STRUCTURE AND COMPOSITION OF MOLECULAR CLOUDS WITH CN ZEEMAN DETECTIONS I: W3(OH)

NICHOLAS S. HAKOBIAN AND RICHARD M. CRUTCHER

Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL, USA; nhakobi2@astro.illinois.edu, crutcher@illinois.edu

Received 2010 June 28; accepted 2011 March 10; published 2011 April 27

ABSTRACT

We have carried out a multi-species study of a region which has had previous measurements of strong magnetic fields through the CN Zeeman effect in order to explore the relationship between CN and N$_2$H$^+$, both of which have evidence that they remain in the gas phase at densities of 10$^5$–10$^6$ cm$^{-3}$. To achieve this, we map the 1 arcmin$^2$ region around the UCHII region of W3(OH) using the Combined Array for Millimeter-wave Astronomy (CARMA). Approximately 105 hr of data were collected in multiple array configurations to produce maps with an effective resolution of $\sim$2$''$5 at high signal-to-noise ratios (S/Ns) in CN, C$^{18}$O, HCN, HCO$^+$, N$_2$H$^+$, and two continuum bands (91.2 GHz and 112 GHz). These data allow us to compare tracer molecules associated with both low- and high-density regions to infer gas properties. We determine that CARMA resolves out approximately 35% of the CN emission around W3(OH) when compared with spectra obtained from the IRAM 30 m telescope. The presence of strong absorption lines toward the continuum source in three of the molecular transitions infers the presence of a cold, dark, optically thick region in front of the continuum source. In addition, the presence of high-velocity emission lines near the continuum source shows the presence of hot clumpy emission behind the continuum source. These data determine that future high-resolution interferometric CN Zeeman measurements which cannot currently be performed (due to technical limitations of current telescopes) are feasible. We confirm that CN is indeed a good tracer for high-density regions; with certain objects such as W3(OH) it appears to be a more accurate tracer than N$_2$H$^+$.

Key words: magnetic fields – molecular data – stars: formation

1. INTRODUCTION

The measurement of magnetic fields harbors several difficulties due to the fact that they are a vector quantity. In order to measure the absolute magnitude and direction of the magnetic field, it is necessary to sample the two components in the plane of the sky and the line-of-sight component. While dust polarization can measure the direction of a magnetic field in the plane of the sky, the line-of-sight component intensity can be directly measured. This is accomplished through the detection of the normal Zeeman effect which occurs when an atom or molecule is in the presence of a magnetic field. Most transitions have a Zeeman splitting factor that is too small to measure unless in dense, spatially compact environments with exceedingly large magnetic field strengths. However, H$^1$, OH, and CN have splitting factors that are large enough to measure the weaker magnetic fields that are expected around sites of active star formation in molecular clouds. The CN $N_1$–1 transition has seven strong hyperfine components (Table 1) that have a large distribution of Zeeman splitting factors. The two strongest hyperfine components, with relative strengths of 27 and 10, respectively, also have large splitting factors.

Falgarone et al. (2008) surveyed 14 molecular cloud cores and measured the line-of-sight magnetic field strength using the CN Zeeman effect. The strongest magnetic field detected was 1.10 ± 0.33 mG toward the Ultra-Compact H II (UCHII) region of W3(OH) (Hoare 2004), a high-mass star formation site in the W3 molecular cloud complex. For these measurements, Falgarone et al. (2008) used the IRAM 30 m telescope. Due to the relatively large beam size of the IRAM 30 m telescope (23$''$ or 46,000 AU in diameter at the 2 kpc distance (Hachisuka et al. 2006) of W3(OH)), only very limited mapping to find the emission peak was performed. From these data, it is not possible to determine the structure of the magnetic field or which material the field is associated with.

W3(OH) contains a high-mass O star and has been extensively studied over the years since the discovery of several OH maser sites within it (Raimond & Eliasson 1969). A star-forming region 6$'$ east of W3(OH) was later discovered by Turner & Welch (1984) in HCN. This smaller region was also studied for maser activity and found to contain several H$_2$O masers (Wynn-Williams et al. 1972). While this second source was initially not observed in the continuum, with the development of more sensitive instruments, it was eventually detected in dust continuum studies (Wilner et al. 1995; Wyrowski et al. 1997).

Within the last few years, further high-resolution studies with instruments such as BIMA have led to the detection of multiple dense cores believed to be sites of active star formation within the Turner–Welch object (Chen et al. 2006).

In order to determine the spatial distribution of the magnetic field, an understanding of the CN gas is needed. There is some question, however, as to the exact physical conditions that CN traces. Hily-Blant et al. (2008) used the IRAM 30 m telescope to conclude that CN in prestellar cores stays in the gas phase at densities close to 10$^6$ cm$^{-3}$ and can serve as a kinematic tracer of high-density gas. They compared their CN maps with N$_2$H$^+$, another high-density tracer, and found the results to be in good agreement. Therefore, it is expected that the measured magnetic field strength derived from CN measurements would be in gas that is associated with high-density regions of active star formation. However, before detailed conclusions can be drawn from these magnetic field measurements, a high angular resolution study of the CN gas distribution is required. An ideal instrument for this is an interferometer such as CARMA, as its high spatial resolution and ability to sample baselines as short as 6 m allow us to sample material both spatially compact and widespread.
2. CARMA OBSERVATIONS

With CARMA (Bock et al. 2006) it is possible to achieve a resolution of approximately 2\′′5 by combining maps generated with the C, D, and E arrays. By using three different array configurations, we have the ability to probe small-scale structure while retaining the ability to image large-scale features that would otherwise be resolved out in the C and D arrays. CARMA currently does not have polarization capability and therefore cannot perform magnetic field measurements; however, by mapping these regions at high resolution we can gain crucial information as to the structure of the regions that are being sampled by the IRAM observations. To assist with this, we use the advanced features of CARMA’s correlator to sample several spectral lines simultaneously, so we can compare the structure of the CN emission with the emission of other well studied tracer molecules. We will also gain information on which regions are possible to map in the Zeeman effect at high resolution and for long integration times with an instrument capable of making dual-polarization measurements, when such an interferometer array becomes available.

