THE COMPACT, TIME-VARIABLE RADIO SOURCE PROJECTED INSIDE W3(OH): EVIDENCE FOR A PHOTOEVAPORATED DISK?

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Received 2013 May 8; accepted 2013 June 6; published 2013 July 17

ABSTRACT

We present new Karl G. Jansky Very Large Array (VLA) observations of the compact (∼0.05), time-variable radio source projected near the center of the ultracompact H II region W3(OH). The analysis of our new data as well as of VLA archival observations confirms the variability of the source on timescales of years and for a given epoch indicates a spectral index of \( \alpha = 1.3 \pm 0.3 (S_\nu \propto \nu^\alpha) \). This spectral index and the brightness temperature of the source (∼6500 K) suggest that we are most likely detecting partially optically thick free–free radiation. The radio source is probably associated with the ionizing star of W3(OH), but an interpretation in terms of an ionized stellar wind fails because the detected flux densities are orders of magnitude larger than expected. We discuss several scenarios and tentatively propose that the radio emission could arise in a static ionized atmosphere around a fossil photoevaporated disk.

Key words: accretion, accretion disks – H II regions – ISM: individual objects (W3(OH)) – radio continuum: stars

Online-only material: color figures

1. INTRODUCTION

Recently formed massive stars produce large amounts of UV photons that ionize the natal material around them, forming H II regions of different morphologies and sizes. Ultracompact H II (UCHII) regions are small (diameters no more than ∼0.1 pc) and dense (electron densities of at least 10^6 cm\(^{-3}\)) volumes of ionized gas produced by one or several massive stars (Wood & Churchwell 1989). W3(OH) is a limb-brightened UCHII region with a shell morphology (Dreher & Welch 1981) that is known to be expanding at a velocity of ∼3–5 km s\(^{-1}\) (Kawamura & Masson 1998). It is located at a distance of 2.04 kpc (Hachisuka et al. 2006) and the total luminosity of the system is 7.1 × 10^3 L\(_{\odot}\) (Hirsch et al. 2012). The region is heavily obscured (AV ∼ 75; Feigelson & Townsley 2008) and there is little direct information on the nature of the ionizing star.

Kawamura & Masson (1998), based on the residual image obtained subtracting maps of different epochs, reported a compact, time evolving (over a scale of several years) source projected near the center of W3(OH) and suggested that it is probably related to the central star. Remarkably, no further research has been published since then on this interesting radio source. Here, we report new radio observations of the W3(OH) region made with the Karl G. Jansky Very Large Array (VLA) of the NRAO.\(^3\) We also used VLA archive observations to complement our study. Our results provide for the first time a direct radio detection and a determination of the parameters of this radio source, possibly associated with the star that ionizes the W3(OH) region.

2. RADIO OBSERVATIONS

The observations were made in the Ka band (26.5–40 GHz) with the VLA centered at a frequency of 32.96 GHz and with a total bandwidth of 2 GHz. The observations were made on 2012 October 13, with the VLA in the A configuration. At the beginning of the observations, we integrated on the standard flux calibrator 3C 48 for ∼3 minutes. This source was also used as the bandpass calibrator. We then spent one minute on the phase calibrator J0244+6228 followed by five minutes on the target; this cycle was repeated until one hour was completed. The angular distance between the phase calibrator and the target is 2:17. Referenced pointing scans at the lower frequency of 9.0 GHz were performed before the beginning of the observation of the flux calibrator and before the start of the phase calibrator–target cycle. These scans are required to assure that the absolute pointing of the antennas is accurate to 5\(^{\prime}\) or better.

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 self-calibrated and imaged with a pixel size of 0.01 arcsec. The weighting scheme used was intermediate between natural and uniform (WEIGHTING=“briggs” with ROBUST=0.0 in CASA). To minimize the extended emission from the H II region, we removed the short spacings generated by baselines below 10 km, suppressing angular structures larger than ∼0.2. The uv range was chosen to provide an optimal compromise between suppressing extended emission and maintaining signal to noise and image quality in the resulting maps. The rms noise level of an image processed in this manner depends on the position considered. In the central part of the final images it was around 50 \( \mu \)Jy beam\(^{-1}\), while in the immediate surroundings of the compact source it reached about 380 \( \mu \)Jy beam\(^{-1}\).

