MOLECULAR CO OUTFLOWS IN THE L1641-N CLUSTER: KNEADING A CLOUD CORE

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ABSTRACT

We present results of 1.3 mm interferometric and single-dish observations of the center of the L1641-N cluster in Orion. Single-dish wide-field continuum and CO(2–1) observations reveal the presence of several molecular outflows driven by deeply embedded protostellar sources. At higher angular resolution, the dominant millimeter source in the cluster center is resolved into a pair of protostars (L1641-N MM1 and L1641-N MM3), each driving a collimated outflow, and a more extended, clumpy core. Low-velocity CO line-wing emission is spread widely over much of the cluster area. We detect and map the distribution of several other molecular transitions (\(^{12}\)CO, \(^{13}\)CO, \(^{13}\)CS, SO, CH\(_3\)OH, CH\(_3\)CN, and OCS). CH\(_3\)CN and OCS may indicate the presence of a hot corino around L1641-N MM1. We tentatively identify a velocity gradient over L1641-N MM1 in CH\(_3\)CN and OCS, oriented roughly perpendicular to the outflow direction, perhaps indicative of a circumstellar disk. An analysis of the energy and momentum load of the CO outflows, along with the notion that apparently a large volume fraction is affected by the multiple outflow activity, suggests that outflows from a population of low-mass stars might have a significant impact on clustered (and potentially high-mass) star formation.

Key words: circumstellar matter — ISM: jets and outflows — stars: formation — turbulence

1. INTRODUCTION

Most stars are born in clustered environments (e.g., Lada & Lada 2003), and their formation may be significantly different than in isolated regions such as the well-studied Taurus cloud. For example, the shape and extent of prestellar cores and their subsequent evolution may be affected through close encounters with other cluster members or the effect of ionizing radiation from massive cluster stars. Protostellar outflows, known to accompany star formation, might also play a different role in clusters. Whereas in the isolated case much of the outflow energy and momentum will likely just be dumped somewhere else in or even outside the cloud, multiple, randomly oriented outflows in a cluster-forming clump might impact a larger volume, significantly affecting or even hindering further star formation.

We present new data on the outflow activity in the L1641-N region in the Orion A giant molecular cloud. As a moderately sized, relatively nearby\(^3\) cluster, L1641-N allows for detailed observations, in a relatively simple example, of the complex processes involved in cluster formation.

The first detection of bipolar CO outflow activity in L1641-N, centered on IRAS 05338–0624, was found by Fukui et al. (1986) and subsequently followed up by Fukui et al. (1988) and Wilking et al. (1990). Near-infrared imaging revealed the presence of an embedded small group of about 20–25 young stars (Strom et al. 1989a; Chen et al. 1993; Hodapp & Deane 1993). Hodapp & Deane (1993) estimated that the cluster grew at a rate of two to three stars every 10\(^5\) yr over about 10\(^6\) yr.

The CO outflow maps have generally been interpreted as evidence for the presence of one roughly north-south-oriented outflow, driven by one protostellar source seen as the mid- to far-infrared source IRAS 05338–0624. Ground-based \(\textit{M}\)-band observations have revealed a source, N1, seen at 5 \(\mu\)m (and longward) only (Chen et al. 1993); this source is also seen as a compact millimeter continuum source in interferometric images (Wilking et al. 1989; McMullin et al. 1994; Chen et al. 1995) but appears not to be the dominant source, at least at mid-infrared wavelengths (Stanke et al. 1998; Ali & Noriega-Crespo 2004, hereafter AN04). Moreover, interferometric CS and SiO observations (McMullin et al. 1994) suggest a southwest-to-northeast-oriented outflow at the very cluster center, as opposed to the predominantly north-south orientation seen on larger scales in CO. Stanke et al. (1998) have proposed that there are indeed two independent outflows: a southwest-to-northeast-oriented flow and a large-scale north-south outflow, driven by the brightest 10 \(\mu\)m source in the field. The southwest-to-northeast flow appears to be driven by the compact millimeter continuum source. Further optical and near-infrared narrowband imaging searches for Herbig-Haro objects and shocked H\(_2\) emission have provided evidence that the L1641-N cluster is indeed the center of multiple outflows (Davis & Eisloffel 1995; Reipurth et al. 1998, Stanke et al. 1998, 2000, 2002, hereafter SMZ02; Mader et al. 1999), some of which extend over several parsecs.

In this contribution we present new 1.3 mm wavelength single-dish and interferometric observations of the L1641-N cluster area in order to shed further light on the protostellar outflow activity. We describe the observations in §2, identify outflows and their driving sources in §3, and provide a summary and conclusions in §4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. IRAM 30 m

We obtained 1.3 mm dust continuum maps in the course of a wider survey over several observing runs between 1999 and

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\(^3\) We assume the canonical Orion distance of 450 pc.
2002, using the 37 channel MAMBO bolometer array at the IRAM 30 m telescope. The data reduction was done with MOPSI\(^4\) and followed standard bolometer reduction procedures, including baseline subtractions, despiking, correction for atmospheric extinction using the results of sky-dip measurements, and flux calibration using planet maps. Correlated sky-brightness variations (sky noise) were removed in an iterative process, using the resulting mosaic of the respective previous iteration as an input source model to the actual sky-noise reduction. Thereafter, the single-beam intensity distribution was restored from the chopped dual-beam data and subsequently combined into the large mosaic. The nine-element heterodyne receiver array (HERA) (Schuster et al. 2004) was used in 2003 November to obtain CO(2–1) maps of the L1641-N region. The cluster center and the area around the driving source of outflow 51 in SMZ02 were each covered with a fully sampled 66\(^\prime\) x 66\(^\prime\) raster map. In addition, an \(\sim 10\times9.5\)\(^\prime\) area was mapped in the coarsely sampled spectral line on-the-fly mode.\(^5\) Data reduction included low-order baseline subtraction and combining the spectra (raster and on-the-fly maps) into one map.

