Detection of Methanol in a Class 0 Protostellar Disk

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ABSTRACT

We report the detection of emission from methanol in a compact source coincident with the position of the L1157 infrared source, which we attribute to molecules in the **disk** surrounding this young, Class 0 protostellar object. In addition, we identify a spectral feature in the outflow corresponding to an ethanol transition. Using the Caltech Owens Valley Millimeter Array with a synthesized beam size of 2″, we detect spatially unresolved methanol in the $2_k - 1_k$ transitions at 3mm, which is coincident in position with the peak of the continuum emission. The gas phase methanol could be located in the central region ($< 100\ AU$ radius) of a flat disk, or in an extended heated surface layer ($\sim 200\ AU$ radius) of a flared disk. The fractional abundance of methanol $X(CH_3OH)$ is $\sim 2\times10^{-8}$ in the flat disk model, and $\sim 3\times10^{-7}$ for the flared disk. The fractional abundance is small in the disk as a whole, but considerably larger in the warm portions. This difference indicates that substantial chemical processing probably takes place in the disk via depletion and desorption.

protostars

Subject headings: Stars: **pre-main sequence** – individual (**L1157**): ISM: molecules – individual (**methanol**)

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1. Introduction

Protostellar disks represent an early stage in the planet formation process. These disks have been studied with interferometric observations to trace their structure, temperature, and chemical composition. Observations to date confirm that at the high densities and low temperatures present in disks, most of the molecules which are readily observable in pre-protostellar cores are depleted onto grains to a significant degree (Blake, van Dishoeck, & Sargent 1992; Dutrey, Guilloteau, & Guélin 1997). Chemical models predict that some of these species are in the gas phase only in the innermost warm regions of the disk (Aikawa *et al.* 1997, Willacy *et al.* 1998). One of the most abundant and chemically important molecules in the ISM is methanol (CH_3OH). This molecular species is observed in both the gas phase (*e.g.* Menten *et al.* 1988; Kalenskii *et al.* 1997; Turner 1998) and frozen on grain surfaces (Dartois *et. al.* 1999).

The L1157 molecular cloud contains the infrared source IRAS 20386+6751, which has an associated bipolar outflow (Umemoto *et al.* 1992; Gueth, Guilloteau, & Bachiller 1996). This object, at a distance of $\simeq$ 440 *pc* (Umemoto *et al.* 1992), has a bolometric luminosity of $\simeq 11L_\odot$ (Gueth *et al.* 1997). The infrared spectral energy distribution is characteristic of a Class 0 source, indicating that it is a young stellar object at an early evolutionary stage. The abundances of methanol (Bachiller *et al.* 1995; Avery & Chiao 1996), ammonia (Tafalla & Bachiller 1995), SiO (Gueth, Guilloteau, & Bachiller 1998; Zhang *et al.* 1995), and other species (Bachiller & Pérez Gutiérrez 1997) have been observed to be dramatically enhanced in the bow shocks of outflows including L1157, as would be expected if these molecular species were being desorbed from the surfaces of dust grains (Charnley, Tielens, & Millar 1992). IR absorption measured with the ISO satellite indicate that CH_3OH is a very abundant ice species towards massive protostars (Dartois *et. al.* 1999), and this is likely to be true towards low mass protostars such as L1157. Thus we can expect that the disk is formed from material with abundant ices on the dust grains. An important question for protostellar chemistry is whether these ice mantles are released into the gas phase in the disk, or whether the molecules remain frozen on the dust grain surfaces. To address this issue we have carried out methanol observations at 3 mm, and in this *Letter* report the first detection of methanol in the disk surrounding a young, protostellar object, as well as a spectral feature in the outflow corresponding to ethanol.