The CARMA observations began in Spring 2007 and were completed in the Fall of 2009. About 66 hr of observing time was used to map a 1 arcmin\(^2\) region around W3(OH). This time was used to observe the following molecular tracers: CN, C\(^{18}\)O, N\(_2\)H\(^+\), HCN, and HCO\(^+\) (Table 2). Due to the design of the CARMA correlator and the relatively large frequency range within the 3 mm band that these tracers span, the measurements had to be performed in two separate tracks: one for CN and C\(^{18}\)O and a second for N\(_2\)H\(^+\), HCN, and HCO\(^+\). Approximately 50 hr (Table 3) was spent for the CN band and 16.2 hr was spent for the N\(_2\)H\(^+\) band (not counting additional time spent in B array, discussed below). In order for us to reach our signal-to-noise goal, the tracks containing N\(_2\)H\(^+\) required much less observing time. Table 3 shows the observing array details. Our pointing center is located on the continuum source, a UCHII region, located at 02:27:03.7 R.A., +61:52:25 decl. (J2000). This is slightly offset from the IRAM pointing position.

We produced maps for 3 mm lines of CN, C\(^{18}\)O, N\(_2\)H\(^+\), HCN, and HCO\(^+\) at a resolution of approximately 2\′′5. The composite CARMA primary beam at half-power at this frequency is slightly more than 60\′′ in diameter, reflected in our maps, which are 64\′′ on a side. Since baselines as short as 6 m are included, the maps are sensitive to structure smaller than about 90\′′, so that the spatial dynamic range is almost 40:1. At the distance of W3(OH) (2 kpc), this means the maps are about 0.62 pc across, and the resolution is about 0.024 pc or 5000 AU. For all of the spectral line observations, we used the 8 MHz spectral line mode, which for CN (N\(_2\)H\(^+\)) provides a velocity coverage of ∼21 km s\(^{-1}\) (∼25.8 km s\(^{-1}\)) and a resolution of 0.335 km s\(^{-1}\) (0.415 km s\(^{-1}\)). The other transitions have similar coverages and resolutions which vary depending on their rest frequency. The large velocity coverage is necessary to simultaneously image several hyperfine components while still maintaining a high spectral resolution. Our data also contain two 500 MHz continuum bands in each track giving us four separate continuum windows between 88 GHz and 113 GHz. These continuum maps, while having a lower spatial resolution than some previously published maps of W3(OH) (Chen et al. 2006), have a significantly higher S/N.

MIRIAD was used for data reduction, specifically with the modifications for use with CARMA. Due to the nature of CARMA, with three distinct primary beams, the data were reduced as a mosaic data set with a common pointing center. Passband calibration was performed on all tracks by utilizing the CARMA system noise source. Even though suitable passband calibrators were observed for every track, it was decided that better passband solutions could be obtained from the noise source. Flux calibration was performed on each individual track with a 15 minute observation of MWC349, Mars, or Uranus, whichever was best suitable at observation time as the intrinsic flux of these sources is very well modeled. Since our data were obtained over such a long period of time, the flux of our primary phase calibrator varied significantly. We determine the flux of the phase calibrator through a bootstrapping process by which our flux calibrator measurements are used to calibrate the flux scale for the point source phase calibrator. It is estimated that there is an inherent 20% error with this flux calibration technique. Phase calibration was performed primarily on 0359+509 with a secondary calibrator 0102+584, used if the primary was...
not visible for a significant portion of the track. The primary phase calibrator had an averaged bootstrapped flux of 6.16 Jy over 10 tracks obtained over a period of 20 months. The flux steadily increased from 3.9 Jy to 10.7 Jy over this time. In order to corroborate the flux measurements, we compared our data with that obtained by the CARMA flux calibration commissioning task. This independent flux measurement of 0359+509 is 9.83 Jy (from Fall 2009), consistent with our measurement of 10.7 Jy from the same time period, assuming the 20% uncertainty mentioned above. Gain and phase calibration was performed with the gfiddle routine which fits an nth order polynomial to the phase measurements on the phase calibrator. This method was chosen in contrast to the more widely used self-cal technique (on the calibrator) due to the weak signal strength of some of our spectral lines. However, the benefits of this technique over the self-cal technique have not been shown; overall, this technique may not have any net advantage. It may be possible to gain an increased S/N by performing self-calibration on W3(OH) itself, as the continuum source in the center of the map remains unresolved in all of the array configurations and is bright enough to perform phase calibration in the spectral channels. However, the absolute position of the phase center of the map is not retained and flux calibration is not guaranteed to succeed. These details are described in detail below in the description of our B-array data.