To convert CO brightness temperatures to molecular gas column densities, we assume the CO to be optically thin, in LTE at a temperature of 30 K, and a CO abundance of \(10^{-8}\) of the H\(_2\) abundance. We derived gas masses as a function of velocity for each channel. Kinetic energies and momenta were derived as \(E_{\text{kin}} = \frac{1}{2} \sum M(v - v_{\text{cen}})^2\) and \(P = \sum M(v - v_{\text{cen}})\), where \(v_{\text{cen}} = 6.8 \text{ km s}^{-1}\). A characteristic timescale was derived by dividing the maximum distance \(l\) at which high-velocity emission was seen by the maximum CO velocity observed. Results for the various outflow lobes identified from the data are listed in Table 1.

We do not attempt to correct for optical depth effects in calculating the CO outflow masses or for outflow gas at radial velocities equal to the ambient cloud velocities; similarly, we do not correct the velocity of the gas for projection effects. Outflow masses, kinetic energies, and momenta are therefore strict lower limits.

### 2.2. Submillimeter Array

We used the Submillimeter Array (SMA) on Mauna Kea, Hawaii, to obtain high-resolution 230 GHz images of the center of the L1641-N cluster. Two tracks were taken, one in the compact configuration (2004 December 19, with antennas 1–6; antenna 8 was flagged) and one in the extended configuration (2004 December 27, with antennas 1–6 and 8). The two configurations yielded projected baselines ranging from about 13 to 220 m. Double sideband receivers were used, with the CO(2–1) line centered in the upper sideband (correlator chunk 14). The 230 GHz zenith opacities were between 0.1 and 0.06 during the first track, with fairly stable phases; system temperatures were between 200 and 250 K throughout most of the track. During the second track, the opacity was initially high, \(\sim 0.2\), but dropped to \(\sim 0.08\) later on; similarly, phase stability improved during the track. System temperatures were around 150 K.

Data calibration and editing were done within the IDL MIR package. The phase center for L1641-N was set to \(\alpha = 05^h36^m18.8^s, \delta = -06^\circ22'10''\) (J2000.0). Observations of Uranus and Callisto were used for bandpass and flux calibration. Flux calibration was obtained using model predictions for Callisto’s flux depending on baseline length as provided on the SMA Web site.\(^6\) Observations of J0423–013 and J0607–157 were taken every 20 minutes to allow for complex phase calibration. Continuum emission was reconstructed from line-free parts of the 2 x 2 GHz range covered by the SMA receivers.

Maps were constructed and deconvolved within MIRIAD. For the emission-line maps, continuum emission was first subtracted from the emission-line visibilities. The continuum and \(^{12}\)CO line SMA data were complemented with short spacing visibilities obtained from the IRAM 30 m mapping described above. Maps were created using a natural weighting scheme, and CLEANing was performed, stopping after new CLEAN components were at about 60% of the rms noise level. The synthesized beam measures 1.7\(\arcsec\) x 1.2\(\arcsec\) at a position angle (P.A.) of 75\(^\circ\) east of north.

#### 2.3. Astrometry

In this paper we use a number of different data sets taken over a wide wavelength range: near-infrared (\(K\)-band) data from SMZ02, Infrared Space Observatory (ISO) data published by AN04, and new single-dish and interferometric millimeter-wavelength data. Good relative astrometry is crucial in understanding what happens in a clustered environment such as L1641-N. The various data sets used in this paper were registered with respect to each

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\(^4\) Developed and maintained by R. Zyka, IRAM, Grenoble, France.

\(^5\) Sampling at 7.6\(\arcsec\); see HERA manual for details, http://www.iram.es/IRAMES/mainWiki/HeraWebPage.

\(^6\) See http://sma1.sma.hawaii.edu/.
other as follows: the infrared K-band data from SMZ02 were recalibrated over the field of interest using Two Micron All Sky Survey coordinates for stellar sources. The ISO maps were registered to the near-infrared using a number of sources seen in the near- and mid-infrared maps. The 1.2 mm dust continuum map was registered with respect to the near-infrared map using one star seen in both maps, located 1.5'' southeast of the cluster center. The interferometer map was not corrected because it is phase-referenced to quasars, yielding high positional accuracy.

3. YOUNG STELLAR OBJECTS AND OUTFLOWS IN L1641-N

Figure 1 shows an overview of the field around the L1641-N cluster in the 1.3 mm dust continuum (contours) and the 2.12 μm narrowband image [gray scale; H₂ v = 1-0 S(1) line + continuum; see Stanke et al. 1998, SMZ02]. Figure 2 shows the CO(J = 2-1) line-wing emission (blue and red contours).

3.1. Wide-Field Mapping

The wide-field 1.3 mm dust continuum map taken with MAMBO shows a number of compact features in the center of the field and more diffuse emission toward the southeast (Fig. 1). This is reminiscent of the head-tail shape of the C^{18}O cloud core as mapped by Reipurth et al. (1998, their Fig. 17a; see also Tatematsu et al. 1993).

The CO line-wing emission maps (Figs. 3 and 4) reveal the presence of a number of well-defined outflow lobes. The dominant feature at redshifted velocities is an ~1.5' broad, collimated lobe extending over 7'' south of the L1641-N cluster center to the edge of the area mapped in CO (labeled “R-S” in Fig. 2). It is also seen as a series of H₂ shocks reaching even farther south (Stanke et al. 2000). Together with a chain of optical Herbig-Haro objects north of the cluster (HH 306–HH 310; Reipurth et al. 1998; Mader et al. 1999), these features form a bipolar giant outflow stretching over several parsecs on both sides of the cluster. Blueshifted CO emission is also seen north of the cluster center in a Y-shaped feature. The channel maps in Fig. 3 show that at high velocities there is a collimated lobe extending northeast of the cluster center (B-NE), which is joined by an apparently also collimated north-south feature (B-N) at intermediate velocities. At low velocities, these features blend with a broad patch of CO emission north of the cluster center. Broadly distributed redshifted emission is also seen to the southwest and west of the cluster center (Fig. 4). High-velocity emission seems to be restricted to a small lobe close to the cluster center, forming a counterlobe.
to B-NE. The MAMBO dust continuum map shows a bright, compact, but resolved peak at the center of these CO outflow lobes, on top of a northeast-to-southwest-oriented ridge, which corresponds to the HCN and HCO\(^+\) ridge found by Fukui et al. (1988).

