A CLUSTER OF COMPACT RADIO SOURCES IN W40

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ABSTRACT

We present deep 3.6 cm radio continuum observations of the H ii region W40 obtained using the Very Large Array (VLA) in its A and B configurations. We detect a total of 20 compact radio sources in a region of 4′ × 4′, with 11 of them concentrated in a band with 30′ of extent. We also present JHK photometry of the W40 cluster taken with the QUIRC instrument on the University of Hawaii 2.2 m telescope. These data reveal that 15 of the 20 VLA sources have infrared counterparts, and 10 show radio variability with periods less than 20 days. Based on these combined radio and IR data, we propose that eight of the radio sources are candidate ultracompact H ii regions, seven are likely to be young stellar objects, and two may be shocked interstellar gas.

Key words: H ii regions – infrared: stars – open clusters and associations: individual (W40) – radio continuum: stars – stars: formation

Online-only material: machine-readable and VO tables

1. INTRODUCTION

The W40 H ii region (denoted as S64 in the Sharpless catalog) is the central object in a rich cloud complex that lies some 3.5 above the Galactic plane at J2000 coordinates 18°31′29″, −02°05′4′′ (Westerhout 1958; Sharpless 1959). W40 is a blister H ii region with a diameter of ∼6′. It is bordered by a molecular cloud that subtends an angle of ∼1°. The dense core of this molecular cloud is located at galactic coordinates 28.77, +3.70 and is labeled TGU 279-P7 in the all-sky cloud atlas of Dobashi et al. (2005).

W40 has been well studied at radio and millimeter wavelengths, leading to a firm understanding of the region’s gaseous structures. Crutcher & Chu (1982) compiled a comprehensive review of the available molecular line and radio continuum data to develop a detailed kinematic picture of the H ii region and its interaction with the molecular cloud. The warm C ii interface between these two principal components of the cloud complex has been extensively studied as well (Vallée 1987; Vallée & MacLeod 1991; Vallée et al. 1992). Additionally, Zeeman measurements of OH absorption lines have revealed a magnetic field of B = −14.0 ± 2.6 μG (Crutcher et al. 1987).

A dense stellar cluster within W40 is apparent in the IR maps of the Two Micron All Sky Survey (2MASS) and DENIS surveys (Reylé & Robin 2002). This cluster is dominated by three central OB stars that constitute the primary excitation sources of the H ii region (Zeilik & Lada 1978; Smith et al. 1985). The stars in this cluster appear to be heavily obscured along our line of sight, with AV ∼ 10 mag of visual extinction (Shuping et al. 1999). W40 IRS2a has been suggested as the dominant source of ionizing radiation in this region (Smith et al. 1985), and millimeter observations have shown evidence for circumstellar dust shells around IRS1a, 2a, and 3a (Smith et al. 1985; Vallée & MacLeod 1994).

From the collective results of these studies we can see that the W40 H ii region has broken through the surrounding molecular cloud in a direction that lies at an angle to our line of sight. Thus, the stellar cluster which powers the H ii region is mostly hidden in the optical and near-IR, but scattered Hα emission marks the blistering edge of the H ii region. The dense core of the molecular cloud is offset from the H ii region and its embedded cluster by ∼2′, and a thin C ii region delineates the boundary between the cool molecular gas and the hot ionized region.

The distance to W40 is not yet well constrained. Several measurements of atomic and molecular lines along the line of sight toward W40 have been used to estimate the distance to W40—assuming that the cloud complex is in a circular orbit around the galactic center (Reifenstein et al. 1970; Downes 1970; Radhakrishnan et al. 1972). Taken together, these measurements produce only a weak constraint of 300–900 pc. Using assumptions about the spectral types of several of the stars in the W40 cluster, distance modulus estimates can only limit the distance to a wide range from 400 to 700 pc (Crutcher & Chu 1982; Smith et al. 1985). Kolesnik & Iurevich (1983) calculated a distance of 600 pc using a novel distance determination technique involving OH line measurements. Hereinafter, we will adopt a distance of 600 pc, which puts the W40 complex at a height of 37 pc above the galactic plane.

More recently, the properties of the W40 region have been summarized in a review by Rodney & Reipurth (2008). Also, Kuhn et al. (2010) have performed a deep X-ray study of W40, and detected about 200 young stellar members of the cluster.