Since CARMA is composed of two types of telescopes of differing sizes, we have to handle the fact that we have multiple primary beam types associated with our data. CARMA has both 10 m and 6 m dishes which form three effective primary beams with the same phase center: one for the pairing of 10 m to 10 m dish, one for 6 m to 6 m, and a third of 10 m to 6 m. At the CN line frequency the 6 m primary beam half-power beamwidth (HPBW) is \(\sim 111''\), the 10 m HPBW is \(\sim 66''\) (at the \(\text{N}_2\text{H}^+\) frequency of 93 GHz, these HPBWs are 135'' and 81'', respectively), while the 6 m–10 m primary beam size is in between that of the other two. We conservatively constrained our maps to \(\sim 1\) arcmin\(^2\) in order to easily compare the other maps with the CN data. The restoring beam size is calculated by fitting the dirty beam with a Gaussian beam. This is the effective resolution of a map and is the value quoted in all of our figures.

Image conversion from the UV data set into the spatial domain was performed by the MIRIAD routine invert. System temperature weighting was used to properly downweight data taken at low elevation or in the unlikely event that data were improperly flagged. The CARMA control system has an intricate flagging mechanism that operates if one of many error conditions are met including: telescope tracking errors, pointing errors, receiver problems (dewar temperature, LO frequency, etc), system temperature, and other computer or correlator errors that could hinder data integrity. All data were additionally inspected for extreme system temperatures, unphysical antenna gains, time regions without converging phase solutions, and poor weather conditions that could influence the quality of the data. In a few cases (usually in older tracks before some automated flagging conditions were introduced), data that contained systematic errors were manually flagged. This additional flagging increased the S/N of these few tracks by a factor of 2–3. In the invert step, we weighted our UV data using a Briggs visibility weighting robustness parameter of 1 (Briggs et al. 1999), which provides a slightly increased S/N over uniform weighting at the expense of a larger synthesized beam size. The relatively weak CN emission prompted the weighting of data in this manner. Since we are detecting low-level emission we did not want large sidelobes to obscure the detections. If we changed the weighting more toward natural weighting, we could have reduced the noise level further; however, the beam size would be significantly larger and we would be affected by significant sidelobes. Cleaning was performed with the MIRIAD task mossdi, the mosaic version of the standard Steer clean routine. We used a multi-step cleaning technique in order to prevent undercleaning the source. A small number of clean iterations were performed in order to remove large-scale beam patterns while leaving much of the low-intensity source features uncleared. From this initial clean, we ran the MIRIAD task restor which used the clean data to produce a map without beam effects. We used the average offline noise level in this map to limit how much flux was cleaned from a second iteration of mossdi and to prevent overcleaning. This second stage mossdi iteration was followed by another invert step to produce a final, deep cleaned map. In theory, this process can be repeated ad infinitum, however, if the noise level calculated in the first step is accurate, and the maximum number of cleaning iterations is large enough such that we are guaranteed to clean down to the noise level, this two-step process is adequate.

3. RESULTS

3.1. CN

Figure 1 shows integrated line maps of the five species, while Figure 2 shows channel maps. The continuum source was removed from the spectral line maps by averaging several offline channels together and subtracting that from each individual channel. Toward the continuum source, we see three of the species strongly in absorption. Besides the Turner–Welch object and the continuum source, there are two other regions that are notable in CN. The western side of the map contains very diffuse CN emission, while the eastern side of the map shows a compact and complex CN emission source. In order to compare the CARMA CN data with the IRAM CN data (Falgarone et al. 2008), we also generated a map where the CARMA channel data were convolved with a 23'' Gaussian beam, effectively smoothing the CARMA data to match the IRAM resolution (see Section 4.2). By comparing these maps, there is evidence that both spectra are dominated by diffuse emission.

Compared to the other molecules, the CN emission appears to be diffuse but “clumpy.” Under closer scrutiny, it is much more complex. Our 8 MHz spectral window is centered at 113,490,982 GHz, the frequency of CN’s strongest hyperfine component. This frequency and window size was chosen to allow us to simultaneously image a second hyperfine component of the CN \(N = 1–0\) transition at 113,488 GHz in the same spectral window. These two hyperfine components are separated by 7.9 km s\(^{-1}\). Since this window covers approximately 21 km s\(^{-1}\) of velocity space, we expect to fully resolve and image both lines. Multiple velocity components in the image make it difficult to determine which hyperfine component some emission belongs to. However, we have been able to identify at least three distinct velocity components, representing separate regions around W3(OH) (Figure 3).

The northwest and southwest components appear to be very diffuse. They are centered at approximately \(-47.25\) km s\(^{-1}\) and \(-44.5\) km s\(^{-1}\), respectively. It is difficult to completely isolate these two velocity components due to blending and overlap of the hyperfine lines. The maps in Figure 3 reflect some of this “blending.” It occurs because the second hyperfine component
of one velocity partially overlaps the primary hyperfine component of the other velocity. For example, the second and third maps in Figure 3 are cross-contaminated. This is easily visible when the positions of the emission in the two maps are compared; they have a significant spatial overlap region.