Another well-defined, highly collimated outflow lobe (R-SW) is seen to the west of the large north-south lobe R-S at a P.A. of about 28° east of north. The CO channel maps (Fig. 4) reveal a distinct velocity structure in this lobe, with the highest velocity emission being found at the southwestern tip and lower velocity emission extending ever farther to the northeast. In fact, close to the ambient CO velocity (Fig. 5) this lobe structure can be clearly followed up to where it intersects with the large, redshifted north-south giant flow lobe. The MAMBO continuum map also shows a faint ridge along the northern portion of this CO lobe. We suggest this is outflow-entrained dust (see Chini et al. 2001). Converting the CO flux densities to broadband flux densities yields flux densities of the order of 2–5 mJy beam\(^{-1}\) (using a conversion factor of 8.6 Jy K\(^{-1}\) as given on the IRAM Web site and a MAMBO bandwidth of 100 GHz estimated from the transmission plots shown on the Max-Planck-Institut für Radioastronomie MAMBO Web site), much less than the 30–50 mJy beam\(^{-1}\) seen in the MAMBO map in the ridge. The R-SW lobe does not have any obvious blueshifted counterlobe. No H\(_2\) shocks have been found that could be associated with this lobe by SMZ02.

A bipolar CO outflow is centered on \(\alpha = 05^h36^m24.8^s, \delta = -66^\circ 22'42''\). It corresponds to SMZ02 outflow 51. The outflow is centered on a northwest-to-southeast-oriented millimeter continuum ridge and an ISO mid-infrared source (source 10 of AN04). Its blueshifted lobe is seen over a large distance from the source as a sequence of large optical HH objects (HH 301 and HH 302) and infrared shocks (Reipurth et al. 1998; Mader et al. 1999; SMZ02). No such features have been found at comparable distances from the source on the redshifted side. We speculate that the flow might have a continuation on the redshifted side in the outflow lobe R-SW, for which we cannot see any other plausible driving source. This would imply a significant change in outflow direction, however, and cannot be due to precession, as only the redshifted lobe shows this bend. We note that at velocities close to the CO ambient cloud velocity the R-SW lobe can be traced back to where it intersects with the R-S lobe. This is also about where the R-E lobe of SMZ02 outflow 51 would intersect with R-S. We therefore speculate that outflow 51 interacts with R-S, its outflowing gas being accelerated in a southerly direction, thus creating the bend in the redshifted flow lobe. Deflection of a jet with a side wind is a candidate mechanism to explain bent jets (e.g., Fendt & Zinnecker 1998), particularly in the case of C-shaped symmetry about the driving source (e.g., Bally et al. 2006). Observations of jets of this type, as well as theoretical and experimental studies, demonstrate that jets can survive (and remain collimated) while interacting with relatively tenuous winds, such as expanding H\(_n\) regions (e.g., Masciadri & Raga 2001; Lebedev et al. 2004) over a large portion of the jet length. In contrast,
in L1641-N the R-SW lobe seems to interact with R-S only over a short total length, and it seems that R-S is heavier than R-SW, as R-S does not show any signs of bending resulting from an interaction with R-SW. That a lighter jet might be able to survive a collision with a heavier flow remains to be shown, but it seems that a collision of two jets and redirection does not necessarily imply a disruption of the flow(s) (Cunningham et al. 2006).

In addition, we identify a small, bipolar CO outflow centered on a near- to mid-infrared (source N31 of Chen et al. (1993), ISO source 13 of AN04) and 1.3 mm continuum source at \( \alpha = 05^h36^m22.0^s, \delta = -06^\circ23'28'' \). The blueshifted lobe is associated with two faint \( \mathrm{H}_2 \) shocks that were not identified by SMZ02.

Finally, the Strom 11 group of embedded stars (Strom et al. 1989b; Chen et al. 1993) is seen superposed on a roughly circular millimeter continuum clump of \( \sim 1'' \) diameter. A faint, narrow lobe of blueshifted CO emission (B-SE2, seen best in the channel maps in Fig. 3, close to the ambient velocity) might have its origin in the Strom 11 group; some more faint, blueshifted emission is seen in Strom 11 and to its south.

3.2. The Central Area: SMA Observations

3.2.1. Continuum

Figure 6 shows the 1.3 mm dust continuum at high angular resolution (SMA and MAMBO data combined). We detect a
bright, compact source centered at \( \alpha = 05^h36^m18.780^s, \delta = -06^\circ22'10.37'' \) (J2000.0), in very good agreement with the position found by Chen et al. (1995). We refer to this source as L1641-N MM1 in the following. The visibilities decrease from 0.3–0.4 Jy at short spacings to 0.1–0.2 Jy at large u-v distances, so the source is resolved. A Gaussian fit to the radially averaged real continuum visibilities implies a FWHM size of 1.0'' ± 0.1''. From elliptical Gaussian fits in the image plane we find a size of 2.1'' × 1.5'' (P.A. 67°), corresponding to a deconvolved size 1.2'' × 0.8'' (P.A. 56°). Fitting the combined MAMBO and SMA data at fluxes >0.02 Jy gives a size of 2.5'' × 1.7'' (P.A. 67°), corresponding to 1.9'' × 1.3'' (P.A. 62°) deconvolved. The image shows a tail of emission running at a similar P.A. away from the source, so the P.A. derived from the Gaussian fit might be biased toward this direction. As the deconvolved source size is significantly smaller than the beam size, the result is likely subject to large errors. Still it seems that the continuum emission is not oriented perpendicular to the outflow direction inferred from the CO observations (see below). As the emission of L1641-N MM1 furthermore blends into more extended core emission, we suggest that L1641-N MM1 traces an envelope structure rather than a disk. The total integrated flux of 0.54 Jy (as measured from the Gaussian fit) corresponds to a circumstellar gas mass of about 1.6 \( M_\odot \), assuming a dust temperature of 20 K and a dust opacity coefficient of 0.01 cm\(^2\) g\(^{-1}\) (Motte et al. 1998).