2.1. Position and Angular Size of the Compact Radio Source

A compact radio source was clearly detected at a position of \( \alpha(2000) = 02^h 27^m 03^s 867, \delta(2000) = 61^\circ 52' 24'' 89 \) (see Figure 1). The source is projected well inside W3(OH) and its total integrated flux density at 32.96 GHz is 14.4 ± 1.0 mJy.

\(^3\) The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
The Submillimeter Array (SMA) is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

with a peak of 6.0 ± 0.4 mJy beam⁻¹. Its deconvolved angular size is 0′.05 ± 0′.01, implying a physical size of 100 ± 20 AU and a peak brightness temperature of $T_B = 6500 ± 2600$ K. This brightness temperature suggests that we are observing optically thick photoionized gas. Assuming that the brightness temperature equals the electron temperature of the gas and using the usual formulation for the parameters of a homogeneous H II region (Schraml & Mezger 1969), we can set lower limits to the electron density, $n_e \geq 1.9 \times 10^5$ cm⁻³, ionized mass, $M_{H II} \geq 9.5 \times 10^{-6} M_\odot$, and ionizing photon rate required by the compact source, $N_i \geq 7.8 \times 10^{15}$ s⁻¹. This photon rate is equivalent to that provided by a B1 or earlier zero-age main-sequence (ZAMS) star.

In Figure 1 we also show the extent of W3(OH) as observed at 8.4 GHz. These data were taken from the VLA archive and are the average of observations made in the A configuration during 1995 July 4 (under project AR341) and 1996 November 15 (under project AR363). We will refer to these averaged 8.4 GHz data as having a mean epoch of 1996.19. These archive data have been discussed and published by Wilner et al. (1999).

We have also compared the position of the compact radio source with that of the UCHII region W3(OH), as traced in the 890 μm data taken with the Submillimeter Array (SMA)⁴ and discussed by Zapata et al. (2011). The total emission of W3(OH) at this wavelength is determined to be 1.8 ± 0.1 Jy and the image is shown in Figure 2. The compact radio source falls near the centroid of the 890 μm emission. There is an offset of ~0′.3 between the centroids of the compact radio source and the SMA submillimeter emission. However, the positional accuracy of the submillimeter emission is ~0′.2 (Cowie et al. 2009) and we cannot attribute significance to this offset.

2.2. Detection of the H58α Line

The Ka-band observations were made centered at 32.96 GHz with a total bandwidth of 2 GHz distributed in 1024 individual channels of 1.95 MHz each (equivalent to an average velocity width of 17.8 km s⁻¹). This frequency coverage includes the H58α radio recombination line that has a rest frequency of 32.852200 GHz. We analyzed the part of the spectrum where this line was expected and a feature was detected (Figure 3). This line was least-squares fitted with a Gaussian profile, obtaining a peak line flux density of $S_{\nu} = 4.6 \pm 1.0$ mJy, a FWHM of $\Delta v = 52.9 \pm 13.1$ km s⁻¹, and a local standard of rest (LSR) radial velocity of $v_{LSR} = -58.5 \pm 5.6$ km s⁻¹. The analysis was made in the spectral cube obtained without short spacings and in the solid angle containing the compact radio source, with a continuum flux density of $S_C = 14.4 \pm 1.0$ mJy.

We believe that this line corresponds to emission from the compact radio source by two reasons. The first is that the $v_{LSR}$ of the line falls in the range of LSR radial velocities reported for radio recombination lines originating in the UCHII region W3(OH) (−63.5 to −50.3 km s⁻¹; Sams et al. 1996). The second reason is that the observed flux density for the line is in agreement with the expected value. Using the formulation of Rodríguez et al. (2009) for radio recombination lines from an ionized wind in local thermodynamic equilibrium, we expect a value of $S_{\nu} = 3.9$ mJy, consistent with the observed value of 4.6 ± 1.0 mJy.

