

Search for Class I methanol masers in low-mass star formation regions

S. V. Kalenskii,^{1*} L. E. B. Johansson,^{2†} P. Bergman,² S. Kurtz,³ P. Hofner,^{4,5,6}
C. M. Walmsley⁷ and V. I. Slysh^{1†}

¹*Astro Space Center, Lebedev Physical Institute, Profsoyuznaya 84/32, Moscow, 117997, Russia*

²*Onsala Space Observatory, SE-439 92 Onsala, Sweden*

³*Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México (Morelia, Michoacan, Mexico)*

⁴*Physics Department, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801, USA*

⁵*National Radio Astronomy Observatory, PO Box 0, Socorro, NM 87801, USA*

⁶*Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany*

⁷*Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy*

Accepted 2010 February 4. Received 2010 January 20; in original form 2009 November 29

ABSTRACT

A survey of young bipolar outflows in regions of low-to-intermediate-mass star formation has been carried out in two Class I methanol maser transitions: $7_0 - 6_1A^+$ at 44 GHz and $4_{-1} - 3_0E$ at 36 GHz. We detected narrow features towards NGC 1333I2A, NGC 1333I4A, HH25MMS and L1157 at 44 GHz, and towards NGC 2023 at 36 GHz. Flux densities of the lines detected at 44 GHz are no higher than 11 Jy and the relevant source luminosities are about 10^{22} erg s⁻¹, which is much lower than those of strong masers in high-mass star formation regions. No emission was found towards 39 outflows. All masers detected at 44 GHz are located in clouds with methanol column densities of the order of or larger than a few $\times 10^{14}$ cm⁻². The upper limits for the non-detections are typically of the order of 3–5 Jy. Observations in 2004, 2006 and 2008 did not reveal any significant variability of the 44 GHz masers in NGC 1333I4A, HH25MMS and L1157.

Key words: masers – ISM: clouds – ISM: jets and outflows – ISM: molecules – radio lines: ISM.

1 INTRODUCTION

Bright and narrow maser lines of methanol (CH₃OH) have been found towards many star-forming regions (Haschick, Menten & Baan 1990; Menten 1991a; Kurtz, Hofner & Alvarez 2004). According to the classification of Menten (1991b), methanol masers can be divided into two classes, I and II, with each class characterized by a certain set of transitions. Class I maser transitions are the $7_0 - 6_1A^+$ transition at 44 GHz, $4_{-1} - 3_0E$ transition at 36 GHz, $5_{-1} - 4_0E$ transition at 84 GHz, $8_0 - 7_1A^+$ transition at 95 GHz, etc., while Class II transitions are the $5_1 - 6_0A^+$ transition at 6.7 GHz, $2_0 - 3_{-1}E$ transition at 12 GHz, the $J_0 - J_{-1}E$ series of transitions at 157 GHz, etc. A list of the most powerful Class I and II transitions is presented in e.g. Cragg et al. (1992). Both Class I and Class II masers are often overlaid upon broad thermal lines. Many methanol transitions, e.g. the series of $2_K - 1_K$ transitions near 96 GHz, $3_K - 2_K$ transitions near 145 GHz, $5_K - 4_K$ transitions near 241 GHz, etc., never exhibit maser features. These transitions are often called ‘purely thermal’.

The nature of methanol masers is still unknown. Plambeck & Menten (1990) suggested that Class I masers arise in post-shock gas

in the lobes of bipolar outflows, where the abundance of methanol is enhanced due to grain mantle evaporation. This hypothesis has further support in the fact that in a number of star-forming regions Class I masers appear to be associated with outflows (Kurtz et al. 2004; Chen, Ellingsen & Shen 2009). However, this hypothesis is not generally accepted because there are no high-velocity Class I masers and the apparent association between the masers and the outflows may be caused by the fact that both of them arise in the same regions of star formation rather than by a physical association between these objects.

The difficulties in the exploration of methanol masers partly appear because until recently the masers have been observed in regions of massive star formation, which are relatively distant (2–3 kpc from the Sun or farther) and highly obscured at the optical and even NIR wavelengths. In addition, high-mass stars usually form in clusters. These properties make it difficult to resolve maser spots and to associate masers with other objects in these regions. In contrast, regions of low-mass star formation are much more widespread and many of them are only 200–300 pc from the Sun; they are less heavily obscured than regions of high-mass star formation, and there are many isolated low-mass protostars. Therefore, the study of masers in these regions might be more straightforward compared to that of high-mass regions, and hence the detection of Class I masers in low-mass regions might have a strong impact on maser exploration.