To the south of L1641-N MM1 a number of extended features form a clumpy core. The most prominent of these are two clumps to the south of L1641-N MM1 (L1641-N MM2 and...
Fig. 5.— Same as Fig. 3, but for velocities around the ambient cloud velocity (3.2–12.8 km s$^{-1}$; note the different gray-scale stretch).

Fig. 6.— The 1.3 mm dust continuum emission in L1641-N. Left: SMA + MAMBO combined map (gray scale, blue contours), with the single-dish MAMBO map overlaid as dotted contours. The SMA beam size is indicated by the black ellipse, and the 30% sensitivity radius of the SMA primary beam is shown as the dashed circle. Right: Gray scale showing a 2.12 $\mu$m near-infrared narrowband image [$K$-band continuum + H$_2$ $v = 1$–0 $S(1)$ line; see SMZ02], with H$_2$ shocks labeled. Dotted contours indicate the ISO 7 $\mu$m map (AN04). The square marks the position of AN04 ISO source 18.
L1641-N MM4 in the following). There appears to be an extension of L1641-N MM1 in a southwest direction, forming a bridge of emission between L1641-N MM1 and L1641-N MM2. Another extension to L1641-N MM1 is seen to protrude toward the east-southeast, which appears as a separate source in some of the observed molecules (see below); we refer to this feature as L1641-N MM3.

Protruding to the northeast of L1641-N MM3 there appears to be a clumpy ridge of emission parallel to the small H2 jet (feature C in Fig. 6). This ridge might outline the wall of a cavity produced by the jet. Finally, some more clumpy emission is seen to the south and west. Generally, there is a good anticorrelation between the millimeter continuum emission and the diffuse infrared emission, indicating that the dust is in the foreground of the diffuse emission.

Notably, the single-dish continuum peak does not coincide with the position of L1641-N MM1; although pointing errors might affect the single-dish peak position, the offset seems to be too large. Note also that the astrometry of the single-dish map has been corrected using a near-infrared source, the position of which should be accurate to better than 1". Thus, the single-dish continuum peak seems to trace the clumpy core south of L1641-N MM1 rather than L1641-N MM1 itself.

3.2.2. $^{12}$CO Line-Wing Emission

Figure 7 shows the spatial distribution of CO line-wing emission over the field observed with the SMA. The emission has been split into a low- and a high-velocity component (right and left panels, respectively). At high velocities, there is evidence for the presence of a well-collimated (although faint) northeast-to-southwest-oriented molecular jet. Apparently, it is not centered on the bright L1641-N MM1 continuum source but on L1641-N MM3. The redshifted lobe of this collimated flow is more pronounced and seen over a larger distance from the driving source. It appears to terminate in a shock feature seen in various other molecular lines (SO and CH$_3$OH, see below; CS and SiO [Chen et al. 1996; McMullin et al. 1994]). The blueshifted lobe appears to be more spurious. Some blueshifted high-velocity emission also seems to be present toward the prominent H$_2$ bow shock A1 seen in the northeast corner of Figure 7.
At lower velocities, CO emission is spread over a wide area. Blueshifted emission is seen over virtually the entire northeastern quadrant, while redshifted CO prevails toward the south and west of the cluster center. There appears to be a narrow, hollow cavity-like structure centered on L1641-N MM1, particularly clear in the blueshifted lobe. The northeast continuum ridge is found just south of the southern edge of the blueshifted CO cavity, apparently outlining the wall of the outflow cavity. The small H$_2$ jet formed by the knots labeled “C” in Figure 6 appears to run right through the CO cavity; however, it cannot be excluded that this is due to residual error in the astrometry for the H$_2$ image.

The data suggest that there are two almost parallel (in projection) outflows in the cluster center. One is marked by the bipolar, high-velocity CO jet and apparently driven by L1641-N MM3. The other is indicated by the presence of the bipolar cavity centered on L1641-N MM1.

It is straightforward to relate the single-dish B-NE lobe and its short, redshifted counterlobe to the flows seen at high resolution with the SMA. The H$_2$ bow shock A1 coincides with the point out to which high-velocity blueshifted CO is seen in the single-dish data; however, at lower velocities, this collimated outflow lobe extends farther out to the northeast. Remarkably, the axis of neither of the two flows seen at high resolution with the SMA really points in the direction of the A1 H$_2$ bow shock. We suggest that it is L1641-N MM1, which creates the A1 bow shock and the bulk of the single-dish B-NE lobe, simply because it seems that L1641-N MM1 is the more massive object.
The molecular outflow from L1641-N has generally been interpreted as a single wide-angle flow. Our SMA and IRAM 30 m CO observations show that this is not true. There is clearly outflow along a southwest-to-northeast axis, marked by the flows seen at high resolution with the SMA and the B-NE lobe. In contrast, the R-S CO lobe, as well as near-infrared and optical shocks, indicates outflow along a north-south axis. The coexistence of outflow features along both axes within the central arcminute around the cluster center (CO lobes, optical and infrared H$_2$ shocks) rules out the possibility that an initially north-south-oriented flow could have changed its orientation to a northeast-southwest orientation, e.g., as a result of an interaction of its driving source in a close encounter with another object. Close inspection of the 30 m CO channel maps also indicates that the north-south outflow axis, defined by B-N and R-S, is shifted by several arcseconds to the east of L1641-N MM1/MM3. We therefore conclude that there are indeed three CO outflows from the cluster center: two, driven by L1641-N MM1 and L1641-N MM3, seen with the SMA along a northeast-southwest orientation and one north-south-oriented giant outflow. As suggested already by Stanke et al. (1998) the dominant mid-infrared source in the cluster as seen in ground-based and ISO observations (AN04 source 18), located about 9° to the east of L1641-N MM1/MM3, appears to drive this outflow.

