

ON THE IDENTIFICATION OF HIGH MASS STAR FORMING REGIONS USING IRAS: CONTAMINATION BY LOW-MASS PROTOSTARS

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ABSTRACT

We present the results of a survey of a small sample (14) of low-mass protostars ($L_{IR} < 10^3 L_{\odot}$) for 6.7 GHz methanol maser emission performed using the ATNF Parkes radio telescope. No new masers were discovered. We find that the lower luminosity limit for maser emission is near $10^3 L_{\odot}$, by comparison of the sources in our sample with previously detected methanol maser sources. We examine the IRAS properties of our sample and compare them with sources previously observed for methanol maser emission, almost all of which satisfy the Wood & Churchwell criterion for selecting candidate UCHII regions. We find that about half of our sample satisfy this criterion, and in addition almost all of this subgroup have integrated fluxes between 25 and 60 μm that are similar to sources with detectable methanol maser emission. By identifying a number of low-mass protostars in this work and from the literature that satisfy the Wood & Churchwell criterion for candidate UCHII regions, we show conclusively for the first time that the fainter flux end of their sample is contaminated by lower-mass non-ionizing sources, confirming the suggestion by van der Walt and Ramesh & Sridharan.

Subject headings: circumstellar matter – ISM: clouds – masers – stars: formation

1. INTRODUCTION

Through their stellar winds, UV radiation, molecular outflows, and eventual death as supernova, high mass stars ($M > 8M_{\odot}$, or earlier than B2) have a profound influence on their local environment and collectively on the Galaxy as a whole. The past 15 years has seen renewed interest in the study of high mass star formation (HMSF). This can be directly traced to three main factors: (1) the use of the IRAS catalog to identify large numbers of candidate HMSF regions, (2) the discovery of Class II methanol maser emission and its clear association with known regions of HMSF, and (3) improvements in both resolution and sensitivity at infrared and longer wavelengths. The recent realization that most stars form in dense clusters adds a new dimension to HMSF studies. Embedded clusters may be the basic unit of star formation (Lada & Lada 2003), many dominated by ionizing OB stars, so the study of the earliest stages of HMSF is of direct importance to star formation as a whole.

The IRAS Point Source Catalog (PSC; Beichman et al. 1985) has been used over the past ~ 15 years to define samples of candidate HMSF regions, in particular ultra-compact HII (UCHII) regions. Wood & Churchwell (1989, hereafter WC89) showed that known embedded O-stars (i.e., UCHII regions) occupy a tight region in IRAS color-color space, which is distinct from other sources that also possess rising spectral energy distributions (SEDs) in the far-infrared (FIR) and from the general population of PSC entries. This pioneering study has served as a starting point and guide for many subsequent studies of large numbers of HMSF regions. In particular, methanol maser and radio continuum surveys of sources selected using the WC89 criterion have identified nu-

merous UCHII regions (Schutte et al. 1993; van der Walt, Gaylard & MacLeod 1995; Walsh et al. 1997). More recently the WC89 criterion together with IRAS flux criteria and an absence of significant radio continuum emission (i.e., no associated UCHII) has been used to identify and study the supposedly younger high mass protostellar objects (HMPOs; Palla et al. 1991; Molinari et al. 1996; Sridharan et al. 2002). Hundreds of HMSF regions have now been identified and detailed studies of subsamples (Walsh et al. 1998, 1999, 2001; Phillips et al. 1998, Beuther et al. 2002a,b,c) and selected objects (Hunter, Phillips & Menten 1997; Hunter et al. 1998, 1999; Molinari et al. 1998; Zhang et al. 1999, 2001, 2002) have been made in recent years.

Maser transitions of methanol are now well established indicators of the early phases of HMSF (Ellingsen 2004). Favored pump mechanisms involve some degree of FIR radiative pumping, coupled with amplification of background HII region continuum radiation for the lower frequency transitions that exhibit high brightness temperatures (Sobolev, Cragg & Godfrey 1997; Cragg et al. 2001). The lower limit for the FIR luminosity for which the maser process can no longer occur is not well constrained observationally. This is partly due to the difficulty in measuring weak maser lines, and in establishing unbiased distances to masing sources. The establishment of the precise conditions under which maser processes occur, and when they are inactive, will assist in our understanding of the structure of star forming regions and the physical processes pertaining to them. In particular, the lower limit to the luminosity required to excite the most widely observed and strongest methanol maser transition at 6.7 GHz has not been established. Only one targeted survey toward known low

TABLE 1
 PROPERTIES OF THE LOW MASS PROTOSTARS OBSERVED FOR METHANOL MASER EMISSION.

