CLUSTERED STAR FORMATION IN W75 N

D. S. Shepherd, 1 L. Testi, 2 and D. P. Stark 3

Received 2002 September 20; accepted 2002 October 23

ABSTRACT

We present 2″–7″ resolution 3 mm continuum and CO(J = 1–0) line emission and near-infrared K, H2, and [Fe ii] 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 greater than 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$^{-1}$ 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 and dust associated with the millimeter cores ranges from 340 to 11 M$_\odot$. The infrared reflection nebula and shocked H$_2$ emission have multiple peaks and extensions which, again, suggests the presence of several outflows. Diffuse H$_2$ emission extends about 0.6 pc beyond the outer boundaries of the CO emission while the [Fe ii] emission is only detected close to the protostars. The infrared line emission morphology suggests that only slow, nondissociative J-type shocks exist throughout the parsec-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.

Subject headings: H ii regions — ISM: jets and outflows — ISM: molecules — stars: formation

1. INTRODUCTION

W75 N is a massive star-forming region with an integrated IRAS luminosity of 1.4 × 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 ~1.5″: W75 N (A), W75 N (B), and W75 N (C). Hunter et al. (1994) later resolved W75 N (B) with ~0.5″ resolution into three regions: Ba, Bb, and Bc. Torellès et al. (1997) then imaged W75 N (B) at ~0.1″ resolution and detected Ba and Bb (which they called VLA 1 and VLA 3), along with another weaker and more compact H ii region, VLA 2.

A parsec-scale molecular outflow originates near the cluster of ultracompact H ii regions (UC H ii) regions in W75 N (B). The mass of the CO outflow has been estimated to be 50–500 M$_\odot$ based on single-dish CO observations (e.g., Fischer et al. 1985; Hunter et al. 1994; Davis et al. 1998a, 1998b; Ridge & Moore 2001). The UC H ii regions have a combined $L_{bol}$ of 4.4 × 10$^4$ L$_\odot$, and most are in a protostellar phase based on the presence of OH, H$_2$O, and methanol masers and compact millimeter continuum emission (Baart et al. 1986; Hunter et al. 1994; Torellès 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 H ii region VLA 1 (Ba) because the position angles (P.A.) of the ionized gas and the CO emission are similar (Hunter et al. 1994; Torellès et al. 1997; Davis et al. 1998a, 1998b). Shepherd (2001) suggested that 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 redshifted lobe and H$_2$ morpholoy supported a jet-driven, bow-shock entrainment scenario in which a steady, overdense 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., Shang et al. 2002; Cabrit, Ferreira, & Raga 1999; Königl 1999; Shu et al. 2000; Königl & Pudritz 2000).

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

---

1 National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
2 Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze.
3 Department of Astronomy, University of Wisconsin–Madison, 475 North Charter Street, Madison, WI 53706.

---
Galileo to compare the morphology of the shocked gas and 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 m 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 hr per pointing center. Cryogenically cooled SIS receivers operating at 4 K produced typical single sideband system temperatures of 200–600 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 (Soville 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 wv 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 bandpass was centered on the local standard of rest velocity (vLSR) 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 wv 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 hr was obtained with OVRO centered on the position of W75 N:MM 1 [α(J2000) = 20h38m31.00, δ = 42°36′51″′0 and α(J2000) = 20h38m41′00, δ = 42°37′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.

2.2. 3 mm Single-Dish Spectra

Observations were made in CO(J = 1–0) and 13CO(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 vLSR = 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 13CO 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 [α = 20h38m36.50, δ = 42°37′33″′5]; and in the southeast and northwest outflow lobes (α = 20h38m31.00, δ = 42°36′51″′0 and α = 20h38m41′00, δ = 42°37′51″′0, respectively). The data could not be flux-calibrated. Line-only images were obtained by subtracting the narrowband 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.