2. Observations and Analysis

The results presented here are based on observations made in 1997-98 with the Owens Valley Radio Observatory Millimeter Array (OVRO–MMA) which is operated by the

California Institute of Technology. Observations were made at 3 mm wavelength using the six antennas in the low–, high–, and ultra high–resolution configurations. The total integration time was 36 hours. We used a central observing frequency of 96.748 GHz and a total correlator bandwidth of 31.3 MHz in 96 channels of 1.0 $km\ s^{-1}$velocity resolution to include four CH_3OH transitions (see Table 1). Simultaneously with the spectral line observations, we obtained continuum data using a 1 GHz bandwidth. We observed the radio source 1928+738 for gain and phase calibration, together with 3C273 and a noise source for bandpass phase and amplitude calibration. The raw visibility data were calibrated using software specific to OVRO–MMA (Scoville *et al.* 1993), and the final maps were made using AIPS.

Figure 1 shows spectra derived from the channel maps obtained with a synthesized 2″ FWHM Gaussian beam at a peak in the blue shifted outflow lobe and at the continuum peak. The position of this local maximum is identified in the upper left panel of Figure 2, and is approximately coincident with peak B1 in the ammonia outflow (Tafalla & Bachiller 1995). The methanol lines in the outflow spectrum shown in the upper panel of Figure 1 are much stronger than those from the protostellar disk, are blue shifted in velocity, and exhibit broad line widths characteristic of bipolar outflows. Here we focus on the disk emission.

At the central position, the continuum emission from the disk is clearly visible, with a flux density of 15 mJy, as is the $2_0 - 1_0$ transition of A–type methanol. Table 1 gives key characteristics of the observed transitions. The three transitions of E–type CH_3OH are individually marginally detected, but when combined yield a statistically significant detection. These disk features all have narrow line widths of $\sim$ 2 $km\ s^{-1}$. The peak flux density of the $2_0 - 1_0$ A–type transition is 29 mJy (above the continuum) which yields T_b = 1.0 K, while the integrated intensity is 2 $K\ km\ s^{-1}$.

In the blue shifted outflow lobe another spectral feature is clearly detected at 96.750 GHz, which is coincident in frequency with the 16(1,16) - 16(0,16) transition of ethanol (CH_3CH_2OH). There is a hint of this emission feature in the disk, but additional observations are required to confirm it.

Figure 2 presents maps of the velocity integrated emission and individual velocity channel maps for the strongest line, the $2_0 - 1_0$ transition of A–type methanol. The continuum emission from the disk is included, but does not make a significant contribution within the 1 $km\ s^{-1}$ channel widths. The disk emission is visible only in the channels centered at 2.6 and 3.6 $km\ s^{-1}$. This feature appears quite distinct from the outflow lobes, and is spatially unresolved ($\leq$ 440 AU diameter, corresponding to one half the synthesized beam size).

Figure 3 summarizes the disk emission as traced by the two species of methanol and the continuum. Our higher spatial resolution continuum map is generally similar to that of

Gueth *et al.* (1997). We find a compact source of size < 2″, or 880 AU diameter, together with low level emission (∼ 4″ by 6″) extended along the outflow axis. The A– and E– type methanol maps (with the dust continuum subtracted) show a compact source centered exactly at the peak of the continuum emission.

Analysis of methanol emission from a protostellar disk is simplified by the high density expected in such a region. The observed 3mm methanol transitions have critical densities $n_c \approx 6 \times 10^4\ cm^{-3}$ (Goldsmith & Langer 1999). Our statistical equilibrium calculations indicate that $n \simeq 10^7\ cm^{-3}$ is required to bring the upper level fractional populations close to LTE. The central portions of protostellar disks are dense enough (Guilloteau & Dutrey 1998; Chiang & Goldreich 1997), so the observed CH_3OH transitions will be thermalized for radii r $\leq$ 400 AU, and the upper level populations will be in LTE at radii $\leq$ 250 AU. These distances are only slightly smaller than our beam (radius of 440 AU at the distance of L1157). The dust temperature and the kinetic temperature will be closely coupled in the inner portions of the disk.