*E-mail: kalensky@asc.rssi.ru

†Deceased.

Bearing this in mind, we performed in 2004 a ‘snapshot’ search for Class I methanol masers towards bipolar outflows driven by low-mass YSOs (Kalenskii et al. 2006) (hereafter Paper I) at 44, 84 and 95 GHz. The source list consisted of five so-called chemically rich outflows, where the abundances of methanol and some other molecules are increased as a result of grain mantle evaporation. The search proved successful: three maser candidates, NGC 1333I4A, HH25 and L1157 were found at 44 GHz. VLA observations of L1157 at 44 GHz confirmed that this source is really a maser (Kalenskii et al. 2010). Therefore a further work in the field looks promising.

In order to obtain a general idea about the main properties of the Class I masers in the regions of low-mass star formation, we performed a more extended search for these objects. The new survey was carried out at the frequency of the $7_0 - 6_1A^+$ transition, but most sources were additionally observed in another Class I maser line, the $4_{-1} - 3_0E$ line at 36 GHz. The physical relation between low-mass protostellar outflows and Class I methanol masers is poorly understood. Hence, it is tempting to make a comprehensive survey of such outflows. Unfortunately, the enormous amount of observing time makes such a survey unrealistic. The naive expectation, supported by the successful search of Paper I, is to find methanol masers towards bright thermal sources of methanol; therefore the basis of our source list consists of outflows where Kalenskii, Promyslov & Winnberg (2007) detected thermal emission in the $5_{-1} - 4_0E$, $8_0 - 7_1A^+$ and/or $2_K - 1_K$ methanol lines. We included also three outflows, IRAS03282, Serpens S68FIRS1 and Serpens SMM4, where Bachiller et al. (1995b) and Garay et al. (2002) found a significant enhancement of methanol abundance relative to that in quiescent gas. Because methanol enhancement has been detected in young, well-collimated outflows from Class 0 and I sources, we included several such objects in our list regardless of whether methanol enhancement had been found there. A subsample of our list consisted of YSOs with known outflows and/or H_2O masers located in Bok globules (Yun & Clemens 1992; Gómez et al. 2006). Like other objects from our list, these YSOs are typically isolated objects of low or intermediate mass, located in nearby (<500 pc) small and relatively simple molecular clouds. In total, our source list consisted of 37 regions which harbour 46 known outflows driven by Class 0 and I low-mass protostars, taken from the literature. The observed sources, positions and the relevant literature are given in Tables 2 and A1.

In addition to the survey we performed second- and third-epoch 44 GHz observations of the maser candidates detected in 2004.

2 OBSERVATIONS

Both the new survey and the multi-epoch observations of previously detected sources were carried out with the same telescope as the 2004 observations, namely the 20-m radio telescope of the Onsala Space Observatory (OSO). The second-epoch observations were made in 2006 December, and the new survey at 44 and 36 GHz was carried out in 2007 December. Several sources, including the three maser candidates detected in 2004, were reobserved at Onsala in 2008 December with the same receiver and spectrometer setup as in 2007. The line rest frequencies and strengths and the main telescope parameters are presented in Table 1. The frequencies were taken from the Lovas data base.¹ The dual beam switching mode with a frequency of 2 Hz and a beam throw of 11 arcmin was applied.

¹ <http://physics.nist.gov/cgi-bin/micro/table5/start.pl>

Table 1. The parameters of the observed lines and those of the OSO 20-m at the line frequencies. The parameters of the lines, observed in the preliminary survey (Paper I), are included for completeness.

Transition	Frequency (GHz)	$S\mu^2$ ^a (Debye)	HPBW (arcsec)	G (Jy K ⁻¹)
$7_0 - 6_1A^+$	44.069 476	6.1380	82	20.5
$5_{-1} - 4_0E$	84.521 206	3.0830	44	22
$8_0 - 7_1A^+$	95.169 516	7.2211	39	25
$2_{-1} - 1_{-1}E$	96.739 393	1.2133	39	25
$2_0 - 1_0A^+$	96.741 377	1.6171	39	25
$2_0 - 1_0E$	96.744 549	1.6167	39	25
$2_1 - 1_1E$	96.755 507	1.2443	39	25
$4_{-1} - 3_0E$	36.169 290	2.5184	105	18

^aThe product of the permanent dipole moment and the line strength from Müller, Menten & Mäder (2004).

Pointing errors were checked using observations of SiO masers and were found to be within 5 arcsec. The data were calibrated using the chopper-wheel method. An autocorrelator configured to either a 12.5 kHz (0.085 km s⁻¹ at 44 GHz) or 25 kHz resolution was used as the spectrometer. An overall check of the system was achieved by regularly observing known sources at 36 and 44 GHz. Typically, we observed several positions per source to cover the whole area occupied by the outflow lobes.

