Clustered Star Formation in W75 N

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ABSTRACT

We present 2" to 7" resolution 3 mm continuum and CO(J=1–0) line emission and near infrared K\textsubscript{s}, H\textsubscript{2}, and [FeII] images toward the massive star forming region W75 N. The CO emission uncovers a complex morphology of multiple, overlapping outflows. A total flow mass of > 255 M\odot extends 3 pc from end-to-end and is being driven by at least four late to early-B protostars. More than 10\% of the molecular cloud has been accelerated to high velocities by the molecular flows (> 5.2 km s\textsuperscript{-1} relative to \(v_{LSR}\)) and the mechanical energy in the outflowing gas is roughly half the gravitational binding energy of the cloud. The W75 N cluster members represent a range of evolutionary stages, from stars with no apparent circumstellar material to deeply embedded protostars that are actively powering massive outflows. Nine cores of millimeter-wavelength emission highlight the locations of embedded protostars in W75 N. The total mass of gas \& dust associated with the millimeter cores ranges from 340 M\odot to 11 M\odot. The infrared reflection nebula and shocked H\textsubscript{2} emission have multiple peaks and extensions which, again, suggests the presence of several outflows. Diffuse H\textsubscript{2} emission extends about 0.6 parsecs beyond the outer boundaries of the CO emission while the [FeII] emission is only detected close to the protostars. The infrared line emission morphology suggests that only slow, non-dissociative J-type shocks exist throughout the pc-scale outflows. Fast, dissociative shocks, common in jet-driven low-mass outflows, are absent in W75 N. Thus, the energetics of the outflows from the late to early B protostars in W75 N differ from their low-mass counterparts – they do not appear to be simply scaled-up versions of low-mass outflows.

\textit{Subject headings:} stars: formation \& nebulae: HII regions \& ISM: jets and outflows \& ISM: molecules

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1. INTRODUCTION

W75 N is a massive star forming region with an integrated IRAS luminosity of $1.4 \times 10^5$ L$_\odot$ (Moore, Mountain, & Yamashita 1991; Moore et al. 1988, 1991). The W75 N cloud is located at a distance of 2 kpc (Dickel, Wendker, & Bieritz 1969), just 15' north of the massive outflow system DR 21 powered by a cluster of OB stars (e.g. Garden et al. 1991 and references therein). Both DR 21 and W75 N are part of the Cygnus-X complex of dense molecular clouds. 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. Torellés 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.

A parsec-scale molecular outflow originates near the cluster of ultracompact HII (UC HII) regions in W75 N (B). The mass of the CO outflow has been estimated to be 50 M$_\odot$ to 500 M$_\odot$ based on single-dish, CO observations (e.g Fischer et al. 1985; Hunter et al. 1994; Davis et al. 1998a, b; Ridge & Moore 2001). The UC HII regions have a combined $L_{bol}$ of $4.4 \times 10^4$ L$_\odot$ and most are in a protostellar phase based on the presence of OH, H$_2$O, & methanol masers, and compact millimeter continuum emission (Baart et al. 1986; Hunter et al. 1994; Torellés et al. 1997; Minier, Conway, & Booth 2000, 2001; Shepherd 2001; Hutawarakorn, Cohen, & Brebner 2002; Slysh et al. 2002; Watson et al. 2002). Several studies have assumed the flow is dominated by a single massive star: the central source in the UC HII region VLA 1 (Ba) because the position angles of the ionized gas and the CO emission are similar (Hunter et al. 1994; Torellés et al. 1997; Davis et al. 1998a, b). Shepherd (2001) suggested VLA 3 (Bb) and, perhaps, VLA 2 may be the primary powering sources based on the presence of compact millimeter continuum emission. More recently, Hutawarakorn et al. (2002) suggested VLA 2 is the dominant source powering the outflow based on OH maser emission. Given the sheer number of interpretations, it is clear that W75 N is a confused region.

Assuming a primary driving source for the CO outflow, Davis et al. (1998b) suggested that the CO red-shifted lobe and H$_2$ morphology supported a jet-driven, bow-shock entrainment scenario in which a steady, over-dense molecular jet, developed to explain highly-collimated outflows from low-mass protostars, was applied to W75 N (Lada & Fich 1996; Smith et al. 1997; & Suttner et al. 1997). The proposed model implied a jet radius of 0.03 pc at 1.3 pc from the star with a jet opening angle of about 2.6' (Richer et al. 2000). If a powerful, well-collimated jet was being driven by an OB protostar in W75 N, it would provide strong constraints on outflow/accretion theories for luminous protostars (see, e.g.,

To obtain a better understanding of the number of sources driving outflows and the energetics of the flow(s), we have made interferometric mosaics of the W75 N region in CO(J=1–0) and millimeter continuum using the Owens Valley Radio Observatory and obtained images at near-infrared wavelengths using the Telescopio Nazionale Galileo to compare the morphology of the shocked gas & infrared nebulosity with the CO emission.

2. OBSERVATIONS

2.1. Owens Valley Observations in the 3 mm band

Observations in 2.7 mm continuum and CO(J=1–0) line were made with the Owens Valley Radio Observatory (OVRO) array of six 10.4 m telescopes between 1999 March 15 and 1999 December 4. Projected baselines ranging from 15 to 115 meters provided sensitivity to structures up to about 16″. The final ~5′ × 1.5′ mosaic images of both line and continuum emission are made up of 17 fields with primary beam 65″ (FWHM) spaced 30″ apart. The total integration time on source was approximately 3.25 hours pointing center. Cryogenically cooled SIS receivers operating at 4 K produced typical single sideband system temperatures of 200 to 600 K. The gain calibrator was the quasar BL Lac and the bandpass calibrators were 3C 454.3 and 3C 345. Observations of Uranus, Neptune, or 3C 273 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 using the MIRIAD software package (Sault et al., 1995) and deconvolved with a maximum-entropy-based algorithm designed for mosaic images (Cornwell & Braun, 1988).

The CO $uv$ data at 115.27 GHz were convolved with a 5″ taper resulting in a synthesized beam of 6.46″ × 6.28″ (FWHM) at P.A. −54.7°. The spectral resolution was 2.6 km s$^{-1}$ and the RMS noise was 0.13 Jy beam$^{-1}$. The spectral band pass was centered on the local standard of rest velocity ($v_{LSR}$) of 10.0 km s$^{-1}$ (the assumed systemic velocity of the W75 N cloud), taken from the CS(J=7–6) emission peak (Hunter et al., 1994). Simultaneous 2.7 mm continuum observations were made in a 1 GHz bandwidth channel with central frequency 112.77 GHz. The $uv$ data were convolved with a 6″ taper resulting in a synthesized beam 7.29″ × 7.13″ (FWHM) at P.A. −62.9°. The RMS noise was 3.6 mJy beam$^{-1}$.