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 near-infrared imager (Lisi et al. 1996; Hunt et al. 1996) was used to obtain images in the H₂ narrowband filter and in the Ks broadband filter. ARNICA is equipped with an HgCdTe NICMOS3 infrared array. The pixel scale, when coupled with the TNG, is 0″355 pixel⁻¹, and the corresponding field of view is 1.5 × 1.5 arcmin² per frame. The seeing at the time of the observations was about 0″9.

To search for H₂ emission beyond the CO emission, a 14-pointing mosaic pattern was employed covering an area of approximately 9 × 2 arcmin² 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 Ks band and 30 minutes in the H₂ 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 Ks-band observations were calibrated using standard stars from the ARNICA list (Hunt et al. 1998). The H₂ mosaic was calibrated assuming that a set of stars have the same flux density in the narrow- and broadband filters. The broadband mosaic was then used to subtract the continuum emission from the H₂ mosaic. Integrated line fluxes are then estimated assuming the width of the H₂ filter as measured by Vanzi et al. (1998). The calibration accuracy is expected to be within 20%. Accurate (≤0″5) astrometry was derived for both mosaics using stellar positions from the Two Micron All Sky Survey (2MASS) second incremental data release.

Additional observations of two ~4′ × 4′ fields centered northeast and southwest 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 H₂ (λ = 2.12 μm) and [Fe II] (λ = 1.64 μm) narrowband filters and in two narrowband continuum filters, K_cont and H_cont (a detailed characterization of all of 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 narrowband 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.

4 Due to the different optical configuration used at the TNG with respect to that used at the TIRGO telescope, the narrowband filters do not suffer from the effective field of view reduction discussed by Vanzi et al.
3. RESULTS

3.1. \textit{H$_2$} and [Fe \textit{ii}] Morphology

Infrared reflection nebulosity is associated with two distinct regions of ionized gas (Fig. 1): W75 N (A) at position \( \alpha(J2000) = 20^h38^m38^s, \delta(J2000) = 42^\circ 37^\prime 59^\prime\) and W75 N (B) at position \( \alpha(J2000) = 20^h38^m37^s, \delta(J2000) = 42^\circ 37^\prime 32^\prime\) (e.g., Haschick et al. 1981; Moore et al. 1988). Shock-excited \textit{H$_2$} emission (Figs. 2 and 3) is present in the northeast [near \( \alpha(J2000) = 20^h38^m52^s, \delta(J2000) = 42^\circ 39^\prime 00^\prime\)] and along the CO emission boundaries (see also Davis et al. 1998a, 1998b). Our \textit{H$_2$} images also show that faint, patchy \textit{H$_2$} emission extends nearly an arcminute (0.6 pc at a distance of 2 kpc) beyond the southwest CO flow [\( \alpha(J2000) = 20^h38^m22^s-18^s, \delta(J2000) = 42^\circ 36^\prime 10^\prime\)].

The continuum-subtracted \textit{H$_2$} mosaic is shown in Figure 2. Following the nomenclature used by Davis et al. (1998a, 1998b) for the southwest portion of the \textit{H$_2$} flow, all previously known \textit{H$_2$} knots and filaments are marked with solid lines. These are labeled SW-A to SW-H in the southwest flow, C-A and C-B in the central region, and NE-A to NE-F in the northeast flow. In addition, Figures 2 and 3 reveal faint diffuse \textit{H$_2$} emission beyond the tip of the southwest flow and within the northeast flow. These new features are marked with dashed lines and labeled SW-I to SW-K and NE-G to NE-I. Faint, diffuse \textit{H$_2$} features as well as the filamentary structure of the emission in knots NE–D, NE–E, and NE–F are confirmed by observations obtained in 2002 August. Figure 3 presents an overlay of the continuum subtracted [Fe \textit{ii}] emission (contours) on the \textit{H$_2$} (gray scale) images from the 2002 August observations. [Fe \textit{ii}] line emission is only detected close to the UC \textit{H II} regions in W75 N B and near the exciting star of W75 N A. No [Fe \textit{ii}] emission is detected in the outer flow regions. The nondetection of [Fe \textit{ii}] far from the protostars does not appear to be due to higher extinction since we clearly detect 2.12 \micron \textit{H$_2$} emission beyond the CO outflow boundaries, and we detect [Fe \textit{ii}] emission near the cloud core where the column density is higher.