The data were reduced using the Grenoble CLASS package.

3 RESULTS

Based on the single-dish observations, we confirmed the existence of the three maser candidates at 44 GHz, reported in Paper I, detected broad lines at 36 GHz towards them and found six new sources at 36 or 44 GHz or both. The spectra of the detected sources are shown in Fig. 1 and the Gaussian parameters of the detected lines are presented in Table 2. Fig 1 shows the spectra of maser candidates observed in 2004 in addition to the emission detected in 2007 or 2008.

Only one source, newly detected at 44 GHz in 2007, NGC 1333I2A, shows narrow spectral features, which may be masers. In the case of S68N and Serpens CB2, the lines at 44 GHz are broad, 5–6 km s⁻¹. A fairly narrow line was detected at 36 GHz towards the blue lobe of an extreme high-velocity outflow in the vicinity of the bright reflection nebula NGC 2023. Offset measurements show that the source is compact with respect to the 105-arcsec beam. The line has no counterpart at 44 GHz. Its LSR velocity, ~ 6.4 km s⁻¹, is different from the systemic velocity of about 10 km s⁻¹ (Sandell et al. 1999).

With the exception of NGC 2023, only broad lines were detected at 36 GHz.

Negative results are presented in Table A1. No emission was detected in 39 outflows. The upper limits for the non-detections are typically of about 3–5 Jy. Thus, masers in these regions are fairly rare and/or weak objects. It is of interest to perform a similar survey with higher sensitivity of 1 Jy or better.

Fig. 2 presents the 44 GHz spectra of the three maser candidates detected in 2004 December, 2006 December and 2008 December. The spectra do not show notable variation between the epochs. Slight changes in line shapes and a decrease of flux densities of all three sources in 2008, about 30 per cent, can be attributed to poor signal-to-noise ratios, calibration uncertainties and different spectral resolution (0.17 km s⁻¹ in 2008 versus 0.085 km s⁻¹ in 2004