An additional on-source integration time of 4.6 hours was obtained with OVRO centered on the position of W75 N:MM 1 ($\alpha(J2000) = 20^h 38^m 36.36^s$, $\delta(J2000) = 42^\circ 37' 33.5''$). Observations were made on 1999 March 29 and 2001 March 18. Baselines between 35 and
240 meters provided sensitivity to structures up to 6". The CO uv data (spectral resolution 2.6 km s\(^{-1}\)) were convolved with a 1.5" taper resulting in a synthesized beam of 2.04" × 1.77" (FWHM) at P.A. —80.5°. The final RMS noise was 50 mJy beam\(^{-1}\) in each channel.

2.2. 3 mm single dish spectra

Observations were made in CO(J=1–0) and \(^{13}\)CO(J=1–0) with the Kitt Peak 12 m telescope on 2000 May 9 using the SIS 3 mm receiver with 1 MHz filter banks centered on \(v_{\text{LSR}} = 10.0\) km s\(^{-1}\) to give a velocity resolution of 2.6 km s\(^{-1}\) and a total bandwidth of 650 km s\(^{-1}\). System temperatures ranged from 230 K for \(^{13}\)CO to 360 K for CO(J=1–0). The half-power beam width (HPBW) at 115 GHz is about 60".

Single dish spectra were obtained at three positions (J2000 coordinates): centered on W75 N:MM 1 (\(\alpha = 20^\text{h}38^\text{m}36.50^\text{s}\ \delta = 42^\circ37'33.5"\); and in the south-east and north-west outflow lobes (\(\alpha = 20^\text{h}38^\text{m}31.00^\text{s}\ \delta = 42^\circ36'51.0''\) and \(\alpha = 20^\text{h}38^\text{m}41.00^\text{s}\ \delta = 42^\circ37'51.0''\), respectively). The data were reduced with the NRAO UniPOPS software package. The resulting spectra were used to estimate the optical depth in CO(J=1–0) as a function of velocity and position in the W75 N region.

2.3. Near-Infrared Observations

Near-infrared observations of the W75 N region were made on 2000 June 16, at the 3.5 m Telescopio Nazionale Galileo (TNG) at the Roque de los Muchachos Observatory on the Spanish island of La Palma. The ARNICA NIR imager (Lisi et al. 1996; Hunt et al. 1996) was used to obtain images in the H\(_2\) narrow band filter and in the K\(_s\) broad band filter. ARNICA is equipped with a HgCdTe 256 × 256 NICMOS3 infrared array. The pixel scale, when coupled with the TNG, is 0.355 arcsec/pixel, and the corresponding field of view is 1.5 × 1.5 arcmin\(^2\) per frame. The seeing at the time of the observations was about 0.9".

To search for H\(_2\) emission beyond the CO emission, a 14 pointing mosaic pattern was employed covering an area of approximately 9×2 arcmin\(^2\) that was roughly aligned with the CO flow. The mosaic was repeated several times, dithering the telescope by a few pixels each time, until the desired integration time was achieved. The final integration times per sky position was 8 minutes in K\(_s\)-band and 30 minutes in the H\(_2\) filter.

Data reduction and analysis were performed using the IRAF software package. Following standard flat-fielding and sky subtraction, the individual images were registered and the final mosaic was produced. The K\(_s\)-band observations were calibrated using standard stars from
the ARNICA list (Hunt et al. 1998). The H$_2$ mosaic was calibrated assuming that a set of stars have the same flux density in the narrow- and broad-band filters. The broad-band mosaic was then used to subtract the continuum emission from the H$_2$ mosaic. Integrated line fluxes are then estimated assuming the width of the H$_2$ filter as measured by Vanzi et al. (1998). The calibration accuracy is expected to be within 20%. Accurate ($\leq 0.5$) astrometry was derived for both mosaics using stellar positions from the 2MASS second incremental data release.

Additional observations of two $\sim 4' \times 4'$ fields centered north-east and south-west of W75 N were obtained in 2002 August 21 using the TNG near infrared camera spectrograph (NICS, Baffa et al. 2001). Each of the two fields was observed through the H$_2$ ($\lambda=2.12$ $\mu$m) and [FeII] ($\lambda=1.64$ $\mu$m) narrow-band filters and in two narrow-band continuum filters, $K_{cont}$ and $H_{cont}$; a detailed characterization of all these filters can be found in Ghinassi et al. (2002). The observations were reduced and astrometrically calibrated following the procedure outlined above. The weather conditions were not photometric during the observations so the data could not be flux calibrated. Line-only images were obtained by subtracting the narrow-band continuum images from the line+continuum images. The subtraction was not perfect on strong stellar sources or on stars with very red or very blue spectra.

3. RESULTS

3.1. H$_2$ and [FeII] morphology

Infrared reflection nebulosity is associated with two distinct regions of ionized gas (Fig. 1): W75 N (A) at position $\alpha(J2000) = 20^h38^m38^s$ $\delta(J2000) = 42^\circ37'59''$ and W75 N (B) at position $\alpha(J2000) = 20^h38^m37^s$ $\delta(J2000) = 42^\circ37'32''$ (e.g. Haschick et al. 1981, Moore et al. 1988). Shock-excited H$_2$ emission (Figs. 2 & 3) is present in the north-east (near $\alpha(J2000) = 20^h38^m52^s$ $\delta(J2000) = 42^\circ39'00''$) and along the CO emission boundaries (see also Davis et al. 1998a,b). Our H$_2$ images also show that faint, patchy H$_2$ emission extends nearly an arcminute (0.6 pc at a distance of 2 kpc) beyond the south-west CO flow ($\alpha(J2000) = 20^h38^m22^s$ $\delta(J2000) = 42^\circ36'10''$).

The continuum subtracted H$_2$ mosaic is shown in Fig. 2. Following the nomenclature

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4Due to the different optical configuration used at the TNG with respect to that used at the TIRGO telescope, the narrow-band filters do not suffer from the effective field of view reduction discussed by Vanzi et al. (1998).
used by Davis et al. (1998a,b) for the south-west portion of the H$_2$ flow, all previously known H$_2$ knots and filaments are marked with solid lines. These are labeled SW–A to SW–H in the south-west flow, C–A and C–B in the central region, and NE–A to NE–F in the north-east flow. Additionally, Figs. 2 & 3 reveal faint diffuse H$_2$ emission beyond the tip of the south-west flow and within the north-east flow. These new features are marked with dashed lines and labeled SW–I to SW–K and NE–G to NE–I. Faint, diffuse H$_2$ features as well as the filamentary structure of the emission in knots NE–D, NE–E, & NE–F are confirmed by observations obtained in 2002 August. Figure 3 presents an overlay of the continuum subtracted [FeII] emission (contours) on the H$_2$ (grayscale) images from the 2002 August observations. [FeII] line emission is only detected close to the UC HII regions in W75 N B and near the exciting star of W75 N A. No [FeII] emission is detected in the outer flow regions. The non-detection of [FeII] far from the protostars does not appear to be due to higher extinction since we clearly detect 2.12μm H$_2$ emission beyond the CO outflow boundaries and we detect [FeII] emission near the cloud core where the column density is higher.

