The Nature of the Massive Young Stars in W75 N

D. S. Shepherd\textsuperscript{1}, S. E. Kurtz\textsuperscript{2}, L. Testi\textsuperscript{3}

\textbf{ABSTRACT}

We have observed the W75 N massive star forming region in SiO(J=2–1 \& J=1–0) at 3′′–5′′ resolution and in 6 cm, 2 cm, and 7 mm continuum emission at 1.4′′–0.2′′ resolution. The abundance ratio of [SiO]/[H\textsubscript{2}] \sim 5 - 7 \times 10^{-11} which is typical for what is expected in the ambient component of molecular clouds with active star formation. The SiO morphology is diffuse and centered on the positions of the ultracompact HII regions - no collimated, neutral jet was discovered. The ionized gas surrounding the protostars have emission measures ranging from 1 - 15 \times 10^6 pc cm\textsuperscript{-6}, densities from 0.4 - 5 \times 10^4 cm\textsuperscript{-3}, and derived spectral types of the central ionizing stars ranging from B0.5 to B2. Most of the detected sources have spectral indices which suggest optically thin to moderately optically thick HII regions produced by a central ionizing star. The spread in ages between the oldest and youngest early-B protostars in the W75 N cluster is 0.1 - 5 \times 10^6 years. This evolutionary timescale for W75 N is consistent with that found for early-B stars born in clusters forming more massive stars (M\textsubscript{*} > 25M\odot).

\textit{Subject headings:} circumstellar matter – jets and outflows – stars: formation – stars: mass loss – HII regions

\textsuperscript{1}National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801
\textsuperscript{2}Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, C.P. 58089, Morelia, Mich. Mexico
\textsuperscript{3}INAF – Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze
1. INTRODUCTION

Molecular outflows from young, early-B protostars have many characteristics in common with those from lower mass young stellar objects (YSOs) while the HII regions produced by the central stars often look similar to those produced by O stars. For example, the outflow momentum and the mass of circumstellar material both scale with the bolometric luminosity of the driving source (e.g. Levreault 1988; Cabrit & Bertout 1992; Rodríguez et al. 1996; Shepherd & Churchwell 1996; Chandler & Richer 2000). Some mid- to early-B YSOs have ionized or molecular jets that are well-collimated close to the YSO (e.g. IRAS 20126+4014: Hofner et al. 1999; Cep A HW2: Torrelles et al. 1993; Rodríguez et al. 1994; Garay et al. 1996); at least one source, HH 80–81, has a well-collimated, parsec-scale ionized jet that appears to be a scaled version of a Herbig-Haro jet from a low-mass YSO (Martí, Rodríguez, & Reipurth 1993; Heathcote, Reipurth, & Raga 1998). Yet despite these similarities, recent observations have shown that the characteristics of early-B star outflows and disks may also be diverging from their low-mass counterparts. In particular, molecular outflows from early-B stars tend to be less collimated than those from low-mass YSO even when there is a well-collimated, ionized jet (e.g. HH 80–81: Yamashita et al. 1989; IRAS 20126+4014: Shepherd et al. 2000), and some outflows show no evidence for a collimated jet (G192.16–3.82: Shepherd, Claussen, & Kurtz 2001), instead sporting a classic ultracompact (UC) HII region at the protostellar position.

One early-B star cluster with outflows that may exhibit some differences from low-mass flows is W75 N: a massive star forming region with an integrated IRAS luminosity of $1.4 \times 10^5 \, L_{\odot}$ forming mid- to early-B stars (Haschick et al. 1981; Hunter et al. 1994; Torrelles et al. 1997).

At the heart of the W75 N outflows is a cluster of four UC HII regions embedded in a millimeter core W75 N:MM 1. Haschick et al. (1981) identified three regions of ionized gas in W75 N at a resolution of $\sim 1.5''$: W75 N (A), W75 N (B), and W75 N (C). Hunter et al. (1994) later resolved W75 N (B) with $\sim 0.5''$ resolution into three regions: Ba, Bb, and Bc. Torrelles et al. (1997) then imaged W75 N (B) at $\sim 0.1''$ resolution, and detected Ba and Bb (which they called VLA 1 & VLA 3), along with another weaker, and more compact HII region, VLA 2. Within a 10'' radius of MM 1 are three, compact millimeter cores (MM 2-4). None of these sources have discernible near-infrared counterparts although there is substantial near-infrared reflection nebulosity in the region (see, e.g., Figs 1, 5, & 10 from Shepherd, Testi, & Stark 2003, hereafter STS03). Mid-infrared emission at 12.5$\mu$m has been detected in the vicinity of the UC HII regions however it is unclear which source(s) are

---

4Names of millimeter cores are shortened to MM 1-5 for the remainder of this paper
producing the emission (Persi et al. 2003). An extended millimeter core (MM 5) is located roughly 30″ north of MM 1 and has an associated reflection nebula (W75 N A) and central star visible in the infrared.

Multiple outflows have been identified originating from the cluster of UC HII regions and millimeter cores with a total flow mass greater than 250 $M_\odot$ (Fischer et al. 1985; Hunter et al. 1994; Davis et al. 1998a, 1998b, Ridge & Moore 2001; Shepherd 2001; STS03, Torrelles et al. 2003). Davis et al. (1998a,b) suggest the outflow is driven by a powerful, well-collimated jet while STS03 find no evidence for a jet. But is there an underlying, undetected neutral jet driving the flow? And what are the properties of the HII regions and are they consistent with what is expected for ionized gas around early-B zero-age-main-sequence (ZAMS) stars? To answer these questions we have observed W75 N in SiO(J=2–1 & J=1–0) line emission to search for evidence of a neutral jet and in centimeter & 7 mm continuum emission to obtain a better understanding of the nature of the powering sources.