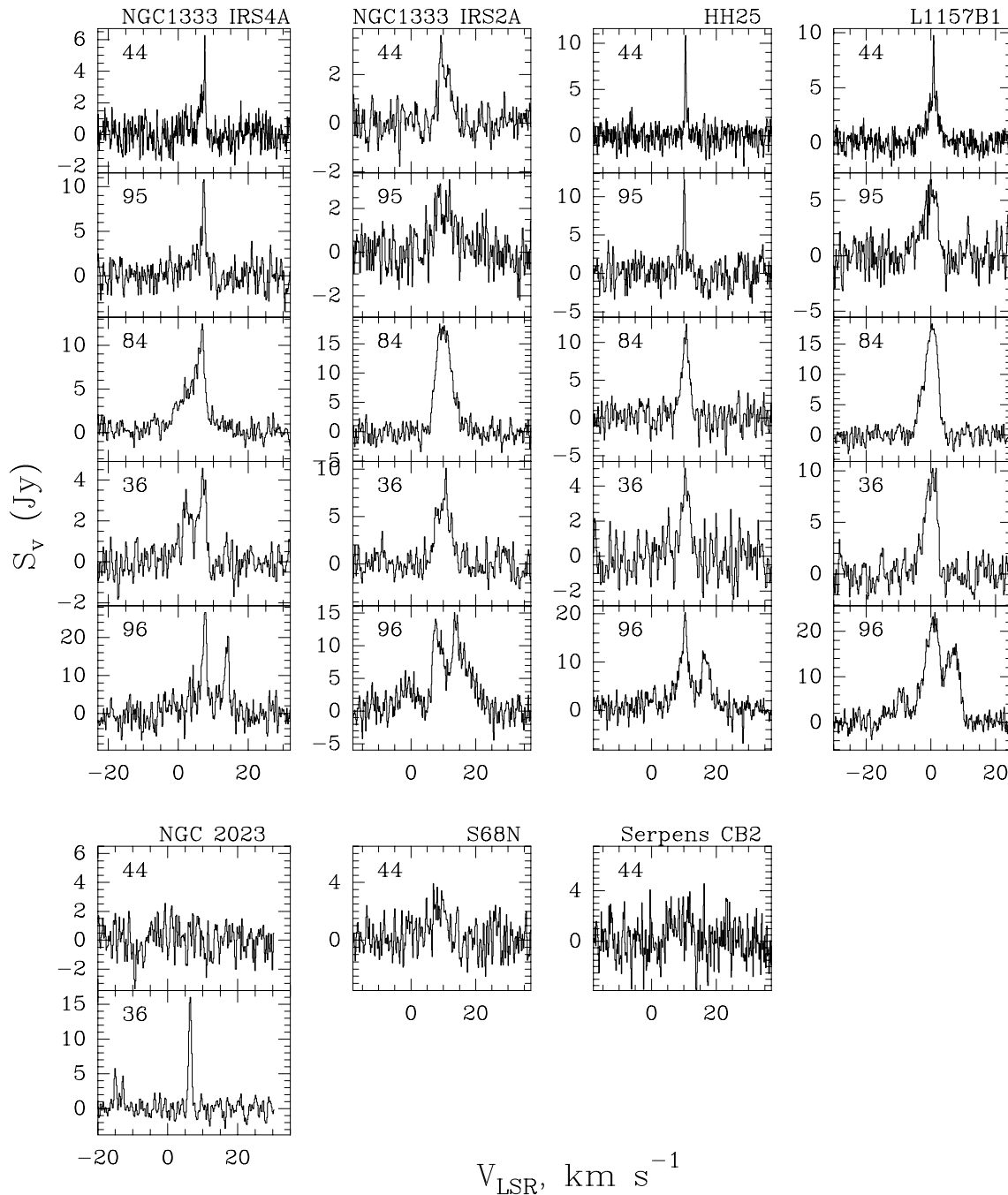


Figure 1. Upper panels: spectra of the regions of low-mass star formation in which maser candidates in the $7_0 - 6_1A^+$ line were detected. Shown from top to bottom are the $7_0 - 6_1A^+$, $8_0 - 7_1A^+$, $5_{-1} - 4_0E$, $4_{-1} - 3_0E$ and $2_K - 1_K$ lines at 44, 95, 84, 36 and 96 GHz, respectively. The horizontal axis plots the radial velocity in km s^{-1} and the vertical axis the spectral flux density in jansky. The 84 GHz, 95 GHz and 96 GHz spectra are taken in 2004 for all sources except L1157, for which the new spectra at all these frequencies except 96 GHz have been taken towards the stronger maser position. Lower panels: spectra of other sources detected at 44 and/or 36 GHz.

and 2006). However, further monitoring of these sources would be desirable.

4 DISCUSSION

4.1 Single-dish observations

The three regions of low-mass star formation, newly detected in 2007 at 44 GHz, NGC 1333I2A, S68N and Serpens CB2, exhibit

weak lines (≤ 4 Jy), making it difficult to determine whether they are masers. The lines are broad, $5\text{--}6 \text{ km s}^{-1}$, which is typical for thermal emission rather than for masers. However, the line detected in NGC 1333I2A is poorly approximated by a single Gaussian and a satisfactory fit is obtained with a narrow line overlaid on a broader component (see Table 2). The lines detected in S68N and Serpens CB2 can be approximated by single Gaussians. Therefore, for the present we consider the line detected in NGC 1333I2A to be a weak maser overlaid on thermal emission, and those detected in S68N

Table 2. The Gaussian parameters of detected lines. Here, 44 denotes the $7_0 - 6_1A^+$ at 44 GHz and 36 the $4_{-1} - 3_0E$ line at 36 GHz. For NGC 2023, the numbers in parentheses show the RA and Dec. offsets in arcsec from the position given in the second and third columns.