The northeastern component is more complex. In addition to containing diffuse emission, multiple denser clumps are visible. The significance of some of these clumps is not clear from the integrated line map. Between the larger southernmost clump and the smaller, northern clump are a string of small, presumably unresolved clumps only seen in a single channel each. When viewing an averaged line map, many of these features are spatially smoothed and are not prominent (as in Figure 3). The densest portions of this region are concentrated in two lobes, not unlike the typical signature of an outflow. Figure 4 shows channel maps of the 15 channels around the strongest hyperfine component. There does not appear to be any blending as was seen in the south–west component, so we are confident that this channel map is not contaminated. An averaged contour plot (Figure 5) shows the physical comparison between the two “lobes” of the emission. The top (redshifted) lobe is averaged from the six channels from −47.6 km s\(^{-1}\) to −49.2 km s\(^{-1}\), while the bottom (blueshifted) lobe is averaged from the six channels from −49.2 km s\(^{-1}\) to −50.8 km s\(^{-1}\). While this does have the signature of a typical outflow, it is not accompanied by any coincident emission from any of the other species, nor is there any accompanying IR emission source visible in publicly available IR catalogs. Due to the extent of the low-level emission around the whole region, and lack of evidence of an outflow generating source, it is more likely that this is not an outflow, but rather bulk rotation of a clump of gas.

3.2. HCN, HCO\(^+\), C\(^{18}\)O

The maps for HCN, HCO\(^+\), C\(^{18}\)O all appear to be tracing the same material, which does not coincide with either the CN or N\(_2\)H\(^+\) emission (see Figures 6–8 for channel maps). However, the peak position of these spectral lines coincides with the HCN detection of the Turner–Welch object first reported in Turner & Welch (1984). At 2^h5\(^{\circ}\) resolution, we do not appear to be resolving the object; previous high-resolution (subarcsecond) studies have been conducted in order to resolve this object in the continuum (Chen et al. 2006), which resulted in the detection of multiple cores. Previous HCO\(^+\) studies (Wink et al. 1994) had similar spatial resolution to our data, however, our data have significantly better S/N and sample material that was resolved out in the previous study. In the HCO\(^+\) spectrum of the Turner–Welch object, a weak, secondary velocity component at −44 km s\(^{-1}\) is visible (Figure 9). This velocity component is not reported in any previous studies. The HCN spectra toward the Turner–Welch object shows an unexpected peak at an apparent velocity of −39 km s\(^{-1}\) (Figure 9); comparing relative positions of these two peaks, the anomalous HCN peak would be the \( F = 0–1 \) transition of a secondary velocity component at −44 km s\(^{-1}\). The other hyperfine lines from this velocity component are being masked by the hyperfine lines from the primary velocity component. This can only happen if the separation between the hyperfine lines is approximately the separation between the two velocity components. The C\(^{18}\)O line may also show this secondary component, however, it cannot be confirmed due to the relatively low S/N of the C\(^{18}\)O emission.

The C\(^{18}\)O map does not show any absorption toward the continuum source, unlike HCN, HCO\(^+\), and CN. This is consistent
Figure 2. CN Channel maps, rebinned to 1 km s$^{-1}$ velocity increments. The velocity scale is centered on the strongest CN hyperfine component at 113.490 GHz. The spatial resolution of this map is 2.9 × 2.4 arcsec. The contour levels are −80, −40, 20, 40, 60, 80, and 100 times 0.00989 Jy beam$^{-1}$. The ⭐ and ▲ represent the peak continuum positions of W3(OH) and the Turner–Welch object, respectively.

Figure 3. Integrated line maps of CN velocity components in W3(OH). These are the three distinct velocity components present in the CN window. Each map is averaged over the two hyperfine components present. The figure (a) is averaged from −52.7 to −48.5 km s$^{-1}$, figure (b) from −48.2 to −46.3 km s$^{-1}$, and figure (c) from −46.3 to −43.1 km s$^{-1}$. Notable features include the dense clumps in the northeast corner of (a), and the continuum source which can be seen in absorption. The contours are 2, 4, 6, and 8 times the noise level of about 0.03 Jy beam$^{-1}$. The ⭐ and ▲ represent the peak continuum positions of W3(OH) and the Turner–Welch object, respectively.
Figure 4. Channel maps of the CN clump in the northeastern corner of the CN map. Displayed are 15 channels from $-46.92$ km s$^{-1}$ to $-51.44$ km s$^{-1}$. There are two visible “lobes,” the northern one which peaks at $-48.64$ km s$^{-1}$, and the southern one which peaks at $-49.83$ km s$^{-1}$. The contour levels are 5, 8, 11, 14, and 17 times 0.05 Jy beam$^{-1}$.

with observations done by Wink et al. (1994), in which they surmised that the line excitation temperature of HCO$^+$ is significantly lower than the kinetic temperature of 90 K, but the C$^{18}$O excitation temperature is not low enough to produce absorption. However, our observed absorption in other lines is significant and can yield information about the regions around the continuum source. The HCO$^+$ spectra, seen in absorption (Figure 9), looks similar to an inverse P Cygni profile which could indicate an expanding shell-like structure or a strong stellar wind. The multiple hyperfine components of HCN make it difficult to tell which gas is causing the absorption; however, it has the same central velocity and line width as the HCO$^+$ absorption indicating that both features are being generated from the same region. The CN absorption also appears to have similar spectral features as HCN; however, the redshifted CN emission feature is at a level of less than 1$\sigma$ of the noise level and cannot be considered as a positive detection.