2. OBSERVATIONS

2.1. Owens Valley Radio Observatory

Observations in SiO(v=0, J=2–1) and SiO(v=1, J=2–1) were made with the Owens Valley Radio Observatory (OVRO) millimeter-wave array of six 10.4 m telescopes between 1999 May 26 and 1999 November 12. The 64 channel spectral bandpass was centered on the local standard of rest velocity ($v_{\text{LSR}}$) of 10 km s$^{-1}$ with a spectral resolution of 1.726 km s$^{-1}$ for SiO(v=0) and 1.738 km s$^{-1}$ for SiO(v=1). Gain calibration used the quasar BL Lac while observations of Neptune and/or Uranus provided the flux density calibration scale with an estimated uncertainty of ∼20%. Calibration was carried out using the Caltech MMA data reduction package (Scoville et al. 1993). Images were produced and analyzed using the MIRIAD software package (Sault, Teuben, & Wright 1995). SiO(v=1, J=2–1) was not detected. SiO(v=0, J=2–1) was detected and images were made with and without a Gaussian taper of 3″ FWHM to optimize sensitivity to extended structure and more compact features, respectively. A summary of the observational parameters is presented in Table 1. The largest angular scale that can be accurately imaged, $\theta_{\text{LAS}}$, is ∼20″.
Table 1: Observational Summary

<table>
<thead>
<tr>
<th>Image</th>
<th>Rest Freq (GHz)</th>
<th>Beam FWHM (arcsec)</th>
<th>Beam P.A. (deg)</th>
<th>RMS (mJy/beam)</th>
<th>Peak† Flux Density (mJy/beam)</th>
<th>Total† Flux Density (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 cm continuum</td>
<td>4.88</td>
<td>1.36 × 1.12</td>
<td>29.2</td>
<td>0.11</td>
<td>4.5</td>
<td>128.5</td>
</tr>
<tr>
<td>2 cm continuum</td>
<td>14.96</td>
<td>0.46 × 0.38</td>
<td>34.5</td>
<td>0.23</td>
<td>4.4</td>
<td>112.7</td>
</tr>
<tr>
<td>7 mm continuum</td>
<td>43.34</td>
<td>0.27 × 0.20</td>
<td>89.4</td>
<td>0.31</td>
<td>5.4</td>
<td>8.3</td>
</tr>
<tr>
<td>SiO(v=0, J=1–0)</td>
<td>43.42</td>
<td>0.40 × 0.36</td>
<td>65.8</td>
<td>4.0</td>
<td>14.0</td>
<td>14.0</td>
</tr>
<tr>
<td>SiO(v=0, J=2–1)</td>
<td>86.85</td>
<td>5.35 × 4.15</td>
<td>−60.3</td>
<td>45.0</td>
<td>640.0</td>
<td>42,300.</td>
</tr>
<tr>
<td>SiO(v=0, J=2–1)†</td>
<td>86.85</td>
<td>3.17 × 2.56</td>
<td>−61.5</td>
<td>39.0</td>
<td>330.0</td>
<td>17,700.</td>
</tr>
<tr>
<td>SiO(v=1, J=2–1)</td>
<td>86.24</td>
<td>4.87 × 3.83</td>
<td>−68.3</td>
<td>45.0</td>
<td>···</td>
<td>···</td>
</tr>
</tbody>
</table>

† Flux densities measured in the primary beam corrected image. Total flux density given is the combined value for all sources in the field.

†† Higher resolution, the more extended emission, 58% of the total flux density, has been resolved out.

2.2. Very Large Array

Observations of 43.3399 GHz (7 mm) continuum emission were made with the National Radio Astronomy Observatory’s Very Large Array (VLA) in the “C” configuration on 2000 April 24 and in the “B” configuration on 2001 March 22. Baselines between 35 m and 11.4 km could detect a largest angular emission scale, $\theta_{\text{LAS}} \sim 18''$. The total bandwidth was 200 MHz. The quasar 2012+464 was used as a phase calibrator and 3C286 was the flux calibrator. The estimated uncertainty of the flux calibration is $\sim 10\%$. Calibration and imaging was performed using the AIPS++ data reduction package. The data were imaged using natural $uv$ weighting and the image was deconvolved with a CLEAN-based algorithm.

Observations of 4.8851 GHz (6 cm) and 14.9649 GHz (2 cm) continuum emission were made with the VLA in the “B” configuration on 2001 March 22. Baselines between 0.21 km and 11.4 km detected a largest angular scale $\theta_{\text{LAS}} \sim 26''$ at 6 cm and 9'' at 2 cm. The quasar 2012+464 was used as a phase calibrator, the quasars 3C286 & 0410+769 were used as flux calibrators. The estimated uncertainty of the flux calibration is $\sim 1\%$ for both 2 cm and 6 cm. Calibration and imaging was performed using the AIPS++ data reduction package. The data were imaged using robust $uv$ weighting. The 2 cm image was deconvolved with

---

5The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
a CLEAN-based algorithm while the 6 cm image was deconvolved using both a standard
CLEAN-based algorithm and a multi-scale CLEAN algorithm. The multi-scale image was
CLEANed with six component scale sizes with diameters of 0″, .6″, 1.2″, 2″, 4″, & 6″.
Both 6 cm images gave essentially the same flux however the image generated with multiple
scales provided the best sensitivity to extended emission in the HII region W75 N A while
preserving the compact structure in the UC HII regions in W75 N B. In contrast, the 2 cm
(and 7 mm) observations resolved out most of the flux in W75 N A to the point where it
could not be imaged properly and the standard CLEAN algorithm was the most effective
deconvolution method.

SiO(v=0, J=1–0) line emission was observed with VLA in the “C” configuration on
2000 April 24. The observations were made using 32 channels centered on $v_{LSR}$ with
a spectral resolution of 2.7 km s$^{-1}$ and a total bandwidth of 86.4 km s$^{-1}$. The quasar
2012+464 was used as a phase calibrator and 3C286 was the flux calibrator. The estimated
uncertainty of the flux calibration is $\sim$ 10%. Baselines between 35 m and 3.4 km provided a
synthesized beam of approximately 0.4″ over the 1′ field of view. The largest angular scale
that the VLA is sensitive to at this frequency, $\theta_{LAS}$, is $\sim$ 18″. Calibration and imaging
was performed using the AIPS data reduction package. The data were imaged using robust
uv weighting and deconvolved with a CLEAN-based algorithm. At 0.4″ resolution, a single
14 mJy beam$^{-1}$ peak (3$\sigma$) in one channel was recovered near the UC HII region positions.
Convoluting the uv data with a Gaussian taper to yield a 3″ beam resulted in a peak emission
of $\sim$ 30 mJy beam$^{-1}$.