2. OBSERVATIONS

We have used the Very Large Array (VLA) of the NRAO in its A and B array configurations to observe W40 at 3.6 cm, under the NRAO program code AR551. The B configuration observations were made on 2003 November 3, while the A configuration observations were made on 2004 September 18. Our phase center was at α(J2000) = 18h31m23s; δ(J2000) = −02°05′29″. The amplitude calibrator was 1331 + 305, with an adopted flux density of 5.18 Jy, and the phase calibrator was 1804 + 010, with flux densities of 0.76 ± 0.01 and 0.82 ± 0.01 Jy for the first and second epochs of observation, respectively. The half-power contour of the synthesized beams were 0′.88 × 0′.76; +17° (for configuration B data) and 0′.26 × 0′.22; +16° (for configuration A data), for images made with the ROBUST parameter of the task IMAGR set to 0 (Briggs 1995). The
data were analyzed in the standard manner using the NRAO AIPS package. The data for the two epochs were self-calibrated in phase separately and then concatenated to obtain a final image with the highest sensitivity possible. The half-power contour of the synthesized beam for this concatenated data was 0.36 × 0.30; +28° for images made with the ROBUST parameter of the task IMAGR set to 0 (Briggs 1995).

A total of 20 sources were detected in a field of 4′ × 4′ in this image. Following Fomalont et al. (2002), we estimate that in a field of 4′ × 4′ the a priori number of expected 3.6 cm sources above ∼0.2 mJy is only ∼0.3. We then conclude that perhaps one out of the 20 sources could be a background object, but that we are justified in assuming that all the detected sources are associated with W40.

Infrared photometry was carried out with the QUIck Infrared Camera (QUIRC; Hodapp et al. 1996) on the University of Hawaii 2.2 m telescope from 2003 June 17–19. Data were obtained in the J, H, and K′ filters of the Mauna Kea Observatories (MKOs) filter set (Tokunaga & Vacca 2005). These IR images were reduced and combined using the Gemini Observatory’s QUIRC package in IRAF. Our data were collected under non-photometric conditions, and errors in the telescope guiding combined with persistent focus problems made it impossible to pursue photometry by fitting the point-spread function (PSF), as is preferred for crowded fields. Thus, aperture photometry was performed using the NOAO DIGIPHOT package. The four brightest IR stars were saturated even in our shortest (1 s) exposures, so without PSF fitting we were only able to obtain upper limits on the magnitudes, which agree well with previous work.

We find over 1000 IR sources with detections in at least one of the three bands, of which 271 have reliable photometric measurements in all three bands. A subset of 118 sources that have good JHK′ photometry in our QUIRC data and good JHK photometry in the 2MASS catalog were used as calibration stars to translate the entire data set to the standard MKO system. This calibration step is the dominant source of error in our IR photometry, because it relies on transformation equations which convert our measured K′ photometry into the K band and take the 2MASS JHK magnitudes into the MKO JHK system (M. Connelley 2005, private communication; Leggett et al. 2006).

In Figure 1, we demonstrate the scatter in our calibration step by plotting the J magnitudes we have measured and calibrated to the MKO system using the same transformation equations as is preferred for crowded fields. The four brightest IR stars were saturated even in our shortest (1 s) exposures, so without PSF fitting we were only able to obtain upper limits on the magnitudes, which agree well with previous work.

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In Figure 1, we demonstrate the scatter in our calibration step by plotting the J magnitudes we have measured and calibrated to the MKO system against the J-magnitude reported by 2MASS, also translated to the MKO system. We estimate that this calibration procedure introduces about 0.1 mag of error into our final photometry values. Table 1 presents calibrated JHK photometry for all 271 well-measured IR sources (the full table is available in the online version of the journal).

Of the 20 radio sources detected in our VLA data, 15 have counterparts in our IR data with positions matched to within 1″. In Table 2, we list the positions and flux densities of these 20 radio sources, averaged over our two observations. We also note in Column 5 if they were found to be radio variable or not, by comparing the observations of the two epochs and restricting the (u, v) coverage of the images for comparison to the range of 16–300 kλ, a coverage in common for the A and B configurations. The number given in parentheses for the variable sources is the ratio between the largest and the smallest flux density observed. Columns 6–8 provide the measured J, H, and K magnitudes of the IR counterparts, if any. As noted above, the four brightest IR counterparts (VLA-1, 7, 13, and 15) were saturated in our data. For these sources we have translated the published magnitudes in the 2MASS catalog to the MKO system using the same transformation equations employed for our calibration procedure. Typical internal errors on our measured IR values are <0.1 mag.

3. OVERALL CHARACTERISTICS OF THE SAMPLE OF RADIO SOURCES

A composite JHK′ image of the entire W40 region is shown in Figure 2. This field encompasses a region of ∼7′ centered around the stellar cluster and the middle of the η region. The two boxes in this figure indicate regions shown with greater detail in Figures 3 and 4. Figure 3(a) displays a radio contour map containing the entire radio cluster detected at 3.6 cm. Out of the 20 detected radio sources, 11 of them—including the 2 brightest—are concentrated in a band with 30′′ of extent, as shown in Figure 4(a). Figures 3(b) and 4(b) show the same regions in the K′ filter, revealing that most of the radio sources can be associated with IR counterparts.

