., Smith, L.J., Hillier, D.J., & Schmutz, W. 1995, A&A 293, 427
DeGioia-Eastwood, K., Throop, H., Walker, G., et al. 2001, ApJ 549, 578
Donati, J.-F., Wade, G.A., Babel, J., et al. 2001, MNRAS 326, 1265
Donati, J.-F., Babel, J., Harries, T.J., et al. 2002, MNRAS 333, 55
Dougherty, S.M., Williams, P.M., & Pollaco, D.L. 2000, MNRAS 316, 143
Dougherty, S.M., & Williams, P.M. 2000, MNRAS 319, 1005
Drew, J.E. 1989, ApJS 71, 267
Eichler, D., & Usov, V. 1993, ApJ 402, 271
Evans, N.R., Seward, F.D., Kraus, M.I., et al. 2003, ApJ 589, 509
García, B. Malaroda, S., Levato, H., et al. 1998, PASP, 110, 53
Hog, E., Kuzmin, A., Bastian, U., et al. 1998, A&A 335, L65 (Tycho-1)
Hog, E., Fabricius, C., Makarov, V.V., et al. 2000, A&A 355, L27 (Tycho-2)
Humphreys, R., & McElroy, D.B. 1984, ApJ 284, 565
van der Hucht, K.A. 2001, New Astronomy 45, 135
van der Hucht, K.A., Setia Gunawan, D.Y.A., Williams, P.M., et al. 2001, in "Interacting Winds from Massive Stars", eds. A.F.J. Moffat & N. St-Louis, ASP Conf. Ser. 165, p. 267
van der Hucht, K.A. 2002, Astrophysics & Space Science 281, 199
Lamers, H.J.G.L.M., & Leitherer, C. 1993, ApJ 412, 771
Langer, N., Hamann, W.-R., Lennon, M. et al. 1994, A&A 290, 819
Leitherer, C., Chapman, J.M., & Koribalski, B.S. 1995, ApJ 450, 289
Levato, H., Malaroda, S., Morrell, et al. 2000, PASP 112, 359
Longair, M.S. 1997, High Energy Astrophysics, Vol. 2, Cambridge University Press, Cambridge
Maíz-Apellániz, J., & Walborn, N. R. 2002, in "A Massive Star Odyssey: from Main Sequence to Supernova", eds. K. A. van der Hucht, A. Herrero, & C. Esteban, ASP Conf. Ser. 212, p. 560
Mason, B.D., Gies, D.R., Hartkopf, W.I., et al. 1998, ApJ 115, 821

Mason, B.D., Wycoff, G.L., Hartkopf, W.I., et al. 2001, AJ 122, 3466
Massey, P., & Johnson, J. 1993, AJ 105, 980
Massey, P., & Hunter, D.A. 1998, ApJ 493, 180
Miley, G.K. 1980, Ann. Rev. Astron. Astrophys. 18, 165
Miralles, M.P., Rodríguez, L.F., Tapia, M. et al. 1994, A&A 282, 547
Morrell, N., García, B., & Levato, H. 1988, PASP 100, 1431
Panagia, N., & Felli, M. 1975, A&A 39, 1
Penny, L.R., Gies, D.R., Hartkopf, W.I., et al. 1993, PASP 105, 588
Persi, P., Tapia, M., Rodríguez, L.F., et al. 1990, A&A 240, 93
Prinja, R.K., Barlow, M.J., & Howarth, I.D. 1990, ApJ 361, 607
Puls, J., Kudritzki, R.P., Herrero, A., et al. 1996, A&A 305, 171
Rauw, G., Vreux, J.-M., & Bohannan, B. 1999, ApJ 517, 416
Reed, B.C., & Beatty, A.E. 1995, ApJS 97, 189
Reynolds, J. 1994, "A Revised Flux Scale for the AT Compact Array", ATNF Internal Report, AT/39.3/040
Scuderi, S., Panagia, N., Stanghellini, et al. 1998, A&A 332, 251
Setia Gunawan, D.Y.A., de Bruyn, A.G., van der Hucht, K.A., & Williams, P.M. 2000, A&A 356, 676
Setia Gunawan, D.Y.A., van der Hucht, K.A., Williams, P.M., et al. 2001, A&A 376, 460
Simon, K.P., Jonas, G., Kudritzki, R.P. et al. 1983, A&A 125, 34
Tapia, M., Roth, M., Vázquez, R.A. et al. 2003, MNRAS 339, 44
Taresch, G., Kudritzki, R.P., Hurwitz, M., et al. 1997, A&A 321, 531
Usov, V. 1992, ApJ 389, 635
Vacca, W.D., Garmany, C.D., & Schull, J.M. 1996, ApJ 460, 914
Vázquez, R.A., Baume, G., Feinstein, A., et al. 1996, A&AS 116, 75
Vink, J.S., de Koter, A., & Lamers, H.J.G.L.M. 2000, A&A 362, 295
Walborn, N.R. 1973, ApJ 179, 517
Walborn, N.R. 1982, AJ 87, 1300
Walborn, N.R. 1992, ApJ 393, L13
Walborn, N.R. 2002, in "A Massive Star Odyssey: from Main Sequence to Supernova", eds. K. A. van der Hucht, A. Herrero, & C. Esteban, ASP Conf. Ser. 212, p. 13
Walborn, N.R., Howarth, I.D., Lennon, D.J., et al. 2002, AJ 123, 2754
Waldron, W.L., Corcoran, M.F., Drake, S.A. & Smale, A.P. 1998, ApJS 118, 217
Worley, C.E., & Douglass, G.G. 1997, A&AS 125, 523
White, R.L. 1985, ApJ 289, 698
Wright, A.E., & Barlow, M.J. 1975, MNRAS 170, 41