3. RESULTS

3.1. Continuum Emission

The locations of the HII regions discussed in Section 1 are shown in images of the ionized
gas in 6 cm, 2 cm, and 7 mm continuum emission (Fig. 1). Peak and total flux densities are
given in Table 2 and the spectral energy distributions (SEDs) for each UC HII region are
shown in Fig. 2.

Continuum emission at 7 mm wavelength can be due to a mixture of warm dust and
ionized gas emission. Figure 2 (and Table 2) shows that the flux density of the UC HII regions
at 7 mm is consistent with or lower than what is expected for ionized gas (either optically
thin emission, $S_\nu \propto \nu^{-0.1}$, or moderately optically thick). How much 7 mm continuum
emission is expected to be due to warm dust? Using the 3 mm flux densities of Shepherd
(2001) and assuming the thermal dust emission between 3 & 7 mm has a spectral index of
Table 2: Measured Flux Density ($S_\nu$) of Continuum Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Position (h m s) $^{\circ'}''$</th>
<th>Total $S_{6cm}$ (mJy)</th>
<th>Peak $S_{6cm}$ (mJy beam)</th>
<th>Total $S_{2cm}$ (mJy)</th>
<th>Peak $S_{2cm}$ (mJy beam)</th>
<th>Total $S_{7mm}$ (mJy)</th>
<th>Peak $S_{7mm}$ (mJy beam)</th>
<th>Spectral Index $^{\dagger}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA 1 (Ba)</td>
<td>20 38 36.455 $^{+3} - 34.80$</td>
<td>5.3</td>
<td>3.5</td>
<td>4.0</td>
<td>1.5</td>
<td>...</td>
<td>...</td>
<td>0.2 ± 0.3</td>
</tr>
<tr>
<td>VLA 2</td>
<td>20 38 36.491 $^{+3} - 34.30$</td>
<td>...</td>
<td>...</td>
<td>1.5</td>
<td>1.2</td>
<td>2.6</td>
<td>2.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>VLA 3 (Bb)</td>
<td>20 38 36.491 $^{+3} - 33.50$</td>
<td>2.7</td>
<td>2.7</td>
<td>5.8</td>
<td>4.5</td>
<td>5.7</td>
<td>5.4</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>Bc</td>
<td>20 38 36.527 $^{+3} - 31.50$</td>
<td>4.4</td>
<td>2.8</td>
<td>1.7</td>
<td>1.2</td>
<td>...</td>
<td>...</td>
<td>-0.3 ± 0.6</td>
</tr>
<tr>
<td>W75 N (A)</td>
<td>20 38 37.780 $^{+3} - 59.00$</td>
<td>116.1</td>
<td>4.5</td>
<td>&gt; 99.7</td>
<td>0.8</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

$^{\dagger}$ Spectral index derived from this data and data from Torrelles et al. (1997) and Hunter et al. 1994.

2, we expect to detect about 36 mJy of combined flux at 7 mm from thermal dust emission near the UC HII regions. Only 8.3 mJy is recovered suggesting that at least 80% of the thermal dust emission is being resolved out. In the millimeter cores MM 2, MM 3, & MM 4, 6–9 mJy is expected while none is detected, again consistent with the thermal dust emission being resolved out by the 0.2″ resolution.

Source Bc is detected at 6 and 2 cm with a spectral index of $\alpha = -0.3 \pm 0.6$. In a 1.3 cm continuum image, Torrelles et al. (1997) found that Bc was marginally recovered at the 3σ level when a Gaussian taper was applied to the data suggesting that the source was being resolved out by their higher 0.1" resolution. Thus, the negative spectral index derived for Bc may be due to missing flux at short wavelengths (higher resolution) rather than an intrinsic property of the source. Bc is not detected in 7 mm continuum emission with ~ 0.2" resolution. Based on the peak flux density at 2 cm with 0.4" resolution, the expected peak emission at 7 mm is ~ 0.3 mJy beam$^{-1}$ which is just under 1σ in the 7 mm image. Thus, the surface brightness of the emission in Bc is below our sensitivity limit.

VLA 3(Bb) is detected at all observed wavelengths. The source is marginally resolved at 2 cm & 7 mm and the spectral index between 6 cm and 7 mm, $\alpha = 0.5 \pm 0.3$, is consistent with a moderately optically thick HII region.

VLA 2 is detected between 2 cm and 7 mm with a spectral index $\alpha = 0.4 \pm 0.1$, consistent with a moderately optically thick HII region. At 6 cm wavelength, the 1.2" resolution was not adequate to isolate VLA 2 from VLA 1(Ba) or VLA 3(Bb).

VLA 1(Ba) is detected at 6 and 2 cm. The elongation of the 2 cm emission along the H$_2$O maser axis is consistent with that found by Torrelles et al. (1997). The spectral index between 6 and 1.3 cm is $\alpha = 0.2 \pm 0.3$. Assuming constant $\alpha = +0.2$ between 1.3 cm
and 7 mm, the expected total flux density at 7 mm due to ionized gas is 8.9 mJy while the expected peak flux density should be roughly one fourth the peak found at 2 cm, i.e., \( \sim 0.4 \) mJy beam\(^{-1}\) (assuming the peak emission scales with the area of the synthesized beam). Figure 1 shows that there are a few peaks at the 3\(\sigma\) level near the position of VLA 1(Ba) however the surface brightness sensitivity is not adequate to recover the source structure.

Continuum emission associated with the extended HII region W75 N A is detected at a wavelength of 6 cm. At 2 cm, most of the flux has been resolved out, leaving only low-level emission and a few 3\(\sigma\) peaks. Previous images of the ionized gas in 6 cm continuum emission were not able to recover the complex structure of this extended source due to limited uv coverage (Haschick et al. 1981).