NAME	ASSOCIATION	IRAS FLUXES (Jy)				DISTANCE (pc)	L_{IR} (L_{\odot})	WC89 ^a	[25-12]	[60-12]	$\log(F_{25-60})$
		12 μ m	25 μ m	60 μ m	100 μ m						
IRAS 08076-3556	CG 30	0.63	3.73	18.25	47.54	400 ^b	9	y	0.77	1.46	13.8
IRAS 08242-5050	HH 46/47	0.82	6.31	26.31	58.27	400 ^b	13	y	0.89	1.50	14.0
IRAS 08261-5100	BHR 41	0.91	2.50	4.29	10.91	400 ^b	4	n	0.44	0.67	13.4
IRAS 10501-5630	...	0.25L	1.43	8.1	36.1	3100 ^c	305	y	>0.76	>1.51	13.4
IRAS 11278-5940	...	1.32	1.72	4.6	37.3	4400 ^d	680	n	0.11	0.54	13.3
IRAS 11590-6452	BHR 71	0.25L	6.53	77.38	192.9	200 ^d	8	y	>1.42	>2.49	14.3
IRAS 13224-5928	BHR 87	1.20	2.35	8.19	37.21	1000 ^e	40	n	0.29	0.83	13.5
IRAS 16293-2422	L1689	0.25L	1.82	25.5	103.2	160 ^f	14	y	>0.86	>2.00	15.2
IRAS 16295-4452	Sa187	1.2	5.4	27.1	52.8	700 ^g	38	y	0.65	1.35	14.0
IRAS 16289-4449	HH 57	9.3	31.5	68.0	69.9	700 ^g	120	n	0.53	0.86	14.5
IRAS 17193-4319	BHR 140	0.25L	0.68	4.74	22.98	700 ^h	10	(y)	>0.43	>1.28	13.2
R CrA	...	127.6	228.2	627.0	1231.4	130 ⁱ	45	n	0.25	0.69	15.4
VV CrA	...	31.9	69.1	131.0	95.2	130 ⁱ	10	n	0.33	0.61	14.8
TY CrA	...	31.0	57.0	496.7	719.1	130 ⁱ	21	n	0.25	1.20	15.2

NOTE. — An “L” in the IRAS flux columns refers to an upper limit. Each L_{IR} value is the far infrared luminosity calculated as described in Casoli et al. 1986. Definitions for [25-12], [60-12] and $\log(F_{25-60})$ are in the text.

^aEntered in the WC89 column refer to whether the source satisfies the selection criterion of Wood & Churchwell (1989), i.e., if [25-12] \geq 0.57 and [60-12] \geq 1.3. A “y” in parentheses indicates a borderline case.

^bVela cometary globules – Reipurth 1983; Zealey et al. 1983; Knude & Nielsen 2000; Woermann, Gaylard & Otrupcek 2001

^cHenning & Launhardt 1998

^dBourke et al. 1997

^eR. Sutherland et al. 1992, private communication

^fOphiuchus molecular cloud (Wilking 1992)

^gReipurth et al. 1997

^hReddening (revised distance from Bourke et al. 1995b)

ⁱCrA molecular cloud (Graham 1992)

and intermediate mass protostars has been reported by Minier et al. (2003). Minier et al. searched for 6.7 GHz methanol maser emission toward 57 southern protostars and 65 pre-protostellar (i.e., starless) dense cores. They did not detect any maser emission toward bona fida low mass sources. The theory of Sobolev et al. (1997) requires gas kinetic temperatures of \sim 30 K and dust temperatures $>$ 150 K with enhanced methanol abundances and moderate densities to excite these masers, conditions that might be found in some outflows from low mass protostars (e.g., BHR 71 [Bourke et al. 1997, Garay et al. 1998] and L1157 [Tafalla & Bachiller 1995; Bachiller et al. 1995; Benedettini et al. 2002]) or within low mass hot core regions (e.g., IRAS 16293-2422 - Kuan et al. 2004, Cazaux et al. 2003, Ceccarelli et al. 1999, 2000). Luminosities of sources selected using the WC89 criterion are often difficult to determine because of a lack of velocity information or to the difficulty in breaking the near/far distance ambiguity. Because it is now assumed a priori that methanol masers are only associated with HMSF regions, deciding on the near/far ambiguity is often achieved by assuming an ionising source.

In this paper we present the results of a search for 6.7 GHz methanol maser emission from a small sample of low mass protostars that predates Minier et al. 2003. No masers were found. The most luminous source in our sample with $L_{IR} \sim$ 680 L_{\odot} is almost as luminous as the least luminous sources showing methanol maser emission, \sim 1000 L_{\odot} . This leads us to examine the nature of WC89 sources with low fluxes, as some of our sample satisfy the WC89 criterion for candidate UCHII regions based solely on their IRAS colors. For the first time we are able to show that some low mass protostars contaminate the low flux end of the WC89 sam-

ple, a result that was suggested by van der Walt (1997) and Ramesh & Sridharan (1997) but that has not previously been confirmed observationally. We also estimate the contamination level of WC89 by low mass protostars.

2. SOURCE LIST

As this was intended only as a pilot survey to examine whether any low luminosity young stellar objects exhibit 6.7 GHz methanol maser emission, the source list was not selected with rigor. However, we did aim to observe low-luminosity sources with a range of luminosities, from a few to a few hundred solar luminosities. Sources were selected from lists of IRAS sources associated with southern dark molecular clouds (Persson & Campbell 1987, 1988; Persi et al. 1990; Bourke, Hyland & Robinson 1995a). Because of their association with dark clouds, it was assumed that these sources are relatively nearby (mostly $<$ 1kpc, and almost always $<$ 2kpc), and so are low- to intermediate-mass objects. The source list is given in Table 1. The distance to all sources in Table 1 was not well established at the time of the observations. For sources with unknown distances we selected those with low IRAS fluxes. Subsequent distance estimates (as indicated in Table 1) do indicate that the majority satisfy our luminosity requirement. We attempted to confirm the large distance estimates for IRAS 10501-5630 and IRAS 11278-5940 by using the Galactic rotation curve derived by Brand & Blitz (1993) and the values of V_{LSR} determined by Bronfman, Nyman & May 1996 (-13.4 km s⁻¹ for IRAS 10501-5630) and Brand et al. 1987 (-13.1 km s⁻¹ for IRAS 10501-5630 and -21.8 km s⁻¹ for IRAS 11278-5940). However it was not possible to use this method to obtain sensible results. As noted in Table 1, approximately 7 out of 14 sources satisfy the WC89