2.3. Spectral Index

We used the VLA archive deep observations of W3(OH), previously reported by Kawamura & Masson (1998; see their paper for a detailed description of the observations) made in the years 1986, 1990, and 1995. We removed short spacings...
generated by baselines below 8 km. The source is detected in the three epochs (see Table 1). It is strongly variable on a timescale of years, showing minima in 1990 and 1995 and rising again to its 1986 levels in our 2012 observations. Even when the observations are made at different frequencies, it is clear that the flux densities of 1990 and 1995 represent minima with respect to the other epochs after correcting for the spectral index determined from the 1986 observations (see below). Its flux densities for 1986, 1990, and 1995 are consistent with the negative values reported by Kawamura & Masson (1998) in their residual difference maps.

In epoch 1986.38 the source was detected at the two observed frequencies, allowing us to determine a spectral index of \( \alpha = 1.3 \pm 0.3 \) (\( \propto \nu^{-\alpha} \)) for this epoch. This spectral index is similar to the one reported for the compact radio source at the center of the H II region NGC 6334E (\( \alpha = 1.0 \pm 0.7 \)), that Carral et al. (2002) interpreted as produced by a stellar ionized wind. We also imaged the Stokes V parameter in all the epochs and detected no circular polarization at levels of \(~1\%-10\%\) (4\(\sigma\) upper limits). The long timescale variability, along with the lack of polarization, the positive spectral index, the possible presence of recombination line emission, and the brightness temperature of \(~10^3\) K favor optically thick free–free as the emission process. Gyrosynchrotron radiation from a magnetically active young star of low mass would likely be variable on short timescales (hours), show some degree of circular polarization, have a negative spectral index and a high (\(~10^2\) K) brightness temperature (e.g., Dzib et al. 2011; Torres et al. 2012).

3. DISCUSSION

3.1. Proper Motions

In our analysis of the available data we have used the improved positions for the phase calibrators available in the VLA Calibrator Manual. This procedure permits absolute systematic errors in the range of \(~0.01-0.02\) (e.g., Gómez et al. 2005).

With the positions presented in Table 1, we determine the proper motion of the compact radio source to be

\[
\begin{align*}
\mu_\alpha \cos \delta &= -2.3 \pm 0.6 \phantom{0} \text{mas yr}^{-1} \\
\mu_\delta &= -1.1 \pm 0.7 \phantom{0} \text{mas yr}^{-1}.
\end{align*}
\]

Systematic contributions of 0\(\prime\).010 and 0\(\prime\).01 in the \(\alpha\) and \(\delta\) positions, respectively, were added in quadrature to the positional errors obtained from a Gaussian fit (task IMFIT in CASA), in order to obtain a \(\chi^2\) of 1. The positions as a function of the epoch are presented in Figure 4.

Does this proper motion have any significance with respect to the nature of the source? To estimate the characteristic proper motion of the region, we compared our 2012 observations with those made at 8.4 GHz for epoch 1996.19 for the TW sources A and C (Turner & Welch 1984; Reid et al. 1995), located about 7\(''\) to the east of W3(OH). As can be seen in Figure 5, there is a small displacement to the west for the more recent data. TW-A is extended in the east–west direction and not adequate for a proper motion determination that requires sources as compact as possible. Fortunately, TW-C is very compact and for it we estimate a proper motion of

\[
\begin{align*}
\mu_\alpha \cos \delta &= -2.7 \pm 0.3 \phantom{0} \text{mas yr}^{-1} \\
\mu_\delta &= -0.3 \pm 0.3 \phantom{0} \text{mas yr}^{-1}.
\end{align*}
\]