### 3.2.3. Other Lines

The SMA provides a frequency coverage of 2 GHz in each of the upper and lower sidebands and allows several lines to be observed simultaneously. Centering the CO(2–1) line in the upper sideband yields the isotopomers $^{13}$CO and C$^{18}$O in the lower sideband. In addition to the CO lines, we find some CH$_3$OH transitions, $^{13}$CS, OCS, SO, and the first few transitions of the CH$_3$CN(12–11) series. Figure 8 shows a compilation of spectral line maps, with emission close to the rest velocity (5–8.6 km s$^{-1}$) and line-wing emission (red contours, 8.6–13.4 km s$^{-1}$; blue contours, 0.2–5 km s$^{-1}$) plotted separately, and Table 2 gives a list of detected lines. Besides the lines shown in Figure 8, there is a marginal detection of the HNCO 10(0,10) transition at 219.798 GHz, which is, however, too faint for mapping and is not discussed further.

The isotopomers $^{13}$CO and C$^{18}$O trace a more extended structure (the former clearly affected by missing short-spacing information), with some emission associated with L1641-N MM1 and L1641-N MM3. The brightest peak in $^{13}$CO and C$^{18}$O is significantly offset toward the southwest of L1641-N MM1. L1641-N MM3 is coincident with the second-brightest $^{13}$CO peak and a

### Table 2: Molecular Lines Detected and the Features in Which the Lines Are Seen

| $\nu_{\text{rest}}$ (GHz) | $\nu_{\text{obs}}$ (GHz) | Species     | Transition | L1641-N MM1 | Southwest Shock | Outflow | L1641-N MM3 |
|--------------------------|--------------------------|-------------|------------|-------------|----------------|---------|-------------|
| 219.5604 registered.... | 219.5601                 | C$^{18}$O   | 2–1        | X           | ...            | ...     | X           |
| 219.9494 registered.... | 219.9497                 | SO          | 6(5)–5(4)  | X           | X              | X       | X           |
| 220.0785 registered.... | 220.0789                 | CH$_3$OH    | 8(0.8)–7(1,6) E | X      | X              | ...     | (X)         |
| 220.3987 registered.... | 220.3994                 | $^{13}$CO   | 2–1        |            | ...            | X       | X           |
| 220.6411 registered.... | 220.6424                 | CH$_3$CN    | 12(5)–11(5) |            | ...            | ...     |            |
| 220.7090 registered.... | 220.7098                 | CH$_3$CN    | 12(3)–11(3) | X           | ...            | X       | (X)         |
| 220.7303 registered.... | 220.7307                 | CH$_3$CN    | 12(2)–11(2) | X           | ...            | (X)     |             |
| 220.7430 registered.... | 220.7432                 | CH$_3$CN    | 12(1)–11(1) | X           | ...            | (X)     |             |
| 220.7473 registered.... | 220.7469                 | CH$_3$CN    | 12(0)–11(0) | X           | ...            | (X)     |             |
| 229.5891 registered.... | 229.5875                 | CH$_3$OH    | 15(4,11)–16(3,13) E | X      | ...            | ...     | X           |
| 229.7588 registered.... | 229.7574                 | CH$_3$OH    | 8(–1.8)–7(0,7) E | X      | X              | ...     | X           |
| 230.0270 registered.... | 230.0261                 | CH$_3$OH    | 3(–2.2)–4(–1.4) E | X      | ...            | ...     |             |
| 230.5380 registered.... | 230.518                  | CO          | 2–1        |             | ...            | ...     |             |
| 231.0610 registered.... | 231.0601                 | OCS         | 19–18      |             | ...            | ...     |             |
| 231.2208 registered.... | 231.2185                 | $^{13}$CS   | 5–4        | (X)         | ...            | ...     |             |
| Continuum (mJy)..       |                           |             |            |             | 470            | 79      |             |

Note.—An X means detected, (X) means marginally detected, and ellipses mean not detected.

### Figure 9

**Top:** CH$_3$CN map (gray scale, integrated over the $K = 0$ and 1 lines; contours, SMA + MAMBO combined continuum map; cross, phase center; ellipse, beam). **Bottom:** CH$_3$CN spectrum of L1641-N MM1, along with model spectrum (gray line; model parameters: $T = 130$ K, $N_{\text{H}_2}$ = $4 \times 10^{15}$ cm$^{-2}$; $\Delta v = 4.1$ km s$^{-1}$, source size 0.42°). The dip in the spectrum close to the $K = 5$ line is caused by a number of particularly noisy channels.
faint C^{18}O peak; the second brightest C^{18}O peak is seen toward the northeast continuum emission ridge. Another C^{18}O peak is found some 17" north of L1641-N MM1, roughly coinciding with CS peak 3 found by Chen et al. (1996). Besides CS peak 1, none of the other CS peaks found by Chen et al. (1996) are seen in $^{13}$CO or C^{18}O. Clear signs of emission in the line-wing bins are shown in $^{13}$CO, in a bipolar fashion around L1641-N MM1; particularly, the blueshifted emission corresponds well to the structure seen at the base of the cavity seen in $^{12}$CO at moderate velocities. No $^{13}$CO line-wing emission is obviously related to L1641-N MM3, in agreement with our suggestion that L1641-N MM1 is the more massive outflow.

The other molecules show pronounced differences in their distribution. SO emission is found toward L1641-N MM1, L1641-N MM3, and an extended feature to the southwest of the cluster center. Besides two compact features corresponding to L1641-N MM1 and L1641-N MM3 there is also some more extended emission surrounding these sources, which is seen in the central velocity bin, as well as in the line-wing bins, mostly to the east of L1641-N MM1. In the integrated spectrum the blueshifted wing of the SO line is much more pronounced than the red wing, whereas in the map the red wing seems to dominate, particularly due to strong emission seen toward the southwest shock; some more redshifted SO emission is seen between the cluster center and the southwest shock. The SO channel maps (not shown here) suggest that most of the blueshifted SO emission is in extended, low surface brightness emission toward the blueshifted lobe of the flow from L1641-N MM1, which is too faint to show up in the map in Figure 8.