TABLE 2
METHANOL MASER FLUXES FOR “STANDARD” SOURCES

Name	FLUX (Jy)	
	Caswell et al. (1995)	This Work
G323.74-0.26	2860	2728
G344.42+0.05 (IRAS 16586-4442)	15	10
G351.42+0.64 (NGC 6334F)	3300	3322

UCHII criterion, a point we will revisit.

3. OBSERVATIONS

The observations were undertaken between 1992 December 15 and 17 using the dual-channel cooled HEMT 6.7/12.2 GHz receiver at the Parkes 64 m radio telescope. At the rest frequency of 6.668 GHz the half power beamwidth of the Parkes antenna is 3'.3. For all observations the Parkes autocorrelator was split into two sections of 1024 channels, each covering 4 MHz and one of two orthogonal linear polarizations. The velocity range covered for each observation was 179 km s⁻¹, with a spectral resolution of 0.35 km s⁻¹ after Hanning smoothing of the data.

On source integration times were 20 minutes. Reference spectra of 20 minutes taken at regular intervals throughout the observing period were used to form quotients with the on source observations. The resulting spectra for the two polarizations were then averaged, baselined and Hanning smoothed. Because of poor weather during the observing period, system temperatures were typically 80 – 90 K, and the resulting 3 σ sensitivity level of the observations were typically ~ 0.2 Jy.

Since no maser emission or absorption was detected, no “true” flux calibrators were observed. However, three sources that have previously been reported (G323.74-0.26, G344.42+0.05, G351.42+0.64) were observed as test observations and thus provide sufficient flux calibration. Flux calibration of these sources was undertaken by Caswell et al. (1995) in the observing period immediately following ours, and the data presented here have been calibrated by comparison with the fluxes given in Caswell et al. (1995). Table 2 presents a comparison of the Caswell et al. (1995) fluxes with those obtained here.

4. RESULTS AND DISCUSSION

As indicated in Table 3, no maser emission was detected. The sensitivity of our survey (0.2 Jy, 3 σ) is comparable to or better than previous single-dish surveys of IRAS selected sources (e.g., Schutte et al. 1993 – 3 Jy; van der Walt et al. 1995 – 5 Jy; Walsh et al. 1997 – 0.3 Jy; MacLeod et al. 1998 – 0.3-0.6 Jy), which have detected a large number of methanol masers, so this is not an explanation for our zero-detection rate, unless methanol masers from low-mass protostars are intrinsically weaker and so below our detection threshold. However, subsequent studies of methanol maser emission show that this null result is not surprising for the sources we have observed (van der Walt et al. 1996; Minier et al. 2003). Most large surveys for 6.7 GHz methanol maser emission have concentrated on IRAS sources selected using the WC89 IRAS two-color criterion for UCHII regions, $[25-12] \geq 0.57$ and $[60-12] \geq 1.3$, where $[\lambda_2 - \lambda_1] \equiv \log(S_{\lambda_2}/S_{\lambda_1})$ and S_{λ} is the IRAS flux in Jy at wavelength λ . Because of possible contamination from non-UCHII regions some of these surveys also

TABLE 3
METHANOL MASER SURVEY RESULTS.

NAME	R.A. (J2000)	Dec. (J2000)	1 σ rms (Jy)
IRAS 08076-3556	08 09 31.6	-36 04 47	0.06
IRAS 08242-5050	08 25 44.4	-51 00 05	0.09
IRAS 08261-5100	08 27 37.4	-51 10 41	0.09
IRAS 10501-5630	10 52 15.5	-56 46 28	0.09
IRAS 11278-5940	11 30 09.1	-59 57 26	0.07
IRAS 11590-6452	12 01 37.1	-65 09 06	0.05
IRAS 13224-5928	13 25 48.6	-59 42 53	0.06
IRAS 16289-4449	16 32 32.3	-44 55 38	0.07
IRAS 16293-2422	16 32 22.9	-24 28 36	0.07
IRAS 16295-4452	16 33 03.5	-44 58 30	0.06
IRAS 17193-4319	17 22 55.0	-43 22 37	0.05
R CrA	19 01 51.4	-36 56 52	0.05
VV CrA	19 03 05.8	-37 12 50	0.06
TY CrA	19 01 38.9	-36 54 00	0.05

NOTE. — No masers were detected and 1 σ rms values are listed. Velocity coverage was typically ± 90 km s⁻¹ with a channel separation of 0.35 km s⁻¹. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

impose flux limits on their samples (e.g., Schutte et al. 1993 – $S_{60} > 150$ Jy and $S_{100} > 400$ Jy; van der Walt et al. 1995 and MacLeod et al. 1998 – $S_{60} > 100$ Jy and $S_{100} > 100$ Jy), or impose other criteria such as association with radio continuum emission indicating the presence of an HII region (Walsh et al. 1997). Approximately half of the sources in our study satisfy the WC89 criterion (6, maybe 7, of 14, as the lower limits on the 12 μ m flux of IRAS 17193-4319 do not exclude it from the WC89 region), but none of these have $S_{60} > 100$ Jy as used in the major surveys listed above. The methanol maser survey by van der Walt et al. (1995) of sources selected using the WC89 criterion with $S_{60} > 100$ Jy had a much lower detection rate than a similar survey by Schutte et al. (1993), which used $S_{60} > 150$ Jy, suggesting that the brightest WC89 sources are more likely to be associated with methanol maser emission. The results presented here do not contradict this viewpoint.