It is reasonable to assume LTE level populations in the warm region of the disk where the methanol is in the gas phase. Assuming that the CH_3OH emission is optically thin, we calculate the upper level column density appropriate for a source filling the beam from the usual formula (*e.g.* Goldsmith & Langer 1999) $N_u = 8\pi k\nu^2 W/hc^3 A_{ul}$, where W is the integrated line intensity in $K\ km\ s^{-1}$. For the 2_0 – 1_0 (A) transition with W = 2 $K\ km\ s^{-1}$, $N_{2_0} = 1.1{\times}10^{13}\ cm^{-2}$. We have computed the partition function from a statistical equilibrium code, and find that Z = $0.35T^{1.57}$ for temperatures between 10 K and 60 K (see also Lees 1973; Townes & Schawlow 1975). At a temperature of 50 K, which is a reasonable value for the portion of the disk where methanol is predominantly in the gas phase, the total column density of A– type methanol is $4{\times}10^{14}\ cm^{-2}$. The solid angle of the synthesized beam is $1.1{\times}10^{-10} sr$, and the total number of observed gas phase methanol molecules in the disk is $1.6{\times}10^{47}$, assuming equal amounts of A– and E– type CH_3OH.

The continuum emission is somewhat extended relative to our beam, unlike the methanol emission which looks essentially point like. The peak continuum flux density with our 2″ FWHM beam is 17 mJy, while the total in a deconvolved source size of 1.6″ is 30 mJy. Using the same mass absorption coefficient as Gueth *et al.* (1997) yields a similar mass of 0.3 $M_\odot$, but this may well be a lower limit if smaller values of K apply (*cf.* values given in Goldsmith, Bergin, & Lis 1998). If the methanol is uniformly mixed throughout the entire observed disk, the fractional abundance of this species relative to molecular hydrogen is X(CH_3OH) = $8{\times}10^{-10}$. However, based on chemical and thermal models of circumstellar disks, we expect gas phase methanol to be limited to the warmer disk material within a much smaller volume, making this fractional abundance estimate a lower limit.

3. Discussion

The varying temperature within a circumstellar disk will almost certainly have a major effect on the distribution of the gas phase methanol, due to the very significant issue of depletion of this species onto dust grains. The details depend on the assumed binding energy (BE) of the molecules to the grain surface and the temperature profile of grains within the disk. Willacy *et al.* (1998) model the chemistry in the midplane of a flat disk. Using the larger BE value of Sandford & Allamandola (1993) they find that dust temperature must be $\geq 90\ K$ to have gas phase CH_3OH. If the smaller BE calculated by Hasagawa & Herbst (1993) is used, then CH_3OH should be present where the dust temperature $\geq 40\ K$. Together with the dust temperature distribution within the disk, this temperature dependent depletion–desorption will determine the effective source size of gas phase methanol.

Our observations directly constrain the source size to be $\leq 880\ AU$, but it is plausible that the source size is much smaller, given expected disk temperature distributions. For a uniform circular source of radius a(AU), the source temperature is given by $T_s = 1.4T_b(440/a)^2$, where T_b is the observed peak main beam brightness temperature of the emission line, which is $\simeq 1\ K$ for the 2_0-1_0 CH_3OH (A) transition. Our data indicate that the methanol emission is optically thin, and certainly not optically thick. This is because even if the abundance of the E– species is somewhat less than that of the A–species (as suggested by *e.g.* Menten *et al.* 1988; Turner 1998), a high optical depth would produce roughly equal fluxes for the same transitions of the two species, which is not what is observed. Hence, we also require a solution in which the methanol optical depth is less than unity. We can thus set a lower limit to the source size, since if the source size is too small, the implied source temperature (T_s) will significantly exceed the expected dust temperature, which contradicts the assumption of equal dust and gas temperatures discussed above. Rather, we require a solution in which the dust temperature exceeds the brightness temperature, corrected for beam dilution, which allows for optically thin methanol emission.

Models of flat disks heated primarily by radiation from a 1 $L_\odot$ central star (*e.g.* Backman & Paresce 1993; Cantó, D'Allesio, & Lizano 1995; Chiang & Goldreich 1997) offer no solutions consistent with our data. If we use a somewhat higher central source luminosity of 11 $L_\odot$, the dust temperature given by Backman & Paresce (1993) allows solutions with source radius a $\geq 65\ AU$, for which value the dust temperature and the source brightness temperature are both close to 60 K. For a source radius of 100 AU, the dust temperature is approximately 50 K and the brightness temperature is 27 K, consistent with moderate optical depth. For a relatively low BE for methanol, this model is fully consistent with our data, and the dilution factor of the methanol emission is approximately a factor of 30, yielding a fractional abundance X(CH_3OH) = 2×10^{-8} within the 100 AU radius. This value is considerably less than that observed to be frozen onto grains along the line of sight to higher–luminosity embedded IR sources (*e.g.* Dartois *et. al.* 1999).