A chain of H$_2$ knots, apparently unrelated to the main flow, are detected near α(J2000) = 20h38m32s − 36° δ(J2000) = 42°39′30″ − 60″ (Fig. 3). This jet is outside of the CO and infrared mosaic fields. The knots may be associated with a jet from a young star north of the main complex discussed in this paper.

### 3.2. CO outflows and their driving sources

A high-velocity CO outflow, centered near W75 N (B), measures 3 pc from end-to-end (projected length) and extends well beyond the infrared reflection nebula (Figs. 1 & 4). Red and blue-shifted CO emission exists both in the north-east and south-west. The CO mosaic did not include areas to the north-west and south-east so it is unclear if high-velocity CO exists in these regions. The boundaries and flux density of the CO outflow are well determined on the red-shifted side of the line, however, at velocities between 0 and −5.6 km s$^{-1}$ the DR 21 cloud ($v_{LSR} = −2.5$ km s$^{-1}$) confuses the identification of the outflow structure.

Nine millimeter continuum peaks showing the locations of warm dust emission are identified in Fig. 5 & Table 1 (W75 N:MM 1 through W75 N:MM 9$^5$). MM 1 – MM 4 are near the origin of the outflow activity and lie 5 − 10′′ from the W75 N (B) reflection nebulosity to the north and west. MM 5 is associated with the more extended HII region,

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$^5$Names of millimeter cores are shortened to MM 1 to MM 9 for the remainder of this paper.
W75 N (A), while MM 6 – MM 9 are not associated with any previously known sources. Infrared counterparts do not exist for the millimeter sources (except MM 5) suggesting that these sources are too deeply embedded to be detected at 2μm. Figure 5 also shows the 2″ resolution image from Shepherd (2001) for comparison. The 2″ resolution resolved the individual millimeter cores MM 1–4 but resolved out the more extended emission associated with MM 5 and MM 6. Millimeter cores MM 7–9 were outside of the primary beam of the Shepherd (2001) observations and thus, were not detected. Figure 5 also compares the MM 5 millimeter source with narrow-band H₂+continuum emission and K₂ broad-band emission in W75 N (A). The central star of W75 N (A) (spectral type B0.5; Haschick et al. 1981) is clearly visible in the infrared and is surrounded by a 20″ shell of thermal dust emission. Diffuse reflection nebulosity is centered on the star and a wisp of H₂ emission is visible just east of the star (α(J2000) = 20h38m38.3s  δ(J2000) = 42°38′00″).

Compact, high-velocity CO emission appears to originate from the UC HII regions VLA 1 (Ba) & VLA 3 (Bb) and from MM 2 (Figs. 6, 7, & 8). The 2 – 5″ resolution is not sufficient to determine if VLA 2, located only 0.5″ north of VLA 3 (Bb), is also associated with high-velocity CO gas. A detailed discussion of each of the proposed outflows is given below.

The outflow from VLA 1 (Ba): VLA 1 (Ba) is a thermal jet source associated with H₂O and OH masers (Baart et al. 1986, Torrelles et al. 1997). It is embedded in the MM 1 core detected in 1 & 3 mm continuum emission (Shepherd 2001). The spectral type of the powering source is unknown since the observed centimeter continuum emission is likely due to the ionized jet rather than emission from an ionization-bounded UC HII region. Red-shifted emission to the north-east of MM 1 can be traced to the jet-like ionized flow from VLA 1 (Ba). Figure 7 presents a 6″ image of the integrated CO emission from the flow as well as a position-velocity diagram from a slice along the proposed flow axis (P.A. 51°). A ridge of CO emission extends to the north-east with projected velocity greater than 25 km s⁻¹ (relative to v₇₅₀) almost an arcminute from the UC HII region. High-velocity CO emission is also centered on the UC HII regions (position offset −18″ in the PV diagram of Fig. 7). A 2″ resolution image (Fig. 6, top left) shows that this red-shifted emission near the base of the outflow appears to be produced by VLA 1 (Ba) as well as VLA 3 (Bb) and possibly VLA 2. The 2″ resolution of Fig. 6 resolves out much of the extended emission in the flow leaving only compact clumps visible along the flow axis. The P.A. is similar to the elongation of the ionized emission in VLA 1 (Ba) (P.A. ~ 43°) and a line of H₂O masers detected along the jet (Torrelles et al. 1997). The molecular flow is also seen in Fig. 1 as a well-collimated, red-shifted lobe extending to the north-east from the MM 1 core. The outflow is shown as one-sided in Figs. 6 & 7 because only one side of the flow is detected. The counterflow may exist however it may be too extended to image at this high-resolution
or it may be expanding into a less dense medium that would not create appreciable CO emission.

The outflow from VLA 3 (Bb): VLA 3 (Bb) is a compact UC HII region in MM 1 with a central star of spectral type B0.5 to B0. It is associated with a single H$_2$O maser and compact 1 & 3 mm continuum emission. A lower limit on the mass of warm gas and dust within 2000 AU of the protostar is 5 M$_\odot$ (Shepherd 2001). Figure 6 illustrates that compact red-shifted emission to the east and blue-shifted emission to the west of MM 1 can be traced to VLA 3 (Bb) with P.A. $\sim 101^\circ$. There are no obvious features in the extended emission that correspond to an outflow with this orientation, however, the CO mosaic did not extend to the north-west or south-east so a large-scale outflow could have been missed (Fig. 1). The molecular gas morphology does not seem to be correlated with that of the ionized gas or H$_2$O masers near the source: the ionized gas is slightly elongated along P.A. 149$^\circ$ and the H$_2$O maser is located near the southern boundary of the ionized gas.