4.1. Detection toward faint IRAS sources

The survey of van der Walt et al. (1996) of 241 IRAS sources satisfying WC89 with $S_{60} < 100$ Jy for methanol maser emission at 6.7 GHz detected only five new masers. Because of this low detection rate van der Walt et al. (1996) investigated the nature of the IRAS sources toward which methanol masers had previously been detected. An examination of the IRAS flux integrated between 25 and 60 μ m (van der Walt et al. 1996; Casoli et al. 1986),

$$F_{25-60} = \int_{25\mu\text{m}}^{60\mu\text{m}} S(\lambda) d\lambda = \left(\frac{S_{25\mu\text{m}}}{2} + \frac{S_{60\mu\text{m}}}{3.9} \right) \times 10^{13} \text{ Jy Hz}, \quad (1)$$

shows that almost all 6.7 GHz methanol masers are associated with sources with $\log F_{25-60} > 14$ Jy Hz, and that the detection rate of methanol masers decreases rapidly with decreasing values of F_{25-60} . The survey of van der Walt et al. (1996) included 191 WC89 sources with $14 < \log F_{25-60} <$

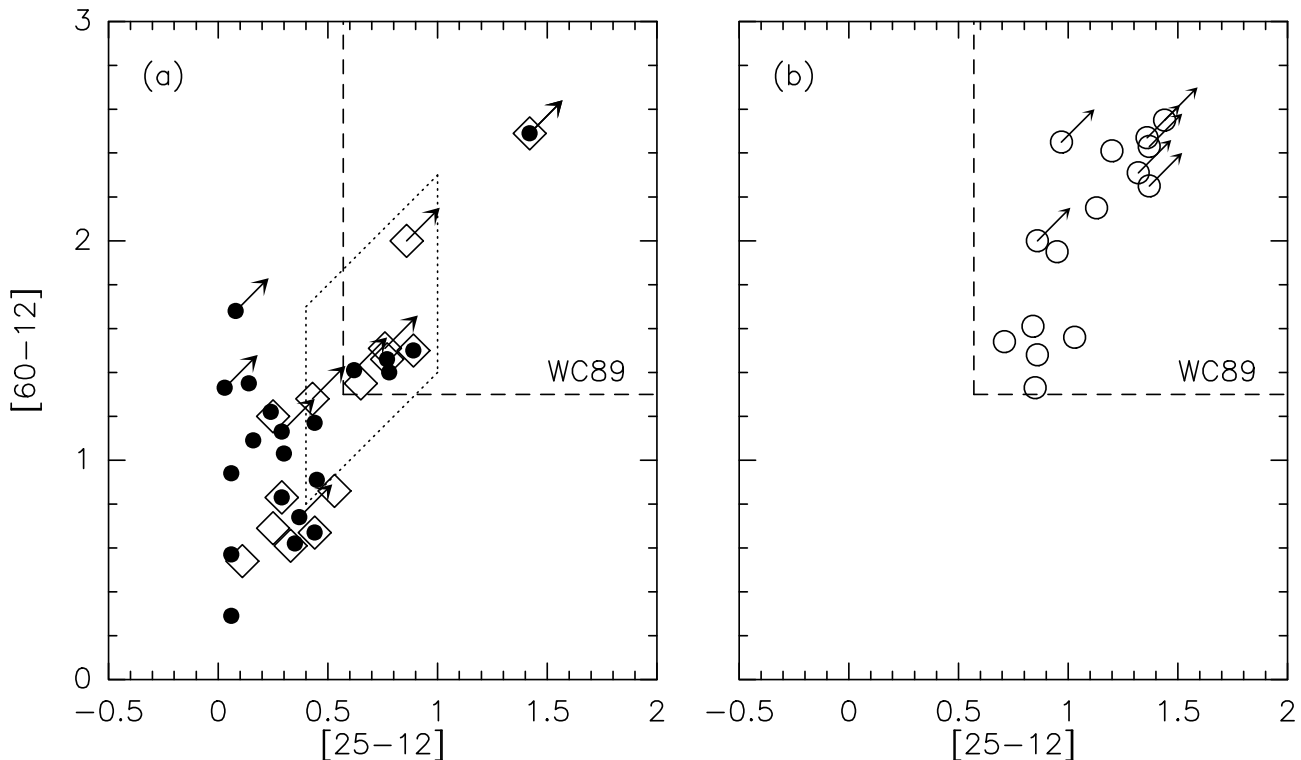


FIG. 1.— (a) Two-color IRAS diagram showing the locations of the sources observed for methanol maser emission in this paper (*open diamonds*), with upper limits to IRAS fluxes indicated with arrows. The filled circles represent IRAS sources with colors of low-mass protostellar objects located in southern Bok globules (Bourke et al. 1995a). Only those sources from Bourke et al. with $F_{60} > F_{25} > F_{12}$ and detected at 60 and 25 μm are shown. The space occupied by UCHII regions identified by WC89 is indicated by dashed lines, and the embedded colors region of Emerson (1987) by the dotted parallelogram. (b) Two-color IRAS diagram showing the locations of known low-mass protostellar objects satisfying WC89 and $\log F_{25-60} > 14$ (Table 4).