These proper motions are consistent with those found for the compact radio source and suggest that we are simply observing the secular proper motions of the region. From Very Long Baseline Array observations, Xu et al. (2006) measure a mean proper motion of

\[
\begin{align*}
\mu_\alpha \cos \delta &= -1.20 \pm 0.02 \phantom{0} \text{mas yr}^{-1} \\
\mu_\delta &= -0.15 \pm 0.01 \phantom{0} \text{mas yr}^{-1}
\end{align*}
\]

for methanol masers associated with W3(OH). To obtain the expected galactic proper motions, we used the galactic rotation model of Brand & Blitz (1993) and the velocity of the Sun with respect to the LSR from Schönrich et al. (2010). We obtain

\[
\begin{align*}
\mu_\alpha \cos \delta &= -0.8 \pm 1.0 \phantom{0} \text{mas yr}^{-1} \\
\mu_\delta &= -0.4 \pm 1.0 \phantom{0} \text{mas yr}^{-1},
\end{align*}
\]

where the associated error range is derived assuming that the observed region could have peculiar velocities of up to \(~10\) km s\(^{-1}\) (Stark & Brand 1989). We then conclude that the observed proper motions are roughly consistent with those expected for a source at the position of W3(OH).

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**Figure 3.** \(\text{H}_5\alpha\) emission from the compact radio source in W3(OH). The dashed line is the least-squares fit to the spectrum.

**Table 1**

| Position, Flux Density, and Observed Frequency of the Compact Radio Source in the Different Epochs |
|-------------------------------------------------------------|
| Epoch | \(\alpha(J2000.0)\) \(2^\circ27'\) | \(\sigma_\alpha\) (s) | \(\delta(J2000.0)\) | \(\sigma_\delta\) (arcsec) | \(F_\nu\) (mJy) | \(v\) (GHz) |
|-------|-------------------------------|-----------------|-----------------|-----------------|-----------------|---------|
| 1986.38 | 03.8709 | 0.0002 | 24.919 | 0.003 | 09.1 ± 0.5 | 14.99 |
| 1986.38 | 03.8707 | 0.0002 | 24.906 | 0.003 | 15.6 ± 1.3 | 22.46 |
| 1990.19 | 03.8770 | 0.0004 | 24.953 | 0.005 | 03.8 ± 0.4 | 14.94 |
| 1995.48 | 03.8707 | 0.0003 | 24.890 | 0.005 | 02.6 ± 0.2 | 14.94 |
| 2012.78 | 03.8670 | 0.0001 | 24.887 | 0.002 | 14.4 ± 1.0 | 32.92 |

5 We do not include epoch 1990.19 in our proper motion analysis because its position does not follow the trend presented by the others, with a difference of \(~0.05\).
3.2. Counterparts at Other Wavelengths

At the epoch of the Kawamura & Masson (1998) indirect detection of the compact radio source, there were no known counterparts at other wavelengths. More recent studies indicate the presence of counterparts at several wavelengths. A Class 0/I infrared young stellar object was detected by Rivera-Ingraham et al. (2011) at a position $\alpha(2000) = 02^h27^m03^s86$, $\delta(2000) = 61^\circ52'25.32''$. As they used Spitzer data, we assume that their astrometric errors are between 0''35 and 1''0 (Fadda et al. 2006). Thus, within positional errors, this infrared source coincides with the radio source.

We also searched in the Two Micron All Sky Survey (2MASS) catalog (Cutri et al. 2003) and found a source, 2MASS
02270391+6152255, at an angular distance of 0.5 from the position of the radio source. Since the positional accuracy of the 2MASS survey, with respect to the International Celestial Reference System, is 0.5 (Skrutskie et al. 2006), we also consider this 2MASS source a counterpart to the compact radio source. However, since the star is enshrouded in an optically thick shell (τ ∼ 2.8 at 37.1 μm; Hirsch et al. 2012), the emission observed with Spitzer and 2MASS is probably coming from the outer edge of this dust shell, at thousand to tens of thousands of AU from the star (Stecklum et al. 2002; Hirsch et al. 2012).