The outflow from MM 2: MM 2 is a molecular core identified by compact, warm dust emission at 1 & 3 mm and H$_2$O maser emission (Torrelles et al 1997, Shepherd 2001). The mass of the core is 30 – 50 M$_\odot$. No ionized gas has been detected indicating that the spectral type is less than a B2 star or high accretion is preventing the formation of a UC HII region. High-velocity, blue-shifted emission (13 to 36 km s$^{-1}$ projected velocity relative to $v_{LSR}$) can be traced from the MM 2 core to the south-east (P.A. 124$^\circ$). Figure 8 presents a 6$''$ image of the integrated emission from the flow as well as a position-velocity diagram from a slice along the proposed flow axis. The velocity of the jet relative to $v_{LSR} = 10$ km s$^{-1}$ increases away from the position of MM 2 and remains well collimated. Diffuse emission at velocities greater than $v = -5$ km s$^{-1}$ is due to the W75 N & DR 21 clouds. Figure 6 shows the more compact emission in the flow. Three clumps of high-velocity gas are detected extending away from MM 2 along with faint emission at the location of the core. The compact clumps appear to trace a shell of dense gas surrounding the outflow axis. The molecular outflow is identified as one-sided because the red-shifted counterflow was not detected.

The diffuse millimeter core MM 4 is located along the axis of the proposed MM 2 outflow. Although no H$_2$O or OH maser emission has been detected toward MM 4, nor has centimeter or 1 mm continuum emission been detected, there is diffuse warm dust emission traced by 3 mm continuum. Thus, MM 4 may harbor an embedded protostar. Assuming the MM 4 core is heated internally, the lack of maser activity, compact warm dust emission at 1 mm, and the absence of ionized gas emission at centimeter wavelengths suggest that MM 4 is a low-mass protostar (Shepherd 2001). With the current resolution and sensitivity, we can not determine if the MM 4 protostar is contributing to the observed flow dynamics.

The proposed position angles of the outflowing gas (illustrated by arrows in Figs. 6,
7, & 8) are 51° for VLA 1 (Ba), 101° for VLA 3 (Bb), and 124° for MM 2. The position angle of the parsec-scale outflow detected in H$_2$ and CO (Fig. 1) is 62.5°. Although the orientation of the VLA 1 (Ba) outflow is similar to that of the parsec-scale flow, it does not appear likely that VLA 1 (Ba) is the powering source. Assuming the VLA 1 (Ba) flow is symmetric, a blue-shifted counterflow is expected in the south-west, not a red-shifted flow.

Thus, our observations do not identify the source responsible for the 3 pc outflow which dominates the large-scale morphology and kinematics of the region.

### 3.3. Mass & Kinematics of the Outflows

The mass associated with CO line emission is calculated following the method proposed by Scoville et al. (1986). The CO excitation temperature near the millimeter continuum emission varies from about 35 to 75 K with ~ 50 K being the median value near the MM 1 peak (Davis et al. 1998b). Rotational temperatures derived from CH$_3$CN in the cloud core vary from 47 to 78 K, consistent with the Davis et al. estimates (Kalenskiï et al. 2000). We assume the gas is in LTE, at a temperature of 50 K, with [CO]/[H$_2$] = 10$^{-4}$, and [CO]/[13CO] = 71 at the galacto-centric distance of 8.5 kpc (Wilson & Rood 1994). The CO optical depth as a function of velocity and position is calculated using single dish CO(J=1–0) and 13CO(J=1–0) spectra taken at three positions within the W75 N region (Fig. 9). We assume 13CO is optically thin at all velocities which is probably valid in the line wings; however, 13CO is likely to be optically thick near the line core. In channels where no 13CO emission is detected, we assume the CO is optically thin. The CO channel images (Fig. 4) show that the emission near $v_{LSR}$ is almost entirely resolved out by the interferometer. If high-velocity (> 5.2 km s$^{-1}$) structures exist that are larger than the largest angular scale that can be imaged (> 16") then our mass estimate represents a lower limit.

Because multiple, overlapping flows are present, it is not possible to obtain a reasonable estimate of the inclination of each flow. Thus, we assume an inclination angle of 45° which minimizes errors introduced by inclination effects. Table 2 summarizes the physical properties of the molecular gas in the combined outflows originating within MM 1 and from the blue-shifted MM 2 outflow lobe. The total flow mass $M_f$ is given by $\sum M_i$ where $M_i$ is the flow mass in velocity channel $i$ corrected for optical depth. The momentum $P$ is given by $\sum M_i v_i$ and the kinetic energy $E$ by $\frac{1}{2} \sum M_i v_i^2$ where $v_i$ is the central velocity of the channel relative to $v_{LSR}$. The characteristic flow timescale $t_d$ is $R_f / < V >$, where the intensity-weighted velocity $< V >$ is given by $P/(\sum M_i)$ (Cabrit & Bertout 1990) and $R_f$ is the flow radius. The mass outflow rate $\dot{M}_f$ is $\sum M_i / t_d$ and the force $F$ is $P / t_d$. Assuming $D=2$ kpc, the total molecular mass in outflowing gas ($v > 5.2$ km s$^{-1}$ relative to $v_{LSR}$) is
> 255 M\(_{\odot}\). The values presented in Table 2 are derived assuming all flows have the same systemic velocity. This is a reasonable assumption for the driving sources of the combined MM 1 outflows since the observed UC HII regions are embedded within the same molecular clump and have a projected separation of only 0.5 to 1\(^\circ\) (1000 - 2000 AU at a distance of 2 kpc). The source driving the outflow from the MM 2 molecular core has a projected separation of about 5\(^\circ\) (10,000 AU or 0.05 pc) from MM 1. It is possible that MM 2 could have a slightly different systemic velocity from MM 1 that we cannot detect in our images or single dish spectra. If the systemic velocity of the MM 2 core is different by a factor of \(\Delta v\) from the assumed velocity of 10 km s\(^{-1}\), then the error in the momentum estimates will be proportional to \(|\Delta v|\) and mechanical energy to \(|\Delta v^2|\).

The combined MM 1 outflows have a total mass of at least 165 M\(_{\odot}\) and energy, E > 3.4 \times 10^{47}\) ergs. The MM 2 outflow has a total mass > 90 M\(_{\odot}\), E > 1.8 \times 10^{47}\) ergs. The CO mosaic did not extend in the south-east direction of the MM 2 flow, thus, the full outflow was not imaged and age and \(\dot{M}\) should be considered a lower limit. Despite the uncertainties, the flow masses and energies are consistent with those for outflows driven by young, early B stars. This is in agreement with the estimated spectral types of the stars powering the UC HII regions in MM 1 (B2 to O9; Hunter et al. 1994; Torrelles et al. 1997; Shepherd 2001; Slysh et al. 2002).

