RADIO EMISSION VARIABILITY AND PROPER MOTIONS OF WR 112

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RESUMEN

Analizamos 64 observaciones en radio a la frecuencia de 8.4 GHz de la estrella Wolf-Rayet WR 112, tomadas de los archivos del *Very Large Array*. Las observaciones cubren una línea de base temporal de 13 años, de junio del 2000 a julio de 2013. La estructura de WR 112 es consistente con ser una fuente puntual en todas las épocas y su densidad de flujo varía entre 0.6 mJy y 2.1 mJy. Intentamos buscar periodicidades en estas variaciones sin éxito. También buscamos emisión extendida asociada con la nebulosa infrarroja que rodea a WR 112, y encontramos límites superiores de 50 μJy. Finalmente, usamos las observaciones con resolución más alta para medir los movimientos propios de WR 112, y obtenemos $\mu_\alpha \cos\delta = -2.6 \pm 1.1$ mas yr^{-1}, y $\mu_\delta = -5.4 \pm 1.4$ mas yr^{-1}. Estos movimientos propios son menores que los reportados previamente, pero continúan sugiriendo movimientos peculiares significativos.

ABSTRACT

We analyzed 64 radio observations at the frequency of 8.4 GHz of the Wolf-Rayet star WR 112, taken from the *Very Large Array* archive. These observations cover a time baseline of 13 years, from June 2000 to July 2013. The radio structure of WR 112 is consistent with it being a point source in all the epochs and with its flux density varying from 0.6 mJy to 2.1 mJy. We tried to search for periodicities in these variations but our results were not conclusive. We also looked for extended emission from the infrared nebula that surrounds WR 112, setting upper limits of 50 μJy. Finally, we used the highest angular resolution images to measure the proper motions of WR 112, obtaining $\mu_\alpha \cos\delta = -2.6 \pm 1.1$ mas yr^{-1}, and $\mu_\delta = -5.4 \pm 1.4$ mas yr^{-1}. These proper motions are smaller than those previously reported, but still suggest significant peculiar motions for WR 112.

1. INTRODUCTION

A small fraction of the Wolf-Rayet (WR) stars are known to be dust-producing sources. How the dust is formed in these hostile environments and whether or not is this dust production episodic or continuous are issues still not understood. Among this dust-producing WR stars we have WR 112, which belongs to the carbon subclass and has been classified as WC9 (Massey & Conti 1983). (Marchenko et al. 2002) suggested that it is a binary system with a period of 25 years, with the companion being an OB star. However, there has not been a direct detection of this proposed companion. WR 112 is located at a distance of 4.15 kpc (van der Hucht 2001). The dust production rate for WR 112 is estimated to be $\sim 6.1 \times 10^{-7} M_\odot$ yr^{-1} (Marchenko et al. 2002). The dust exhibits a pinwheel-like morphology around WR 112 at arcsecond scales (Marchenko et al. 2002), that could extend down to sub-arcsecond scales (i.e., Ragland & Richichi 1999). WR 112 also shows variable radio emission (Monnier et al. 2002) and significant proper mo-