Of the 20 sources detected, 10 were found to be time variable from one observation to the other (see Column 5 in Table 1). This percentage (50%) of time variable sources is very similar to the value of 47% found in Orion by Zapata et al. (2004). However, this percentage is larger than the value of 32% found in NGC 2024 by Rodriguez et al. (2003). We searched unsuccessfully for circular polarization in the sample. We measured the angular size of the sources using the AIPS task IMFIT, with a correction for bandwidth smearing. With the exception of sources VLA 8, VLA 13, and VLA 19, all sources were found to be unresolved, θ ∼ 0.2.

4. DISCUSSION

There are several mechanisms that can produce compact centimeter radio sources in regions of star formation. In regions of low-mass star formation, thermal jets and gyrosynchrotron emitters can be present. In regions of high-mass star formation, we also have strong ionizing radiation available and, in
Figure 2. Composite JHK' image of the W40 region. Two rectangles delineate the fields shown in Figures 3 and 4.

Table 1
Extended Photometry Table of W40 IR Sources

| Index | α2000 | δ2000 | J     | H     | K     |
|-------|-------|-------|-------|-------|-------|
| 001   | 277.762394 | −2.031111 | 16.608 ± 0.145 | 14.838 ± 0.203 | 13.809 ± 0.272 |
| 002   | 277.764807 | −2.005333 | 14.185 ± 0.144 | 13.045 ± 0.203 | 10.861 ± 0.272 |
| 003   | 277.767017 | −2.136254 | 15.328 ± 0.144 | 12.772 ± 0.203 | 11.734 ± 0.272 |
| 004   | 277.767545 | −2.181531 | 13.621 ± 0.144 | 10.963 ± 0.203 | 9.666 ± 0.272 |
| 005   | 277.767801 | −2.154991 | 15.387 ± 0.144 | 13.509 ± 0.204 | 12.394 ± 0.272 |
| 006   | 277.767999 | −2.010032 | 13.318 ± 0.144 | 13.530 ± 0.203 | 11.754 ± 0.272 |
| 007   | 277.769254 | −2.033301 | 16.745 ± 0.146 | 14.706 ± 0.203 | 13.349 ± 0.272 |
| 008   | 277.770824 | −2.054937 | 10.947 ± 0.144 | 11.471 ± 0.203 | 10.242 ± 0.272 |
| 009   | 277.770948 | −2.046558 | 13.686 ± 0.144 | 12.726 ± 0.203 | 11.683 ± 0.272 |
| 010   | 277.771923 | −2.109518 | 14.602 ± 0.145 | 13.211 ± 0.203 | 12.122 ± 0.273 |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 2
Parameters of the 3.6 cm VLA Sources

| W40-VLA Number | R.A. (α2000) | Decl. (δ2000) | Flux (mJy) | Time Variable? | J     | H     | K     | W40-IRS Designationa |
|----------------|-------------|-------------|-----------|----------------|-------|-------|-------|----------------------|
| 1              | 18 31 26.21 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 2              | 18 31 19.75 | −02 05 17.06 | 1.63      | N              | 13.50 | 11.68 | 10.47 | ...                  |
| 3              | 18 31 19.57 | −02 05 17.06 | 1.63      | N              | 13.50 | 11.68 | 10.47 | ...                  |
| 4              | 18 31 26.21 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 5              | 18 31 17.41 | −02 05 17.06 | 1.63      | N              | 13.50 | 11.68 | 10.47 | ...                  |
| 6              | 18 31 18.75 | −02 05 17.06 | 1.63      | N              | 13.50 | 11.68 | 10.47 | ...                  |
| 7              | 18 31 18.75 | −02 05 17.06 | 1.63      | N              | 13.50 | 11.68 | 10.47 | ...                  |
| 8              | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 9              | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 10             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 11             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 12             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 13             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 14             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 15             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 16             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 17             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 18             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 19             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |
| 20             | 18 31 17.41 | −02 05 17.02 | 3.27      | Y(8.3)         | 10.74 | 9.09  | 8.15  | IRS 1c               |

Notes.

a From Smith et al. (1985).
b Source was saturated in shortest exposure. Magnitudes quoted here are from 2MASS, translated to the MKO system.
addition to the two mechanisms present in low-mass star-forming regions, we can have ionized stellar winds, ultracompact H II regions, and radio proplyds. It is possible to distinguish between these various possibilities with high angular resolution, multifrequency observations made with the required sensitivity.