A chain of \textit{H$_2$} knots, apparently unrelated to the main flow, are detected near \( \alpha(J2000) = 20^h38^m32^s-36^s, \delta(J2000) = 42^\circ 39^\prime 00^\prime\) and along the CO emission boundaries (see also Davis et al. 1998a, 1998b). Our \textit{H$_2$} images also show that 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 and 3). Red- and blueshifted CO emission exists in both the northeast and southwest. The CO mosaic did not include areas to the northwest and southeast, 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 redshifted side of the line; however, at velocities between 0 and \( -5.6 \text{ km s}^{-1}\) the DR 21 cloud (\( v_{LSR} = -2.5 \text{ km s}^{-1}\)) confuses the identification of the outflow structure.

Nine millimeter continuum peaks showing the locations of warm dust emission are identified in Figure 5 and Table 1 (W75 N:MM 1 through W75 N:MM 9\textsuperscript{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.

\textsuperscript{5} Names of millimeter cores are shortened to MM 1 to MM 9 for the remainder of this paper.

\begin{figure}[h]
\centering
\includegraphics{fig1}
\caption{Integrated CO redshifted (red lines) and blueshifted (blue lines) emission contours from 36.0 to 17.8 km s\textsuperscript{-1} and \(-0.4 \to -26.4 \text{ km s}^{-1}\), respectively. The images have an rms of 23.5 Jy beam\textsuperscript{-1} km s\textsuperscript{-1} with a peak of 56.0 Jy beam\textsuperscript{-1} km s\textsuperscript{-1} in the redshifted emission image and 100.6 Jy beam\textsuperscript{-1} km s\textsuperscript{-1} in the blueshifted 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. \(-54.7\). \textit{H$_2$} line-s-continuum emission is shown as gray scale displayed as the square root of the intensity with a peak of 7.45 x 10\textsuperscript{-11} ergs cm\textsuperscript{-2} s\textsuperscript{-1} arcsec\textsuperscript{-2}. W75 N (A) is located at position \( \alpha(J2000) = 20^h38^m38^s, \delta(J2000) = 42^\circ 37^\prime 59^\prime\) and W75 N (B) at position \( \alpha(J2000) = 20^h38^m37^s, \delta(J2000) = 42^\circ 37^\prime 32^\prime\). UC \textit{H II} 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.}
\end{figure}
MM 5 is associated with the more extended H II region, 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 2 μm. 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 narrowband H 2+continuum emission and Ks broadband 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

**Fig. 2.**—Continuum-subtracted H2 line mosaic of W75 N. The H2 image is displayed on a linear scale from −0.6 to a peak intensity of $2.6 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$. Individual knots of H2 emission are labeled NE-A through I, C-A and B, and SW-A through K. Features observed by Davis et al. (1998a, 1998b) are identified by solid lines; previously undetected H2 features that are more diffuse are shown as dashed lines. Large dashed boxes outline the fields shown in Fig. 3.

**Fig. 3.**—Continuum-subtracted H2 emission shown in gray scale with [Fe ii] emission shown as contours. The [Fe ii] contours begin at 5 σ and continue with a spacing of 8 σ. The left panel shows the central and northeast outflow regions. The strong, diffuse [Fe ii] emission is coincident with the W75 N (A) and (B) reflection nebulae. The right panel shows the southwest outflow. [Fe ii] contours coincident with point sources are due to imperfect continuum subtraction.
Diffuse reflection nebulosity is centered on the star and a wisp of H$_2$ emission is visible just east of the star [C11 \(\alpha (J2000) = 20^h38^m38^s, \delta (J2000) = 42^\circ38'00''\)].