### 3.4. Circumstellar material near embedded protostars

The mass of gas and dust associated with warm dust being heated by the central protostars is estimated from the millimeter continuum emission using \(M_{gas+dust} = \frac{F_\nu D^2}{B_\nu(T_d) \kappa_\nu}\)

where D is the distance to the source, \(F_\nu\) is the continuum flux density due to thermal dust emission at frequency \(\nu\), and \(B_\nu\) is the Planck function at temperature \(T_d\) (Hildebrand 1983). Assuming a gas-to-dust ratio of 100, the dust opacity per gram of gas is taken to be \(\kappa_\nu = 0.006(\nu/10^{12}\text{Hz})^\beta\) cm\(^2\) g\(^{-1}\) where \(\beta\) is the opacity index (see Kramer et al. 1998; and the discussion in Shepherd & Watson 2002). This value of \(\kappa\) agrees with those derived by Hildebrand (1983) and Kramer et al. (1998) to within a factor of 2. The opacity index \(\beta = 1.5\) appears to be appropriate between wavelengths of 650 microns and 2.7 mm for sub-micron to millimeter-sized grains expected in warm molecular clouds and young disks (Pollack et al. 1994). We assume the emission is optically thin and the temperature of the dust can be characterized by a single value. Using values of \(T_d = 50\) K and \(\beta = 1.5\), we find the total mass of gas and dust associated with the 2.7 mm continuum emission is approximately 475 M\(_{\odot}\) (Table 1). Our results are consistent with those of Shepherd (2001) and Watson et al. (2002) to within the errors.
4. DISCUSSION

The total molecular mass of outflowing gas from the MM 1 and MM 2 combined flows ($v > 5.2 \text{ km s}^{-1}$ relative to $v_{LSR}$) is $> 255 \text{ M}_{\odot}$. Hunter et al. (1994) found $M_f = 48 \text{ M}_{\odot}$ with a rough scaling performed to take into account an optical depth correction. However, their image covered only the inner region of the flow so their estimate should be considered a lower limit. Based on single dish observations of CO($J=3–2$), Davis et al (1998a) estimated a total flow mass of $M_f = 272 \text{ M}_{\odot}$, uncorrected for optical depth effects. This mass estimate is extremely high for an optically thin approximation. Examination of their Fig. 11, $T_A$ vs. $(v - v_o)$, shows that the blue-shifted lobe has an order of magnitude increase in the integrated flux at the velocity of DR 21 ($-2.5 \text{ km s}^{-1}$). It appears that their single-dish map may have been significantly contaminated by emission from the DR 21 cloud, which introduced uncertainties in the mass and kinematics estimates. Ridge & Moore (2001) estimated the outflow mass of the red-shifted lobe only to be $273 \text{ M}_{\odot}$ based on a CO($J=2–1$) single dish image corrected for optical depth. The mass of blue-shifted gas was not estimated by Ridge & Moore due to the contamination by the DR 21 cloud. This value is significantly higher than our estimate and may be due to missing extended emission in the interferometer image, especially at low velocities. Despite this problem, interferometric imaging also provided benefits: it was easier to distinguish between outflow gas and the DR 21 cloud and to identify flows from multiple sources in the cluser.

The total cloud core mass of W75 N has been estimated to be $1800–2500 \text{ M}_{\odot}$ based on observations at submillimeter wavelengths (Moore, Mountain, & Yamashita, 1991) and $1200 \text{ M}_{\odot}$ based on CS($J=7–6$) emission (Hunter et al. 1994). The gravitational binding energy of the cloud, $GM_{\text{cloud}}^2/c_1r$, is $1–2 \times 10^{46} \text{ ergs}$, where we take the radius $r = 0.25 \text{ pc}$ (Moore et al. 1991) and $c_1$ is a constant which depends on the mass distribution ($c_1 = 1$ for $\rho \propto r^{-2}$). More than 10% of the molecular cloud is participating in the outflow and the combined outflow energy is roughly half the gravitation binding energy of the cloud. The observed W75 N outflows are injecting a significant amount of mechanical energy into the cloud core and may help prevent further collapse of the cloud.

Our CO($J=1–0$) images suggest that high-velocity gas is associated with at least two UC HII regions: VLA 1 (Ba) and VLA 3 (Bb) and an embedded source in the millimeter core MM 2. The position angles of the individuals outflows are not aligned, ranging from $51^\circ$ to $124^\circ$. The $\text{H}_2$ morphology is diffuse and patchy both in the north-east and south-west. The irregular morphology of the infrared reflection nebula with fingers of nebulosity radiating out from the MM 1/MM 2 millimeter cores supports the conclusion that multiple energetic outflows are carving large cavities in the molecular cloud.

Low surface brightness $\text{H}_2$ emission extends well beyond the CO outflow while [FeII]
emission is only detected close to the protostellar cluster. It is generally believed that [FeII] line emission associated with low-mass outflows requires the presence of fast, dissociative shocks that disrupt dust grains and release heavy elements just behind a Jump-shock (J-shock) boundary. H$_2$ emission, on the other hand, appears to be produced in slow, non-dissociative J-type shocks (e.g. Hollenbach & McKee 1989; Smith 1994; Gredel 1994; Beck-Winchatz et al. 1996). Continuous-shocks (C-shocks) cannot easily produce emission from ionized species such as [FeII] nor can they produce the observed column densities typically seen in H$_2$ toward Herbig Haro objects from low-mass protostars (Gredel 1994). In fact, Nisini et al. (2002) find that there appears to be no correlation between H$_2$ and [FeII] emission in outflows from low-mass YSOs which supports the interpretation that physically different mechanisms are responsible for producing H$_2$ and [FeII] emission. In a sample of Herbig Haro objects produced by jets from low-mass protostars, both H$_2$ and [FeII] is found toward all sources and the morphology of H$_2$ and [FeII] emission is similar on large scales although it differs in the detail (Gredel 1994; Reipurth et al. 2000). These observations indicate that jets from low-mass protostars produce both fast, dissociative regions where [FeII] emissions arises and slower, non-dissociative regions where H$_2$ emission arises. In contrast, [FeII] emission toward W75 N is only detected close to the central sources and does not show a jet-like morphology as in outflows from low- and intermediate-mass young stellar objects (e.g. Lorenzetti et al. 2002; Nisini et al. 2002; Reipurth et al. 2000). The outflows from W75 N appear to exhibit only slow, non-dissociative J-type shocks which produce copious H$_2$ emission throughout the outflow region but the fast, dissociative shocks responsible for [FeII] emission are absent in the outer regions of the flow. Instead, the diffuse [FeII] line emission in W75 N is coincident with the brightest K$_\alpha$-band reflection nebulosity. One possibility may be that the [FeII] emission traces photo-dissociation regions (PDRs) along cloud surfaces illuminated by the massive protostars in the MM 1 core. This situation is also observed in the Orion Bar PDR (e.g. Walmsley et al. 2000) suggesting that the W75 N nebula may exhibit similar excitation conditions to those in Orion.