Let us first consider the subset of 15 sources that have IR counterparts. It is possible that these objects are ultracompact H II (UCH II) regions, centered around young massive stars. The radio emission can then be explained as optically thin free–free radiation, and the familiar photoionization equilibrium equations (e.g. Osterbrock 1974) can be used to determine physical parameters of the system. However, UCH II regions are not expected to exhibit short-period time variability, as is seen in 8 of the 15 radio/IR sources. The remaining seven sources can be considered as UCH II candidates. Among this group are the two brightest radio sources, VLA-18 and VLA-14, as well as the brightest IR source, VLA-15 = IRS1a. With an assumed electron temperature of $10^4$ K and a distance of 600 pc, we can estimate that a B0 zero-age main sequence (ZAMS) star would be required to maintain the ionization in each of these UCH II regions (Panagia 1973; Thompson 1984).

As for the sources that show time variability, these are more likely to correspond to young stellar objects (YSOs) with active magnetospheres. The gyrosynchrotron radiation from such objects is expected to show substantial variation over timescales of a few days. One of the brightest radio/IR sources that may be placed in this category is VLA-7 = IRS 2a. The spectral energy distribution (SED) of this object has been examined from near-IR to millimeter wavelengths, and it indicates that the star is surrounded by approximately $0.1 \, M_\odot$ of circumstellar material (Vallée & MacLeod 1994). This finding is consistent with our tentative classification of VLA-7 as a YSO, since many stars remain shrouded in their natal envelopes all the way to the main sequence. It is important to note that this classification is at odds with the results of Smith et al. (1985) and Vallée & MacLeod (1991), who label this source as
a deeply embedded OB star that is powering the ionization of the W40 H\(\text{ii}\) region. Based on the data presented here, the radio sources VLA-14, 15, and 18 may be equally valid candidates for supporting the H\(\text{ii}\) region.

Of the five radio sources that do not have IR counterparts, VLA-17 and 19 are of particular interest. VLA-19 is offset by 7.5 (0.02 pc) to the north of VLA-18, and VLA-17 is only 0.7 (0.002 pc) away to the northwest. These radio sources are both relatively weak, do not vary with time on short periods, and have mildly non-circular radio contours. All of this evidence suggests that these two radio sources may correspond to shock fronts from a thermal jet interacting with the ambient interstellar medium. Based on its position and proximity, VLA-18 = IRS1b could well be the star which powers this radio jet.

In order to unambiguously determine the nature of these compact radio sources, further information is required. A good indicator of UCH\(\text{ii}\) regions is the spectral index at radio frequencies. Free–free emission from a UCH\(\text{ii}\) region should have a very flat radio spectrum, so a spectral index more negative than \(-0.1\) is a clear indication that the object is not a UCH\(\text{ii}\) region (Rodríguez et al. 1993). This measurement could be made using the EVLA to observe W40 with similar angular resolution at 6 cm, for example. Another important observation to further our understanding of the W40 cluster will be to gather X-ray data to determine the high-energy characteristics of the dominant radio/IR sources. Gyrosynchrotron emitters should produce detectable X-ray emission, with measurable time-variability signatures. A combination of high angular resolution radio observations at longer wavelengths plus X-ray measurements with XMM–Newton or Chandra would enable us to definitively determine the astrophysical nature of these sources. A first Chandra study of W40 is currently in preparation (Kuhn et al. 2010).

5. CONCLUSIONS

We have carried out the first detailed, high-resolution study of the center of the W40 region at 3.6 cm, supplemented by deep IR imaging of the entire W40 complex. Previous radio observations of W40 were not able to separate individual sources, but our data have revealed a cluster of some 15–20 radio sources. Many of these sources are clustered together in a narrow band at the center of the W40 cluster. A substantial fraction of these radio objects are also present in our JHK\(\text{\prime}\) images, and a number of them show significant variability over timescales of a few days to weeks. The combination of this high-resolution radio data and our IR maps allows us to speculate on the nature of these sources, possibly distinguishing between YSOs, UCH\(\text{ii}\) regions, and shocked interstellar gas.

W40 is a rich, nearby star-forming region that has not benefited from the same intense scrutiny afforded to regions such as Orion, Ophiuchus, and others. This is largely due to the veil of gas and dust which hides most of W40\’s compact objects from view. Radio and IR observations such as those described here are necessary to penetrate the obscuring shell to investigate the interior. X-ray observations and further high-resolution radio measurements at longer wavelengths will be very beneficial in unmasking the W40 cluster.

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