LETTER TO THE EDITOR

High angular resolution 7 mm images toward the UC HII region W3(OH)^{★,★★}

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ABSTRACT

Context. Recent high angular resolution radio observations of the ultracompact HII region W3(OH) confirm the presence of an extremely compact (0''.05), time-variable source near its center.

Aims. We use new, sensitive high angular resolution observations of radio continuum and recombination lines to study the compact source in W3(OH) and the ultracompact HII region itself.

Methods. We reduced and analyzed extensive Jansky Very Large Array observations of W3(OH) in the continuum at 41.0 GHz and in the H54 α and He54 α lines.

Results. Our images confirm there is the compact source and show that it is connected by a linear filament to the brightest part of W3(OH). We discuss several possible explanations for this structure and propose future observations that may clarify its nature.

Key words. ISM: jets and outflows – stars: formation – accretion, accretion disks – ISM: individual objects: W3(OH) – HII regions

1. Introduction

Understanding the morphology of ultracompact (UC) and hypercompact (HC) HII regions helps gain information on the original density distribution of the natal cloud. There are large surveys of these classes of HII regions (e.g., Wood & Churchwell 1989; and Kurtz et al. 1994), as well as theoretical studies that model their dynamics (e.g., Hollenbach et al. 1994; Lugo et al. 2004; Arthur & Hoare 2006; Roth et al. 2014).

In the literature, the UC HII regions are described as small regions, ≤ 0.1 pc in extent, which are bright in the far infrared since the young OB star heats the surrounding dust. They are too embedded in their parent molecular cloud to be detected in the optical. The photoionization of ambient gas creates free-free emission that can be detected in the radio regime, with electron densities in excess of 10^4 cm⁻³ and emission measures of 10^7 pc cm⁻⁶ or more. On the other hand, HC HII regions are probably in an intermediate evolutionary stage between the hot core (an earlier phase of massive star formation), and UC HII region phases of massive stellar evolution (see González-Avilés et al. 2005). They have very high electron densities, approximately $>10^5$ cm⁻³, and sizes <0.01 pc, and their bright emission measure is $>10^8$ pc cm⁻⁶ (Churchwell 2004). HC HII regions have intrinsically broad radio recombination lines (>40 km s⁻¹, Sewilo et al. 2004), while the line widths for UC HII regions are typically between 25 and 30 km s⁻¹ (Wood & Churchwell 1989).

W3(OH) is a limb-brightened HII region with a shell morphology that has a total extent of $\sim 1''$ (Dreher & Welch 1981), electron densities of $>2 \times 10^5$ cm⁻³, and emission measures in excess of $>10^9$ pc cm⁻⁶ (Kawamura & Masson 1998). Even though it is widely recognized in the literature as UC HII region, some of its properties resemble those of an HC HII region. Nonetheless, we still refer to it as UC HII region. It is known to be expanding in the plane of the sky at a velocity of $\sim 3\text{--}5$ km s⁻¹ (Kawamura & Masson 1998). It is located at a distance of 1.95 ± 0.04 kpc (Xu et al. 2006), and the total luminosity of the system is $7.1 \times 10^4 L_{\odot}$ (Hirsch et al. 2012). The region is heavily obscured ($A_V \sim 75$ mag; Feigelson & Townsley 2008). The nature and position of its ionizing star are still being debated in the literature. Harvey-Smith & Cohen (2006) suggest that the radio continuum peak hosts the excitation center because it is associated with strong 6.7 GHz methanol (CH₃OH) maser emission. This radio peak is surrounded by arcs of OH masers (Baudry & Diamond 1998), and it contains the strongest magnetic field in W3(OH) (Etoka et al. 2005). On the other hand, the extremely compact ($\sim 0''.05$), ionized and time-variable radio source reported first by Kawamura & Masson (1998) has also been proposed as directly associated with the ionizing star of the region (Kawamura & Masson 1998; Dzib et al. 2013). This possible association is based on the result that this compact region is projected very near the center of the UC HII region. It is unlikely to be a freely expanding structure because then its kinematic age would only be ~ 50 yr. Dzib et al. (2013) tentatively suggest that this compact source could be produced by a fossil photoevaporated disk around the exciting star of W3(OH).