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TABLE 1

VLA OBSERVATIONS OF WR112 AT 8.4 GHz

Epoch dd/mm/yyyy	MJD	Config.	Project	Flux (mJy)
20/06/2000	51715	CD	AM661	2.08 ± 0.04
09/09/2000	51796	D	AM661	1.24 ± 0.06
17/10/2000	51834	A	AM661	0.94 ± 0.07
23/12/2000	51901	A	AM661	0.87 ± 0.06
21/02/2001	51961	AB	AM661	0.77 ± 0.03
04/05/2001	52033	B	AM661	1.08 ± 0.11
13/09/2001	52165	C	AM687	0.93 ± 0.11
13/11/2001	52226	D	AM687	1.15 ± 0.11
18/01/2002	52292	A	AM687	0.82 ± 0.06
07/05/2002	52401	A	AM727	0.97 ± 0.07
06/06/2002	52431	AB	AM727	1.31 ± 0.08
17/08/2002	52503	B	AM727	0.85 ± 0.05
11/09/2002	52528	B	AM727	1.11 ± 0.13
14/10/2002	52561	C	AM727	0.63 ± 0.07
22/11/2002	52600	C	AM727	0.92 ± 0.06
05/01/2003	52644	C	AM727	0.96 ± 0.02
22/02/2003	52692	D	AM727	0.91 ± 0.05
17/03/2003	52715	D	AM727	1.01 ± 0.04
06/07/2003	52826	A	AM766	0.69 ± 0.07
19/09/2003	52901	A	AM766	0.82 ± 0.09
17/10/2003	52929	AB	AM766	0.85 ± 0.08
10/11/2003	52953	B	AM766	0.81 ± 0.09
14/12/2003	52987	B	AM766	0.58 ± 0.07
26/01/2004	53030	BC	AM766	0.87 ± 0.05
13/02/2004	53048	BC	AM766	0.93 ± 0.06
20/03/2004	53084	C	AM766	0.66 ± 0.04
16/04/2004	53111	C	AM766	0.93 ± 0.05
22/05/2004	53147	C	AM793	0.76 ± 0.04
12/07/2004	53198	D	AM727	0.86 ± 0.05
21/09/2004	53269	A	AM793	0.71 ± 0.07
12/01/2005	53382	A	AM793	1.05 ± 0.10
30/01/2005	53400	AB	AM793	0.99 ± 0.10

TABLE 1 (CONTINUED)

VLA OBSERVATIONS OF WR112 AT 8.4 GHz

Epoch dd/mm/yyyy	MJD	Config.	Project	Flux (mJy)
03/02/2005	53404	AB	AM793	0.76 ± 0.05
11/02/2005	53412	AB	AM793	1.36 ± 0.23
24/03/2005	53453	B	AM793	1.06 ± 0.23
16/04/2005	53476	B	AM793	0.81 ± 0.05
20/05/2005	53510	B	AM793	0.82 ± 0.06
06/06/2005	53527	B	AM793	0.94 ± 0.08
04/07/2005	53555	BC	AM831	0.81 ± 0.06
22/08/2005	53604	C	AM831	0.85 ± 0.05
02/09/2005	53615	C	AM831	0.99 ± 0.06
16/10/2005	53659	C	AM831	0.79 ± 0.09
24/12/2005	53728	D	AM831	0.67 ± 0.04
11/02/2006	53777	A	AM831	0.72 ± 0.07
22/04/2006	53847	A	AM831	0.79 ± 0.06
30/07/2006	53946	B	AM862	0.80 ± 0.10
25/11/2006	54064	C	AM862	0.92 ± 0.07
05/03/2007	54164	D	AM862	1.17 ± 0.09
03/10/2007	54376	AB	AM901	0.86 ± 0.07
09/12/2007	54443	B	AM901	1.22 ± 0.18
26/03/2008	54551	C	AM901	1.45 ± 0.14
12/07/2008	54659	D	AM952	0.92 ± 0.10
21/12/2008	54821	A	AM952	0.94 ± 0.08
21/08/2009	55064	C	AM952	1.17 ± 0.11
17/10/2009	55121	D	AM983	1.06 ± 0.04
21/04/2010	55064	D	AM983	1.24 ± 0.05
23/10/2010	55492	C	10B-100	1.25 ± 0.06
22/03/2011	55642	B	10B-100	1.22 ± 0.03
03/08/2011	55776	A	10B-100	1.15 ± 0.05
02/01/2012	55928	D	11B-001	1.25 ± 0.05
04/05/2012	56051	C	11B-001	1.19 ± 0.03
23/07/2012	56131	B	11B-001	0.96 ± 0.04
12/01/2013	56304	A⇒D	12B-005	0.95 ± 0.03
23/07/2013	56496	C	12B-005	0.88 ± 0.05

tions (Dzib & Rodríguez 2009). Whether this radio emission is periodic or not and how it is related to its proper motions, the periods of the possible companions and the periods of dust formation are points that remain unknown.