We see CH$_3$OH emission mainly toward L1641-N MM1 and toward L1641-N MM3 in the $8(-1,8)-7(0,7)E$ line and maybe marginally in the $8(0,8)-7(1,6)E$ line. Around L1641-N MM1 and L1641-N MM3 the emission in the $8(-1,8)-7(0,7)E$ line appears to be somewhat extended. The southwest shock is seen in the $8(-1,8)-7(0,7)E$ and $8(0,8)-7(1,6)E$ lines, with a clear redshifted component in the $8(-1,8)-7(0,7)E$ line; its emission is spread out to velocities around 15–16 km s$^{-1}$, consistent with the results of McMullin et al. (1994) and Chen et al. (1996) (CS peak 2). The CH$_3$OH 15(4,11)–16(3,13) line is seen as a faint, compact feature toward L1641-N MM1 only; in addition, the $3(-2,2)-4(-1,4)$ line is marginally seen in L1641-N MM3.

Although it is only seen very faintly in the map, $^{13}$CS appears to be spread out over an area similar to that of C$^{18}$O. OCS is only seen as a compact feature coincident with L1641-N MM1. CH$_3$CN is clearly detected as a compact feature coincident with L1641-N MM1 and marginally toward L1641-N MM3 (Fig. 9, top). The SO, CH$_3$OH $8(-1,8)-7(0,7)$, CH$_3$OH $8(0,8)-7(1,6)$, and $^{13}$CO lines show significant line-wing emission in spectra integrated over the area covered by the SMA primary beam; faint wing emission might also be seen in C$^{18}$O. The wing emission is more pronounced on the blueshifted side, but fainter redshifted emission is also present. Single-dish C$^{18}$O, SO, and CH$_3$OH spectra (CSO, ~30" beam; McMullin et al. 1994) tend to show more prominent emission in the red wing, suggesting that there is a significant extended component that is resolved out by the interferometer. The remaining lines (CH$_3$OH, CH$_3$CN, $^{13}$CS, and OCS), as well as the cores of the lines associated with wing emission, are resolved, with FWHMs around 3 km s$^{-1}$. L1641-N MM2 and L1641-N MM4 are not seen in any of the lines.

Complex organic molecules are thought to form in the dense, dusty environments around young protostars as the products of grain surface chemistry are evaporated and react with each other (Bottinelli et al. 2007). Whereas CH$_3$OH is also clearly associated with the outflows, this seems not to be the case for CH$_3$CN and OCS in L1641-N. We have used the XCLASS extension to the CLASS software (P. Schilke 2005, private communication) to simulate the CH$_3$CN spectrum to estimate the temperature, column density, and size of the emitting region (Fig. 9, bottom). We used a jansky-to-kelvin conversion factor of 12, corresponding to an observed convolved source size of 1.4", i.e., unresolved by our beam; this is a valid assumption, as the line fluxes integrated over the source are found to correspond well to the peak fluxes per beam). The detection of the $K = 4$ and 5 lines ($E_r = 183$ and 247 K) suggest a temperature of more than 100 K, and their brightness with respect to the lower $K$ lines limits the temperature to less than 200 K. The $K = 0, 1, 2,$ and 3 lines are of similar brightness.
brightness, which suggests that they are somewhat optically thick (for the adopted temperature range, the $K = 3$ line [$E_u = 133$ K] should be clearly brighter than the $K = 2$ line if it is optically thin, due to its high statistical weight). The observed line intensities then imply a CH$_3$CN column density of the order of a few times $10^{15}$ cm$^{-2}$ and a source size of the order of 0.4", i.e., 150–200 AU. This is significantly smaller and somewhat cooler than the CH$_3$CN emission regions found in hot cores in massive star-forming regions [e.g., W3(H$_2$O); Chen et al. 2006] but is comparable to the hot "corinos" that have now been found in a handful of other low-mass protostars (e.g., Bottinelli et al. 2004; Jørgensen et al. 2005).

3.2.4. Evidence for a Rotating Disk in L1641-N MM1

In Figure 10 (left) the positions of the emission maxima, as derived from Gaussian fits, are plotted for individual 1.2 km s$^{-1}$ wide channels for the CH$_3$CN $K = 0, 1, 2,$ and 3 lines and the OCS line. Only channels in which emission above 5 $\sigma$ is seen are used. We choose to use only CH$_3$CN and OCS lines in this plot, as it is in these molecules that we see the least contamination by outflow-related emission.

Overall, the positions of the emission maxima define a southeast-to-northwest-oriented elongated structure (P.A. $\sim 120^\circ$). This is unlikely to be the result of positional measurement errors, as this would tend to produce a distribution that is elongated along the beam's major axis, which is at a P.A. of about 75°. There is a clear trend for the lower velocity center positions to cluster to the southeast of the L1641-N MM1 central position and the higher velocity positions to be found to its northwest. To illustrate this further, Figure 10 (right) shows the channel velocities as a function of the offset along the disk plane. Although the positional errors are larger than the offsets, a trend for velocities increasing from southeast to northwest is consistently seen in all transitions. Clearly, better data are needed to confirm this observation.

We tentatively suggest that the positional arrangement of the emission maxima indicates a flattened structure around the protostellar source embedded in L1641-N MM1; a similar result has been obtained by Cesaroni et al. (1997, 1999) for the intermediate-mass protostar IRAS 20126+4104 and has been interpreted as evidence for a circumstellar disk. The velocity gradient hints at rotation, with a rotation axis that is roughly parallel to the axis of the outflow from L1641-N MM1. This would imply that the CH$_3$CN and OCS emission arises from grain mantle evaporation in a heated disk rather than the dense, infalling envelope. However, higher angular resolution observations resolving the source are required to definitively discriminate between these scenarios (is it spherical or flattened?). Also, neither the angular resolution, the velocity resolution, nor the sensitivity of our data are good enough to derive estimates of the central object’s mass or the size of the disk.