For a flared disk, the stellar optical radiation directly heats a thin absorbing layer (A_v $\sim 1 - 2$ mag). In consequence, the temperature in the surface layers of flared disks is considerably larger than in the midplane at the same distance from the star (Kenyon & Hartmann 1987; Chiang & Goldreich 1997). Chiang & Goldreich find temperatures in the surface layer above 90 K within $\sim$ 100 AU of low mass protostars, and $>$ 50 K out to 300 AU. The fraction of the disk mass in the warm surface layer in this model is about 0.003, implying that in this region of the disk, the fractional abundance of methanol is $\sim 3\times10^{-7}$. This value is consistent with those estimated by Bachiller *et al.* (1995) in the shock layer of the outflow, $X(CH_3OH) = 10^{-7}$ to 10^{-6}. The methanol desorbed from the grains in the warm surface layers returns to the icy grain mantles in the cooler interior of the disk, where it is available to become part of the composition of solar-like bodies, such as comets, formed in the outer circumstellar region. This first millimeter–wavelength detection of a complex organic molecule in a young protostellar disk has implications for disk structure and chemical evolution. The CH_3OH fractional abundance in the disk as a whole is small, but it is considerably higher in the warm portions of the disk. This difference indicates that substantial chemical processing, desorption and depletion, takes place in the evolution of material in the disk.

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REFERENCES

Aikawa, Y., Umebayashi, T., Nakano, T., & Miyama, S. 1997, ApJ, 486, L51.

Avery, L.W. & Chiao, M. 1996, ApJ, 463, 642

Bachiller, R., Liechti, S., Walmsley, C.M., & Colomer, F. 1995, A&A, 295, L51

Bachiller, R. & Pérez Gutiérrez, M. 1997, ApJ, 487, L93

Backman, D.E. & Paresce, F. 1993, Protostars and Planets III, eds. E. H. Levy and J. I. Lunine, (Tucson: Univ. of Arizona Press), p.1253

Blake, G.A., van Dishoeck, E.F., & Sargent, A.L. 1992, ApJ, 391, L99

Cantó, J., D'Alessio, P., & Lizano, S. 1995, RevMexAA (Serie de Conferencias), 1, 217

Charnley, S.B., Tielens, A.G.G.N., & Millar, T.J. 1992, ApJ, 399, L71

Chiang, E.I. & Goldreich, P. 1997 ApJ, 490, 368

Dartois, E., Schutte, W., Geballe, T.R., Demyk, K., Ehrenfreund, P. & d'Hendecourt, L. 1999, A&A, 342, L32.

Dutrey, A., Guilloteau, S., & Guélin, M. 1997, A&A, 317, L55

Goldsmith, P.F., Bergin, E.A., & Lis, D.C. 1998, ApJ, 491, 615

Goldsmith, P.F. & Langer, W.D. 1999, ApJ, May 1999

Gueth, F., Guilloteau, S., & Bachiller, R. 1996, A&A, 307, 891

Gueth, F., Guilloteau, S., Dutrey, A., & Bachiller, R. 1997, A&A, 323, 943

Gueth, F., Guilloteau, S., & Bachiller, R. 1998, A&A, 333, 287

Hasagawa, T. I. & Herbst, E. 1997, MNRAS, 261, 83

Kalenskii, S.V., Dzura, A.M., Booth, R.S., Winnberg, A., & Alakoz, A. 1997, A&A, 321, 311