Another notable feature of the continuum absorption lines is their shape. There is a double trough shape seen in HCO$^+$, the strongest hyperfine component of HCN, and in CN (these spectra are centered on the strongest hyperfine component). There is also some evidence of this feature in the other hyperfine components; however, they are weaker and, as a result, noisier. According to the results of Wink et al. (1994), within the UCHII region of W3(OH) there is an embedded O7 star. It is very likely that W3(OH) is a region surrounding a bright massive star embedded in a dense cloud with a strong solar wind clearing out the region around the star. In looking at a velocity moment map in HCO$^+$ (HCO$^+$ was chosen due to its lack of hyperfine components and contamination), there appears to be an east–west velocity gradient on the order of 3 km s$^{-1}$. Since W3(OH) is unresolved in these maps, higher resolution data of W3(OH) are required to quantify and describe this effect (see below).

3.3. $N_2H^+$

Figure 10 shows $N_2H^+$ channel maps. If $N_2H^+$ were tracing the same dense material as CN, we would expect to see very similar emission (and absorption) spectra. Most notable is the lack of an absorption feature toward the continuum source, or alternatively, of any emission in $N_2H^+$ at the continuum position. Also, the rotation feature in CN noted above is not seen in $N_2H^+$. The $N_2H^+$ emission appears to be concentrated in the southwestern
of the N$_2$H$^+$ emission. In the −51 km s$^{-1}$ and −50 km s$^{-1}$ panels, it appears that the N$_2$H$^+$ emission borders on the regions with emission in the other species. If we assume that the two molecules do trace the same density gas, it is quite possible that some of these regions are undergoing a chemical reaction that selectively annihilates N$_2$H$^+$. 

3.4. B-array Observations

From the observations described above, several significant features warranted even higher resolution observations. The continuum source is seen in absorption in some species; however, it remains unresolved. CARMA’s B-array should be able to probe the region at significantly higher resolution than in our previous data. This will additionally allow us to study the velocity structure of gas near the continuum source. A velocity map of HCO$^+$ shows an east–west velocity gradient of ∼3 km s$^{-1}$. HCO$^+$ was chosen specifically since it does not have multiple hyperfine components which, due to blending, could pollute the velocity map, and shows absorption toward the continuum source. In addition, with these data we can see if we can resolve the individual cores of the Turner–Welch object. Previous high-resolution continuum maps have shown evidence of multiple cores within the Turner–Welch object which we would expect to also see in corresponding high-resolution spectral line maps. We previously chose to map the region with the C, D, and E arrays to study large-scale features; with B-array alone we are able to map features that require higher spatial resolution. If we combine the B-array data with the rest, we will produce a map with a synthesized beam that is larger than the beam of the B-array data alone, and larger than some of the smallest features, obscuring them. In addition, the necessity to self-calibrate the data and issues with gain calibration (discussed in detail below) make a separate analysis more informative.

Self-calibration results in several issues that need to be overcome. W3(OH)’s physical size is 0.01 pc in diameter (Kawamura & Masson 1998) which corresponds to an angular size of ∼1″. This means that many of the longer baselines in B-array will be resolving the W3(OH) continuum source. Data from these baselines will make it difficult to self-calibrate the data as it assumes a point source model for the source (or requires an accurate model of the source features which we do not have). Running self-cal on the full data set (including resolved baselines) generates a solution that is appropriate for the data up until a UV-radius of 130 kλ, at which the solution fails. This UV-radius corresponds to a physical size of

$$\Theta \sim \frac{\lambda}{D} \sim \frac{\lambda}{2 \times \text{UVr}} \sim 0.79''.$$ 

Therefore, running self-cal on the full data set assuming a point source will result in large errors in the self-cal solution due to long, resolved baselines. If we “cut” the data set so we only use the data with UV-radius <130 kλ for use in calculating the phase solution, we will not have this issue.

The self-cal technique fits the phase center of the data to the brightest point source in the map. Our C, D, and E array data is slightly offset in position from the pointing center, so this will result in a slight position offset between the two maps. This can be corrected for by manually fitting and entering the center position of the continuum source from our C, D, E maps.
however, this is not necessary since we will not be directly combining our B-array data with the rest, since the resulting maps at full angular resolution would have a very low S/N.

This self-calibration technique also poses several problems with regards to flux and amplitude calibration. Several dishes primarily have long baselines, with only a few baselines that fall under our UV-radius limit of 130 kλ. While this worked well for phase calibration, the results of amplitude self-cal was very poor. Many of the amplitude gains, which should be flat and close to unity, were noisy and had many data points corresponding to unphysical gains that directly translates to poor image quality. The few remaining baselines also tend to have low S/N which further increases the problem.

In the attempt to apply correct gain calibration, several other techniques were tested to amplitude calibrate the data. We attempted to amplitude calibrate our data using the dedicated phase calibrator measurements and transferring the resulting solution to our source. This also failed, and while it produced better results than the amplitude self-cal technique described above, the high-resolution, low-intensity features were washed out in the final maps. This is most likely due to the gain calibrator being 10° from our source, far enough that the telescopes are viewing different enough atmosphere to negatively affect the calculated gains. This problem does not affect our C, D, E array data because the maximum baseline length is significantly smaller in these arrays and are not as sensitive to atmospheric fluctuations as the longer B-array baselines. Since these several techniques turned out poor results, it was decided not to use amplitude (flux) calibration on the B-array data, which is not an uncommon result when using self-cal. This is another reason why we do not combine this data with our C, D, E data as we would need an accurate gain solution to provide proper weights to combine the data sets.