Source	RA (J2000)	Dec. (J2000)	Line	$\int S_\nu dV$ (K·km s ⁻¹)	V_{LSR} (km s ⁻¹)	FWHM (km s ⁻¹)	S_ν (Jy)	Obs. (yr)	Notes ^a	Refs
NGC 1333I2A	03 29 01.0	31 14 20	44	4.92(1.64)	9.24(0.12)	1.66(0.42)	2.81	2007	r	1,2
				5.74(1.64)	11.57(0.31)	2.71(0.79)	1.97			
			36	13.7(1.44)	-7.10(0.37)	7.88(1.04)	1.64	2007		
				13.7(2.70)	8.07(0.15)	2.00(0.26)	6.43			
				10.4(4.14)	12.48(1.25)	6.72(1.36)	1.46			
NGC 1333I4A	03 29 10.3	31 03 13	36	33.7(4.86)	10.54(0.08)	2.49(0.25)	12.71	2007	c	1,3
				10.6(1.98)	2.73(0.38)	4.61(1.22)	2.14			
			44	7.56(1.44)	7.11(0.16)	1.97(0.34)	3.60	2007		
				3.28(0.41)	6.49(0.26)	5.10(0.59)	1.95			
				1.85(0.41)	7.51(0.02)	0.33(0.05)	5.13			
NGC 2023(0,0) (0,0) (20,20) (-60, -60) (60, -60) (60,60) (-60, 60)	05 41 28.5	-02 19 19	44				<3.60	2007	b	4
				36	15.3(0.7)	6.46(0.02)	0.92(0.05)			
			36	18.5(0.82)	6.39(0.02)	0.99(0.05)	17.39	2008		
							<3.6			
							<3.0			
			36	0.63(0.04)	6.55(0.04)	1.36(0.11)	0.44	2008		
							<3.6			
HH25MMS	05 46 06.5	-00 13 54	44	5.33(0.82)	10.51(0.04)	0.48(0.09)	10.41	2007	r,mo	1,5
			36	11.9(1.08)	10.56(0.12)	2.93(0.28)	3.82			
S68N	18 29 47.5	01 16 51	44	12.3(1.64)	8.86(0.32)	5.18(0.83)	2.23	2007	c,mo	6
Serpens CB2	18 29 58.4	01 13 35	44	8.61(1.63)	8.13(0.64)	6.10(0.87)	1.32	2007	b,mo	7
L1157	20 39 08.1	68 01 14	44	12.0(0.60)	0.69(0.08)	3.82(0.24)	3.4	2004		1,8,
				2.40(0.20)	0.75(0.01)	0.37(0.03)	6.2			
			36	36.6(3.60)	-0.70(0.20)	3.97(0.31)	8.6	2008		
				10.8(3.20)	1.40(0.12)	1.66(0.27)	6.2			
				44	15.1(0.57)	0.61(0.08)	3.90(0.20)		3.6	
			2.0(0.32)	0.91(0.03)	0.53(0.08)	3.5				

^ar, red wing; b, blue wing; c, central position; q, quiescent gas; mo, multiple outflows; m, maser position determined with the VLA. 1 – Kalenskii et al. (2007); 2 – Bachiller et al. (1998); 3 – Blake et al. (1995); 4 – Sandell et al. (1999); 5 – Gibb & Davis (1998); 6 – Garay et al. (2002); 7 – Davis et al. (1999); 8 – Bachiller et al. (1995b); 9 – Bachiller et al. (2001); 10 – Benedettini et al. (2007).

and Serpens CB2 to be thermal lines. Poor signal-to-noise ratios in all these cases prevented us from accurately measuring line shapes; more sensitive observations may alter our interpretation.

The nature of the 36 GHz line towards the blue lobe of the bipolar outflow in NGC 2023 is unclear. On the one hand, the line is fairly narrow, and offset measurements (Table 2) show that the source is compact with respect to the 105-arcsec Onsala beam. These properties indicate that the source is probably a maser. This assumption has further support in the fact that the line LSR velocity, ≈ 6.5 km s⁻¹, is slightly less than the systemic velocity of about 10 km s⁻¹. On the other hand, the line has no counterpart at 44 GHz, which is more typical for thermal emission. Note, however, that there are known masers at 36 GHz without 44-GHz counterparts; in particular, no 44 GHz emission was found at the velocity of a fairly strong 36-GHz maser detected 3 arcmin north of DR21(OH) by Pratap et al. (2008). Therefore, we preliminarily conclude that the narrow line in NGC 2023 is a maser.

An examination of Tables 2 and A1 shows that outflows with masers at 44 GHz exhibit the strongest thermal emission at 36 GHz among all sources from our list. As the intensities of optically thin thermal lines are roughly proportional to column densities, this result indicates that methanol masers arise in regions of low-mass star formation with the highest column densities of methanol. This conclusion can be confirmed on the basis of the results by Kalenskii et al. (2007) on thermal emission of methanol towards outflows driven by low-mass YSOs. Kalenskii et al. (2007) observed thermal

emission in the $5_{-1} - 4_0E$, $8_0 - 7_1A^+$ and a series of $2_K - 1_K$ methanol lines at 3 mm. Their angular resolution was about 40 arcsec, corresponding to a linear resolution of about 0.06 pc at a typical distance of 300 pc. Moreover, their source list was essentially a subsample of our list. Column densities of methanol, derived for NGC 1333I2A and I4A, HH25, and L1157 using rotational diagrams are about 10^{15} cm⁻² or more. According to the results of LVG modelling, these column densities may be overestimated by a factor of 3–8 (Kalenskii et al. 2007); therefore we conclude that masers at 44 GHz can arise in regions with methanol column densities no less than several times 10^{14} cm⁻². Because the number of detected masers is small, this conclusion is not statistically robust.