Kenyon, S.J. & Hartmann, L. 1987, ApJ, 323, 714

Lees, R.M. 1973, ApJ, 184, 763

Menten, K.M., Walmsley, C.M., Henkel, C., & Wilson, T.L. 1988, A&A, 198, 253

Sandford, S.A. & Allamandola, L.J. 1993, ApJ, 417, 815

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

Tafalla, M., & Bachiller, R. 1995, ApJ, 443, L37

Townes, C.H. & Schawlow, A.L. 1975, Microwave Spectroscopy (New York: Dover) 101

Turner, B.E. 1998, ApJ, 501, 731

Umemoto, T., Iwata, T., Fukui, Y., Mikami, H., Yamamoto, S., Kameya, O. & Hirano, N. 1992, ApJ, 392, L83

Willacy, K., Klahr, H.H., Millar, T.J., & Henning, Th. 1998, A&A, 338, 995

Zhang, Q., Ho, P.T.P., Wright, M.C.H., & Willner, D.J. 1995, ApJ, 451, L71

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TABLE 1

TRANSITIONS AND OBSERVED LINE PARAMETERS

Species and Transition	Frequency (GHz)	E_{upper} (K)	A_{ul} (s^{-1})	Observed T_b (K)[1] Outflow[2]	Disk
Methanol					
$2_{-1} - 1_{-1}$ (E)	96.7394	7.9	2.5×10^{-6}	2.24 ±0.2	0.25 ±0.2
$2_0 - 1_0$ (A)	96.7414	7.0	3.3×10^{-6}	4.27 ±0.2	0.95 ±0.2
$2_0 - 1_0$ (E)	96.7446	13.1	3.3×10^{-6}	1.24 ±0.2	0.45 ±0.2
$2_1 - 1_1$ (E)	96.7555	18.7	2.6×10^{-6}	0.54 ± 0.2	0.35 ±0.2
Average E – Type	-	-	-	1.34 ± 0.12	0.35 ±0.12
Ethanol					
16(1,16) – 16(0,16)	96.7504			0.93 ±0.2	0.27±0.2

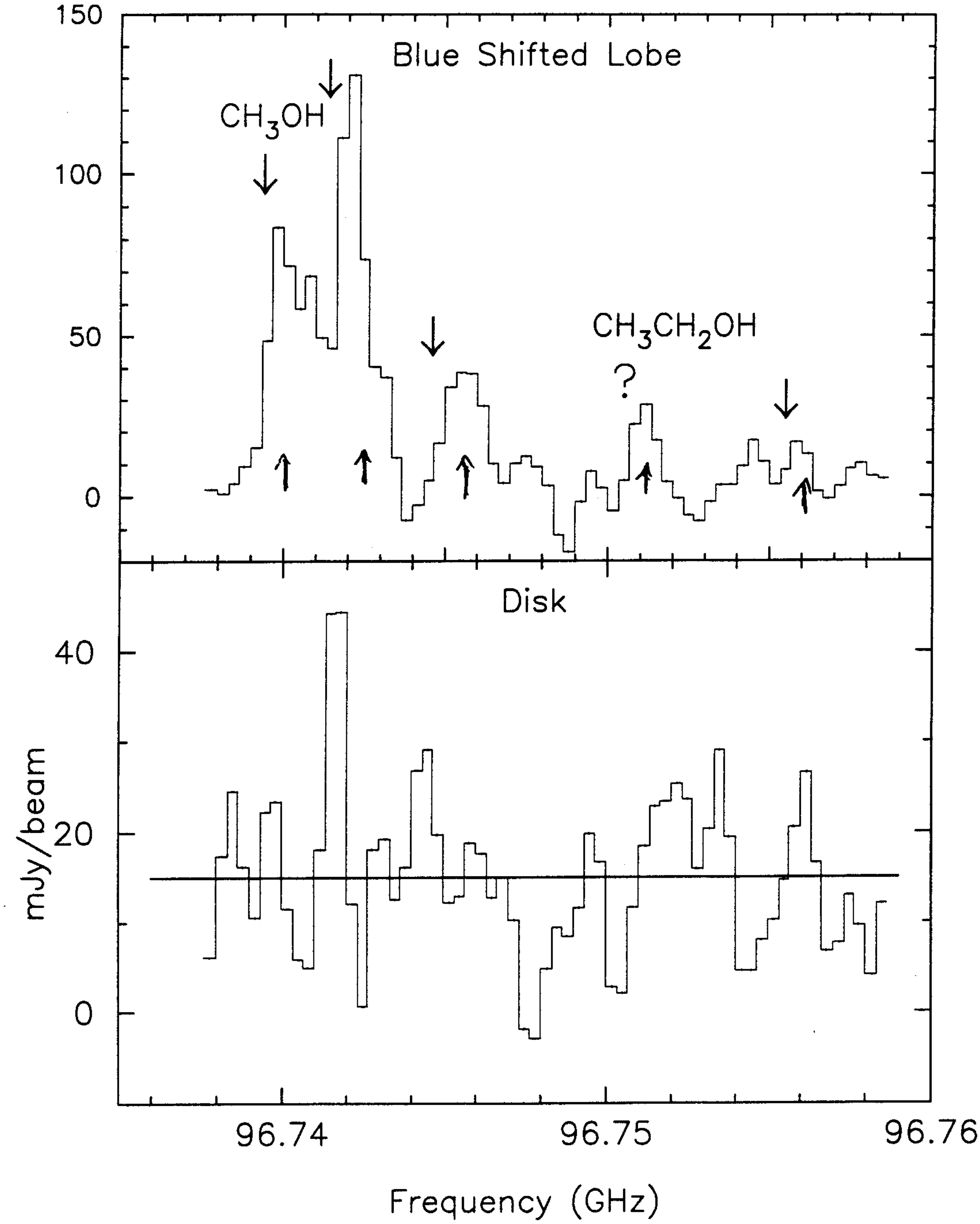
[1] Averaged over half beam area ($1'' \times 1''$) at the peak positions.