### 3.2. SiO emission

SiO(v=0, J=2–1) channel maps with \( \sim 5'' \) and 3'' resolution are shown in Fig. 3. The higher resolution image resolves out 58\% of the flux density suggesting that a significant fraction of the emission is diffuse. SiO(v=0, J=2–1) red-shifted (10 to 17.8 km s\(^{-1}\)) and blue-shifted (2.23 to 10 km s\(^{-1}\)) emission are shown in Fig. 4. A zeroth moment image covering the full velocity range is shown in Fig. 5 along with representative SiO spectra at different locations in the cloud.

Despite the strong detection of SiO(v=0, J=2–1) with the OVRO interferometer, the SiO(v=0, J=1–0) line could not be imaged well at a resolution of \( \sim 0.4'' \). For low J-transition lines, assuming local thermodynamic equilibrium, optically thin emission, and high excitation temperatures (\( T_{ex} \geq 50 \) K), the brightness temperature of SiO(v=0, J=2–1) should be roughly four times that of SiO(v=0, J=1–0) (Goldsmith 1972). Assuming the emission arises in the same region, then:

\[
\frac{S_\nu(1-0)}{S_\nu(2-1)} = \frac{T_B(1-0)}{T_B(2-1)} \frac{\lambda^2(2-1)}{\lambda^2(1-0)} = 0.0625
\]  

Thus, SiO(J=1–0) peak flux densities of the order of 40 mJy beam\(^{-1}\) should be observed, assuming similar uv coverage between the VLA and OVRO. Unfortunately, the uv coverage of the interferometers differed significantly. To compare the two images, a 10 k\(\lambda\) hole was cut out of the OVRO data to match the hole in the VLA uv coverage. This provided a peak flux density in the SiO(v=0, J=2–1) line of about 240 mJy beam\(^{-1}\) at a resolution of 3'' \( \times \) 2.5''. Roughly one third of the total flux was recovered in this image. The VLA continuum-subtracted data cube then had a Gaussian taper applied until the resolution matched that
of OVRO. Although the taper down-weighted a significant fraction of the VLA data, the resulting peak emission in the SiO(v=0, J=1–0) line was \(\sim 30 \text{ mJy beam}^{-1}\) which is close to what is predicted based on equation 1 above. This exercises demonstrates that the SiO(v=0, J=1–0) emission in W75 N is relatively diffuse.

SiO line widths range from about 3 – 10 km s\(^{-1}\) within the W75 N cloud (see Fig. 5). Assuming a rotational temperature of 50K, the total SiO gas mass traced by the (v=0, J=2–1) line is \(2 \times 10^{-6} \text{ M}_\odot\) while the average column density is \(3.5 \times 10^{14} \text{ cm}^{-2}\). The estimated total mass of the cloud core based on submillimeter continuum and CS(J=7-6) observations is \(\sim 1000 - 2000 \text{ M}_\odot\) (Moore, Mountain, & Yamashita 1991; Hunter et al. 1994) which implies an SiO/[H\(_2\)] ratio of \(\sim 5 - 7 \times 10^{-11}\). The measured, average SiO fractional abundance, [SiO]/[H\(_2\)], in typical low-mass dark clouds is between \(10^{-11}\) and \(10^{-12}\) (Ziurys, Friberg, & Irvine 1989) while the average ambient abundance in clouds with active star formation range from \(10^{-10}\) to \(10^{-11}\) (Codella, Bachiller, & Reipurth 1999). In comparison, SiO abundance in the quiescent ridge of Orion is less than \(3 \times 10^{-10}\) (Blake et al. 1987). The SiO abundance calculated for the W75 N cloud is consistent with the typical abundance for ambient gas in both high and low-mass star forming regions.

Note, SiO abundance can be as high as \(10^{-5} - 10^{-6}\) in high-velocity gas (> 20 km s\(^{-1}\) from the systemic velocity of the cloud) which is directly associated with high and low-mass molecular outflows (see, e.g., Martin-Pintado, Bachiller, & Fuente 1992; Shepherd, Churchwell, & Wilner 1997). However, the average abundance enhancement is generally several orders of magnitude less as discussed above.

4. DISCUSSION

4.1. SiO emission and the molecular outflows

Based on a comparison between CO(J=1–0), H\(_2\), and [FeII] emission, STS03 suggested that only slow, non-dissociative J-type shocks exist throughout the parsec-scale outflows produced by the central stars in the W75 N (B) UC HII regions. Fast, dissociative shocks, common in jet-driven low-mass outflows, appear to be absent in W75 N. Thus, the energetics suggest that the outflows from the mid- to early-B protostars in W75 N are not simply scaled-up versions of low-mass outflows. Further, there was no evidence for well-collimated, parsec-scale jets such as those seen in flows from lower mass protostars. However, the observations of STS03 could not rule out the presence of an underlying neutral jet that could drive the CO outflows.

SiO emission in molecular flows is excited in shocks where silicon is first removed from
dust grains and then reacts with OH radicals to form SiO in the post-shock cooling zone. The gas phase abundance of SiO can increase up to a factor of $10^6$ over that found in quiescent molecular clouds and can delineate the axis of highly collimated jet-driven outflows and/or the bow-shock where the head of a jet interacts with dense molecular material (e.g. Haschick & Ho 1990). SiO 'jets' have been detected in well-collimated outflows from low-mass YSOs (e.g. L1448: Guilloteau et al. 1992; HH 211: Chandler & Richer 2001) and in at least one massive outflow from an early-B star (IRAS 20126+4014: Cesaroni et al. 1997, 1999). Thus, SiO has the potential to uncover collimated, molecular jets that may not be obvious in other tracers.

Our SiO observations cover the central 60$''$ field of the molecular outflows mapped by STS03 (the full 5$'$ × 1.5$'$ mosaic was not covered). There is physically diffuse SiO(J=2–1) and SiO(J=1–0) emission centered near the positions of the UC HII regions. The SiO abundance is roughly a factor of 10 higher than abundances toward dark, quiescent clouds and is consistent with what is expected for ambient gas in both low- and high-mass star forming regions. Figure 4 shows the relation between the SiO emission, the locations of the UC HII regions and millimeter cores 2–4, and the proposed outflows from VLA 1 (Ba), VLA 3 (Bb), and MM 2 suggested by STS03. There is no clear relationship between the SiO distribution and the proposed outflows. The higher resolution (3$''$) SiO images (Fig. 3 and right panel of Fig. 4) were made in an attempt to resolve out the extended emission associated with the ambient gas and search for compact, high-velocity, red- and blue-shifted emission that may delineate collimated outflows. There is no clear indication of a jet-like structure from any specific source despite the presence of VLA 1 (Ba), an HII region that appears to be excited by a thermal jet.