There are clear indications that W3(OH) hosts a very young star. The infrared source in W3(OH) has been classified as a

* Appendices are available in electronic form at <http://www.aanda.org>

** Reduced VLA FITS cubes are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/567/L5>

Class 0/I object by Rivera-Ingraham et al. (2011), Broos et al. (2013), and Kuhn et al. (2013). On the other hand, the X-rays properties are also indicative of a deeply embedded young massive star (Feigelson & Townsley 2008). Unfortunately, within the position errors of the infrared and X-ray sources, both the radio continuum peak and the compact radio source can host this young star.

2. Observations

We used seven out of eight observations of the VLA archive data from project 12B-332¹. The observations were made with the VLA in the A configuration using the *Q* band (40.0–50.0 GHz) receivers. The central frequency was 41 GHz, with a total bandwidth of 2 GHz divided in 16 spectral windows of 128 channels of 1 MHz each. The observation epochs are 2012 October 6, 7, 12, 13, and 15².

At the beginning of each observation, the standard flux calibrator 3C 48 was observed for two minutes. Then two minutes were spent on the phase calibrator J0244+6228, followed by four minutes on the target source and one minute again on the phase calibrator. This target-phase calibrator cycle was repeated until 1.5 h were completed. The source J0244+6228 was also used as the amplitude and bandpass calibrator. Referenced pointing scans at the lower frequency of 8.4 GHz were performed before the beginning of the observation of the flux calibrator and before starting the phase calibrator-target cycle. These scans are required to assure that the absolute pointing of the antennas is accurate to 5'' or better.

The data were edited and calibrated in the standard fashion using the Common Astronomy Software Applications package (CASA). After the initial calibration of each epoch, the data sets were concatenated to obtain better UV-coverage and also to improve the signal-to-noise ratio in the final images. The visibilities were imaged in CASA with a pixel size of 0''.002. The weighting scheme used was intermediate between natural and uniform (WEIGHTING = "briggs" with ROBUST = 0.0 in CASA), which is a good compromise between sensitivity and spatial resolution.

The rest frequencies of the H54 α (40.6314 GHz) and He54 α (40.6471 GHz) recombination lines are in the observed frequency range. The channel width of these observations provides a spectral resolution of 7.38 km s⁻¹ at this frequency. The rest frequency of the H54 α line falls at the lower edge of the band covered by the fifth spectral window. Previous detections of other recombination lines from the W3(OH) UC-H II region indicate they are at local standard of rest (LSR) radial velocities of -50 to -60 km s⁻¹ (Sams et al. 1996; and Dzib et al. 2013). On the other hand, the helium radio recombination lines are shifted by -122.2 km s⁻¹ with respect to its hydrogen partner. Then we expect to be detected well inside the fifth spectral window.

The first step for the search of these lines was to image single channels, covering LSR radial velocities between 200 km s⁻¹ and -300 km s⁻¹, with respect to the rest frequency of the H54 α recombination line. Owing to the placement of the various spectral windows, we have no data in the LSR velocity range of 11.1 to 62.8 km s⁻¹. To see the line emission at different scales, we produced a series of these images. First, to see the most extended emission and to obtain a higher signal-to-noise ratio, we used a

Fig. 1. Image of the Stokes *I* parameter of the continuum radio emission from W3(OH) as detected in the *Q* band (41 GHz) observations. Gray scales and contour images are superposed to highlight those zones with less significant emission at the center of the UC H II region. The contours are at -5, 5, 10, 15, 20, 30, 40, 50, and 60 times the 1σ noise level of 140 μ Jy beam⁻¹. The half-power contour of the 41 GHz (0''.044 $\times$ 0''.035; PA = 55°) synthesized beam is shown in the bottom left corner.

natural weighting scheme (ROBUST = 2.0). Second, to study the emission from the most compact objects, we removed the short spacings generated by baselines below 6 km, suppressing angular structures larger than 0''.24 and also using a natural weighting scheme.