Feigelson & Townsley (2008) detected a hard X-ray source coincident within error with the compact radio source. In their words: “The young massive star ionizing W3(OH) is clearly detected in our Chandra observation, at α(2000) = 02°27′03″.84, δ(2000) = 61°52′24″.9. It is a surprisingly hard X-ray source; this hard emission allows it to be seen through a large absorbing column (A_v ∼ 75 mag) inferred from the soft X-ray absorption” (Feigelson & Townsley 2008, p. 358). Their positional error is ∼0.4.

Given that these sources detected in different surveys and at different wavelengths coincide within their positional errors with the compact radio source, we suggest that the latter is related with a very young massive stellar object projected inside the W3(OH) UCHII, possibly its exciting star.

3.3. Similar Sources in the Literature

A previous detection of compact radio sources near the center of the H II regions NGC 6334E and NGC 6334A (both with shell morphologies) was reported by Carral et al. (2002). These compact sources were suggested to be associated with the exciting stars of the H II regions.

4. Interpretation

What is the nature of the compact radio source? Its positional coincidence with an embedded star, brightness temperature, spectral index, and lack of circular polarization seem to favor a free–free emitting ionized stellar wind. There are, however, serious problems with this interpretation. Dzib et al. (2013) have tabulated the expected flux densities for ZAMS stars of different classes. The luminosity of W3(OH) (7.1 × 10^4 L⊙; Hirsch et al. 2012) and the rate of ionizing photons required to maintain its free–free emission of ∼2 Jy in the optically thin regime (∼9 × 10^47 s⁻¹) can be provided by a B0V star, according to the tabulation of Dzib et al. (2013). For a B0V star located at a distance of 2.04 kpc, the expected flux density of its associated stellar wind at 22.64 GHz is only 0.006 mJy, about three orders of magnitude below the observed values. We note that the compact sources detected near the center of the H II regions NGC 6334(A) and NGC 6334(E) (Carral et al. 2002) are much brighter (by about two orders of magnitude) than the expected values for the O7.5 stars needed to ionize them. Furthermore, the compact radio source in W3(OH) shows strong time variation while the wind from a ZAMS star is expected to be steady. Finally, the observed width of the H58α line suggests that we are observing an H II region or a photoevaporated wind, since much larger line widths would be expected for a stellar wind.

Recent radio observations have shown time variability in H II regions on a timescale of years (Franco-Hernández & Rodríguez 2004; Galván-Madrid et al. 2008). Franco-Hernández & Rodríguez (2004) proposed that the time variability may be due to changes in the source of the ionizing radiation, though it may also be due to increased absorption in the rapidly evolving core of the nebula. Peters et al. (2010a, 2010b), Galván-Madrid et al. (2011), and Klassen et al. (2012a, 2012b) have discussed theoretical scenarios that may account for the H II region variability. However, these observations and models address a situation in which the whole of the H II region changes. This does not seem to be the case for W3(OH), where the variation is restricted to the compact component while the whole of the nebula does not vary significantly (Kawamura & Masson 1998).

We tentatively propose that the compact radio source could be the result of either a slow shell ejection by the B0 star or by the passage of a dense gas clump that temporarily engulfs the star. In both cases we will have the dense gas close to the star that is required to explain the free–free emission. These possibilities, however, are rather ad hoc, and we explore the scenario of a photoevaporated disk, a fossil of the star formation process, around the exciting star of W3(OH). Using an expansion velocity of ∼4 km s⁻¹ for W3(OH) (Kawamura & Masson 1998) and a radius of 0.006 pc, W3(OH) has a kinematic age of only 1500 yr and the accretion disk that presumably existed around the star during its formation could still be present.