On a larger scale than was observed in SiO in this work, STS03 found clear evidence for shocked gas associated with the outflows as seen from the H$_2$ line morphology. The shocked gas is diffuse and appears to be caused by interactions between the ambient medium, wide-angle outflowing gas, and ionized gas. Our SiO observations of the center 60$''$ near the outflow driving sources show FWHM line widths up to 10 km s$^{-1}$ (Fig. 5) which suggests that the SiO is produced in shocks. However, the resolution and sensitivity are not sufficient to determine if the SiO abundance enhancement is associated with the CO flows or if it arises from a shocked boundary between the ambient medium and the ionized wind from the UC HII regions.
4.2. Physical properties of the HII regions

Three of four UC HII regions in W75 N (B) (VLA 1 (Ba), VLA 2, & VLA 3 (Bb)) display evidence for on-going outflow/accretion based on high-velocity molecular gas traced to the source and/or the presence of H$_2$O or OH masers (Baart et al. 1986, Hunter et al. 1994, Torrelles et al. 1997, STS03, Torrelles et al. 2003). Thus, it is likely that the ionized gas produced by the central star can escape along the outflow axis. The remaining two HII regions (Bc in W75 N (B) & W75 N (A)) are more extended structures that are recovered in ~ 1.2″ resolution images at 6 cm but are resolved out at 2 cm with higher resolution (~ 0.4″). As discussed in Wood & Churchwell (1989, hereafter WC89), complicated geometries present difficulties for interpretation because physical parameters such as density and surface brightness along a line of sight depend on source structure. Following the method outlined by WC89, we use the integrated flux densities when knowledge of the source structure is not required and, when geometry is important, we estimate peak values using the peak flux densities per beam. Table 3 presents the derived physical parameters of the HII regions in W75 N. For each source, the values listed are: $\nu$, the frequency at which the derivations were made; $\Delta s$, line-of-sight depth at the peak position (taken to be the projected diameter of a sphere on the sky); $T_b$, the synthesized beam brightness temperature; $\tau_\nu$, the peak optical depth assuming the beam is uniformly filled with $T_e = 10^4$ K ionized gas; EM, the emission measure in units of $10^7$ pc cm$^{-6}$; $n_e$, the RMS electron density in units of $10^4$ cm$^{-3}$; U, the excitation parameter of the ionized gas; $N_L$, the number of Lyman continuum photons required to produce the observed emission assuming an ionization-bounded, spherically symmetric, homogeneous HII region; and finally, the spectral type of the central star assuming a single ZAMS star is producing the observed Lyman continuum flux (Panagia 1973, WC89).

Table 3: Derived Parameters for HII regions

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu$ (GHz)</th>
<th>$\Delta s$ (pc)</th>
<th>$T_b$ (K)</th>
<th>$\tau_\nu$</th>
<th>EM/10$^7$ (pc cm$^{-6}$)</th>
<th>$n_e/10^4$ (cm$^{-3}$)</th>
<th>U (pc cm$^{-2}$)</th>
<th>Log$N_L$ (s$^{-1}$)</th>
<th>Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA 1 (Ba)$^\dagger$</td>
<td>14.96</td>
<td>0.006</td>
<td>52</td>
<td>0.005</td>
<td>1.5</td>
<td>5.0</td>
<td>3.2</td>
<td>45.01</td>
<td>B1</td>
</tr>
<tr>
<td>VLA 2</td>
<td>14.96</td>
<td>0.004</td>
<td>42</td>
<td>0.004</td>
<td>0.38</td>
<td>3.2</td>
<td>2.3</td>
<td>44.59</td>
<td>B2</td>
</tr>
<tr>
<td>VLA 3 (Bb)</td>
<td>14.96</td>
<td>0.007</td>
<td>159</td>
<td>0.016</td>
<td>1.1</td>
<td>4.1</td>
<td>3.6</td>
<td>45.17</td>
<td>B1</td>
</tr>
<tr>
<td>Bc</td>
<td>4.88</td>
<td>0.024</td>
<td>108</td>
<td>0.011</td>
<td>0.09</td>
<td>0.6</td>
<td>3.2</td>
<td>45.00</td>
<td>B1.5</td>
</tr>
<tr>
<td>W75 N (A)</td>
<td>4.88</td>
<td>0.121</td>
<td>172</td>
<td>0.017</td>
<td>0.15</td>
<td>0.4</td>
<td>9.9</td>
<td>46.42</td>
<td>B0.5</td>
</tr>
</tbody>
</table>

$^\dagger$ Should be considered an upper limit due to likely strong contamination by ionizing flux produced by shock waves in the jet (see text for discussion).
There are a number of errors associated with the values in Table 3 that are difficult to estimate due to our limited knowledge of the detailed source structure. First, peak properties in Table 1 assume the beam is uniformly filled with $10^4$ K gas. However, the UC HII regions are unresolved, thus peak properties should be considered lower limits due to beam dilution effects. Second, derivations based on the integrated flux density should be considered lower limits for sources with known outflows since the ionized gas can escape along the outflow axis. Third, there is no correction for dust absorption within the ionized gas, which would tend to underestimate $N_L$, and hence the spectral type of the star. Fourth, shock waves within the outflow are expected to contribute to the total ionizing flux, which would result in an overestimate of $N_L$. Finally, accretion rates above $10^{-5}$ to $10^{-4}$ $M_\odot$ yr$^{-1}$, typical for early-B protostars, may inhibit the formation of a UC HII region near the equatorial plane where accretion is highest (see, e.g., Churchwell 1999 and references therein). Despite these uncertainties, the derivations are probably accurate to within a spectral type, except, perhaps, for VLA 1 (Ba). Due to the elongation of the ionized gas along the molecular outflow axis and the presence of H$_2$O masers along the axis, Torrelles et al. (1997) & STS03 argue that VLA 1 (Ba) is a thermal jet source. Thus, a significant fraction of the observed centimeter continuum emission is likely due to the ionized jet rather than emission from an ionization-bounded UC HII region produced by a central, massive star. If this is true, then the estimated spectral type of VLA 1 (Ba) should be considered an upper limit.