We note that the isotropic luminosities of the masers at 44 GHz in the regions of low-mass star formation are about 10^{22} erg s⁻¹, i.e. several orders of magnitude lower than the maser luminosities in regions of massive star formation. Kalenskii, Slysh & Val'ts (2002) observed regions of massive star formation with a linear resolution of about 0.15 pc and determined methanol column densities towards strong Class I masers using an approach similar to that of Kalenskii et al. (2007). They obtained values between $2-74 \times 10^{16}$ cm⁻². Thus, a general trend seems to be as follows: molecular clouds with methanol column densities less than 10^{14} cm⁻² cannot produce masers at 44 GHz; clouds with methanol column densities 10^{14} – 10^{15} cm⁻² can (but do not necessarily) produce weak masers with luminosities of about 10^{22} erg s⁻¹; clouds with methanol column densities higher than 10^{16} cm⁻² can produce strong masers with

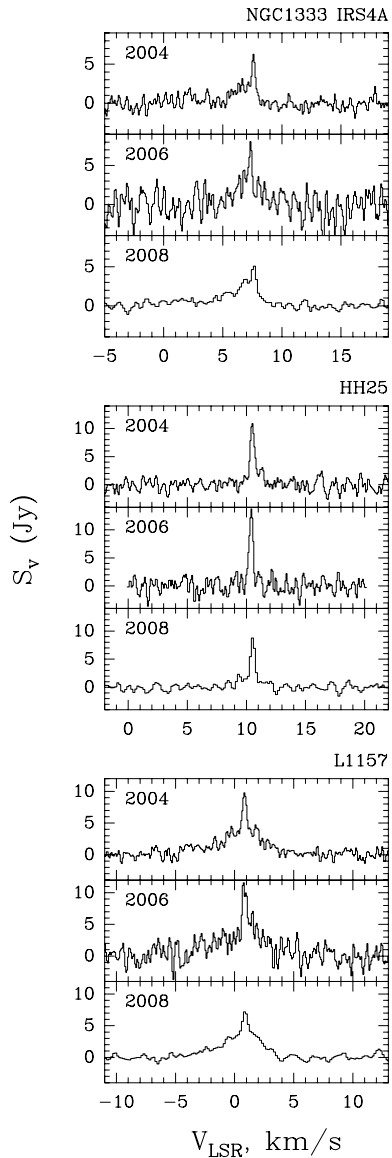


Figure 2. Spectra of three maser candidates, acquired in 2004 December, 2006 December and 2008 December in the $7_0 - 6_1 A^+$ at 44 GHz.

luminosities 10^{24} – 10^{25} erg s^{-1} . Note that here we imply column densities averaged over fairly large regions (about 0.06 pc in the case of low-mass regions and about 0.15 pc in the case of high-mass regions); individual clumps inside these regions may have much higher column densities of methanol.

Several mechanisms of methanol maser excitation have been proposed. Most of them can probably be ‘scaled’ so as to explain the existence of stronger masers only in sources with higher methanol column densities. Among these mechanisms are shocks driven by outflows, turbulence, which can result in a random increase of coherence length along a certain line (Sobolev, Wallin & Watson 1998), and accretion shocks (Kurtz et al. 2004). The two former mechanisms are discussed in more detail by Kalenskii et al. (2010) with respect to the masers in L1157. Currently we cannot rule out any of these mechanisms. It may happen that in different sources different mechanisms are responsible for the maser emission or even that different mechanisms may coexist within the same source.

With the exception of NGC 2023, only broad lines were detected at 36 GHz. Earlier, Kalenskii et al. (2001) detected broad $5_{-1} - 4_0 E$ methanol lines at 84 GHz towards a number of sources and showed that these lines are typically inverted; the fact that they are broad is a result of their low optical depths. These lines arise in extended clouds and in all respects except excitation temperature are similar to thermal lines. Such lines are called quasi-thermal lines. The excitation of the $4_{-1} - 3_0 E$ lines at 36 GHz is similar to that of the $5_{-1} - 4_0 E$ lines, therefore we believe that the broad 36 GHz lines are also quasi-thermal. In analysing extended emission, one need not distinguish between ‘truly thermal’ and ‘quasi-thermal’ lines, but negative excitation temperatures of some transitions may play a role in the appearance of compact maser spots in the corresponding cloud (Sobolev et al. 1998; Kalenskii et al. 2010).