Compact, high-velocity CO emission appears to originate from the UC H II regions VLA 1 (Ba) and VLA 3 (Bb) and from MM 2 (Figs. 6, 7, and 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 H$_2$O and OH masers (Baart et al. [C11]).
It is embedded in the MM 1 core detected in 1 and 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 H II region. Redshifted emission to the northeast of MM 1 can be traced to the jetlike ionized flow from VLA 1 (Ba). Figure 7 presents a 6" image of the

| Source       | $\alpha$(J2000) | $\delta$(J2000) | Peak Flux Density (mJy) | Total Flux Density (mJy) | $M_{(\text{gas+dust})}^a$ ($M_\odot$) |
|--------------|-----------------|-----------------|-------------------------|-------------------------|-------------------------------------|
| MM 1–4       | 20 38 36.36     | +42 37 33.5     | 266                     | 650                     | 340 ± 70                             |
| MM 5         | 20 38 37.78     | +42 37 59.0     | 51                      | 129                     | 68 ± 16                              |
| MM 6         | 20 38 36.31     | +42 37 55.9     | 25                      | 38                      | 20 ± 6                               |
| MM 7         | 20 38 36.56     | +42 38 12.7     | 25                      | 43                      | 22 ± 6                               |
| MM 8         | 20 38 33.68     | +42 38 01.7     | 23                      | 31                      | 16 ± 5                               |
| MM 9         | 20 38 38.70     | +42 38 19.8     | 19                      | 21                      | 11 ± 4                               |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Uncertainty includes ±2 $M_\odot$ due to image rms plus 20% uncertainty in the absolute flux calibration.

Fig. 5.—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 ±3, 4, 5, 7, 10, 20 $\sigma$ and continue with a spacing of 10 $\sigma$. The gray scale is plotted on a linear scale from 7.2 to 265 mJy beam$^{-1}$. The synthesized beam in the lower right corner is 7"9 × 7"13 at P.A. −62°. UC H II 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 −2″ resolution (Shepherd 2001, Fig. 1). Upper panels show the MM 5 millimeter source compared with narrowband H$_2$+ continuum emission and wideband 2.12 μm emission in W75 N (A) (from Fig. 1).
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 northeast with projected velocity greater than 25 km s⁻¹ (relative to vLSR) almost an arcminute from the UC H II region. High-velocity CO emission is also centered on the UC H II regions (position offset -18° in the PV diagram of Fig. 7). A 2″ resolution image (Fig. 6, top left) shows that this redshifted 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 Figure 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 (Torrrelles et al. 1997). The molecular flow is also seen in Figure 1 as a well-collimated redshifted lobe extending to the northeast from the MM 1 core. The outflow is shown as one-sided in Figures 6 and 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 H II region in MM 1 with a central star of spectral type B0.5 to B0. It is associated with a single H₂O maser and compact 1 and 3 mm continuum emission. A lower limit on the mass of warm gas and dust within 2000 AU of the protostar is 5 M⊙ (Shepherd 2001). Figure 6 illustrates that compact redshifted emission to the east and blueshifted emission to the west of MM 1 can be traced to VLA 3 (Bb) with P.A. ~101°. 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 northwest or southeast, 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 H₂O masers near the source: the ionized gas is slightly elongated along P.A. 149°, and the H₂O 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 and 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 H $\text{ii}$ region. High-velocity blueshifted emission (13–36 km s$^{-1}$ projected velocity relative to $v_{\text{LSR}}$) can be traced from the MM 2 core to the southeast (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 $v_{\text{LSR}} = 10$ 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 and 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 redshifted 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 cannot 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, and 8) are 51$^\circ$ for VLA 1 (Ba), 101$^\circ$ for VLA 3 (Bb), and 124$^\circ$ 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 blueshifted counterflow is expected in the southwest, not a redshifted flow. Thus, our observations do not identify the source responsible for the 3 pc outflow that dominates the large-scale morphology and kinematics of the region.