14.4 that had not previously been observed, detecting the five new masers mentioned above. This source list included one of the sources in our list, IRAS 11590-6452, which is clearly not an UCHII region, but a nearby low-mass protostar (Bourke et al. 1997; Garay et al. 1998; Bourke 2001). In our sample seven sources have $\log F_{25-60} \geq 14$ Jy Hz, and all have $\log F_{25-60} > 13$ Jy Hz, which is the lower limit for WC89 sources.

4.2. The nature of the WC89 sample

The probability of detecting methanol maser emission from the fainter sources with WC89 colors is apparently quite low. The question is why? Are these sources more distant HMSF regions, or perhaps nearby low-mass star forming regions that are not expected to show methanol maser emission? The dispersion in scale height for the WC89 sources is greatest at low values of F_{25-60} , being $\sim 4^\circ$ for $\log F_{25-60} \sim 13.5$, and remaining constant at $\sim 1^\circ$ for $\log F_{25-60} > 14.5$, where most of the 6.7 GHz masers are found (van der Walt 1997). The modeling of the distribution of embedded ionizing stars by van der Walt (1997) led to the conclusion that a significant fraction of the faint WC89 sources may be low and intermediate mass (i.e., non-ionizing) nearby young stars. This would neatly explain the lack of 6.7 GHz maser detections for these objects - not all WC89 objects are UCHII regions, and methanol maser emission is not expected from low- to intermediate-mass young stars (Sobolev et al. 1997). This is illustrated in Figure 1(a), which plots the [25–12] versus [60–12] colors for the sources surveyed in this work (*open diamonds*) and the IRAS sources associated with Bok globules from Bourke et al. (1995a) that are detected at 12, 25 and 60 μm with $S_{60} > S_{25} > S_{12}$, and so are most likely to be low-mass protostars. Also shown on

this figure are the regions defined by WC89 for UCHII regions, and by Emerson (1987; see also Bourke et al. 1995a) for embedded, nearby low-mass protostellar “cores” (Beichman et al. 1986). As can be seen in the figure, a number of bona fide low luminosity sources are found within the WC89 region, and the region of low mass cores overlaps with the WC89 region in color-color space. This figure clearly shows that some low luminosity (non-ionizing) protostellar objects have IRAS colors similar to UCHII regions and must contaminate the WC89 sample. This point is supported by Ramesh & Sridharan (1997), who studied the reliability of the WC89 criterion in the selection of UCHII regions. Using a simple model they estimated that $\sim 10\%$ of the WC89 sources have luminosities of $< 1000 L_\odot$.

Bronfman et al. (1996) surveyed 1427 sources selected using the WC89 criterion for CS $J = 2 - 1$ emission with the Swedish-ESO Submillimetre Telescope (SEST). This survey was aimed at detecting dense gas (critical density $\sim 6 \times 10^5 \text{ cm}^{-3}$) toward these regions as a further indicator of their protostellar nature. They detected 843 sources (59%) above their sensitivity threshold. They note that the undetected sources are either faint IRAS sources, or seem to belong to a different population with similar but distinct colors compared to the detected sources. Smaller samples of HMPO candidates selected with addition criteria (flux limits, radio continuum) to that of WC89 (e.g., Sridharan et al. 2002; Beuther et al. 2002a; Brand et al. 2001) detect all of their sources in CS and other molecular lines, regardless of distance. This suggests that the majority of sources not detected by Bronfman et al. cannot be UCHII regions, or even HMSF regions.