3. Results

3.1. Continuum image

The final continuum image is shown in Fig. 1. The image noise is 140 μ Jy beam⁻¹, which is higher than expected. We attribute the high noise to the poor UV-coverage in the short spacings, i.e., we cannot properly reconstruct the more extended emission. From Fig. 1 we see that the shell structure of the W3(OH) UC H II region, as seen at centimeter wavelengths (e.g., Kawamura & Masson 1998; and Wilner et al. 1999), is recovered. The more extended champagne flow to the NE, however, is not present, possibly because we are resolving it out. The compact object reported by Kawamura & Masson (1998) and recently studied in more detail by Dzib et al. (2013) is also present. Interestingly, for the first time we have an image with enough quality to show that there is a bright, narrow structure that seems to connect this compact object with the brightest part of W3(OH), to the NW of the center. The narrow structure, as we call it hereafter, was present in previous radio continuum observations with less angular resolution (see, i.e., Kawamura & Masson 1998), but went unnoticed because the emission is confused with the emission of the shell structure of the UC H II region. The total flux density for the whole W3(OH) region is 3.2 Jy, similar to those reported by Kawamura & Masson (1998) at 15.0 and 22.5 GHz. This supports the idea that the whole UC H II is a non-variable radio source with a flat spectral energy distribution. These characteristics are those expected for free-free emission that is optically thin above ~ 10 GHz.

We searched for day-to-day variability in the continuum emission from the compact source, without finding any evidence of it. This result suggests that the variability is present only on much larger timescales.

¹ The first epoch was affected by problems that render it impossible to calibrate.

² Two observations per day were made on October 6 and 7.

Fig. 2. Radio recombination line spectrum for W3(OH), shown as flux density versus LSR radial velocity (solid line). The dashed line shows the least-squares fit to the spectrum. The continuum has been subtracted with a linear fit. We have no data for the 11.1 to 62.8 km s⁻¹ radial velocity range, and we have interpolated the spectrum for this region with a straight line. The parameters of the recombination lines are given in Table 1.

3.2. Detection of the H54α and He54α recombination lines

We obtained the spectra of the H54α and He54α radio recombination lines by integrating the total flux density for each frequency channel in a polygon containing all detectable emission. The spectrum (see Fig. 2) was least-squares fit with a linear baseline and Gaussian profiles for the lines. The flux density of the continuum was found to be 3.21 ± 0.01 Jy. The resulting parameters for the recombination lines are listed in Table 1. There is an emission excess in the -77.4 km s⁻¹ channel, which we argue in Appendix A is from a CH₃OH transition. The V_{LSR} of the He54α line is calculated using the rest frequency of this transition. The helium-to-hydrogen ratio is determined to be $y^+ = 0.07 \pm 0.01$. Using this ratio and the parameters for the continuum and H54α line and assuming local thermodynamic equilibrium (LTE), we derive an electron temperature of 8200 ± 130 K (i.e. Mezger & Hoglund 1967). This value is in the range of electron temperatures derived from radio recombination line observations of other UC H II regions (Afflerbach et al. 1996).

Finally, we also obtained the H54α parameters of the emission from the compact component near the center of W3(OH). To avoid contamination by the extended structure, we did a second image cube, but cutting baselines below 6 km and using a natural weighting scheme. We clearly detect emission from the compact source but not from the filamentary component. The resulting parameters from a least-squares fit are also listed in Table 1. The continuum and line parameters are consistent, within the noise, with those obtained for the H58α line by Dzib et al. (2013). Assuming the same y^+ as for the main nebula, we derive an LTE electron temperature of 8700 ± 1100 K. We then conclude that the line parameters of the compact component are similar to those of the main nebula. Maps of the extended and compact H54α and He54α emission and the spectrum of the compact source are shown in Appendix B.

4. Discussion

The most interesting feature in the continuum image is the narrow structure between the compact source and the brightest part of the UC HII region. To see whether the three structures are physically related or if they just coincide in the line of sight, we obtained a position–velocity (PV) diagram of the H54α line

Fig. 3. Position–velocity diagram of the H54α line emission, through the compact source (indicated with a circle), the brightest region in W3(OH) (indicated with a cross), and the narrow emission that connects them.

Table 1. Spectral line parameters for W3(OH) and the compact source.