A compact ionized region around a young massive star can be produced by a photoevaporated disk (Hollenbach et al. 1994, hereafter H94). In the case of W3(OH), the compact source has a size of the order of 100 AU. This size corresponds to the gravitational radius rg = GM∗/a², where M∗ is the stellar mass and a is the sound speed of the ionized gas. Beyond this radius, the photoevaporated gas can escape from the potential well of the star. Inside rg the gas is trapped and will form a static atmosphere that can produce the observed free–free emission.

As discussed above, the exciting source of W3(OH) has a luminosity L∗ ≈ 7.1 × 10^4 L⊙. According to Vacca et al. (1996), a ZAMS star with this luminosity has a stellar mass, M∗ ≈ 19.5 M⊙, a stellar radius R∗ ≈ 8.3 R⊙, and a rate of ionizing photons N_i ≈ 1.44 × 10^{48} s⁻¹. For this star, the gravitational radius is rg ≈ 130 AU. The static atmosphere has an exponential electron number density profile n_e(r, z) = n_0(r) exp(−z²/h²), as a function of height z and radius r, where n_0(r) is the electron density at the disk surface and H(r) = r_g(r/r_g)² is the scale height. The number density n_0(r) is given by Equation (3.11) of H94, and one can obtain the free–free optical depth of a face-on disk as a function of radius, assuming an electron temperature of the ionized gas of T_e = 6500 K.

We find that the optical depth at 32.96 GHz decreases as a function of radius and becomes τ_{32.96GHz} ≈ 1 at θ = 0°032. The emission of the optically thick inner region is ∼13 mJy, close to the observed flux. The total emission of the static atmosphere up to r_g ≈ 130 AU is ∼35 mJy, and we assume that the accretion disk has been truncated by the photoevaporation process beyond r_g. Furthermore, as shown in Figure 5 of Lugo et al. (2004), who modeled the photoevaporated disk wind in the source MWC 349A, the static atmosphere can produce a spectral index of the order of 1 for frequencies between 20 and 100 GHz. On the other hand, according to H94, to preserve the static atmosphere one requires a weak stellar wind because a strong wind would blow the static atmosphere up to a radius r_w where the ram pressure of the wind balances the thermal pressure of the ionized gas (see their Figure 1). For the case of W3(OH), the condition that r_w < r_g imposes a condition on the stellar wind momentum M_{wind} < 7.5 × 10^{-2} (Equation (4.3) of H94), where the stellar wind mass-loss rate M_{wind} is normalized to 10^{-8} M⊙ yr⁻¹, and the stellar wind velocity v_{wind} is normalized to 1000 km s⁻¹. Therefore,
this condition implies a critical value for the mass-loss rate, \( M_{\text{crit}} \sim 10^{-7} M_\odot \text{yr}^{-1} \), which agrees with the value compiled by Dzib et al. (2013) for a B0 ZAMS star.

Finally, the flux variation on timescales of years could be explained by a variation in the wind strength: if the wind momentum increases, it can blow away the static ionized atmosphere decreasing the observed radio flux. When the star returns to its low wind state, a static atmosphere will be regenerated and the flux will increase to its high value. Variations in the wind strength could be due to variations in the accretion rate through the disk as observed in young low-mass stars (e.g., Pech et al. 2010). In this scenario, sub-arcsecond sensitive millimetric observations should detect the dust emission from the fossil circumstellar disk that is being ionized by the central star.

5. CONCLUSIONS

In conclusion, the compact radio source projected near the center of W3(OH) coincides positionally with a massive young star and has brightness temperature, spectral index, and polarization characteristics suggestive of partially thick free–free emission. An interpretation in terms of an ionized stellar wind fails because of the large flux densities observed in the source. We tentatively propose that the compact radio source could be the result of either a slow shell ejection or the passage of a dense gas clump. Finally, we discuss a scenario where the emission originates in a static ionized atmosphere around a fossil photoevaporated disk.

S.A.D., L.F.R., S.E.K., L.L., S.L., and L.A.Z. are grateful for the support of DGAPA, UNAM, and CONACyT (México). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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