WR 48a is a carbon-rich WR star, also known as a long-period dust maker and a colliding-wind binary, and thus similar to WR 112. Multi–epoch studies of WR 48a with infrared photometry by (Williams et al. 2012) imply a period for dust emission of ≈ 32 years and suggest that there are also some irregular *mini*-periods of a few years. Determination of the period of the radio variations and the proper motions of WR 112 could give insights into the orbital elements of the companion and how it is related to the dust production. In the present work we will use radio observations taken over a period of 13 years to study the enigmatic WR 112 system.
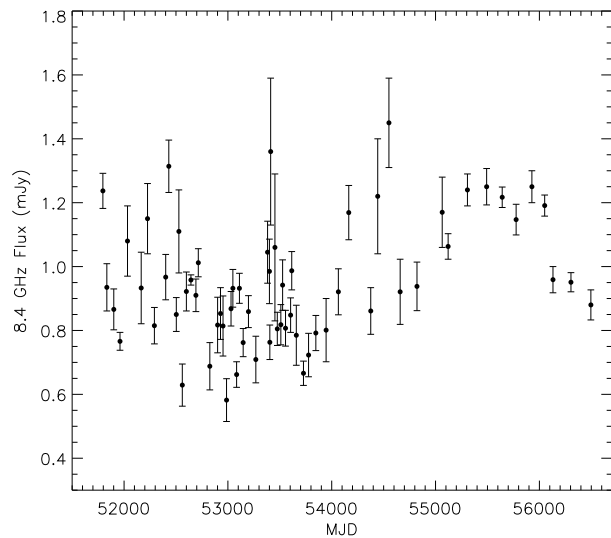
Fig. 1. Flux densities of WR 112 at 8.4 GHz as a function of MJD.

Fig. 2. Multi–epoch image of WR 112 at 8.4 GHz combining VLA C and D configurations. The measured flux density is 0.78±0.02 mJy. Contours levels correspond to -3, 3, 10, 20, 30 and 40 times 16 μJy beam^{-1}, the noise level of the image. The half power contour of the synthesized $(3.\!''5 \times 2.\!''1; P.A. = -8°)$ beam is shown in the bottom left corner.

2. OBSERVATIONS AND DATA CALIBRATION

The radio observations of WR 112 were taken from the archives of the Very Large Array (VLA) of the NRAO[6]. We found a total of 64 observations in the VLA archive at a frequency of 8.4 GHz $(\lambda = 3.6$ cm)[7]. These observations cover the period from June 2000 to July 2013. For some epochs two phase calibrators, J1820-254 and J1832-105, were used. J1820-254 is located at an angular distance of $6.\!°57$ from WR 112, and showed a flux density in the range of 0.63 to 1.20 Jy. Similarly, J1832-105, is located at an angular distance of $9.\!°22$ from WR 112, and showed a flux density in the range of 1.29 to 1.54 Jy. To obtain the best gain transfers it is recommended to choose a phase calibrator close to the target, with a large flux density and pointlike morphology. Furthermore, to obtain accurate absolute astrometry the same phase calibrator must be used at all epochs. Because J1820-254 has a better determined position and is closer to WR 112 than J1832-105, our analysis is restricted only to the observations that are phase calibrated with J1820-254. Fortunately, this calibrator is present at all epochs.

The data were edited, calibrated and imaged in the standard fashion using the Common Astronomy Software Applications package (CASA). After

the initial calibration, the visibilities were imaged with a pixel size of a fifth the size of the resulting synthesized beam at each epoch. The weighting scheme used was intermediate between natural and uniform (WEIGHTING='briggs' with RObust=0.0 in CASA). The rms noise level of the images was typically ≈ 50 μJy beam^{-1}, but it can be slightly different for some epochs.

3. RESULTS AND DISCUSSIONS
3.1. *Radio Emission Variation*

WR 112 was detected at all epochs with a pointlike structure. Its flux density at each epoch was measured using the task IMFIT in CASA, and the values are given in Table 1. The flux densities of WR 112 show variations at levels from 0.58 mJy up to 2.08 mJy (see Table 1). To determine whether these variations are periodic or not, we proceeded as follows.

According to (Monnier et al. 2002), WR 112 was in a very high state of activity reaching up to 4.4 mJy at 8.4 GHz during 1999 September until after 2000 February. Therefore, the observation of June 2000, corresponding to our maximum measured flux density of 2.08 mJy, could be a remnant of the activity that occurred during that period. It was not included in the analysis.