Line	S_L (mJy)	ΔV (km s ⁻¹)	V_{LSR} (km s ⁻¹)
W3(OH)			
H54α (40.6314 GHz)	1270.0 ± 10.0	31.3 ± 0.4	-47.2 ± 0.2
He54α (40.6471 GHz)	120.0 ± 10.0	21.1 ± 3.2	-47.5 ± 1.3
Compact source			
H54α (40.6314 GHz)	11.5 ± 0.7	36.2 ± 3.8	-53.0 ± 1.6

emission along a slice that covers the three objects³, the resulting PV diagram is shown in Fig. 3. We note that the compact source and the elongated emission share a radial velocity component around -55 km s⁻¹, but the peak velocity component is about 10 km s⁻¹ lower for the brightest region in W3(OH). This suggests that the three features are not entirely independent. However, the velocity of the brightest feature of W3(OH) is similar to the systemic velocity of the entire UC HII region, suggesting that the brightest feature is more closely related to the UC HII region than it is to the compact object or the narrow structure.

The narrow structure may correspond to the tail of a cometary structure related with a density gradient in the nebula. The coma in this case is the compact source. The origin of this gradient can be due to a bow shock as a result of the massive star moving in a dense medium or a photoevaporated flow combined with winds, both cases studied by Arthur & Hoare (2006). In these cases, the ionizing star would be located at a position close to and on the west side of the compact source. However, the morphology emission maps resulting from simulations by Arthur & Hoare (2006) differ from these observations because the predicted emission from the tails is extremely weak. Also, in this interpretation we cannot explain the origin of the brightest peak so it must be considered an independent source.

Alternatively, the narrow structure could be related to a proplyd-like object, i.e., a low mass star whose envelope is being photoevaporated by a massive star. Some proplyds are known to show a head with a long tail (Zapata et al. 2004). However, in the images of these authors, the tail is also much fainter than the head. In this interpretation, the ionizing star must be on the east side of the compact source. Again, the brightest peak must be considered as a separate source.

Another possible explanation for this structure could be a photoevaporated filament (elephant trunk), such as those obtained in the process of expansion of an HII region with an inhomogeneous distribution of gas. The heads of the filaments are photoevaporated in a similar way to that of a proplyd. The

³ The position of the slice is shown in Fig. B.3.

simulations of Arthur et al. (2011) and Medina et al. (2014) obtained this kind of structures after 10^5 years. The age derived for W3(OH) from astrochemical models (Kim et al. 2006) is in the range of 10^4 to 10^5 years. This result suggests that W3(OH) has evolved enough to produce these filamentary structures. As in the propylid case, the ionizing star must be to the east of the compact source. The compact source would be the head of the filament, and the narrow structure is the body of the filament. The brightest peak must be examined as a separate source.

Another possibility is that the compact source and the peak emission are being ionized by independent stars, but this possibility leaves the filament without any relation to either of the two sources.

Finally, we speculate that the narrow structure could be a collimated jet (like the one suggested in the MonR2 UC H II region by Jiménez-Serra et al. 2013) from a massive star inside the compact region. Time variability in flux and in position of the compact source was reported by Dzib et al. (2013), and it supports the idea that this is an active component, possibly associated with the ionizing star embedded in the compact component. This hypothetical jet would go through dense material, exciting it and then colliding with denser material thereby helping to produce the brightest zone to the NW of the UC H II region. The apparent asymmetry of the jet can be explained if we assume that the material is less dense on the southeast side. There are several examples of asymmetric jets, although related to low mass protostars (e.g., Rodríguez et al. 2012). An argument against the jet interpretation is that since the LSR velocity derived from the recombination lines is very similar to that of the ambient H II region, the jet would have to be practically in the plane of the sky; i.e., it is a statistically unlikely possibility. Finally, the flux measured in our 41 GHz map from the brightest zone is ~ 400 mJy, thus the rate of photons required to maintain this region ionized is about $2 \times 10^{47} \text{ s}^{-1}$. This implies that the ionizing luminosity required must be greater than $900 L_{\odot}$. The most powerful protostellar jets are known have an ionized mass loss rate on the order of $10^{-6} M_{\odot} \text{ yr}^{-1}$ and velocities on the order of 300 km s^{-1} (Rodríguez et al. 1994; Martí et al. 1999), for a mechanical luminosity of $\sim 8 L_{\odot}$. Thus, the jet hypothesis is also unsatisfactory for explaining the ionization to the NW of the main nebula.