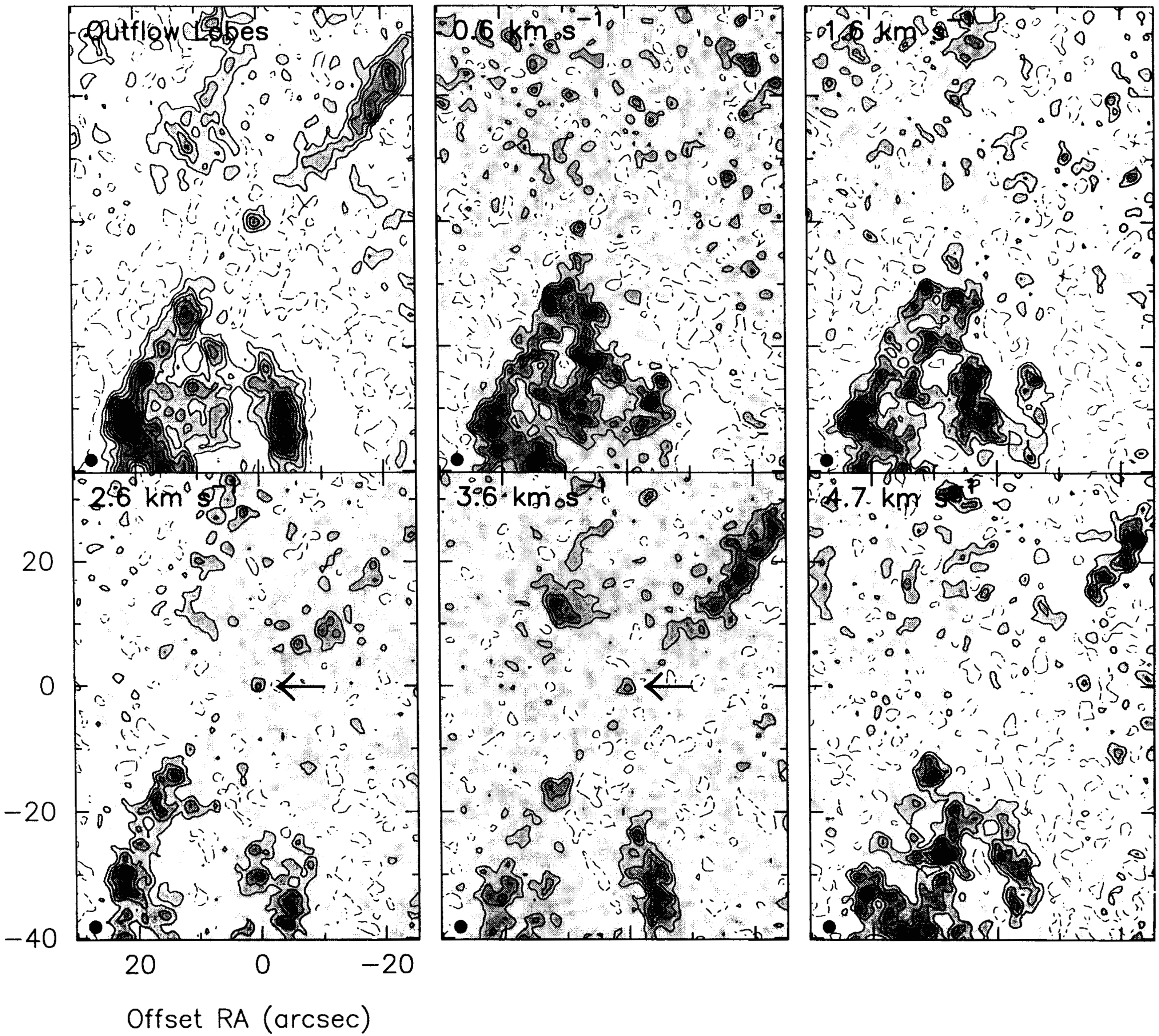
[2] At the peak of the blue-shifted lobe as marked in Fig.2. The line intensities are estimates and are uncorrected for the blending of different transitions.