The H$_2$ and [FeII] line emission in W75 N does not conform to what is expected for shock-excited emission resulting from the interaction between a well-collimated jet and diffuse molecular gas. In this respect, the physical characteristics of the W75 N flows differ from their low-mass counterparts which produce collimated jets observed in both H$_2$ and [FeII] emission.

Many previous authors have assumed that only VLA 1 (Ba) was in an outflow stage based on the elongated morphology of the ionized gas, the presence of H$_2$O maser emission along the UC HII region axis, and because the position angles of the ionized gas and the CO emission were similar. H$_2$O maser emission is also associated with VLA 2 and VLA 3 (Bb) as well as MM 3 and MM 2, however, outflowing material could not be traced to specific sources.
Assuming a single primary driving source for the CO gas, Davis et al. (1998b) suggested that the south-west CO red-shifted lobe and H$_2$ morphology supports a bow-shock entrainment scenario for a molecular outflow driven by a jet from a single massive star. Our CO and millimeter continuum observations do not support this theory that a single source drives the high-velocity CO gas. Further, our infrared observations suggest that the W75 N outflows are not likely to be scaled-up versions of jet-driven outflows from low-mass protostars.

A question remains unanswered by this work: what source powers the 3 pc flow at P.A. 62.5°? The flow mass is $\gtrsim 100$ $M_\odot$, the dynamical age is roughly $10^5$ years, and the mass loss rate $\dot{M}_f \sim 10^{-4}$ to $10^{-3}$ $M_\odot$ yr$^{-1}$. The flow parameters are consistent with those produced by an early B protostar. Hutawarakorn et al. (2002) have modeled the OH maser position-velocity data and find evidence for a massive disk centered on VLA 2 ($M_{\text{disk}} \sim 120$ $M_\odot$ with P.A. = 155°, roughly perpendicular to the outflow axis). A high-velocity, time-variable OH maser cluster is coincident with VLA 2 suggesting an outflow origin. Further, recent observations with the Very Long Baseline Array (VLBA) show that a clump of strong H$_2$O maser emission with high velocity dispersion is centered on VLA 2 (Torrelles et al. 2003). Thus, the OH and H$_2$O maser activity suggests VLA 2 is producing a powerful outflow. Although our observations did not have adequate resolution to isolate high-velocity gas toward VLA 2, we have determined that VLA 1 (Ba), VLA 3 (Bb), and MM 2 are not likely to drive the 3 pc flow that dominates the region dynamics. Thus, it is possible that VLA 2 may drive the large-scale flow. Follow-up observations at a resolution less than 1" will be required to determine if, in fact, VLA 2 drives the 3 pc flow.

Based on the size and velocity of the CO outflows from the W75 N (B) UC HII regions, the region is $> 10^5$ years old. W75 N (A) is more evolved than the sources in MM 1 and the exciting star of W75 N (A) has no detectable high-velocity gas associated with it. The star, detected in the infrared, is centered within a shell of warm dust emission and an extended HII region (Hashick et al. 1981). Figure 10 shows a color-color diagram using data from the 2MASS Point Source Catalog for stars within 1' of MM 1 that were detected at all three bands. The locus of main-sequence stars is represented by the thick, curved line (Bessell & Brett 1988, Koornneef 1983) while the two diagonal lines show reddening vectors up to $A_V = 40$ of dust (adopting the $R_V = 5$ extinction law from Cardelli, Clayton, & Mathis 1989). Sources within the reddening vectors have colors consistent with main-sequence stars reddened by foreground dust. Those to the right of the reddening vectors demonstrate excess emission at 2$\mu$m, consistent with the presence of circumstellar material. The infrared colors of the W75 N (A) exciting star are consistent with those of a main-sequence star reddened by foreground dust. In comparison, the two bright stars to the south-east and south-west of MM 1 (IRS 2 and IRS 3) have excess emission at 2$\mu$m consistent with the presence of circumstellar material. The protostars within MM 1 and MM 2 are not detectable at
infrared wavelengths. W75 N represents a region of clustered star formation which appears to be forming mid to early-B stars which exist at a range of developmental stages.

VLA 1 (Ba) appears to have a well-collimated, outflow based on the ionized gas morphology imaged by Torrelles et al., (1997) and the presence of a relatively well-collimated, red-shifted CO lobe which extends about 0.5 pc north-east of the source. However, the spectral type of the protostar is unknown since the ionized gas appears to be due to thermal jet emission. The well-collimated outflow which appears to be produced by the embedded source in MM 2 is not detected at centimeter wavelengths. Either the powering source is not an early-B star (e.g. it does not have sufficient ionizing radiation to produce a detectable UC HII region) or accretion onto the protostar is sufficiently high that it prevents the formation of a UC HII region (see e.g. Churchwell 1999 and references therein).

There is no evidence for well-collimated flows (collimation ratios, length/width, > 10) from the remaining embedded sources (early-B protostars) or in the large-scale morphology of the CO, H2, & [FeII] emission. The lack of highly-collimated flows from the known, early-B protostars in W75 N suggests that it may be difficult for massive stars to collimate outflowing material. Although a few mid to early-B protostars appear to be powering ionized jets, their molecular outflows tend to be complex and poorly collimated (see, e.g., the review by Shepherd 2002 and references therein). To our knowledge, there is no well-collimated molecular outflow powered by a massive protostar (spectral type early-B to O) and most do not appear to have ionized outflow components that are well-collimated (e.g. Ridge & Moore 2001, Shepherd, Claussen, & Kurtz 2001; Churchwell 1999). Poorly collimated flows could be due to several factors:

- Confusion from multiple outflow sources in a cluster (e.g. W75 N: this work; or DR 21: Garden et al. 1991);
- Large flow precession angles (e.g. PV Ceph: Reipurth, Bally, & Devine 1997, Gomez, Kenyon, & Whitney 1997; or IRAS 20126+4104: Shepherd et al. 2000);
- The presence of a strong wide-angle wind (e.g. Orion I: Greenhill et al. 1998; or G192.16–3.82: Shepherd, Claussen & Kurtz 2001); and/or
- The molecular flow represents only the truncated base of a much larger flow (e.g. HH 80–81: Yamashita et al. 1989, Rodríguez et al. 1994; or G192.16–3.82: Devine et al. 1999).

Our observations of W75 N supports the interpretation that massive protostars may not be able to produce well-collimated molecular outflows. This conclusion does not rule out the possibility that an underlying, neutral jet may still exist as part of the outflow from the massive protostars in W75 N. High-resolution observations in shock tracers such as
SiO(J=1–0,v=0) or SiO(J=2–1,v=0) may be able to determine whether collimated neutral jets are present in W75 N.