[6]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

[7]We found a few other observations at other frequencies, but they were not useful for the purposes of the present work, thus we did not take them into account.
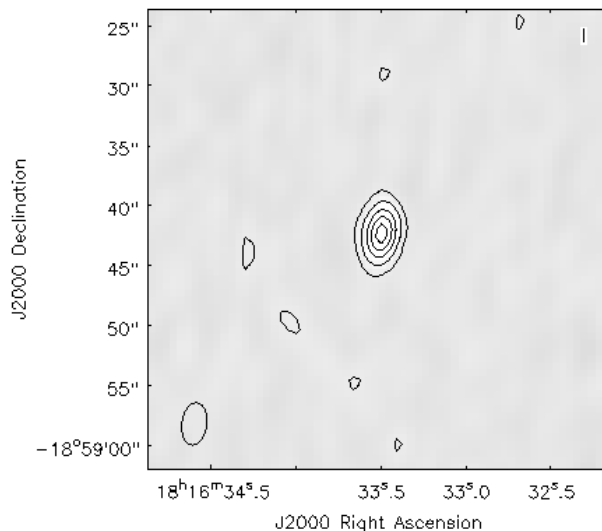
TABLE 2

EQUATORIAL COORDINATES OF WR 112

Epoch	α 18^h16^m	$\Delta\alpha$ $\times10^{-3}$	δ $-18°58'$	$\Delta\delta$ $\times10^{-2}$
2000.80	$33\overset{s}{.}4923$	0.5	$42\overset{''}{.}352$	1.3
2000.98	$33\overset{s}{.}4943$	1.6	$42\overset{''}{.}382$	3.7
2002.35	$33\overset{s}{.}4904$	0.5	$42\overset{''}{.}321$	1.2
2003.51	$33\overset{s}{.}4950$	0.7	$42\overset{''}{.}301$	1.8
2003.72	$33\overset{s}{.}4897$	2.2	$42\overset{''}{.}346$	2.0
2003.79	$33\overset{s}{.}5026$	2.0	$42\overset{''}{.}040$	5.0
2004.73	$33\overset{s}{.}4904$	0.6	$42\overset{''}{.}379$	1.6
2005.03	$33\overset{s}{.}4904$	1.1	$42\overset{''}{.}359$	1.9
2006.12	$33\overset{s}{.}4928$	0.7	$42\overset{''}{.}381$	1.6
2006.31	$33\overset{s}{.}4906$	0.4	$42\overset{''}{.}407$	1.1
2007.76	$33\overset{s}{.}4927$	1.8	$42\overset{''}{.}288$	1.6
2008.97	$33\overset{s}{.}4918$	0.5	$42\overset{''}{.}395$	1.4
2011.59	$33\overset{s}{.}4903$	0.2	$42\overset{''}{.}414$	0.7
2012.62	$33\overset{s}{.}4907$	1.2	$42\overset{''}{.}393$	2.8
2013.03	$33\overset{s}{.}4902$	0.2	$42\overset{''}{.}398$	0.5

The flux densities of the remaining observations (plotted in Figure 1) were used to look for periodicities in the data using the Lomb-Scargle method (Scargle 1982; Lomb 1976; Press et al. 1992). This method estimates a frequency spectrum for an incomplete or unevenly sampled time series. The method uses least squares fits of sinusoidal functions over a determined period range. In our case, we used a range from 10 days to 13 years. We obtained two possible periods, 11.7 years and 18.8 days. However, the false alarm probabilities are 22% and 23%, respectively, and thus the possible periodicities are marginal. In conclusion, we did not find any reliable periodicity in the flux density variations in WR 112.

3.2. Extended Nebula

One of the most important features of WR 112 is that it is a dust producer star and has a circumstellar dust shell detected at 2.2 μm (Ragland & Richichi 1999). Due to the morphology of its envelope –a rotating spiral dust shell extending up to 6''– WR 112 has been classified as a pinwheel nebula. This structure was probably formed in the wind-wind collision region of the binary system(Marchenko et al. 2002). The pinwheel nebula structure could also be present at sizes down to ≈20 mas (Monnier et al. 2007).