Fig. 1.— Methanol spectra in L1157 in 2″ FWHM Gaussian synthesized beams with 1 $km\ s^{-1}$ velocity resolution. Upper panel: spectrum of a peak in the blue–shifted outflow lobe, located 21.5″ east and 33″ south of the protostar and continuum emission peak (Fig. 2). The methanol transitions in this frequency band (see Table 1) are indicated by the arrows (at frequencies appropriate for source velocity V_{lsr} = 3 $km\ s^{-1}$), along with a possibly detected ethanol line. Lower panel: spectrum at the position of peak continuum emission at RA(1950) = $20^h38^m39^s.3$; decl(1950) = 67°51′35.5″. The dust continuum flux level (15 $mJy/beam$) from the disk is shown by the horizontal line. Only the $2_0 - 1_0$ (A) transition is clearly detected, although the presence of the E–type methanol is evident when the three transitions in this band are combined together, as discussed in the text and Table 1.

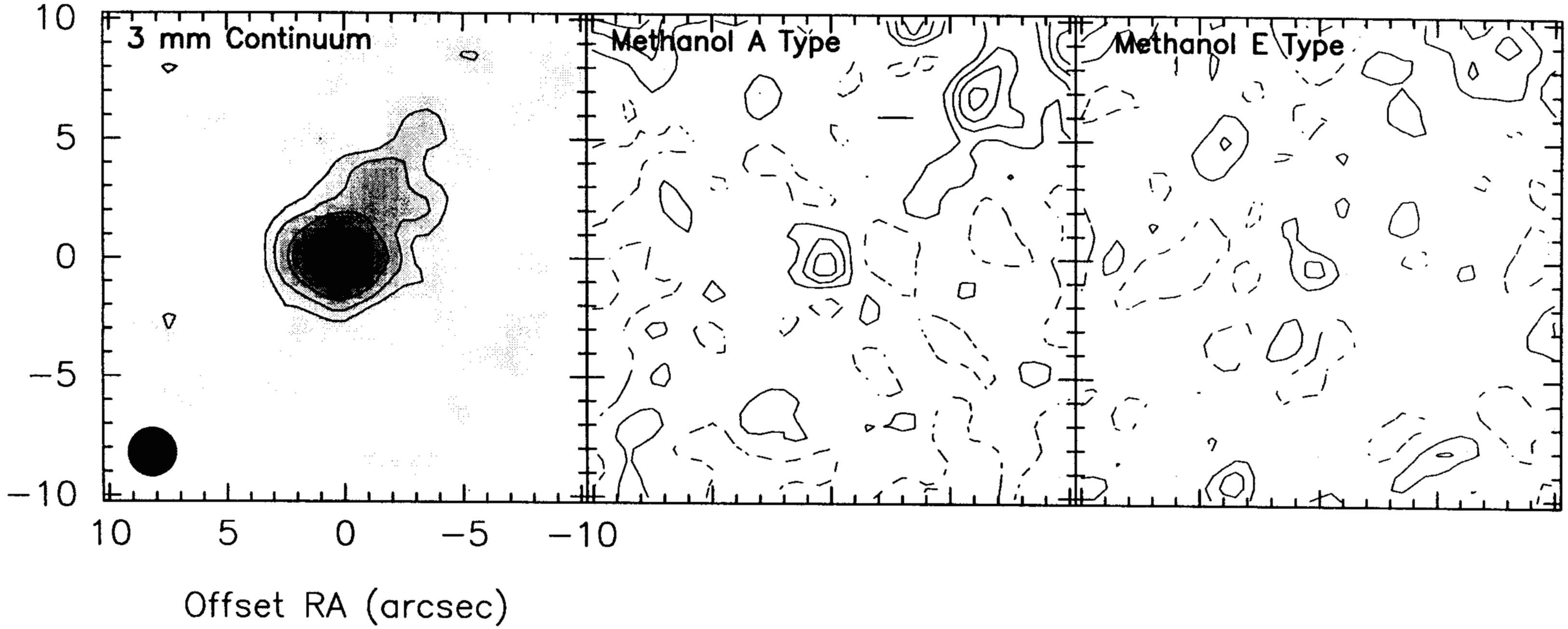
Fig. 2.— Velocity channel maps of $2_0 - 1_0$ A–type CH_3OH emission. The upper left panel is the emission integrated over all velocities. The arrow indicates the position of the protostar (and 3 mm continuum peak; see Fig. 3) having coordinates given in Fig. 1. The offsets from the central position are given in seconds of arc. The emission seen at the (0,0) position at the ambient cloud velocity (2.6 and 3.6 $km\ s^{-1}$ channels) originates in the disk. This component is spatially