Statistical equilibrium calculations (e.g. Cragg et al. 1992) demonstrate that many Class I transitions, in particular $7_0 - 6_1 A^+$, are inverted for a wide range of parameters typical of Galactic molecular clouds. Therefore, the broad lines detected at 44 GHz in S68N and Serpens CB2, as well as the broad line in NGC 1333I2A, are most likely quasi-thermal lines.

5 CONCLUSIONS

A survey of young bipolar outflows in regions of low-to-intermediate-mass star formation has been carried out in two Class I methanol maser transitions, $7_0 - 6_1 A^+$ at 44 GHz and $4_{-1} - 3_0 E$ at 36 GHz. As a result of the survey we detected narrow features at 44 GHz towards NGC 1333I2, NGC 1333I4A, HH25MMS and L1157. One more maser candidate was detected at 36 GHz towards the blue lobe of a bipolar outflow driven by a low-mass YSO in the NGC 2023 region. Flux densities of the lines detected at 44 GHz are no higher than 11 Jy and their luminosities are about 10^{22} erg s^{-1} , which is much lower than those of strong maser lines in regions of high-mass star formation. No emission was found towards 39 outflows. The upper limits for the non-detections are typically of the order of 3–5 Jy. Thus, new masers in regions of low-mass star formation should be searched for with a sensitivity of 1 Jy or better.

Observations at 44 GHz in 2004, 2006 and 2008 did not reveal a significant variability of the masers in NGC 1333I4A, HH25MMS and L1157.

All masers at 44 GHz in these low-mass star formation regions were found in clouds with methanol column densities of several times 10^{14} cm^{-2} at linear scales of about 0.06 pc. Even higher methanol column densities have been reported towards stronger masers in regions of massive star formation. Therefore, the following trend seems to exist: molecular clouds with methanol column densities less than 10^{14} cm^{-2} cannot produce 44 GHz masers; clouds with methanol column densities 10^{14} – 10^{15} cm^{-2} can produce weak masers with luminosities of about 10^{22} erg s^{-1} ; clouds with methanol column densities higher than 10^{16} cm^{-2} can produce strong masers with luminosities 10^{24} – 10^{25} erg s^{-1} .

ACKNOWLEDGMENTS

The authors are grateful to the OSO staff for help during the observations. The work was partially supported by the Russian Foundation for Basic Research (grant nos. 04-02-17057 and 07-02-00248) and the RAS Scientific Research Program ‘Extended Sources in the Universe’. PH acknowledges partial support from NSF grant AST-0908901. The OSO is the Swedish National Facility for Radio Astronomy and is operated by Chalmers University of Technology,

Göteborg, Sweden, with financial support from the Swedish Research Council and the Swedish Board for Technical Development.