4. SUMMARY AND DISCUSSION

We have presented new 1.3 mm dust continuum and molecular line observations of the L1641-N cluster area. Single-dish wide-field CO mapping revealed the presence of several blueshifted and redshifted outflow lobes, which can be grouped into at least four bipolar flows: a north-south-oriented giant outflow, B-N/R-S, driven most likely by AN04 ISO source 18; a shorter northeast-to-southwest-oriented outflow, B-NE/R-W, driven by the dominant millimeter continuum source in the cluster center; another parsec-scale outflow, B-E/R-E/R-SW, corresponding to H$_2$ outflow 51 of SMZ02, driven by an embedded ISO and millimeter source east of the cluster center; and a small flow, B-SE/R-SE, driven by a near-infrared star southeast of the cluster center. Moreover, some CO outflow activity might also be associated with the Strom 11 group farther southeast of the L1641-N cluster center (B-SE2).

The SMA observations show that there are in fact two deeply embedded sources in the very cluster center, L1641-N MM1 and L1641-N MM3, each of which drives a CO outflow, which together make up the B-NE/R-W outflow; L1641-N MM1 is at the center of two cavity-shaped outflow lobes seen at moderate CO velocities, and L1641-N MM3 drives a collimated, faint jet seen only at high velocities. The flow from L1641-N MM1 carries more mass, as only this flow is seen in the optically thin $^{13}$CO. We find $^{13}$CO, C$^{18}$O, and $^{13}$CS emission tracing the core from which L1641-N MM1 and L1641-N MM3 are forming, CH$_3$OH and SO emission tracing the protostellar sources L1641-N MM1 and L1641-N MM3, as well as their outflows, and OCS and CH$_3$CN emission from L1641-N MM1. Analysis of the CH$_3$CN($J = 12–11$) ($K = 0$ to 5) lines suggests that the emitting gas traces a compact (100–200 AU), warm (100–200 K) region deep inside the L1641-N MM1 envelope. This could be the warm, innermost portion of the infalling envelope, i.e., a hot corino, as seen in other low-mass protostars. Alternatively, it may be the heated surface layer of a disk, as suggested by our tentative detection of a velocity gradient over the CH$_3$CN source perpendicular to the L1641-N MM1 outflow axis.

Widespread CO line-wing emission is seen over virtually the entire cluster core area. In total, we estimate that a few solar masses of molecular gas have been set in motion. This estimate does not include corrections for optical depth effects or outflow gas having low radial velocities, however, so the total outflow mass might well be larger by a factor of $\sim$10. The flows are estimated to carry $\sim$16 $M_\odot$ km s$^{-1}$ of momentum and a kinetic energy of $75 M_\odot$ km$^2$ s$^{-2}$, which are also lower limits; correcting the mass for optical depth and for CO with $^{13}$CO yields $8 M_\odot$ km$^2$ s$^{-2}$.

In clusters of low-mass stars, protostellar outflows can impart a significant amount of energy and momentum into their surroundings and, perhaps, thereby regulate the star formation rate (Norman & Silk 1980; Matzner & McKee 2000; Li & Nakamura 2006). They may also play an important role in replenishing turbulence, which hydrodynamic, as well as magnetohydrodynamic, simulations suggest decays on timescales comparable to a cloud’s free-fall timescale $T_f = (3\pi/32G)^{1/2}$ (e.g., MacLow 1999). In order to maintain turbulence, kinetic energy and momentum have to be provided by the flow at a high enough rate to compensate for the loss due to the decay of turbulence.

The mass of the L1641-N cluster-forming core is a few times $100 M_\odot$ (Reipurth et al. 1998; Tatematsu et al. 1993), a certain part of which is in the still inactive "tail" extending southeast of L1641-N/Strom 11; the actual mass involved in directly building the L1641-N cloud core may be up to the $200 M_\odot$, as estimated to carry $\sim 16 M_\odot$ km s$^{-1}$ of momentum and a kinetic energy of $75 M_\odot$ km$^2$ s$^{-2}$.

Using a cloud radius of about 0.5 pc (estimated from the map shown by Reipurth et al. 1998) and a mass $M_{\rm core}$ of $200 M_\odot$, yields $T_f = 4.1 \times 10^5$ yr. We estimate a one-dimensional velocity dispersion $\sigma_{1D}$ of 0.94 km s$^{-1}$ for the L1641-N cloud core based on the addition (in quadrature) of the intrinsic core dispersions of $0.72$ km s$^{-1}$ and core-core motion of $0.6$ km s$^{-1}$ in Tatematsu et al. (1993); cores 67 and 69). The rate $L_{\rm turb} = E_{\rm turb}/\tau_f$ at which kinetic energy is lost due to decaying turbulence is then estimated to be $0.1 L_\odot$ (where $E_{\rm turb} = 3/2M_{\rm core}\sigma_{1D}^2$).

The momentum available in the CO flows has the potential to add significant motions to the cloud core. If the forward momentum were completely transferred to the $200 M_\odot$ of core gas, it would accelerate it by at least $\sim 0.1$ km s$^{-1}$ and possibly up to the
cloud velocity dispersion with the corrections mentioned above. In addition, sideways motions can be excited, which does not affect the flow’s forward-oriented momentum. In terms of energy supply, even the (lower limit on) \( L_{\text{mech}} \) of 1.21 \( L_\odot \) is greater than \( L_{\text{turb}} \). However, a large fraction of that can be expected to be dissipated in shocks.

The rate \( L_{\text{gain}} \) at which the cloud gas gains energy, taking into account radiative losses, can be estimated as follows: we assume that all of the outflow forward momentum is dumped in the clump and used to drive the turbulence, and that the outflows accelerate a fraction \( M_{\text{c}} \) of the clump’s mass to a velocity equal to the clump’s three-dimensional velocity dispersion \( \sigma_{3D} \). The clump mass set in motion per unit time is then \( M_{\text{c}} = F_{\text{out}} / \sigma_{3D} \), where \( F_{\text{out}} \) is the sum of the outflow momentum input rates. Therefore,

\[
L_{\text{gain}} = \frac{1}{2} M_{\text{c}} \sigma^2_{3D} = \frac{\sqrt{3}}{2} F_{\text{out}} \sigma_{1D},
\]

where \( \sigma_{1D} \) is the observed one-dimensional velocity dispersion. With \( \sigma_{1D} = 0.94 \text{ km s}^{-1} \) and a sum of the outflow momentum rates of \( F_{\text{out}} = 13.6 \times 10^{-4} M_\odot \text{ km s}^{-1} \text{ yr}^{-1} \) from Table 1, the energy gain rate is \( L_{\text{gain}} \sim 0.18 L_\odot \). This result is comparable to the estimate of the cloud’s rate of energy loss \( L_{\text{turb}} \sim 0.1 L_\odot \), particularly if we keep in mind that the outflow mass and velocity measurements are lower limits due to optical depth and projection, respectively. The above calculation indicates that the molecular outflows can indeed provide sufficient energy and momentum to sustain cloud turbulence.