High angular resolution observations of molecular lines can help distinguish between the different interpretations. The proposed filamentary options are expected to have only their surfaces ionized, thus molecules can survive inside of them and emit at detectable levels (see, e.g., simulations by Arthur et al. 2011). Thus, the detection of intense molecular line emission will favor a non-jet structure. In contrast, jets are mostly ionized regions, so a weak or lack of detection of these lines will favor the jet nature. Because of the nature of these observations, ALMA would be the ideal instrument for the study. Unfortunately, W3(OH) cannot be observed with this instrument because of its northern declination. The VLA, on the other hand, offers the possibility to observe some molecular line emission with good angular resolution. Additionally, new continuum observations with high sensitivity and resolution at other frequencies can also provide new clues by determining the spectral index of the filamentary structure. Free expanding jets are expected to have a spectral index around 0.6 (e.g. Rodríguez 1999), while an optically thick filament will have an index of 2 at low frequencies.

Additionally, moderate resolution ($\sim 0''.5$) images of the UC H II regions G5.89-0.39, G11.94-0.62, G19.61-0.23, and

G45.45+0.06 from the Wood & Churchwell (1989) catalog suggest of filamentary structures similar to the one we report for W3(OH). High-sensitivity, high angular resolution continuum observations of these sources would be worthwhile, to determine whether such structures are actually present.

5. Conclusions

We studied the UC H II region W3(OH) in the 41 GHz continuum and in the H54 α and He54 α radio recombination lines at high angular resolution ($0''.04$). Our observations confirm the presence of an extremely compact ($\sim 0''.05$) source near the center of W3(OH). Our images also reveal that this source seems to be connected via a narrow structure with the brightest part of W3(OH), to the NW of the nebula. The compact source and the narrow structure have radial LSR velocities similar to those of W3(OH). We discuss several interpretations for this peculiar structure, without reaching a firm conclusion, and propose new line and continuum observations to clarify its nature.

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Fig. A.1. Residuals of the fit, with a narrow feature evident at -77.4 km s^{-1} .

Appendix A: Detection of methanol

The residuals of the fit (presented in the bottom of Fig. A.1) clearly show that in addition to the two recombination lines, there is a narrow feature in the -77.4 km s^{-1} channel. The width of the line is unresolved ($\leq 7.4 \text{ km s}^{-1}$), suggesting that the emission comes from a molecular species. The upper limit to the width of the line is consistent with the values in the range of the 3 to 5 km s^{-1} typically observed in molecular cores with massive star formation (Garay et al. 2010; Qiu et al. 2011). If we assume that this emission has the same LSR radial velocity as the ionized gas, it then has a rest frequency of 40.6346 GHz, in agreement with the expected frequency for torsionally excited CH_3OH ($14_{3,11}-13_{4,10}$) ($v_t = 0$) line emission, whose rest frequency is 40.6351 GHz (Xu & Lovas 1997). Emission of the CH_3OH molecule has been previously reported for this UC HII region (see, e.g., Wyrowski et al. 1999; and Harvey-Smith & Cohen 2006). Since the emission from this line seems to be dominating the emission in the -77.4 km s^{-1} channel, we plot the intensity map of this single channel in Fig. A.2. We see that the emission seems to be concentrated mainly in an extended component on the west side of W3(OH). Filamentary CH_3OH maser emission was found at similar positions inside W3(OH) by Harvey-Smith & Cohen (2006).

