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## NEW VLA OBSERVATIONS OF WR 6 (= HR 50896): A SEARCH FOR AN ANISOTROPIC WIND

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### RESUMEN

La interacción entre un viento estelar y el medio interestelar circundante puede crear burbujas o cavidades de HI. En particular, WR 6 muestra una gran cavidad ovoide de HI a su alrededor, cuya forma no puede explicarse en términos de la teoría normal de las burbujas interestelares y podría requerir de un viento anisotrópico. En este artículo exploramos esta posibilidad con nuevas observaciones a 3.6-cm hechas con el VLA. No encontramos evidencia sólida apoyando la posibilidad de que WR 6 tenga un viento fuertemente anisotrópico y concluimos que los datos son consistentes con un viento isotrópico. Bajo esta suposición hemos determinado el tamaño de la fuente, su temperatura de brillo, y su tasa de pérdida de masa. Comparando nuestros cuatro flujos obtenidos a lo largo de aproximadamente seis meses, no encontramos evidencia de variabilidad fuerte ( $\leq 15\%$ ). Se ha propuesto también que WR 6 podría ser una binaria WR+c, pero las características observadas en el radio no apoyan esta hipótesis.

### ABSTRACT

The interaction between a stellar wind and its surrounding ISM can create HI cavities or bubbles. In particular, WR 6 shows a very large ovoidal HI bubble around it, whose shape cannot be explained in terms of the standard interstellar bubble theory, and may require an anisotropic stellar wind. In this paper, we have studied this possibility using new 3.6-cm VLA observations. We found no firm evidence supporting the possibility that WR 6 has a strongly anisotropic wind and conclude that our data are consistent with an isotropic wind. Under this assumption we have determined the source size, its brightness temperature and its mass loss rate. Comparing our four flux densities obtained over approximately 6 months, we found no evidence of large variability ( $\leq 15\%$ ). It has also been proposed that WR 6 could be a WR+c binary, but the observed radio characteristics do not support this hypothesis.

*Key Words:* **RADIO CONTINUUM: STARS — STARS: INDIVIDUAL (WR 6) — STARS: WOLF-RAYET — STELLAR WINDS**

### 1. INTRODUCTION

Massive stars possess powerful stellar winds that interact strongly with their surrounding medium. These strong winds are moving supersonically with respect to the ambient gas, creating a so-called bubble or cavity. Since the early 1970's Dyson & de Vries (1972), Castor, McCray, & Weaver (1975), Weaver

et al. (1977), and more recently Koo & McKee (1992a,b) studied theoretically the interaction between stellar winds and their surrounding medium. These studies have concluded that the stellar wind forms a thin dense shell of swept material whose dynamical evolution is very similar (at least at early times) to that of a supernova remnant, the only dy-

namical difference being the continuous injection of energy into the cavity by the stellar wind. A remarkable feature is that the expanding shell may be fully or partially ionized by the central star. If the ionization front is trapped in the shell, an outer layer of HI and H<sub>2</sub> is formed. If there is no other early type star in the vicinity, the HII region formed may cool and recombine becoming observable, for example, in radio recombination lines.

Because of their strong stellar winds Wolf-Rayet stars are the best candidates to form an HI cavity around them. Since the middle and late 1980's some studies have been carried out to examine the HI distribution around WR stars and to analyze the dynamics and energetic interactions between their strong stellar winds and the interstellar medium (Cappa de Nicolau & Niemela 1984; Cappa de Nicolau, Niemela, & Arnal 1986; Cappa de Nicolau et al. 1988; Arnal & Mirabel 1991; Arnal 1992).

In particular, WR 6 (= HD 50896) is one of the brightest WR stars that shows an HI cavity around it (Arnal 1992). This object is located at a Galactic longitude of  $l = 234.^{\circ}76$  and a Galactic latitude of  $b = -10.^{\circ}08$  (van der Hucht et al. 1988).

The distance to this star has been a controversial subject but recently it seems that the most accepted value for the distance is the one derived by Howarth & Schmutz (1995), who determined a distance of  $d = 1.8$  kpc based on high-spectral-resolution observations of the interstellar Na D lines. This distance places WR 6 at  $z \simeq 300$  pc below the Galactic plane. WR 6 has been studied at all accessible wavelengths. In the optical region, it has been associated with the ring nebula S308 (Johnson & Hogg 1965). This ring nebula could be the result of the interaction between the stellar wind and a previous mass ejection from the central star during its red giant phase (Esteban et al. 1992). However, based on kinematic and morphological arguments, Chu (1981) has classified it as a wind-blown bubble.