For the sources VLA 2 and VLA 3 (Bb), our estimates of the physical properties of the UC HII regions are lower than those of Torrelles et al. (1997) for two reasons: 1) our estimates based on peak emission likely suffer from beam dilution; and 2) the spectral indicies we estimate from fits of the SEDs suggest optically thin or slightly optically thick emission while Torrelles et al. estimated that the emission was significantly optically thick (based on only two data points). Spectral types from both estimates still only differ by a spectral type.

Comparison of the values in Table 3 with those in WC89 (their Table 17), shows that the physical parameters of the ionized gas in the W75 N sources are consistent with ZAMS stars with spectral types later than B0. Peak values of the emission measure and $n_e$ in the more extended sources Bc & W75 N (A) are roughly an order of magnitude less than what is found in the more compact HII regions. In the absence of confinement, the radius of an HII region is expected to increase with time as the ionization front expands to form an increasingly larger Strömgren sphere with subsequently smaller electron densities. Thus, the lower peak values and increased size of the HII region are consistent with these sources being more evolved than the more compact UC HII regions in W75 N (B). Bc and W75 N (A) also show no evidence for driving an outflow; again consistent with the sources being more evolved.
STS03 assumed all millimeter continuum emission from W75 N (A) was due to thermal dust and they calculated a mass of gas and dust to be 68 $M_\odot$. With a good centimeter continuum image, it is now possible to estimate the likely contribution due to ionized gas and obtain a better estimate for the molecular cloud mass traced by warm dust emission surrounding the Strömgren sphere. Assuming the 6 cm emission from W75 N (A) is optically thin ($S_\nu \propto \nu^{-0.1}$), the expected flux density at 2.7 mm due to ionized gas is 85 mJy. STS03 measured a total flux density at 2.7 mm of 129.5 mJy, thus the expected mass in the dust shell surrounding W75 N (A) is $\sim 23 M_\odot$ (see STS03 for a discussion of the assumptions and errors associated with this estimate).

4.3. Timescale for the formation of early-B stars in W75 N

The timescale for the formation of O star clusters for which $M_\star > 25 M_\odot$ appears to be less than 3 Myrs (Massy, Johnson, & DeGioia-Eastwood 1995). In all the clusters studied by Massy et al., there was evidence for the continued formation of mid to early-B stars (5-10 $M_\odot$) at least 1 Myr after the formation of the O stars. Do clusters where the most massive members are early-B stars have a similar age spread as that found for clusters forming stars more massive than 25 $M_\odot$?

Within a radius of 30$''$ ($\sim 0.3$ pc) from the W75 N (B) UC HII regions are three young early-B stars: the central star in W75 N (A), IRS1 and IRS2 (see, e.g., Fig. 10 of STS03). The early-B stars are embedded in a $\sim 1000 - 2000 M_\odot$ molecular cloud from which multiple flows are emerging with a combined outflow mass of at least 250 $M_\odot$ (Moore et al. 1991, Hunter et al. 1994, STS03). The outflows are driven by at least two of the stars embedded in UC HII regions and one millimeter core (MM 2). No high velocity molecular gas can be traced to the early B stars which are seen in the infrared (W75 N (A), IRS1, and IRS2) which suggests that the infrared stars are older than the central stars of the UC HII regions. From the size and velocity of the CO outflows, STS03 estimate that the central stars of the UC HII regions are $\sim 10^5$ years old.

W75 N (A), a classic example of an expanding Strömgren sphere (Fig. 6), appears to be the oldest B-type star of the cluster. The central B0.5 star is detected in the near-infrared with an irregular reflection nebula surrounding the star. A 12$''$ diameter sphere of ionized gas surrounds the star (0.12 pc at a distance of 2 kpc) which, in turn, is enclosed in an 18$''$ (0.17 pc) diameter shell of molecular gas. The near-infrared colors are consistent with foreground extinction from the molecular shell ($A_V \sim 20$, STS03). IRS1 and IRS2, on the other hand, have excess emission at 2$\mu$m suggesting that they have not had time to disperse their circumstellar material via photoevaporation and stellar winds. Thus, IRS1 & IRS2
appear to be of an intermediate age between W75 N (A) and the embedded stars in the UC HII regions.

Using the 6 cm observations of W75 N (A), we derive the age of W75 N (A) and hence an estimate of the age spread of the early-B stars in W75 N. The age of W75 N (A) can be derived in two ways: 1) from an estimate of the expansion time required for the HII region to reach its current radius; and 2) assuming the central star formed via accretion, from an estimate of the time it would take for the remnant accretion disk to be photodissipated. For the first case, the expansion of an ionization-front at the boundary of an expanding Strömgren sphere increases with time from some initial radius which depends on the ionizing flux from the central star and the density of the ambient medium (Dyson & Williams 1980). Assuming a strong shock approximation at the boundary of the ionization front, the initial radius, \( r_i \), is given by:

\[
    r_i = \left( \frac{3N_L}{4\pi n_o^2 \beta_2} \right)^{\frac{1}{3}}
\]

and the time required for the HII region to expand to a radius \( r(t) \) in a uniform density environment is:

\[
    \tau = \left( \left[ \frac{r(t)}{r_i} \right]^{\frac{7}{4}} - 1 \right) \left( \frac{4r_i}{T_{ci}} \right)
\]

where
- \( N_L \) = the flux of ionizing photons
- \( n_o \) = density of the ambient medium
- \( \beta_2 \) = recombination coefficient to all levels except the ground state at temperature, \( T_e \)
- \( c_i \) = sound speed in ionized gas (\( \sim 10 \) km s\(^{-1}\))

Assuming \( n_o = 2 \times 10^7 \) cm\(^{-3}\) (DePree, Rodríguez, & Goss 1995), \( T_e = 10^4 \) K, \( \beta_2 = 2.6 \times 10^{-10} T_e^{-3/4}\) cm\(^3\) s\(^{-1}\), and \( N_L = 2.6 \times 10^{46} \) s\(^{-1}\) for this B0.5 star, then the initial radius of the Strömgren sphere is \( r_i = 4 \times 10^9 \) km and the expansion timescale for the W75 N (A) HII region is \( \tau = 1.2 \times 10^6 \) years.