3.3. Mass and 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 CH₃CN in the cloud core vary from 47 to 78 K, consistent with the Davis et al. estimates (Kalenik et al. 2000). We assume the gas is in LTE, at a temperature of 50 K, with [CO]/[H₂] = 10⁻⁴ and [CO]/[¹³CO] = 71 at the galactocentric distance of 8.5 kpc (Wilson & Rood 1994). The CO optical depth as a function of velocity and position is calculated using single-dish observations with the Kitt Peak 12 m telescope. Optical depth is derived for 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 vLSR 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 blueshifted MM 2 outflow lobe. The total flow mass Mf 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 vLSR. The characteristic flow timescale \( t_\text{f} \) is \( R_f / \langle V \rangle \), where the intensity-weighted velocity \( \langle V \rangle \) 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 \( \sum M_i / t_\text{f} \), and the force \( F \) is \( P / t_\text{f} \). Assuming \( D = 2 \) kpc, the total molecular mass in outflowing gas \( (v > 5.2 \text{ km s}^{-1} \text{ relative to vLSR}) \) is greater than 255 \( M_\odot \). The values presented in Table 2 are derived assuming all flows have the same systematic velocity. This is a reasonable assumption for the driving sources of the combined MM 1 outflows since the observed UC H II regions are embedded within the same molecular clump and have a projected separation of only 0.5–1″ (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″ (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 \( E > 3.4 \times 10^{47} \text{ ergs} \). The MM 2 outflow has a total mass greater than 90 \( M_\odot \), \( E > 1.8 \times 10^{47} \text{ ergs} \). The CO mosaic did not extend in the southeast direction of the MM 2 flow; thus, the full outflow was not imaged and age and \( M \) 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 H II 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 $M_{\text{gas+dust}} = (F_\nu D^2) / [\nu(B_\nu(T_d)\kappa_\nu)]$, 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 dust is taken to be $\kappa_\nu = 0.006(\nu/245 \text{ GHz})^{\beta} \text{ cm}^2 \text{ g}^{-1}$, 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 $\mu$m and 2.7 mm for submicron 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 ($v > 5.2$ km s$^{-1}$ relative to $v_{\text{LSR}}$) is greater than 255 $M_\odot$. Hunter et al. (1994) found $M_f = 48 M_\odot$ 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 $M_f = 272 M_\odot$, uncorrected for optical depth effects. This mass estimate is extremely high for an optically thin approximation. Examination of their Figure 11, $T_a^*$ versus $(v - v_0)$, shows that the blueshifted lobe has an order of magnitude increase in the integrated flux at the velocity of DR 21 ($-2.5$ 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 redshifted lobe only to be 273 $M_\odot$ based on a CO($J = 2$–$1$) single-dish image corrected for optical depth. The mass of blueshifted 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 cluster.

The total cloud core mass of W75 N has been estimated to be 1800–2500 $M_\odot$ based on observations at submillimeter wavelengths (Moore, Mountain, & Yamashita 1991) and 1200 $M_\odot$ based on CS($J = 7$–$6$) emission (Hunter et al. 1994). The gravitational binding energy of the cloud $GM_d^2/c_1r$ is $(1-2) \times 10^{48}$ ergs, where we take the radius $r = 0.25$ pc (Moore et al. 1991), and $c_1$ is a constant that 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 H II regions: VLA 1 (Bα) and VLA 3 (Bβ) and an embedded source in the millimeter core MM 2. The position angles of the individual outflows are not aligned, ranging from 51° to 124°. The H$_2$ morphology is diffuse and patchy both in the northeast and southwest. 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.