To support the tentative identification of this methanol transition, we inspected our data for signs of emission from other methanol transitions. Our 2 GHz bandwidth includes the transitions CH_3OH ($14_{3,12}-13_{4,9}$), with rest frequency 40.40537 GHz, and CH_3OH ($9_{-4,6}-10_{-3,8}$) with rest frequency 41.11004 GHz. We proceed in a similar fashion to what we did for the recombination lines. Some emission was found for the CH_3OH ($14_{3,12}-13_{4,9}$) transition (see Fig. A.3), but emission from the transition CH_3OH ($9_{-4,6}-10_{-3,8}$) was not detected. The emission peaks of the CH_3OH ($14_{3,12}-13_{4,9}$) detection coincide with those of the excess emission at -77.4 km s^{-1} in the $\text{H}54\alpha$ recombination line, suggesting a similar origin. Both CH_3OH ($14_{3,11}-13_{4,10}$) and CH_3OH ($14_{3,12}-13_{4,9}$) are methanol transitions of A-type, while the CH_3OH ($9_{-4,6}-10_{-3,8}$) is an E-type transition. For radiative transport purposes, these A- and E-type symmetry states can be considered as two different molecules (Laurini et al. 2004). Thus, this could explain why we detect similar intensities for the

Fig. A.2. W3(OH) moment 0 image of the radio emission from the -77.4 km s^{-1} channel. The contours are at $-20, 20, 40, 60$, and 80% of the peak level of $26.3 \text{ mJy beam}^{-1} \text{ km s}^{-1}$. Filled squares show the position of the CH_3OH masers reported by Harvey-Smith & Cohen (2006) and coincides with the observed extended CH_3OH emission.

Fig. A.3. W3(OH) moment 0 image of the radio emission from the CH_3OH ($14_{3,12}-13_{4,9}$) transition. The image corresponds to the channel with $V_{\text{LSR}} = -47.65 \text{ km s}^{-1}$. The contours are at $-20, 20, 40, 60$, and 80% the peak level of $29.5 \text{ mJy beam}^{-1} \text{ km s}^{-1}$. Filled squares show the position of the CH_3OH masers reported by Harvey-Smith & Cohen (2006) and coincides with the observed extended CH_3OH emission.

CH_3OH ($14_{3,11}-13_{4,10}$) and CH_3OH ($14_{3,12}-13_{4,9}$) lines, but not CH_3OH ($9_{-4,6}-10_{-3,8}$). We conclude that the residual line emission is due to the CH_3OH molecule.

Appendix B: Structure of the $\text{H}54\alpha$ and $\text{He}54\alpha$ emission

To show the spatial distribution of the emission of both, the $\text{H}54\alpha$ and the $\text{He}54\alpha$ lines, we plotted the moment 0 intensity maps for the $\text{H}54\alpha$ and $\text{He}54\alpha$ radio recombination lines in Figs. B.1 and B.2, respectively. The structure of the emission of both lines seems to be similar to the continuum map. However, the $\text{He}54\alpha$ emission is only marginally detected in this high angular resolution image.

Fig. B.1. W3(OH) moment 0 image of the radio emission from the H54 α recombination line. Gray scales and contour scales images are superposed to highlight those zones with less significant emission inside the UC HII region. The contours are at -20, 20, 40, 60, and 80% the peak level of 301 mJy beam⁻¹ km s⁻¹.

Fig. B.2. W3(OH) moment 0 image of the radio emission from the He54 α recombination line. The contours are at -20, 20, 40, 60, and 80% the peak level of 50.7 mJy beam⁻¹ km s⁻¹.

We also obtained maps of the intensity-weighted velocity (moment 1) for the H54 α line from the image cube with the full baselines (Fig. B.3). The velocity gradient for the whole W3(OH) UC HII region is consistent with a champagne-like expansion.

The moment 0 for the highest resolution image of the H54 α emission is shown in Fig. B.4. The emission from the compact source is clearly detected. Finally, the spectrum for the compact source and the least-squares fit to it are shown in Fig. B.5.

Fig. B.3. W3(OH) moment 1 image of the radio emission from the H54 α recombination line. The color bar to the right indicates the radial LSR velocity. The solid line shows the position and orientation of the slice where the position-velocity diagram shown in Fig. 3 was made.

Fig. B.4. W3(OH) moment 0 image of the radio emission from the H54 α recombination line from the spectral image cutting baselines shorter than 6 km. The contours are at 20, 40, 60, and 80% the peak level of 111 mJy beam⁻¹ km s⁻¹.

Fig. B.5. Radio recombination line spectrum (solid line) for the compact source near the center of W3(OH). The parameters of the fit (dashed line) are discussed in the main text.