Also in the optical region, Wilson (1948) and Ross (1961) have reported spectroscopic and photometric variations, respectively. In 1980, Firmani et al. (1980) proposed WR 6 as a very likely candidate to be a binary system formed by a Wolf-Rayet star and a collapsed companion (WR+c). However, in the X-ray region Pollock (1987,1995) and Willis & Stevens (1996) found that there is an incompatibility between the observed low X-ray luminosity,  $L_x \sim 10^{32}$  erg s<sup>-1</sup>, and the one expected from a WR+c binary system,  $L_x \sim 10^{36} - 10^{38}$  erg s<sup>-1</sup>. Thus, the binary nature of WR 6 is still an open issue.

As mentioned, there have been radio surveys searching for HI cavities or bubbles around WR stars. Recently, Arnal & Cappa (1996) have carried out low and intermediate HI observations looking for the existence of low HI column density areas (possible bubbles or cavities) which may be physically related to WR 6. Their low resolution observations allow them to examine the large scale distribution of neutral hydrogen while they study the detailed structure of the HI bubble using their intermediate angular resolution data. On the large scale they have found two main features: 1) there is a large elongated cavity (low column density) which shows two relative minima within it, one located to the east and the other one to the west; and 2) WR 6 does not coincide either with the center of the cavity or any of the inner minima. Regarding the two relative minima, they remark that the present hydrodynamic theory of interstellar bubbles cannot explain its nature, since it predicts a single minimum. On the other hand, their intermediate angular resolution data allow them to study the shape and dimensions of the cavity and to conclude that since both characteristics do not vary at different radial velocities the elongated HI bubble is not expanding. Besides, they determine the precise locations of the two relative minima. Finally, they have analyzed several possible explanations for the elongated shape of the HI cavity by relaxing some of the basic assumptions of the standard hydrodynamic stellar wind-blown theory (Castor, Abbott, & Klein 1975). Thus, they have concluded that if the standard theory is to be retained in its original form, the most likely explanation is that the central star has a non-isotropic stellar wind. However, they note that also the interstellar magnetic field may play an important role in the development of elongated HI cavities. Theoretically, this possibility has been proposed by Rimpl (1980).

In this paper, we explore the possibility that WR 6 has a non-isotropic wind interacting with its surrounding medium. It is well known that the free-free emission from the ionized winds of massive stars can be detected and imaged with sensitive radio interferometers. We have thus searched for evidence which could lead us to conclude that the stellar wind is closely related to the observed morphology of the cavity. In the next two sections we describe our observations and discuss the results obtained from them. Finally, in the last section we summarize our conclusions.

## 2. OBSERVATIONS

We present four sets of observations taken with the Very Large Array (VLA) of NRAO<sup>1</sup> at 3.6-cm. The first observing run was carried out on 1996 July 25. At this epoch the array was in the D configuration giving the lowest angular resolution. These data were used to confirm the WR 6 detection made at 6-cm ( $S_\nu = 1.0$  mJy) by Hogg (1982), and to obtain a first determination of the 3.6-cm flux density. The next three observing runs were made on 1996 November 25, December 21, and 1997 January 12. During these epochs the array was in the A configuration giving an angular resolution of  $\sim 0''.2$ . The total on-source integration times varied between  $\sim 2$  and  $\sim 4$  hours among the four observing runs. The amplitude and phase calibrators were the same for all runs, 1328+307 and 0646-306, respectively. Bootstrapped flux densities for the phase calibrator obtained from each observing run are shown in Table 1. The data analysis and reduction were performed using the AIPS software of NRAO following the standard VLA procedures for editing, calibrating and imaging. The first set of maps obtained from our high angular resolution maps showed small protuberances at the  $4\text{-}\sigma$  level emanating in directions that seemed to change from one month to the other. However, a detailed analysis of the data lead us to conclude that we were not dealing with real protuberances but with some kind of systematic error in the observations, present in the second of the two 50 MHz IFs used in the observations. A new set of maps using only the first IF had no evidence of the protuberances. These maps are shown in Figure 1. In Table 1 we present the derived flux densities for WR 6 determined from the analysis of each observing run.