Protopstellar outflows are known to be collimated. In regions forming only a small number of isolated and well-separated protostars, the outflows will only affect a small fraction of the total cloud volume, and their impact is therefore relatively small. However, in regions of clustered star formation, the protostellar density is higher and a larger fraction of the cloud volume will be affected. We have found widespread CO line-wing emission in L1641-N, indicating that the presence of several CO outflows does affect a significant volume of the cluster core. In NGC 1333, Quillen et al. (2005) found a system of cavities permeating the cloud and suggested that, if these are relic outflow events, then \( \sim 10\% \) of the cloud is affected. Williams et al. (2003) found that most of the CO line-wing emission in the OMC-2 and OMC-3 star-forming regions is in broadly dispersed, extended features, which also suggests that a large fraction of the cloud volume is affected by outflows. From the small fraction of the high-velocity emission in young, compact outflows, and using a calculation similar to that above, they also estimated that the energy injection rate was sufficient to maintain cloud turbulence.

L1641-N, NGC 1333, and OMC-2 and OMC-3 are regions forming modest-sized clusters of a few tens to hundreds of stars. In the case of L1641-N, Hodapp & Deane (1993) showed that star formation has been going on for about \( 10^6 \text{ yr} \) at two to three stars every \( 10^5 \text{ yr} \). Assuming that protostars drive powerful CO outflows over the first \( (1-2) \times 10^5 \text{ yr} \) of their evolution, the five CO outflows we found in the region suggest that star formation is continuing at a similar pace. NGC 1333 also shows evidence for star formation over million-year timescales (Lada et al. 1996), which is still going on, and even the IC 348 cluster might still be in the build-up phase (Eislöffel et al. 2003). These modest-sized cluster-forming regions typically feature a handful to one to two dozen energetic outflows. Assuming that the formation of a more massive cluster (a few thousand or 10,000 stars) also proceeds more or less steadily over a few million years rather than in one short burst, one can expect that at any time there are many tens or hundreds of stars in their youngest evolutionary stage and driving very energetic outflows. It can then be expected that virtually the entire cluster volume is affected by outflow activity.

The action of a population of outflows from low-mass protostars might also have consequences for high-mass star formation. In the “turbulent core” scenario (e.g., McKee & Tan 2003), massive stars form from high-density cores formed within a high-pressure, turbulent clump. Accretion rates are high enough to overcome the radiation pressure of the central object. The formation timescale \( t_{\text{sf}} \) is comparable to the free-fall timescale of the surrounding clump, i.e., to the timescale of turbulence decay. Hence, it might not really be crucial to maintain the turbulence while the massive star forms. But it might be a prerequisite to keep the turbulence in the high-pressure environment until the massive star-forming core has formed and reached the point at which it starts to collapse.

The “competitive accretion” scenario (e.g., Bonnell et al. 2001) requires gas to fall into the central region of a forming cluster, allowing the protostars to grow beyond the masses of their original envelopes. This inflow might be counteracted by outflows from the protostars in the cluster center. Furthermore, Krumholz et al. (2005) claim that competitive accretion and collisional growth of protostars (Bonnell et al. 1998) require efficient removal of kinetic energy from the cluster-forming gas, which could also be prevented by low-mass protostar outflows.

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REFERENCES

Ali, B., & Noriega-Crespo, A. 2004, ApJ, 613, 374 (AN04)
Bally, J., Lich, D., Smith, N., & Walawender, J. 2006, AJ, 131, 473
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 2001, MNRAS, 323, 785
Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93
Bottinelli, S., Cecarelli, C., Williams, J. P., & Loefloch, B. 2007, A&A, 463, 601
Bottinelli, S., et al. 2004, ApJ, 617, L69
Cesaroni, R., Felli, M., Jennes, T., Neri, R., Olmi, L., Robberto, M., Testi, L., & Walmsley, C. M. 1999, A&A, 345, 949
Cesaroni, R., Felli, M., Testi, L., Walmsley, C. M., & Olmi, L. 1997, A&A, 325, 725
Chen, H., Tokunaga, A. T., Strom, K. M., & Hodapp, K.-W. 1993, ApJ, 407, 639
Chen, H., Zhao, J. H., & Ohashi, N. 1995, ApJ, 450, L71
Chen, H., Zhao, J. H., Ohashi, N., & Unemoto, T. 1996, AJ, 112, 717
Chen, H.-R., Welch, W. J., Wilner, D. J., & Sutton, E. C. 2006, ApJ, 639, 975
Chini, R., Ward-Thompson, D., Kirk, J. M., Nielbock, M., Reipurth, B., & Sievers, A. 2001, A&A, 369, 155
Cunningham, A. J., Frank, A., & Blackman, E. G. 2006, ApJ, 646, 1059
Davis, C. J., & Eislöffel, J. 1995, A&A, 300, 851
Eislöffel, J., Froebrich, D., Stanke, T., & McCaughrean, M. J. 2003, ApJ, 595, 259
Fendt, Ch., & Zinnecker, H. 1998, A&A, 334, 750
Fukui, Y., Sugitani, K., Takaba, H., Iwata, T., Mizuno, A., Ogawa, H., & Kawabata, K. 1986, ApJ, 311, L85
Fukui, Y., Takaba, H., Iwata, T., & Mizuno, A. 1988, ApJ, 325, L13