### 3.5. Continuum

Figure 12 represents the combined C, D, E array and B-array only continuum maps. Each map was produced using multi-frequency synthesis on two 500 MHz windows, one in the N$_2$H$^+$ band (average frequency of 91.2 GHz, not shown), and one in the CN band (average frequency of 112 GHz, shown). In Figure 12(a), neither the Turner–Welch object nor W3(OH)
are resolved. The peak flux of W3(OH) decreases by a factor of two from 91.2 GHz to 112 GHz, while the center of the Turner–Welch object increases in flux by a factor of two over the same range. In the B-array only data (Figure 12(b)), we resolve two individual clumps within the Turner–Welch object and slightly resolve structure within W3(OH) (note the off-center position of the highest level contour in Figure 12(b)). This structure supports the findings of Chen et al. (2006). We additionally see the same change in relative fluxes in the B-array maps as we saw in the C, D, E array maps, over the same frequency range.

4. DISCUSSION

4.1. W3(OH) Absorption Feature

As stated above, W3(OH) itself is a UCHII region with an embedded O7 star. Our data show that several of the molecular tracers we have observed can be seen in absorption toward this source. The nature and structure of this colder absorbing gas may be able to give us some insight into the properties of W3(OH). Figure 13 shows three spectra sampled across the continuum source in HCO+. HCO+ was chosen for this since it does not have any hyperfine components that could cause line profile confusion. C^{18}O, while also not having any hyperfine components, was not chosen to trace this feature as it is not seen in emission or absorption toward W3(OH). The composite emission and absorption spectra are consistent with a dense, hot region (containing HCO+) surrounded by one or more cold, less-dense layers which also contain HCO+. The absorption feature is evidence of cold, optically thick gas which is at a velocity of $-46$ km s$^{-1}$ and has an FWHM of $4$ km s$^{-1}$. In looking at non-continuum subtracted spectra (Figure 13(b)), this absorption line is saturated and extends completely down to zero flux. This implies that this cold region is in front of the emission region and the continuum source. The absorption feature is also seen in CN and HCN, however, it is seen slightly in emission in C$^{18}$O. The C$^{18}$O emission feature is also centered at $-46$ km s$^{-1}$ and has an FWHM of $4$ km s$^{-1}$, the same as the HCO+ absorption. It is very likely that it is from the same region, implying that the gas density is sufficient to raise the excitation temperature of the C$^{18}$O line above that of the brightness temperature of the continuum source so the line appears in emission, while the higher critical densities of the HCO+, HCN, and CN transitions lead their excitation temperatures to be less than that brightness.
temperature, so they are seen in absorption. To note: Figure 13 is resolution limited since it is formed with C, D, and E array data and its three positions only cover an area of 1.5–2 beamwidths. This was part of the motivation to acquire B-array data as the same region would cover 5–8 beamwidths in a B-array map.

From the B-array spectra (Figure 14(c)), we only see HCO+ in absorption against the continuum emission. The lack of emission either means that it is being resolved out at this high spatial resolution, or that the beam is completely filled by continuum emission, so we see no emission from the sides of the beam. In either case, this means that the emission does not come from the same gas that produces the absorption. To support this, we produced spectra that only includes E-array (largest beam size, shortest baselines) in order to inspect large-scale emission. The E-array data (Figure 14(a)) shows emission toward the continuum between $-43$ km s$^{-1}$ and $-50$ km s$^{-1}$ with a self absorption feature at $-46$ km s$^{-1}$. This high velocity gas is not seen in C$^{18}$O and therefore seems to be hot, optically thin gas that is behind the continuum source.

Therefore, we propose a multi-layered model of the region around W3(OH). Behind the UCHII region is a high velocity, hot, large spatial scale, optically thin region which appears to peak in intensity toward the Turner–Welch object (and may very well be associated with it). The UCHII region is optically thin, and has a small spatial scale of about 0′′.7 in diameter which is extremely bright in the continuum, enough such that the narrow band 2 MHz windows are contaminated by continuum emission. In front of the continuum is a very cold, optically thick region at a velocity of $-46$ km s$^{-1}$ which we primarily see in absorption, but we see slightly in emission in C$^{18}$O.

4.2. CARMA Flux

Our maps are comprised of C, D, and E array data and do not cover the entire UV space. We do not have zero-spacing data which would be required in order to reconstruct the most accurate map of the region. The IRAM data consists of only a single pointing and its beam does not cover the full area of the CARMA maps. In order to quantify the amount of flux that could be resolved out by using CARMA, we examined the single dish data taken by Falgarone et al. (2008). Since the IRAM 30 m telescope has a resolution of 23″, we smoothed our CARMA maps to match by convolving the data with a 23″ Gaussian beam (Figure 15). Spectra (Figure 16) were then
Figure 9. Sample spectra for each species, toward both the continuum source (W3(OH)) and the Turner–Welch object. For the CN, HCN, and N2H+ spectra, multiple hyperfine components are present. The velocity scale for all of these corresponds to that of the strongest hyperfine component. Three of the sources can be seen in absorption toward the continuum source, while the other two have little to no emission.

extracted from the position corresponding to the IRAM 30 m pointing center, as well as two other positions centered on the northeastern and northwestern components. According to the IRAM technical documentation (IRAM2009), the main beam efficiency is 78% for the band that includes CN. To compare the flux values, an estimate of CARMA’s main beam efficiency is needed (White & Zauderer 2008). CARMA does not have published main beam efficiency measurements, however, it can be estimated from single-dish aperture efficiency measurements which vary from 55% to 70% depending on the individual dish. From this, we estimate that the main beam efficiency (per dish) would be \(~70\%–80\%\). By adopting a value of 75%, approximately the same as IRAM’s, we can directly compare the IRAM and CARMA spectra. The IRAM peak was 2.2 K, while CARMA’s was 1.4 K. This means that the peak of the CARMA spectra was at 64% of IRAM’s (the area of the CARMA spectra is 48% of the IRAM spectra). CN is also seen in strong absorption toward the central source (W3(OH)), however, this absorption feature is not present in any of the IRAM data. This is possible for several reasons. First, the relatively small spatial size of the absorption feature covers a small fraction of the total IRAM beam. Any measured absorption would be diluted across the entire beam and masked by the significantly greater emission. In addition, the IRAM data baseline fitting procedure could contribute to hiding the presence of a weak absorption feature.