### Table 2

| Source                  | MM 1 Combined Flows | MM 2           |
|-------------------------|---------------------|----------------|
| CO radius of outflow (pc) | 1.8                 | >0.5           |
| Assumed inclination angle (deg) | 45               | 45             |
| Outflow mass a           |                      |                |
| Western outflow ($M_f$)  | 68                  | ...            |
| Eastern outflow ($M_f$)  | 97                  | >90            |
| Total ($M_f$)            | 165                 | >90            |
| Momentum ($M_f$ km s$^{-1}$) | $2.2 \times 10^4$ | $1.1 \times 10^4$ |
| Kinetic energy (ergs)    | $3.4 \times 10^4$   | $1.8 \times 10^4$ |
| Dynamical timescale (yr) | $1.5 \times 10^4$   | $3.8 \times 10^4$ |
| $M_f$ ($M_\odot$ yr$^{-1}$) | $1.2 \times 10^{-3}$ | $2.3 \times 10^{-3}$ |
| Momentum supply rate (force) ($M_f$ km s$^{-1}$ yr$^{-1}$) | $1.8 \times 10^{-2}$ | $2.9 \times 10^{-2}$ |
| Mechanical luminosity ($L_m$) | 23                | <38            |

| a | MM 1 eastern outflow emission measured at velocities 2.2–4.8 km s$^{-1}$ and 15.2–36 km s$^{-1}$. MM 1 western outflow emission measured at velocities 8.2–4.8 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$^{-1}$. |
Low surface brightness $H_2$ emission extends well beyond the CO outflow, while $[\text{Fe}\, ii]$ emission is only detected close to the protostellar cluster. It is generally believed that $[\text{Fe}\, ii]$ 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, nondissociative J-type shocks (e.g., Hollenbach & Mckee 1989; Smith 1994; Grebel 1994; Beck-Winchatz et al. 1996). Continuous shocks (C-shocks) cannot easily produce emission from ionized species such as $[\text{Fe}\, ii]$, nor can they produce the observed column densities typically seen in $H_2$ toward Herbig-Haro objects from low-mass protostars (Grebel 1994). In fact, Nisini et al. (2002) find that there appears to be no correlation between $H_2$ and $[\text{Fe}\, ii]$ emission in outflows from low-mass young stellar objects, which supports the interpretation that physically different mechanisms are responsible for producing $H_2$ and $[\text{Fe}\, ii]$ emission. In a sample of Herbig-Haro objects produced by jets from low-mass protostars, both $H_2$ and $[\text{Fe}\, ii]$ are found toward all sources and the morphology of $H_2$ and $[\text{Fe}\, ii]$ emission is similar on large scales although it differs in the detail (Grebel 1994; Reipurth et al. 2000). These observations indicate that jets from low-mass protostars produce both fast, dissociative regions where $[\text{Fe}\, ii]$ emissions arise and slower, nondissociative regions where $H_2$ emission arises. In contrast, $[\text{Fe}\, ii]$ emission toward W75 N is only detected close to the central sources and does not show a jetlike 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, nondissociative J-type shocks, which produce copious $H_2$ emission throughout the outflow region, but the fast dissociative shocks responsible for $[\text{Fe}\, ii]$ emission are absent in the outer regions of the flow. Instead, the diffuse $[\text{Fe}\, ii]$ line emission in W75 N is coincident with the brightest $K_s$-band reflection nebulosity. One possibility may be that the $[\text{Fe}\, ii]$ emission traces photodissociation 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 nebulosity may exhibit similar excitation conditions to those in Orion.

The $H_2$ and $[\text{Fe}\, ii]$ 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 that produce collimated jets observed in both $H_2$ and $[\text{Fe}\, ii]$ 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 $H_2O$ maser emission along the UC $H_\alpha$ region axis, and because the position angles of the ionized gas and the CO emission were similar. $H_2O$ 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 southwest CO redshifted 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. Furthermore, 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 $10^5$ yr, and the mass-loss rate $M_\ell \sim 10^{-4} - 10^{-3} M_\odot$ 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. Furthermore, recent observations with the Very Long Baseline Array show that a clump of strong $H_2O$ maser emission with high-velocity dispersion is centered on VLA 2 (J. M. Torrelles et al. 2003, in preparation). Thus, the OH and $H_2O$ 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 $H_\alpha$ regions, the region is greater than $10^4$ yr 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 $H_\alpha$ region (Hashchick 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 southeast and southwest 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 that appears to be forming mid- to early-B stars that 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, redshifted CO lobe that extends about 0.5 pc northeast 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 that 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 H II region) or accretion onto the protostar is sufficiently high that it prevents the formation of a UC H II 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, and [Fe II] 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 2003 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:

1. confusion from multiple outflow sources in a cluster (e.g., W75 N; this work; or DR 21: Garden et al. 1991);
2. large flow precession angles (e.g., PV Ceph: Reipurth, Bally, & Devine 1997, Gomez, Kenyon, & Whitney 1997; or IRAS 20126+4104: Shepherd et al. 2000);
3. 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
4. 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 [Fe II] emission is only located close to the protostellar cluster. The CO, H2, and [Fe II] 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.

Research at the Owens Valley Radio Observatory is supported by the National Science Foundation through NSF grant number AST 99-81546. Star formation research at Owens Valley is also supported by NASA’s Origins of Solar Systems program, grant NAGW-4030, and by the Norris...
Planetary Origins Project. D. P. S. acknowledges support from the National Science Foundation Research Experience for Undergraduate program. This paper is partly based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. The ARNICA and NICS observations were performed in service mode by the TNG staff; we especially acknowledge the help of Francesca Ghinassi, Juan Carlos Guerra, and Antonio Magazzù. This paper makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

REFERENCES

Baart, E. E., Cohen, R. J., Davies, R. D., Norris, R. P., & Rowland, P. R. 1986, MNRAS, 219, 145
Baffa, C., et al. 2001, A&A, 378, 722
Beck-Winchatz, B., Böhm, K.-H., & Noriega-Crespo, A. 1996, AJ, 111, 346
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Cabrit, S., & Bertout, C. 1990, ApJ, 348, 530
Cabrit, S., Ferreira, J., & Raga, A. C. 1999, A&A, 343, L61
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Churchwell, E. 1999, in The Origin of Stars and Planetary Systems, ed. C. J. Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cornwell, T., & Braun, R., 1988, in ASP Conf. Ser. 6, Synthesis Imaging in
Davis, C. J., Moriarty-Schieven, G. H., Eislo¨ffel, J., Hoare, M. G., & Ray, T. P. 1998a, AJ, 115, 1118
Davis, C. J., Smith, M. D., & Moriarty-Schieven, G. H. 1998b, MNRAS, 299, 825
Devine, D., Bally, J., Reipurth, B., Shepherd, D., & Watson, A. 1999, AJ, 117, 2919
Dickel, H. R., Wendker, H. J., & Bieritz, J. H. 1969, A&A, 1, 270
Diamond, P. J. 1998, Nature, 396, 650
Doyle, W. R., Evans, I. N., & Scoville, N. Z. 1986, ApJL, 303, 416
Garden, R. P., Hayashi, M., Gatley, I., Hasegawa, T., & Kafu, N. 1991, ApJ, 374, 540
Ghini, A., Lada, C., & Lisi, F. 1998, A&A, 369, 278
Ghinassi, F., Riccardo, J., Oliva, E., Baffa, C., Checcucci, A., Conotinotto, G., Gennari, S., & Marzoni, G. 2002, A&A, 386, 1157
Gomez, M., Kenyon, S. J., & Whitney, B. A. 1997, AJ, 114, 265
Gredel, R., et al. 2001, A&A, 374, 580
Greenhill, L. J., Gwinn, C. R., Schwartz, C., Moran, J. M., & Diamond, P. J. 1998, Nature, 396, 650
Haschick, A. D., Reid, M. J., Burke, B. F., Moran, J. M., & Miller, G. 1981, ApJ, 244, 76
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hollenbach, D., & McKee, C. F. 1989, ApJ, 342, 306