The spectral line data allows us to investigate the nature of

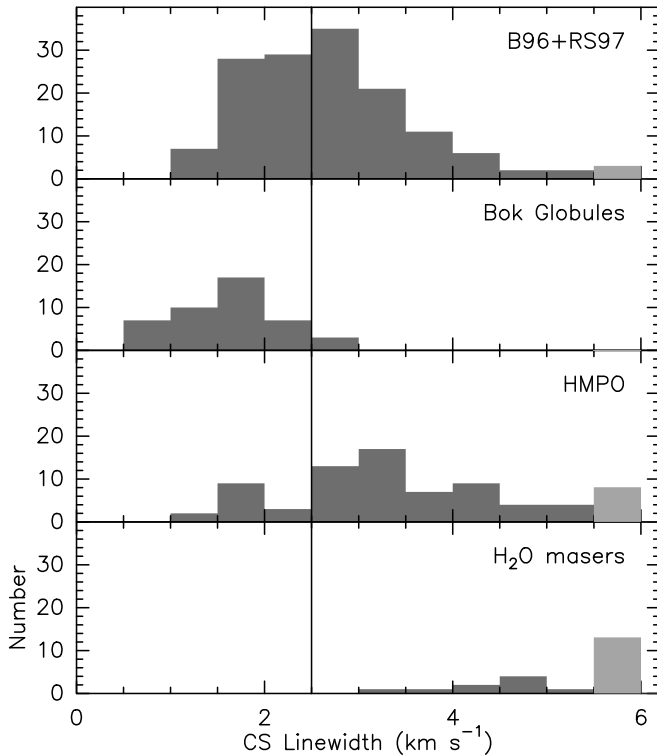


FIG. 2.— Distribution of CS line widths for different samples of molecular clouds as explained in the text. The panel labeled “B96+RS97” shows sources detected by Bronfman et al. (1996) that are FIR faint and radio quiet according to Ramesh & Sridharan (1997). The panel labeled “Bok Globules” shows Bok globules detected by Launhardt et al. (1998) and Henning & Launhardt (1998). The panel labeled “HMPO” shows high mass protostellar candidates from the surveys of Brand et al. (2001) and Beuther et al. (2002a). The panel labeled “H₂O masers” shows compact HII regions associated with water masers detected by Juvela (1996). The vertical line at 2.5 km s⁻¹ indicates the approximate division between known low mass and high mass protostars. In all panels, all sources with line widths >5.5 km s⁻¹ are included in the last bin (lightly shaded region), even if their line width is >6 km s⁻¹.

the detected sources. In particular the CS linewidth, ΔV , can be used to determine whether a given source is a candidate high mass or low mass star forming region. HMSF regions (star cluster forming regions without strong ionizing sources) show larger line widths most likely because of a greater level of turbulence. However, there is no clear a priori separation in linewidth between the high mass and low mass star forming regions for any molecular tracer, and so we examined published surveys using similar sized telescopes to estimate the typical CS linewidth of low and high mass star forming regions.

For low mass protostars we used the Bok globule survey of Launhardt et al. (1998) for northern sources, who observed 38 IRAS sources identified as low mass protostars, and the survey of Henning & Launhardt (1998) for southern sources, who observed 33 IRAS sources with $L < 1000L_{\odot}$. These surveys used the FCRAO 14 m telescope and the 15 m SEST. They find that the majority of the sources have $\Delta V < 2$ km s⁻¹, and essentially all have $\Delta V < 2.5$ km s⁻¹. For high mass protostars we have examined the CS surveys of Brand et al. (2001) and Beuther et al. (2002a) for the youngest high mass systems, and Juvela (1996) for more evolved regions (i.e., compact HII regions with associated water masers). The first two surveys generally have $\Delta V > 2$ km s⁻¹, while the Juvela

sample all have $\Delta V > 3$ km s⁻¹ (Figure 2). We conclude that sources in the WC89 sample with CS line widths $\Delta V \leq 2$ km s⁻¹ are good candidates to be regions that are not forming high mass ionising stars, or clusters without ionizing sources.

Larionov et al. (1999) observed a mixture of high and low mass star forming regions in CS $J = 2 - 1$; for sources associated with Class I methanol masers they find a mean CS linewidth $\Delta V = 6.2$ km s⁻¹, and $\Delta V = 4.8$ km s⁻¹ for Class II methanol masers. By inspection of their source list the methanol masers are associated with previously identified HMSF regions with radio continuum emission (ie HII regions), supporting the result of Juvela (1996).

Plume et al. (1997) observed CS $J = 2 - 1$ and higher transitions toward 150 water masers assumed to be associated with HMSF regions (most certainly true). They do not list mean linewidths, but inspection of their results indicate that 41 sources have $\Delta V < 3.0$ km s⁻¹, and 15 (10%) have $\Delta V < 2.0$ km s⁻¹. Many of the sources with narrower linewidths are only listed by their IRAS name, and so may be HMPOs similar to that of Beuther et al. (2002a). Again the basic premise holds true; regions with $\Delta V < 2$ km s⁻¹ are good candidates to be low mass star forming regions.

In the Bronfman et al. (1996) sample we find that 66 of 843 sources detected in CS have $\Delta V < 2$ km s⁻¹. These numbers suggest that of the sources in WC89 that are clearly associated with molecular gas (and are therefore likely to be star forming regions), $\sim 10\%$ are forming only low mass non-ionising stars. This suggestion is supported by the recent survey of HMSF regions by Faúndez et al. (2004), who surveyed 146 of the CS detected Bronfman et al. sources for 1.2 mm continuum emission. Of their sample $\sim 9\%$ have luminosities $< 10^4 L_{\odot}$, i.e., later than B0.5, and at least two are truly low mass, IRAS 08076-3556 and IRAS 11590-6452, which are included in our list. Ramesh & Sridharan (1997) divided up the WC89 sample into four classes, based on a combination of whether they were FIR bright or faint ($S_{60} < 90$ Jy), and radio-loud or radio-quiet (based on their 5 GHz emission). For 1522 sources within $|b| < 2.5^{\circ}$, they find $\sim 27\%$ are both FIR faint and radio quiet, which are the properties expected of nearby low mass star forming regions. In Figure 2 we plot the distribution of CS linewidths for those sources detected by Bronfman et al. (1996) that are also FIR faint and radio quiet according to Ramesh & Sridharan (1997). This figure shows that the majority of sources have $1.5 < \Delta V < 2.9$ km s⁻¹. Of the 144 sources in common, 35 (24%) have $\Delta V < 2$ km s⁻¹, and 64 (44%) have $\Delta V < 2.5$ km s⁻¹, indicating that a large fraction of faint, quiet sources associated with dense molecular gas (confirming their star-forming nature) have linewidths typical of low mass protostars or clusters without ionizing sources. If we include all sources with $\Delta V < 3.0$ km s⁻¹ then we find 99 sources (69%). From these numbers we conclude that about 50% of the FIR faint and radio quiet WC89 sources are actually low to intermediate mass star forming regions (including non-ionizing clusters). About one quarter of the WC89 sample are FIR faint and radio quiet according to Ramesh & Sridharan (1997), so we conclude for the sample as a whole that the contamination level is $\sim 10\% - 15\%$.