## 3. DISCUSSION

The main goal of this study was to look for evidence that could support the idea that WR 6 has a non-isotropic wind. The presence of an anisotropic stellar wind in WR 6 is important because it could be or could have been in the past closely related to the elongated HI bubble observed by Arnal & Cappa (1996) at a larger scale. It was then important to resolve angularly the source both to detect any possible deviation from the spherical symmetry and to measure the brightness temperature that could help determine if the source has a classical thermal wind (with characteristic brightness

<sup>1</sup>The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1  
DERIVED FLUX DENSITIES

Observing Run	0646-306 $S_\nu$ (Jy)	WR 6 $S_\nu$ (mJy)
July 25, 1996	$0.804 \pm 0.006$	$1.56 \pm 0.03$
November 26, 1996	$0.867 \pm 0.005$	$1.62 \pm 0.03$
December 21, 1996	$0.875 \pm 0.005$	$1.35 \pm 0.03$
January 12, 1997	$0.880 \pm 0.004$	$1.38 \pm 0.03$

temperatures of order  $10^4$  K, in contrast to much larger values observed in non-thermal winds). Unfortunately, since the source is not clearly resolved in any of the data sets and it is fairly weak, it was not possible to determine its dimensions directly from the maps. A fit to the  $u, v$  data using a Gaussian ellipsoid function gives full widths at half maximum of  $0''.12 \pm 0''.04 \times 0''.09 \pm 0''.02$  with the major axis along a position angle of  $-14^\circ \pm 38^\circ$ . This result rules out large (major axis/minor axis  $\geq 2$ ) anisotropies in the shape of the source and, within the error, is consistent with spherical symmetry. White & Becker (1982) have shown that it is possible to determine with good accuracy the size of a source directly from the  $u, v$  data, assuming a spherically symmetric source. Besides, Escalante et al. (1989) have shown that for a marginally resolved wind source the observed flux density depends linearly with the projected baseline separation. Thus, it is possible to determine the source size by making a linear fit to the data in the  $u, v$  plane and furthermore to determine its brightness temperature from the same fit. A least squares fit was applied to the real part of all our high angular resolution data using the following equation:

$$V(b) = S_\nu (1 - Ab),$$

where  $b$  is the projected baseline separation, given in wavelengths,  $S_\nu$  is the total flux density, that is, the flux density at a zero projected baseline ( $b = 0$ ), and  $A$  is the fitted slope. In our case, we have obtained the following values for the slope and the total flux density:  $A = 4.6 \pm 0.6 \times 10^{-7}$  and  $S_\nu = 1.52 \pm 0.03$  mJy (Figure 2).

Thus, the angular diameter of the source within which half of the flux density is originated can be obtained from the equation:

$$\left[ \frac{\theta}{''} \right] = 1.19 \times 10^5 A,$$

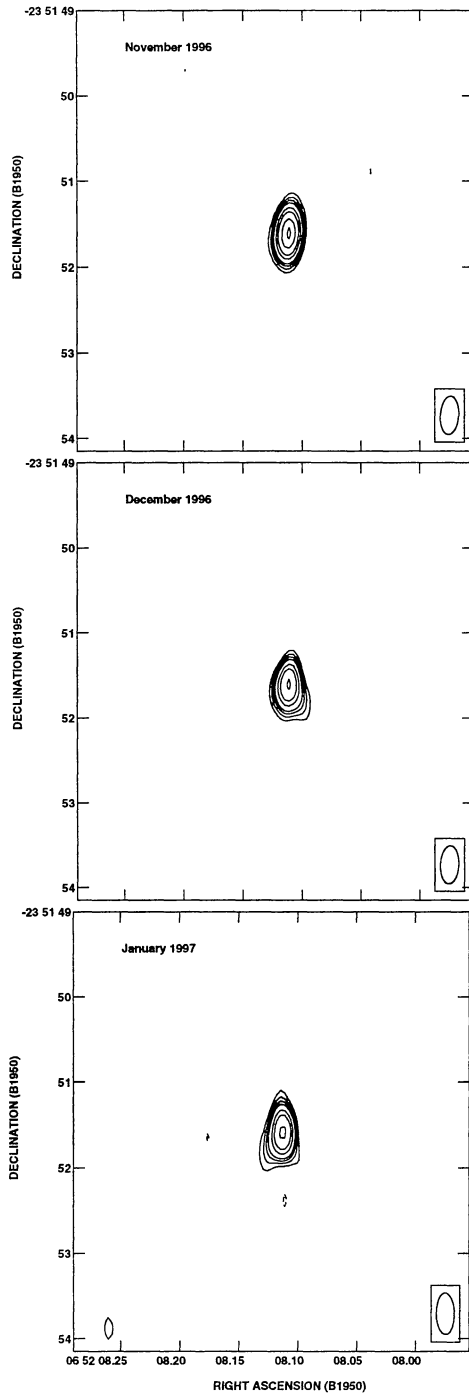


Fig. 1. VLA CLEANed 3.6-cm maps for the three high angular resolution data sets. The maps were obtained using the AIPS routine IMAGR with an intermediate  $(u, v)$  data weight (ROBUST=0). In all three maps the source appears practically unresolved (see beams at right bottom corner). Contours are  $-4, 4, 6, 8, 10, 15, 20, 30,$  and  $40$  times the average rms noise of  $36 \mu\text{Jy beam}^{-1}$ .