4.3. N2H+ Chemical Reaction

In regions with standard CO abundances (i.e., regions that are not depleted in CO), one of the formation mechanisms of HCO+ is the destruction of N2H+ by CO (Bergin et al. 2002; Jorgensen et al. 2004). Since there is significant support that CN remains in the gas phase at densities greater than \(10^5 \text{ cm}^{-3}\) (same as N2H+) we would expect CN and N2H+ to have a very similar spatial distribution, however, there are some regions and velocities where we would expect to see more N2H+ emission than we do. The particular reaction that is thought to occur is

\[ \text{N}_2\text{H}^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{N}_2. \]  

If we compare the regions of strong N2H+ and HCO+ emission, we would expect them not to be coincident. In addition, we expect CO to be depleted in regions of strong N2H+ emission, as the presence of CO would cause the formation of HCO+, while regions with significant CO emission must be weak in N2H+, or the reaction between these two molecules would occur.

In the region surrounding the Turner–Welch object we can see considerable emission from both CO and HCO+, however, there is no N2H+ within our detection limit. This depletion of N2H+ could be caused by the amount of C18O present along this sightline. Since there is significant CN emission from this region, we would also expect to see N2H+. The presence of
Figure 10. N$_2$H$^+$ Channel maps, rebinned to 1 km s$^{-1}$ velocity increments. The velocity scale is centered on the strongest CN hyperfine component at 93.17348 GHz. The spatial resolution of this map is 3.4 $\times$ 2.6 arcsec. The contour levels are 20, 40, 60, 80, and 100 times 0.0129 Jy beam$^{-1}$. The “⋆” and “▲” represent the peak continuum positions of W3(OH) and the Turner–Welch object, respectively.

CN and the relative strengths of HCO$^+$ and C$^{18}$O is significant evidence of this reaction occurring and that N$_2$H$^+$ is being consumed by this reaction.

Above, we showed that there was a cold, dark region of gas toward the continuum source where HCO$^+$ is seen in strong absorption along with CN and HCN. Discounting the contribution from the continuum source, C$^{18}$O is seen slightly in emission and N$_2$H$^+$ is seen slightly in emission and absorption. The presence of CN absorption implies conditions where N$_2$H$^+$ should also be strongly detectable. If we assume that the primary formation mechanism of HCO$^+$ in this region is by the CO and N$_2$H$^+$ chemical reaction, the relative depletion of these two chemical species in this cold dark cloud can be understood.

In regions with conditions similar to that of W3(OH), CN may be a more reliable tracer than N$_2$H$^+$ to directly sample regions at high densities. However, since the strongest CN hyperfine transition has significantly weaker line emission than the strongest hyperfine transitions of N$_2$H$^+$, it would require significantly greater telescope time to achieve a comparable S/N. In our case, these sets of maps show not only that this chemical reaction is occurring, but is happening most strongly both along the sightlines associated with an active star-forming clump, and in a cold cloud in front of an extremely bright UCHII region.

4.4. Structure of the Region Surrounding W3(OH)

Wilson et al. (1991) developed a model of the region surrounding W3(OH) based on C$^{18}$O, C$^{34}$S, and methanol (among others). They proposed a multi-layer model of low-density molecular gas surrounding a high-density molecular core. This low-density cooler region extends in front of W3(OH) as well. Self-absorption in their CS data supports this model. In addition, the $v_{\text{LSR}}$ of the self-absorption was up to 2 km s$^{-1}$ more positive than the $v_{\text{LSR}}$ of the hotter emitting region. This implies that the cloud envelope is contracting relative to the cloud core. We see similar offsets in the E-array spectrum of HCO$^+$ seen in Figure 14(a), however, the offset appears to decrease at higher angular resolutions (Figure 13).

We can compare the range of radial velocities at which we see molecular material. Wilson et al. (1991) data showed that C$^{18}$O
peaks toward W3(OH) at a radial velocity of $-46.6$ km s$^{-1}$, and peaks toward the Turner–Welch object at $-48$ km s$^{-1}$. We see the same radial velocities in our C$^{18}$O data (even though our data set was at 3 mm, and theirs was at 1 mm). For other species that trace related density regimes (HCN and HCO$^+$), we see them peak at a velocity of $-47$ km s$^{-1}$ toward the Turner–Welch object. These species are seen strongly in absorption toward W3(OH), which makes it difficult to determine its radial velocity. These data show that the region around W3(OH) is extremely complex.
Figure 13. Panels (A)–(C) are HCO⁺ spectra of W3(OH) at three positions with no continuum subtraction. This shows the change in emission and absorption spectra in HCO⁺ across the W3(OH) Ultra-Compact H ii region. Panel (A) is 2 ″ SE of the W3(OH) center position, and Panel (C) is 2 ″ NW of the W3(OH) center position. The positions of spectra A–C are marked on Figure 12(a) for reference.