4.3. Low mass, low luminosity protostars in the WB89 sample

We have seen that attempting to select UCHII regions based solely on their IRAS colors is insufficient to produce a clean sample. Further criteria are needed. Ramesh & Sridharan (1997) have suggested the addition of centimeter radio contin-

TABLE 4
 PROPERTIES OF LOW LUMINOSITY PROTOSTARS SATISFYING WC89 AND $\log F_{25-60} > 14$.

NAME	ASSOCIATION	IRAS FLUXES (Jy)				DISTANCE (pc)	L_{IR} (L_{\odot})	[25-12]	[60-12]	$\log(F_{25-60})$
		12 μ m	25 μ m	60 μ m	100 μ m					
03225+3034	L1448 IRS3	0.6	5.3	52.2	374.0	350 ^a	31	0.95	1.95	14.2
03245+3002	L1455 RNO15	0.2L	4.2	48.8	82.2	350 ^a	13	>1.37	2.43	14.2
04287+1801	L1551 IRS5	9.7	105.0	356.0	420.0	140 ^b	18	1.03	1.56	15.2
04365+2535	TMC 1A	1.2	8.6	36.0	39.3	140 ^b	2	0.86	1.48	14.1
08194-4925	Re4	0.1L	2.3	29.8	74.6L	400 ^c	<12	>1.36	>2.47	13.9
08196-4931	Re5	0.3	7.1	53.3	74.6L	400 ^c	<19	>1.37	>2.25	14.2
11590-6452	BHR 71	0.3L	6.5	77.4	192.9	200 ^d	8	>1.42	>2.49	14.3
14564-6254	Circinus MM1	1.4	7.1	48.6	94.0	700 ^e	63	0.71	1.54	14.2
16293-2422	L1689	0.25L	1.82	25.5	103.2	160 ^f	14	>0.86	>2.00	15.2
18148-0440	L483	0.3L	6.9	89.1	165.5	200 ^g	8	>1.44	>2.55	14.4
Serpens FIRS1	...	0.6L	5.6	170.0	435.0	310 ^h	41	>0.97	>2.45	14.7
21388+5622	SFO 37	2.4	17.4	52.7	74.8	750 ⁱ	69	0.85	1.33	14.4
21391+5802	IC 1396	0.6	8.9	144.6	425.5	750 ⁱ	226	1.20	2.40	14.6
22051+5848	L1165	0.25L	5.22	51.6	94	300 ^j	11	>1.32	>2.31	14.2
23011+6126	Cepheus	0.43	5.77	61.0	112.0	730 ^k	76	1.13	2.15	14.3
22376+7455	L1251B	0.8	5.6	32.3	66.8	300 ^l	8	0.84	1.61	14.0

NOTE. — Last four columns are as defined in Table 1 and the text. The IRAS name is given in the first column except for Serpens FIRS1 which is confused within the IRAS beam ($\sim 1'$). An “L” in the IRAS flux columns refers to an upper limit.

^aPerseus (Herbig & Jones 1983)

^bTaurus (Elias 1978)

^cVela cometary globules (see Table 1)

^dBourke et al. 1997

^eBally et al. 1999

^fOphiuchus molecular cloud (Wilking 1992)

^gTafalla et al. 2000

^hSerpens (De Lara, Chavarria & Lopez-Molina 1991)

ⁱMatthews 1979

^jDobashi et al. 1994

^kHarju et al. 1993

^lKun & Prusti 1993

uum information, a technique used successfully and independently by Walsh et al. (1997). Surveys for methanol masers toward UCHII candidates selected using WC89 have shown that for sources with $\log F_{25-60} < 14.0$ the detection rate is essentially zero, and so this might be a useful cut-off for selecting between UCHII regions and non-ionising sources. Though earlier studies (van der Walt 1997; Ramesh & Sridharan 1997) did not actually examine the true nature of the individual faint WC89 sources, they concluded that they are probably young embedded non-ionizing stars. A sample of low luminosity ($L < 1000L_{\odot}$, i.e., non-ionizing) protostellar sources that satisfy WC89 and also have $\log F_{25-60} > 14.0$ are plotted in Figure 1(b), and are listed in Table 4. This list is not meant to be complete, but lists a number of well known low-mass protostellar objects, including the well studied regions in our survey associated with IRAS 08242-5050 (HH 46/47 – Olberg et al. 1992; Eislöffel et al. 1994; Heathcote et al. 1996; Noriega-Crespo et al. 2004) and IRAS 11590-6452 (BHR 71 – Bourke et al. 1997; Garay et al. 1998; Bourke 2001). However, it should be noted that almost all of the sources listed in Table 4 have $S_{60} < 100$ Jy. Thus, a requirement that sources satisfying WC89 also satisfy $\log F_{25-60} > 14.0$ and $S_{60} > 100$ Jy may select a sample with a high percentage of UCHII regions, though it would not be a complete Galactic census.