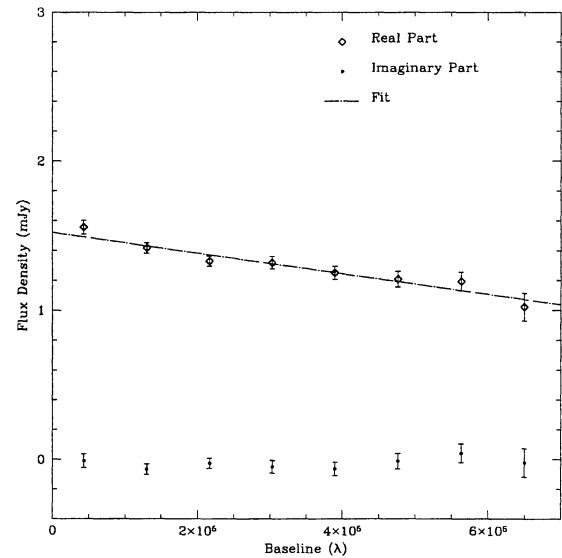


Fig. 2. Real and imaginary parts of the flux density as a function of the projected baseline separation. The broken line corresponds to the least squares fit used to obtain the source size and the total flux density,  $S_\nu$ .

while the brightness temperature is obtained from the relation:

$$\left[ \frac{T_B}{10^4 \text{ K}} \right] = \left[ \frac{9.48 \times 10^{-15}}{A^2} \right] \left[ \frac{S_\nu}{\text{mJy}} \right] \left[ \frac{\lambda}{\text{cm}} \right]^2.$$

Both relations were derived by Escalante et al. (1989). Then, using these expressions we have obtained the angular size and brightness temperature for WR 6:  $\theta = 0''.06 \pm 0''.01$  and  $T_B = 9000 \pm 2500 \text{ K}$ . The angular size corresponds to a dimension of  $\sim 100 \text{ AU}$  at an assumed distance of  $1.8 \text{ kpc}$ . As we can see, the brightness temperature value is consistent with a classical thermal wind. Additional evidence for a classic thermal wind comes from the spectral index  $\alpha = 0.8 \pm 0.2$ , obtained from the average of our observations and the 6-cm value of Hogg (1982). The 6, 2, 1.3, and 0.13-cm observations discussed by Leitherer & Robert (1991) give a spectral index of  $\alpha = 0.6 \pm 0.1$ .

Finally, we have obtained the mass loss rate,  $\dot{M} = 2.8 \pm 1.0 \times 10^{-5} M_\odot \text{ yr}^{-1}$ , using the formulation of Panagia & Felli (1975) and a terminal wind velocity of  $2700 \text{ km s}^{-1}$  (Barlow, Smith, & Willis 1981). This value is consistent with the mass loss rate reported by Barlow et al. (1981), using free-free IR data.

Then, regarding the main goal of our study, we have not found any firm evidence supporting the

possibility of WR 6 having an anisotropic wind, at least one that is evident at scales of  $0''.2$  or larger. Therefore, we cannot provide evidence for a relation between an anisotropy in the stellar wind and the ovoidal shape of the HI cavity found by Arnal & Cappa (1996). Instead, our data appear consistent with an isotropic thermal wind. Based on this assumption we have estimated the source size, its brightness temperature and its mass loss rate. Comparing the four flux densities that we have (Table 1) we found no clear evidence for large variability,  $\leq 15\%$ , in approximately 6 months. Thus, we can conclude that the WR 6 wind is a classic thermal wind, non-variable in time and most likely isotropic. Its radio parameters are different to those of binaries with a collapsed companion (Mirabel & Rodríguez 1999). Close binaries with a collapsed companion are known to exhibit strong, time-variable, non-thermal emission associated with relativistic ejections of magnetized plasma. It should be noted, however, that since at 3.6-cm the radio “photosphere” has a radius of order 50 AU it is not possible to detect possible non-thermal radiation originating inside this optically-thick radius. Despite the well established period of 3.765 days from spectroscopic and photometric observations (Georgiev et al. 1999), WR 6 seems to lack the expected characteristics of a close binary with collapsed companion at X-ray and radio wavelengths.

#### 4. CONCLUSIONS

We have studied with the VLA at four epochs the star WR 6. Our results suggest that the wind from this star is thermal, non-variable in time and most likely isotropic. Therefore, we cannot provide evidence for a relation between an anisotropy in the stellar wind and the ovoidal shape of the HI cavity. Finally, the radio parameters of WR 6 are different to those of binaries with a collapsed companion, a classification that has been proposed in the past for WR 6.

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