5. SUMMARY

W75 N represents an example of clustered, massive star formation. The cluster covers a wide range of evolutionary stages; from stars with no apparent circumstellar material to deeply embedded protostars actively powering massive outflows. The CO outflow measures more than 3 pc from end-to-end and is produced by at least four individual sources. H₂ emission extends well-beyond the CO boundaries while [FeII] emission is only located close to the protostellar cluster. The CO, H₂ & [FeII] morphology does not conform to what is expected for shock-excited emission resulting from the interaction between a well-collimated jet and diffuse molecular gas. The irregular morphology of the infrared reflection nebula with fingers of nebulosity radiating out from the millimeter cores supports the conclusion that multiple energetic outflows are carving large cavities in the molecular cloud. More than 10% of the molecular cloud is outflowing material and the combined outflow energy is roughly half the gravitational binding energy of the cloud. Thus, the observed W75 N outflows are injecting a significant amount of mechanical energy into the cloud core and may help prevent further collapse of the cloud.

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Table 1: W75 N 2.7 mm continuum emission

<table>
<thead>
<tr>
<th>Source</th>
<th>Position (J2000)</th>
<th>Peak Flux Density (mJy)</th>
<th>Total Flux Density (mJy)</th>
<th>$M_{\text{gas+dust}}$ (M$_\odot$) †</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM 1-4</td>
<td>$20^h38^m36.36^s$ +42°37'33.5&quot;</td>
<td>266</td>
<td>650</td>
<td>340 ± 70</td>
</tr>
<tr>
<td>MM 5</td>
<td>$20^h38^m37.78^s$ +42°37'59.0&quot;</td>
<td>51</td>
<td>129</td>
<td>68 ± 16</td>
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<tr>
<td>MM 6</td>
<td>$20^h38^m36.31^s$ +42°37'55.9&quot;</td>
<td>25</td>
<td>38</td>
<td>20 ± 6</td>
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<tr>
<td>MM 7</td>
<td>$20^h38^m36.56^s$ +42°38'12.7&quot;</td>
<td>25</td>
<td>43</td>
<td>22 ± 6</td>
</tr>
<tr>
<td>MM 8</td>
<td>$20^h38^m33.68^s$ +42°38'01.7&quot;</td>
<td>23</td>
<td>31</td>
<td>16 ± 5</td>
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<tr>
<td>MM 9</td>
<td>$20^h38^m38.70^s$ +42°38'19.8&quot;</td>
<td>19</td>
<td>21</td>
<td>11 ± 4</td>
</tr>
</tbody>
</table>

† Uncertainty includes ±2 M$_\odot$ due to image RMS plus 20% uncertainty in the absolute flux calibration.

Table 2: W75 N Outflow Parameters

<table>
<thead>
<tr>
<th>Source:</th>
<th>MM 1 combined flows</th>
<th>MM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO radius of outflow</td>
<td>1.8 pc</td>
<td>&gt; 0.5 pc</td>
</tr>
<tr>
<td>Assumed inclination angle</td>
<td>45°</td>
<td>45°</td>
</tr>
<tr>
<td>Outflow Mass†:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western outflow</td>
<td>68 M$_\odot$</td>
<td>...</td>
</tr>
<tr>
<td>Eastern outflow</td>
<td>97 M$_\odot$</td>
<td>&gt; 90 M$_\odot$</td>
</tr>
<tr>
<td>165 M$_\odot$</td>
<td>&gt; 90 M$_\odot$</td>
<td></td>
</tr>
<tr>
<td>Momentum</td>
<td>$2.2 \times 10^3$ M$_\odot$ km s$^{-1}$</td>
<td>&gt; $1.1 \times 10^3$ M$_\odot$ km s$^{-1}$</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>$3.4 \times 10^{47}$ ergs</td>
<td>&gt; $1.8 \times 10^{47}$ ergs</td>
</tr>
<tr>
<td>Dynamical time scale</td>
<td>$1.5 \times 10^5$ yr</td>
<td>&gt; $3.8 \times 10^4$ yr</td>
</tr>
<tr>
<td>$\dot{M}_f$</td>
<td>$1.2 \times 10^{-3}$ M$_\odot$ yr$^{-1}$</td>
<td>&lt; $2.3 \times 10^{-3}$ M$_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>Momentum Supply Rate (Force)</td>
<td>$1.8 \times 10^{-2}$ M$_\odot$ km s$^{-1}$ yr$^{-1}$</td>
<td>&lt; $2.9 \times 10^{-2}$ M$_\odot$ km s$^{-1}$ yr$^{-1}$</td>
</tr>
<tr>
<td>Mechanical Luminosity</td>
<td>23 L$_\odot$</td>
<td>&lt; 38 L$_\odot$</td>
</tr>
</tbody>
</table>

† MM 1 eastern outflow emission measured at velocities 2.2 to 4.8 km s$^{-1}$ and 15.2 to 36 km s$^{-1}$.
MM 1 western outflow emission measured at velocities −8.2 to 4.8 km s$^{-1}$ and 15.2 to 36.0 km s$^{-1}$.
MM 2 outflow emission measured between −26.4 and 2.2 km s$^{-1}$.
Figure Captions

Figure 1. Integrated CO red-shifted (red lines) and blue-shifted (blue lines) emission contours from 36.0 km s\(^{-1}\) to 17.8 km s\(^{-1}\) and -0.4 km s\(^{-1}\) to -26.4 km s\(^{-1}\), respectively. The images have an RMS of 23.5 Jy beam\(^{-1}\) km s\(^{-1}\) with a peak of 56.0 Jy beam\(^{-1}\) km s\(^{-1}\) in the red-shifted emission image and 100.6 Jy beam\(^{-1}\) km s\(^{-1}\) in the blue-shifted emission image. Contours begin at 10% of the peak emission and continue at increments of 20%. The synthesized beam is 6.46" x 6.28" at P.A. -54.7°. H\(_2\) line + continuum emission is shown as grey scale displayed as the square root of the intensity with a peak of 7.45 \(\times\) 10\(^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\). W75 N (A) is located at position \(\alpha(J2000) = 20^h38^m38^s\) \(\delta(J2000) = 42^\circ37'59''\) and W75 N (B) at position \(\alpha(J2000) = 20^h38^m37^s\) \(\delta(J2000) = 42^\circ37'32''\). UC HII regions embedded in the core of MM 1 are shown as filled triangles while the millimeter cores MM 2–9 are shown as open circles. The large open circle (MM 5) is coincident with the infrared emission associated with W75 N A. The solid black line delineates the boundaries of the CO mosaic.

Figure 2. Continuum-subtracted H\(_2\) line mosaic of W75 N. The H\(_2\) image is displayed on a linear scale from -0.6 to a peak intensity of 2.6 \(\times\) 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). Individual knots of H\(_2\) emission are labeled NE–A through I, C–A & B, and SW–A through K. Features observed by Davis et al. (1998a,b) are identified by solid lines, previously undetected H\(_2\) features which are more diffuse are shown as dashed lines. Large dashed boxes outline the fields shown in Fig. 3.