Ko¨nigl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. Boss & S. Russell (Tucson: Univ. Arizona Press), 867
Kramer, C., Alves, J., Lada, C., Lada, E., Sievers, A., Ungerechts, H., & Walmsley, M. 1998, A&A, 329, L33
Lada, C. J., & Fich, M. 1996, ApJ, 499, 638
Lisi, F., et al. 1996, PASP, 108, 364
Lorenzetti, D., Giannini, T., Vitali, F., Massi, F., & Nisini, B. 2002, ApJ, 564, 839
Minier, V., Conway, J. E., & Booth, R. S. 2000, A&A, 362, 1093
Moore, T. J. T., Mountain, C. M., & Yamashita, T. 1991, MNRAS, 248, 79
Moore, T. J. T., Mountain, C. M., Yamashita, T., & McLean, I. S. 1991, MNRAS, 248, 377
Nisini, B., Caratti o Garatti, A., Giannini, T., & Lorenzetti, D. 2002, A&A, 393, 1035
Pollack, J. B., Hollembach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. 1994, ApJ, 421, 615
Reipurth, B., Bally, J., & Devine, D. 1997, AJ, 114, 2708
Richer, J. S., Shepherd, D. S., Cabrit, S., Bachiller, R., & Churchwell, E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. Boss & S. Russell (Tucson: Univ. Arizona Press), 867
Ridge, N. A., & Moore, T. J. T. 2001, A&A, 378, 495
Rodríguez, L. F., Garay, G., Curiel, S., Ramírez, S., Torrelles, J. M., Gomez, Y., & Velazquez, A. 1994, ApJ, 430, L65
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco: ASP), 433
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., Phillips, J. A., Scott, S. L., Tilanus, R. P. J., & Wang, Z. 1993, PASP, 105, 1482
Scoville, N. Z., Sargent, A. I., Sanders, D. B., Claussen, M. J., Masson, C. R., Lo, K. Y., & Phillips, T. G. 1986, ApJ, 303, 416
Shang, H., Glasgold, A. E., Shu, F. H., & Lizano, S. 2002, ApJ, 564, 853
Shepherd, D. S. 2001, ApJ, 546, 345
———. 2003, in ASP Conf. Ser. 287, Galactic Star Formation Across the Stellar Mass Spectrum, ed. J. M. De Buizer & N. S. van der Bliek (San Francisco: ASP), 333
Shepherd, D. S., Claussen, M. J., & Kurtz, S. E. 2001, Science, 292, 1513
Shepherd, D. S., & Watson, A. M. 2002, ApJ, 566, 966
Shepherd, D. S., Yu, K. C., Bally, J., & Testi, L. 2000, ApJ, 535, 833
Shu, F. H., Najita, J. R., Shang, H., & Li, Z.-Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. Boss & S. Russell (Tucson: Univ. of Arizona Press), 789
Slysh, V. I., Migenez, V., Val’ts, I. E., Lyubchenko, S. Yu., Horiiuchi, S., Altunin, V. I., Fomalont, E. B., & Inoue, M. 2002, ApJ, 564, 317
Smith, M. D. 1994, A&A, 289, 256
Smith, M. D., Suttner, G., & Yorke, H. W. 1997, A&A, 323, 223
Suttner, G., Smith, M. D., Yorke, H. W., & Zinnecker, H. 1997, A&A, 318, 595
Swenson, J. M., Gomez, J. F., Rodriguez, L. F., Ho, P. T. P., Curiel, S., & Vázquez, R. 1997, ApJ, 489, 744
Vani, L., Gemini, S., Chion, M., & Testi, L. 1998, Exp. Astron., 8, 177
Walmsley, C. M., Natta, A., Oliva, E., & Testi, L. 2000, A&A, 364, 301
Watson, C., Churchwell, E., Pankonin, V., & Bieging, J. H. 2002, ApJ, 577, 260
Wilson, T. L., & Rood, R. T. 1994, ARA&A, 32, 191
Yamashita, T., Suzuki, H., Kaifu, N., Tamura, M., Mountain, C. M., & Moore, T. J. T. 1989, ApJ, 347, 894