Figure 14. Comparison between spectra toward the center of the continuum source in panels (a) E-array only, (b) combined C, D, E array maps, and (c) B-array only. In all three instances, the spectra are seen in absorption at the same velocities and with roughly the same line width which supports a model of a cold dark, optically thick cloud in front of the continuum source and emission regions in our map.

Figure 15. Smoothed CARMA CN map to the same resolution as the IRAM measurements (23 ″). This was produced by convolving a 23 ″ Gaussian beam with the integrated line map seen in Figure 1. The contour levels are in increments of 0.158 Jy beam⁻¹ from 1.89 Jy beam⁻¹ to 3.47 Jy beam⁻¹.

5. CONCLUSIONS

We mapped the 1 arcmin² region around W3(OH) with CARMA, in which previous single-dish CN Zeeman observations detected a strong magnetic field. In determining which gas was producing the magnetic field, we were able to see the following features and make the following conclusions from their presence.

1. A strong absorption feature in HCO⁺, HCN, and CN was detected toward the continuum source whose strength and line saturation implies the existence of a cold, optically thick region in front of the continuum source.

2. Comparison between CARMA spectra and spectra obtained with the IRAM 30 m telescope (Falgarone et al. 2008) yields that CARMA detects approximately 65% of the material in this region.

3. Selective depletion of N₂H⁺ in comparison with the CN and HCO⁺ distribution indicates that N₂H⁺ is reacting with CO to form HCO⁺. This reduces the effectiveness of N₂H⁺ as a high-density tracer, and favors the use of species, such as CN, in objects with similar chemical composition to W3(OH). These measurements additionally support the usefulness of CN as a high-density tracer and confirms the hypothesis that CN Zeeman mapping will probe the magnetic field strength in the high-density regions of molecular cloud clumps.

These conclusions lead to the result that future CN Zeeman mapping at high resolution with an interferometer is feasible and that W3(OH) is an ideal target to perform such mapping on.

Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the James S. McDonnell Foundation, the Gordon and Betty Moore Foundation, the
Figure 16. CARMA spectrum overlaid with the IRAM spectrum at a point near the IRAM pointing center. Note that there are two CN hyperfine lines in these spectra, separated by about 8 km s$^{-1}$. The velocity scale is for the stronger hyperfine line (at $\sim$48 km s$^{-1}$). The intensity scale is estimated by comparing the main beam efficiencies of IRAM and CARMA, however, there is an inherent 20% error in the CARMA flux measurements. From this, we estimated that CARMA resolves $\sim$65% of the CN emission within the IRAM beam.

Kenneth T. and Eileen L. Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement (NSF AST 08-38226), and by the CARMA partner universities. In addition, this project was supported in part by grant NSF AST 10-07713.

REFERENCES

Bergin, E. A., Alves, J., Huard, T., & Lada, C. J. 2002, ApJ, 570, 101
Bock, D. C.-J., et al. 2006, Proc. SPIE, 6267, 36
Briggs, D. S., Schwab, F. R., & Sramek, R. A. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco, CA: ASP), 127B
Chen, H.-R., Welch, W. J., Wilner, D. J., & Sutton, E. C. 2006, in ASP Conf. Ser. 356, Revealing the Molecular Universe: One Antenna is Never Enough, ed. D. C. Backer, J. W. Moran, & J. L. Turner (San Francisco, CA: ASP), 270
Falgarone, E., Troland, T. H., Crutcher, R. M., & Paubert, G. 2008, A&A, 487, 247
Hachisuka, K., et al. 2006, ApJ, 645, 337
Hily-Blant, P., Walmsley, M., Pineau des Forêts, G., & Flower, D. 2008, A&A, 480, 5
Hoare, M. G. 2004, ApSS, 295, 203
IRAM 2009, IRAM 30 m Efficiencies http://www.iram.es/IRAMES/mainWiki/Iram30mEfficiencies
Jørgensen, J. K., Schoier, F. L., & van Dishoeck, E. F. 2004, A&A, 416, 605
Kawamura, J. H., & Masson, C. R. 1998, ApJ, 509, 270
Raimond, E., & Eliasson, B. 1969, ApJ, 155, 817
Tieftrunk, A. R., Megeath, S. T., Wilson, T. L., & Rayner, J. T. 1998, A&A, 336, 991
Turner, J. L., & Welch, W. J. 1984, ApJ, 287, 81
White, S. M., & Zauderer, B. A. 2008, CARMA Memorandum Series 49, Single-Dish Aperture Efficiency Measurements at CARMA, http://www.mmarray.org/memos/carma_memo49.pdf
Wilner, D. J., Welch, W. J., & Forster, J. R. 1995, ApJ, 449, 73
Wilson, T. L., Gaume, R. A., & Johnston, K. J. 1993, ApJ, 402, 230
Wilson, T. L., Johnston, K. J., & Mauersberger, R. 1991, A&A, 251, 220
Wink, J. E., Duvert, G., Guilloteau, S., Güsten, R., Walmsley, C. M., & Wilson, T. L. 1994, A&A, 281, 505
Wynn-Williams, C. G., Becklin, E. E., & Neugebauer, G. 1972, MNRAS, 160, 1
Wyrowski, F., Hofner, P., Schilke, P., Walmsley, C. M., Wilner, D. J., & Wink, J. E. 1997, A&A, 320, 17