As discussed in DePree, Rodríguez, & Goss (1995), this calculation assumes that the molecular gas has a constant density and infinite extent. If this were the case, then one would expect W75 N (A) to reach pressure equilibrium at a radius of only 0.01 pc, which does not match the observed radius of > 0.1 pc. Instead, we expect the molecular gas density to decrease with radius which suggests that, for timescales \( \gtrsim 10^5 \) years, UC HII regions are probably not in pressure equilibrium and should be expanding. At the same time, the molecular material surrounding the Strömgren sphere is expected to expand at a slower rate (\( \sim 1 \) km s\(^{-1}\)) due to the lower temperature and molecular composition. Thus,
the exact expansion timescale of the HII region and the stability of the molecular envelope surrounding the ionized gas are quite uncertain.

For the second method, we assume the central star formed via accretion. Although competing theories exist for how the most massive O stars formed (e.g. coalescence or accretion), observational evidence for disks around early-B stars and the similarity between outflows produced by low-mass stars and those from mid- to early-B stars, suggest that stars up to spectral type B0 or O9 most likely form via accretion (see, e.g., the review by Shepherd 2003 and references therein). If the central star of W75 N (A) once had a massive accretion disk, then the lifetime of the UC HII region could be lengthened due to the photoevaporation of the circumstellar disk by the stellar wind (Hollenbach et al. 1994). The disk material would have provided high-density, ionized gas thus, the UC HII region would persist as long as the disk survived the mass loss (assuming the disk is no longer being fed by material from the surrounding molecular core). Since the near-infrared colors suggest there is no current disk, we assume the disk has been completely photo-evaporated and the timescale for this to occur would represent a lower limit to the age of W75 N (A). For the “weak wind” case of Hollenbach et al. appropriate for early-B stars, the lifetime of the disk is given by:

$$\tau_{\text{disk}} = 7 \times 10^4 \Phi_{49}^{-1/2} M_1^{-1/2} M_d \ [\text{yrs}]$$

where

- $\Phi_{49}$ = ionizing Lyman continuum flux in units of $10^{49}$ s$^{-1}$
- $M_1$ = the mass of the central star in units of 10 $M_\odot$
- $M_d$ = disk mass in units of $M_\odot$

For W75 N (A), $\Phi_{49} = 2.6 \times 10^{-3}$ and $M_1 \sim 1.5$. Shu et al. (1990) showed that an accretion disk becomes gravitationally unstable when it reaches a mass of $M_d \sim 0.3 M_*$ where $M_*$ is the mass of the central protostar. During the initial collapse of the cloud core, the disk mass may be maintained close to the value of 0.3$M_*$. When infall ceases and the disk mass falls below the critical value, disk accretion onto the star may rapidly decline and photoevaporation may be the dominant mechanism which disperses the remaining gas and dust (Hollenbach et a. 1994). Based on this scenario, we assume an initial disk at the edge of stability, that is $M_d \sim 0.3 M_* = 4.5 M_\odot$. Errors in the estimate for the photoevaporative timescale would scale directly as $M_d$. We find that $\tau_{\text{disk}} = 5 \times 10^6$ years.

Both estimates for the lifetime of W75 N (A) have numerous assumptions about, e.g. characteristic cloud densities, disk mass, & temperature of the ionized gas. None-the-less, they are probably reasonable to within an order of magnitude. These derivations suggest that the B0.5 star in W75 N (A) is roughly $1 - 5 \times 10^6$ years old while the youngest B stars forming are $\sim 10^5$ years old. Thus, the spread in ages between young B-stars in this cluster is $\Delta \tau = 0.1 - 5 \times 10^6$ years.
Efremov & Elmegreen (1998) and Elmegreen et al. (2000) suggest that the duration of star formation tends to vary with the size, $S$, of the cluster as something like the crossing time for turbulent motions, e.g. $\Delta \tau \propto S^{0.5}$. Given a cluster diameter of W75 N of $\sim 1'$ (0.6 pc), the expected age would be roughly 0.8 Myrs, which is somewhat lower than our estimates although still within the errors. Comparing with other observations, clusters forming stars with $M_\star > 25 M_\odot$ have a typical spread in ages, $\Delta \tau$, of about 2 Myrs for the O stars while mid- to early-B stars continue to form for at least another million years (Massy, Johnson, & DeGioia-Eastwood 1995). Thus, the early-B stars in W75 N are formed over a period that is consistent with the timescale for early-B stars formed in clusters with more massive stars.

5. SUMMARY

We have observed the W75 N massive star forming region in SiO(J=2–1) & (J=1–0) to search for well-collimated neutral jets from the early-B protostars and in centimeter and 7 mm continuum emission to examine the nature of the driving sources. The SiO emission is diffuse with no clear indication of a neutral, collimated jet from the region. This does not, however, completely rule out the presence of a jet since enhanced SiO emission does not always trace known jet structure.

The ionized gas surrounding the protostars have emission measures, densities, and derived spectral types which are consistent with early-B stars. Most of the detected sources have spectral indicies which suggest optically thin to moderately optically thick HII regions produced by a central ionizing star.

By comparing the oldest and youngest B stars in the cluster, an estimate for the duration of early-B star formation in W75 N is obtained. The oldest star in the cluster is roughly $1 - 5 \times 10^6$ years old while the youngest, B protostars are $\sim 10^5$ years old. Thus, the spread in ages is $0.1 - 5 \times 10^6$ years. The age spread for W75 N is consistent with that found for early-B stars born in clusters forming more massive stars ($M_\star > 25M_\odot$).