In order to learn about the pinwheel structure of WR 112, sensitive observations at several wavelengths are needed. The intensity of dust emission rises rapidly with frequency and it is expected to be more important at frequencies higher than 8.4 GHz. However, high sensitivity observations at such frequencies have not been carried out with the VLA to our knowledge. Thus, we attempted to detect possible ionized material related to the pinwheel-nebula at the 8.4 GHz frequency of the observations analyzed.

This structure is not present in any of our final single–epoch images. One way to gain more sensitivity is by combining the visibilities of the single epochs producing a multi–epoch image. We notice, however, that the highest resolution could be affected by movements of the star and its more immediately surrounding material, see also next section. Then, we use the observations of the more compact VLA configurations, C and D. We concatenated all the observations corresponding to these configurations and WR 112 still looks as a point source with a $3\overset{''}{.}5 \times 2\overset{''}{.}1$ resolution (see Figure 2). No extended structures are detected at levels above 50 μJy. Sensitive images at higher frequencies could detect the dust emission of the pinwheel nebula in WR 112.

3.3. Proper Motions

For the determination of the proper motion we used the data sets of the epochs with the VLA in its A configuration, the most extended. We also used the July 2012 (2012.62) epoch, obtained in the B configuration, for two reasons. First, it was observed with the new Karl G. Jansky VLA system, and the signal to noise level reached for this epoch was better than in any of the previous B configuration observations, and thus we could determine a good position. Second, it helps to have a longer time baseline, which improves the astrometric measurements.

With the positions presented in Table 2, we determine the proper motions of WR 112 to be[8]:

$$\mu_\alpha \cos\delta = -2.6 \pm 1.1 \text{ mas yr}^{-1}$$
$$\mu_\delta = -5.4 \pm 1.4 \text{ mas yr}^{-1}.$$

Systematic contributions of $0\overset{''}{.}010$ and $0\overset{''}{.}009$ in the α and δ positions, respectively, were added in

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[8]We do not include epochs 2003.79 and 2007.76 in our proper motion analysis because their positions do not follow the trend presented by the others epochs, with a difference of up to $\sim 0\overset{''}{.}15$.
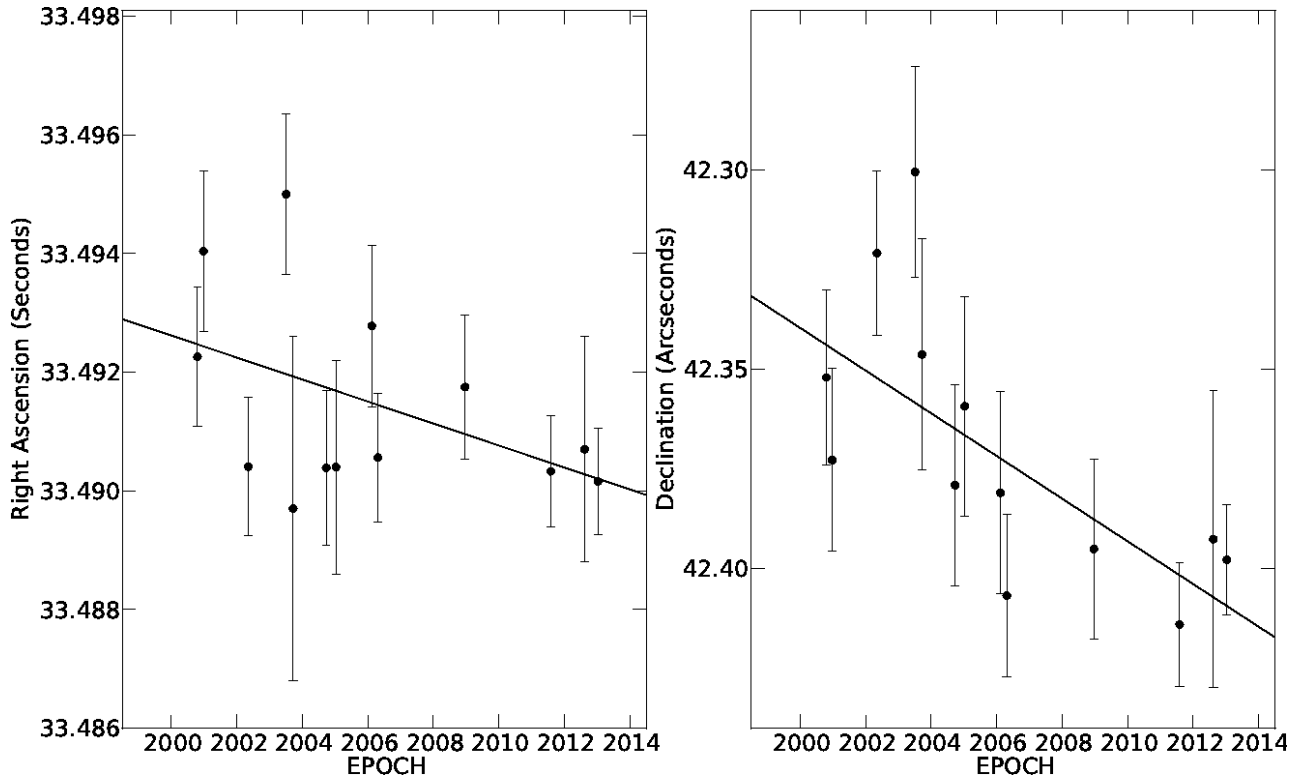
Fig. 3. Positions of WR 112 as a function of time. The right ascension is 18^h16^m and the declination is -18°58′. The solid lines are the least squares best fits to the positions.