Figure 3. Continuum-subtracted H\(_2\) emission shown in grey scale with [FeII] emission shown as contours. The [FeII] contours begin at 5\(\sigma\) and continue with a spacing of 8\(\sigma\). The left panel shows the central and north-east outflow regions. The strong, diffuse [FeII] emission is coincident with the W75 N (A) and (B) reflection nebulae. The right panel shows the south-west outflow. [FeII] contours coincident with point sources are due to imperfect continuum subtraction.

Figures 4a & 4b. CO channel images at 2.6 km s\(^{-1}\) spectral resolution between 32.1 and -27.7 km s\(^{-1}\). The central velocity is indicated in the upper right of each panel. The LSR velocity is 10 km s\(^{-1}\). The RMS is 0.13 Jy beam\(^{-1}\) and the peak emission is 16.9 Jy beam\(^{-1}\). In the first 12 and last 12 panels, contours are plotted from \(\pm4, 8, 12, 16, 20 \sigma\) and continue with a spacing of 10 \(\sigma\). In the central 6 panels (8.7 to -4.3 km s\(^{-1}\)), contours begin at \(\pm10,30 \sigma\) and continue with a spacing of 20\(\sigma\). Panels at velocities 32.1 \& -27.7 km s\(^{-1}\) show the synthesized beam in the bottom right corner (6.46" x 6.28" at P.A. -54.7°) and a scale size of 0.9 pc. The plus symbol in each panel represents the location of the peak emission in MM 1. No other emission was detected outside of this velocity range.
**Figure 5.** The bottom left image shows continuum emission at 2.7 mm. No other continuum sources were detected within the mosaic field. The image has an RMS of 3.6 mJy beam\(^{-1}\). Contours begin at \(\pm 3, 4, 5, 7, 10, 20\sigma\) and continue with a spacing of \(10\sigma\). The greyscale is plotted on a linear scale from 7.2 to 265 mJy beam\(^{-1}\). The synthesized beam in the lower right corner is \(7.29'' \times 7.13''\) at P.A. \(-62.9^\circ\). UC HII regions in the center of MM 1 are identified by filled triangles, MM 2–4 are shown as open circles. A scale size of 0.15 pc is represented by a bar in the lower left corner. The bottom right inset shows 3.3 mm continuum emission obtained with \(\sim 2''\) resolution (Figure 1 from Shepherd 2001). Upper panels show the MM 5 millimeter source compared with narrow-band H\(_2\)+-continuum emission and wide-band 2.12\(\mu\)m emission in W75 N (A) (from Fig. 1).

**Figure 6.** The relationship between compact, high velocity CO emission, infrared emission, millimeter continuum peaks, and UC HII regions in W75 N (B). Red- and blue-shifted CO emission (upper panels) is plotted from 20.4 to 36.0 km s\(^{-1}\) and \(-5.6\) to \(-23.8\) km s\(^{-1}\), respectively. The RMS in both images is 0.5 Jy beam\(^{-1}\) km s\(^{-1}\); contours are plotted from \(-3, 2, 3, 4\) \(\sigma\) and continue at spacings of \(1\sigma\). Millimeter core positions for MM 2–4 are shown as filled circles, UC HII regions embedded in MM 1 are represented as filled triangles. Proposed outflows are identified by arrows from UC HII regions VLA 1 (Ba), VLA 3 (Bb), and MM 2. The synthesized beam \((2.04'' \times 1.77''\) at P.A. \(-80.5^\circ\)) is shown in the top right image and a scale size of 0.1 pc is represented by a bar in the top left image. The bottom two images show the K\(_s\) and H\(_2\) emission relative to the proposed outflows. Both images are displayed as the square root of the intensity.

**Figure 7.** Top: Integrated emission (zeroth moment) from 17.8 km s\(^{-1}\) to 36.0 km s\(^{-1}\). The RMS in the image is 1.2 Jy beam\(^{-1}\) km s\(^{-1}\), contours are plotted from 4 to 20\(\sigma\) with increments of \(2\sigma\) and then from 20 to 45\(\sigma\) with increments of \(5\sigma\). Greyscale is plotted from \(3\sigma\) to a peak of 56.0 Jy beam\(^{-1}\) km s\(^{-1}\). Millimeter cores are identified as filled circles, UC HII regions by filled triangles. The synthesized beam in the bottom left corner is \(6.46'' \times 6.28''\) at P.A. \(-54.7^\circ\). Bottom Position-Velocity plot along the length of the high-velocity, redshifted outflow. Contours are plotted at 2, 5, 10, 15, 20, 30, 40, 50, 70, & 90% of the peak.

**Figure 8.** Top: Integrated emission (zeroth moment) from \(-5.6\) km s\(^{-1}\) to \(-26.4\) km s\(^{-1}\). The RMS in the image is 0.96 Jy beam\(^{-1}\) km s\(^{-1}\), contours are plotted from 4 to 20\(\sigma\) with increments of \(2\sigma\), greyscale is plotted from \(3\sigma\) to a peak of 20.0 Jy beam\(^{-1}\) km s\(^{-1}\). Millimeter cores are identified as filled circles, UC HII regions by filled triangles. The synthesized beam in the bottom right corner is \(6.46'' \times 6.28''\) at P.A. \(-54.7^\circ\). Bottom Position-Velocity plot along the length of the high-velocity, blue-shifted outflow. Contours are plotted at 3, 5, 7, 9, 20, 40, 60, 80, & 100% of the peak.
Figure 9. CO(J=1–0) optical depth as a function of velocity based on single-dish observations with the Kitt Peak 12 m telescope. Optical depth is derived for three positions within the outflow: in the north-east lobe (Top); centered on the MM 1 core (Center); and in the south-west lobe (Bottom). CO emission was measured in each channel image of the interferometer mosaic and an optical depth correction was made to the mass estimate based on the location and velocity of the emission.

Figure 10. **Left:** Three color image using data from The Two Micron All Sky Survey (2MASS). The image is 1.5′ on a side. The J-band image at 1.25μm is shown as blue, H-band at 1.65μm is green, & Ks-band at 2.17μm is red. The + symbol represents the location of the MM 1 peak. **Right:** A color-color diagram using data from the 2MASS Point Source Catalog for stars within 1′ of MM 1 that were detected at all three bands. The locus of main-sequence stars is represented by the thick, curved line while the two diagonal lines show reddening vectors up to $A_V = 40$ of dust.
Figure 3.
Figure 4a.
Figure 4b.
Figure 6.
Figure 7.
Figure 8.
Figure 9.
Figure 10.