Acknowledgments: Research at the Owens Valley Radio Observatory is supported by the National Science Foundation through NSF grant number AST 96-13717. Star formation research at Owens Valley is also support by NASA’s Origins of Solar Systems program, grant NAGW-4030 and by the Norris Planetary Origins Project. S. Kurtz acknowledges support from Project IN118401 and CONACyT Project E-36568. D. Shepherd would like to thank Sally Oey for useful discussions on the evolutionary timescales of young clusters.
REFERENCES


This preprint was prepared with the AAS LaTeX macros v4.0.
Figure Captions

Figure 1. Continuum emission from W75 N (A) and UC HII regions within W75 N (B) at 6 cm (top), 2 cm (lower left), and 7 mm (lower right) wavelength is plotted in both contours and greyscale. **Top:** The 6 cm image RMS is $0.11 \, \text{mJy beam}^{-1}$; contours are plotted at $-3, 3, 5 \sigma$ and continue with spacings of $5 \sigma$; greyscale is displayed on a linear scale from $0.33 \, \text{mJy beam}^{-1}$ to $4.5 \, \text{mJy beam}^{-1}$. The synthesized beam, plotted in the lower left corner, is $1.36'' \times 1.12''$ at position angle $29.2^\circ$. The extended emission from W75 N (A) coincides with the millimeter core MM 5 and a near-infrared reflection nebula and star (Shepherd, Testi, & Stark 2003). Locations of UC HII regions in W75 N (B) that are detected in 6 cm continuum emission are identified by filled triangles. The dashed box around the W75 N B sources shows the area displayed in the lower two images at 2 cm and 7 mm. **Lower left:** The 2 cm image RMS is $0.23 \, \text{mJy beam}^{-1}$; contours are plotted at $-3, 3, 4, 5, 6, 8, \sigma$ and continue with spacings of $2 \sigma$; greyscale is displayed from $0.46 \, \text{mJy beam}^{-1}$ to $4.42 \, \text{mJy beam}^{-1}$. The synthesized beam, plotted in the lower right corner, is $0.44'' \times 0.36''$ at P.A. $31.4^\circ$. **Lower right:** The 7 mm image RMS is $0.31 \, \text{mJy beam}^{-1}$; contours are plotted at $-3, 3, 5, 7 \sigma$ and continue with spacings of $2 \sigma$; greyscale is displayed from $0.62 \, \text{mJy beam}^{-1}$ to $5.4 \, \text{mJy beam}^{-1}$. The synthesized beam, plotted in the lower right corner, is $0.27'' \times 0.20''$ at P.A. $89.4^\circ$. UC HII region Bc is not detected. The locations of the UC HII regions in the field are indicated with filled triangles. Water masers are shown as crosses (Torrelles et al. 1997); OH maser positions are represented as filled circles (Baart et al. 1986).

Figure 2. The spectral energy distributions of the UC HII regions in W75 N (B). Asterisks represent data from this work, squares represent data from Hunter et al. (1994), circles are from Torrelles et al. (1997), and the triangle represents the $0.9''$ resolution 1 mm data from Shepherd (2001). Upper limits ($3\sigma$) are shown as symbols with arrows. In all cases, estimated errors are smaller than the symbols. Solid lines show linear least squares fits to the SEDs for data between 6 cm and 7 mm. The slope of the fit (spectral index) is shown in the lower right corner of each plot.

Figure 3. **Top:** SiO($v=0, J=2–1$) channel maps at 1.726 km s$^{-1}$ spectral resolution between 0.5 and 19.5 km s$^{-1}$. The velocity is indicated in the upper right of each panel. The RMS is $45 \, \text{mJy beam}^{-1}$. Contours are plotted from $\pm 3, 4, 5, 6 \sigma$ and continue with a spacing of $2 \sigma$. The last panel (velocity 19.5 km s$^{-1}$) shows the synthesized beam in the lower right corner ($5.35'' \times 4.15''$ at P.A. $-60.3^\circ$) and a scale size of 0.1 pc is represented by a bar in the lower left corner. The locations of four millimeter continuum peaks in W75 N (B) are shown as plus signs (MM 1 – MM 4, Shepherd 2001) while positions for the UC HII regions VLA 1(Ba), VLA 2, VLA 3(Bb), and Bc are indicated by small triangles (Hunter et al. 1994; Torrelles et al. 1997). **Bottom:** SiO($v=0, J=2–1$) channel maps made with a higher spatial
resolution of $3.17'' \times 2.56''$ at P.A. $-61.5^\circ$ (beam shown in lower right panel). The RMS is $39 \, \text{mJy beam}^{-1}$. Contours are plotted from $\pm 3, 4, 5, 6 \, \sigma$ and continue with a spacing of $2 \, \sigma$.

**Figure 4.** Blue-shifted (2.23 to 10 km s$^{-1}$; thin lines) and red-shifted (10 to 17.8 km s$^{-1}$; thick lines) SiO(v=0, J=2–1) emission contours. The left panel shows the lower resolution data while the right panel shows the higher resolution data. The synthesized beam is shown in the lower right corner of each image. Millimeter cores MM 2, MM 3, and MM 4 are shown as filled circles, UC HII regions within MM 1 are indicated by filled triangles. Position angles of outflows proposed by Shepherd, Testi, & Stark (2003) are illustrated by arrows.

**Figure 5.** W75 N SiO(v=0, J=2–1) zeroth moment map and SiO spectra. The SiO(v=0) image (lower left) has an RMS of $0.3 \, \text{mJy beam}^{-1} \, \text{km s}^{-1}$; contours begin at $\pm 3, 4, 6 \, \sigma$ and continue with spacings of $2 \, \sigma$. The synthesized beam of $5.35'' \times 4.15''$ at P.A. $-60.3^\circ$ is shown in the lower right corner while a scale size of 0.1 pc is shown in the lower left corner. Millimeter cores MM 2, MM 3, and MM 4 are shown as filled circles, UC HII regions within MM 1 are indicated by filled triangles. SiO(v=0, J=2–1) spectra are shown at different locations in the cloud. The dashed vertical line in each plot represents $v_{\text{LSR}} = 10 \, \text{km s}^{-1}$.

**Figure 6.** W75 N (A): White contours represent the 6 cm continuum emission tracing ionized gas in the Strömgren sphere surrounding the central B0.5 star (contours are the same as in Fig. 1). Greyscale shows the near-infrared K-band reflection nebula and central star while the black contours represent the 3 mm continuum emission from the warm dust shell surrounding the ionized gas (from Fig. 5 of STS03).