quadrature to the positional errors obtained from a Gaussian fit (task IMFIT in CASA), in order to obtain a χ^2 of 1. The positions as a function of the epoch are presented in Figure 3.

The measured proper motions are significantly smaller than those found by (Dzib & Rodríguez 2009): $\mu_\alpha \cos\delta = -11.2 \pm 3.1$ mas yr^{-1}, $\mu_\delta = -13.5\pm5.5$ mas yr^{-1}. (Dzib & Rodríguez 2009) noted that the movements of WR 112 seemed to be affected by an abrupt change between two epochs. Inspecting Figure 3, we can note that the positions present some dispersion and that abrupt changes in position are also present. These changes are more prominent in the declination direction, in agreement with those noticed by (Dzib & Rodríguez 2009). Since we used more epochs than (Dzib & Rodríguez 2009), the dispersion is smoothed and allows us to measure more reliable proper motions. The noise of the new proper motions are 2 to 3 times smaller than those of (Dzib & Rodríguez 2009).

In galactic coordinates the new proper motions are $\mu_l \cos b = -6.0 \pm 1.7$ mas yr^{-1}, $\mu_b = -0.3 \pm 0.3$ mas yr^{-1}. At the position of WR 112 the expected proper motions for a source that is stationary with respect to its local standard of rest are $\mu_l \cos b = -1.1$ mas yr^{-1}, $\mu_b = -0.3$ mas yr^{-1} (Dzib & Rodríguez 2009). Then, WR 112 has residual proper motions of -4.9 ± 1.7 mas yr^{-1} in galactic longitude and of 0.0 ± 0.3 mas yr^{-1} in galactic latitude. These results are consistent with no peculiar motions in galactic latitude and a peculiar motion of -100 ± 34 km s^{-1} in galactic longitude. Even though the measurement is significant only at the 3-σ level, it suggests significant peculiar motions for WR 112. (Moffat et al. 1998) give as the criterion for a runaway star a velocity in excess of 42 km s^{-1} with respect to its local standard of rest. Then, WR 112 could be a runaway star and more accurate proper motions determinations are required to test this possibility.

4. CONCLUSIONS

We have analyzed the multi–epoch radio emission of the Wolf-Rayet star WR 112 at 8.4 GHz, from the VLA archive. Our main results are:

1. WR 112 is a variable radio source. We attempted to detect periodicity in scales of days to years, with no success.

2. The large structure of the infrared pinwheel nebulae is not visible at 8.4 GHz at levels of 50 μJy.

3. The proper motions derived here suggest significant peculiar motions for WR 112.

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