unresolved by the synthesized 2″ FWHM Gaussian beam indicated by the filled circles. The contour interval is 20 $mJy/beam$ and the rms noise in the map is 12 $mJy/beam$. The location of the peak emission in the blue-shifted outflow, where the spectrum in Fig. 1 was obtained, is marked by the cross.

Fig. 3.— Integrated intensity maps of the central 20″ region containing the protostellar disk and inner portion of the outflow. The continuum emission is displayed in the left hand panel, the emission in the $2_1 - 1_1$ transition of A–type methanol is shown in the central panel, and the emission summed over three E–type transitions is shown in the right hand panel. The dust continuum from the disk has been subtracted in the methanol line intensity maps. The rms fluxes in the methanol maps are 24 and 20 $mJy/beam\ km\ s^{-1}$ for A– and E–type methanol, respectively. The contour interval in the methanol maps is 24 $mJy/beam\ km\ s^{-1}$. The rms fluxes in the continuum map are 0.4 $mJy/beam$, and the contours are at levels of 1, 2, 4, 8, and 16 $mJy/beam$. The filled circle represents the beam size.


Blue Shifted Lobe
CH_3OH
CH_3CH_2OH
?
Disk
mJy/beam
150
100
50
0
40
20
0
96.74
96.75
96.76
Frequency (GHz)



Outflow Lobes
0.6 km s^{-1}
1.6 km s^{-1}
2.6 km s^{-1}
3.6 km s^{-1}
4.7 km s^{-1}
20
0
−20
−40
20
0
−20
Offset RA (arcsec)



3 mm Continuum
Methanol A Type
Methanol E Type
10
5
0
−5
−10
10
5
0
−5
−10
Offset RA (arcsec)