Two recent comprehensive studies of HMPOs have been undertaken, by Palla and Molinari and their collaborators (Palla et al. 1991; Molinari et al. 1996, 1998, 2000; hereafter the PM sample), and by Sridharan and Beuther and their collaborators (Sridharan et al. 2002; Beuther et al. 2002a,b,c;

hereafter the SB sample). We now briefly examine the possible contamination level in both samples.

In the PM sample of 260 sources, 125 satisfy WC89, which PM call “high”, while the rest have colors of compact molecular clouds (Richards et al. 1987), and are call “low”. In SB all 69 of their sources satisfy WC89. Both groups attempted to discriminate against HII regions by selecting sources without significant 5 GHz continuum emission, and against low luminosity sources by selecting sources with $S_{60} \geq 100$ Jy (PM) or $S_{60} > 90$ Jy and $S_{100} > 500$ Jy (SB). As we have seen in this paper, these criteria should eliminate low luminosity sources. In particular we have seen that the SB sample has CS linewidths significantly larger than that of Bok globules, which only form low mass stars. No equivalent survey is available for PM. They did observe a large percentage of their list in NH_3 (1,1) and (2,2) (163 sources), finding mean linewidths of 1.73 km s^{-1} for their high sample and 1.47 km s^{-1} for the low sample. In comparison, Benson & Myers (1989) detected NH_3 (1,1) from 78 low mass dense cores, finding a mean linewidth of 0.43 km s^{-1} for those associated with IRAS sources ($\sim 50\%$), while Bourke et al. (1995b) detected 84 Bok globules in NH_3 (1,1), with typical line widths $< 1 \text{ km s}^{-1}$. These numbers suggest the PM sample is not likely to be contaminated by low luminosity sources at any significant level, if at all, although individual objects with NH_3 linewidths $< 1 \text{ km s}^{-1}$ should be examined in detail.

4.4. The lower luminosity limit for methanol maser emission

It is difficult to determine the luminosity and hence spectral type of protostellar sources, so it is presently unclear whether non-ionizing sources are able to produce methanol masers. It would be interesting to carefully determine L_{IR} for all the known methanol masers to approximate the lower luminosity for maser emission (although IR counterparts for a number of methanol masers are unknown), as well as the luminosity of all those sources that been searched for methanol maser emission with null results. This large task is beyond the scope of this paper. A preliminary examination of published values of L_{IR} of methanol maser sources shows that almost all sources have $L_{IR} > 10^3 L_{\odot}$ (i.e., earlier than B3), with IRAS 17463–3128 (van der Walt et al. 1995) at $880 L_{\odot}$ the lowest we could find (cf. IRAS 11278–5940 with $L_{IR} \sim 680 L_{\odot}$ is a null detection in the current work). If we assume that at least 20% of the total luminosity is not accounted for by L_{IR} , then the lower luminosity limit for methanol maser emission is $\geq 10^3 L_{\odot}$.

Minier et al. (2003) discuss their non-detection of 6.7 GHz methanol masers from low-mass protostars in terms of the mass limit for maser emission. However, protostellar masses are almost impossible to determine except approximately, as they are not directly measurable. It would be interesting to determine the luminosity of protostars in the Minier sample (as opposed to the starless cores), and to compare these to the values quoted here and for faint IRAS sources showing maser emission (a task once again beyond the scope of this paper). Minier et al. claim to have observed all southern low mass protostars known at the time of their observations (2000), although they did not observe well studied sources such as IRAS 08242-5050 and IRAS 11590-6452 (included in this work) which were identified many years earlier. This omission does not change their conclusions; low mass protostars do not show 6.7 GHz methanol maser emission.

5. SUMMARY AND CONCLUSIONS

We have undertaken a survey of a small sample of low-mass protostars for methanol maser emission at 6.7 GHz. No masers were detected. This is not surprising, as methanol maser emission is not expected to be present in the environ-

ment of low luminosity sources (Sobolev et al. 1997). The maximum luminosity of the sources in our sample is $L_{IR} \sim 680 L_{\odot}$, compared to the lowest luminosity of a source showing methanol maser emission of $L_{IR} \sim 880 L_{\odot}$. These results suggest that the lower luminosity limit for methanol maser emission is $\geq 10^3 L_{\odot}$.

Previous studies of the IRAS properties of sources selected using the WC89 criterion and searched for 6.7 GHz methanol maser emission find that the number of sources showing maser emission drops with decreasing IRAS flux, and is essentially zero for sources with $\log F_{25-60} < 14.0$. Approximately half of our sample have $\log F_{25-60} > 14.0$. Most of these also satisfy the WC89 IRAS two-color criterion for selecting candidate UCHII regions. These results suggest that a number of the fainter sources satisfying WC89 with IRAS fluxes similar to known methanol maser sources might in fact be non-ionizing lower mass protostars, as predicted by van der Walt (1997) and Ramesh & Sridharan (1997).

To show this conclusively for the first time, we identified a number of low-mass protostars in this work and from the literature that satisfy the WC89 IRAS two-color criterion for candidate UCHII regions, and have $\log F_{25-60} > 14.0$, which is the observation cut off limit for 6.7 GHz methanol maser emission. This result clearly shows that the lower flux end of sources satisfying this criterion is contaminated by low-mass protostars. We estimate that the WC89 sample as a whole is contaminated by low mass (i.e., nonionizing) protostars at least at the 10% level, or greater.

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