REFERENCES

- Anglada G., Sepulveda I., Gomez J. F., 1997, *A&AS*, 121, 255
 Avery L. W., Hayashi S. S., White G. J., 1990, *ApJ*, 357, 524
 Bachiller R., Terebey S., Jarrett T., Martin-Pintado J., Beichman C. A., Van Buren D., 1994, *ApJ*, 437, 296
 Bachiller R., Guilloiteau S., Dutrey A., Planesas P., Martin-Pintado J., 1995a, *A&A*, 299, 857
 Bachiller R., Liechti S., Walmsley C. M., Colomer F., 1995b, *A&A*, 295, L51
 Bachiller R., Codella C., Colomer F., Liechti S., Walmsley C. M., 1998, *A&A*, 335, 266
 Bachiller R., Perez Gutierrez M., Kumar M. S. N., Tafalla M., 2001, *A&A*, 372, 899
 Benedettini M., Viti S., Codella C., Bachiller R., Gueth F., Beltran M. T., Dutrey A., Guilloiteau S., 2007, *MNRAS*, 381, 1127
 Blake G. A., Sandell G., van Dishoeck E. F., Groesbeck T. D., Mundy L. G., Aspin C., 1995, *ApJ*, 441, 689
 Brinch C., Crapsi A., Hogerheijde M. R., Jørgensen J. K., 2007, *A&A*, 461, 1037
 Chen X., Ellingsen S. P., Shen Z.-Q., 2009, *MNRAS*, 396, 1603
 Chernin L. M., 1996, *ApJ*, 460, 711
 Chini R., Reipurth B., Ward-Thompson D., Bally J., Nyman L.-Å., Sievers A., Billawala Y., 1997, *ApJ*, 474, L135
 Clemens D. P., Berkovitch M., Yun J. L., Patel N., Xie T., 1996, *ApJ* 457, 743
 Cragg D. M., Johns K. P., Godfrey P. D., Brown R. D., 1992, *MNRAS*, 259, 203
 Davis C. J., Eisloffel J., Ray T. P., Jenness T., 1997a, *A&A*, 324, 1013
 Davis C. J., Ray T. P., Eisloffel J., Corcoran D., 1997b, *A&A*, 324, 263
 Davis C. J., Mattheys H. E., Ray T. P., Dent W. R. F., Richer J. S., 1999, *MNRAS*, 309, 141
 de Gregorio-Monsalvo I., Gómez J. F., Suárez O., Kuiper T. B. H., Rodríguez L. F., Jiménez-Bailón E., 2006, *ApJ*, 642, 319
 Dobashi K., Yonekura Y., Mizuno A., Fukui Y., 1992, *AJ*, 104, 1525
 Dutrey A., Guilloiteau S., Bachiller R., 1997, *A&A*, 325, 758
 Froebrich D., 2005, *ApJS*, 156, 169
 Fuente A., Neri R., Martin-Pintado J., Bachiller R., Rodríguez-Franco A., Palla F., 2001, *A&A*, 366, 873
 Garay G., Mardones D., Rodríguez L. F., Caselli P., Bourke T. L., 2002, *ApJ*, 567, 980
 Gibb A. G., Davis C. J., 1998, *MNRAS*, 298, 644
 Gibb A. G., Heaton B. D., 1993, *A&A*, 276, 511
 Gómez J. F., de Gregorio-Monsalvo I., Suarez O., Kuiper T. B. H., 2006, *AJ*, 132, 1322
 Haschick A. D., Menten K. M., Baan W., 1990, *ApJ*, 354, 556
 Hirano N., Liu S.-Y., Shang H., Ho P. T. P., Huang H.-C., Kuan Y.-J., McCaughrean M. J., Zhang Q., 2006, *ApJ*, 636, L141
 Kalenskii S. V., Slysh V. I., Val'ts I. E., Winnberg A., Johansson L. E. B., 2001, *Astron. Rep.*, 45, 26
 Kalenskii S. V., Slysh V. I., Val'ts I. E., 2002, *Astron. Rep.*, 46, 96
 Kalenskii S. V., Promyslov V. G., Slysh V. I., Bergman P., Winnberg A., 2006, *Astron. Rep.*, 50, 289 (Paper I)
 Kalenskii S. V., Promyslov V. G., Winnberg A., 2007, *Astron. Rep.*, 51, 44
 Kalenskii S. V., Kurtz S., Slysh V. I., Hofner P., Walmsley C. M., Johansson L. E. B., Bergman P., 2010, *Astron. Rep.*, submitted
 Knee L. B. G., Sandell G., 2000, *A&A*, 361, 671
 Kurtz S., Hofner P., Alvarez C. V., 2004, *ApJS*, 155, 149
 Ladd E. F., Hodapp K.-W., 1997, *ApJ*, 475, 749
 Launhardt R., Henning T., 1997, *A&A*, 326, 329
 Lee C.-F., Mundy L. G., Stroke J. M., Ostriker E. C., 2002, *ApJ*, 576, 294
 Lee C.-F., Ho P. T. P., White S. M., 2005, *ApJ*, 619, 948
 Lee C.-F., Ho P. T. P., Beuther H., Bourke T. L., Zhang Q., Hirano N., Shang H., 2006, *ApJ*, 639, 292
 Lefloch B., Cernicharo J., Reipurth B., Pardo J. R., Neri R., 2007, *ApJ*, 658, 498
 Meehan L. S. G., Wilking B. A., Claussen M. J., Mundy L. G., Wootten A., 1998, *AJ*, 115, 1599
 Menten K. M., 1991a, *ApJ*, 380, L75
 Menten K. M., 1991b, in Haschick A. D., Ho P. T. P., eds, *ASP Conf. Ser. Vol. 16, Atoms, Ions, and Molecules: New Results in Spectral Line Astrophysics*. Astron. Soc. Pac., San Francisco, p. 119
 Müller H. S. P., Menten K. M., Mäder H., 2004, *A&A*, 428, 1019
 Myers P. C., Heyer M., Snell R. L., Goldsmith P. F., 1988, *ApJ*, 324, 907
 O'Connell B., Smith M. D., Froebrich D., Davis C. J., Eisloffel J., 2005, *A&A*, 431, 223
 Ohashi N., Hayashi M., Kawabe R., Ishiguro M., 1996, *ApJ*, 446, 317
 Plambeck R. L., Menten K. M., 1990, *ApJ*, 364, 555
 Pratap P., Shute P. A., Keane T. C., Battersby C., Sterling S., 2008, *AJ*, 135, 1718
 Sandell G. et al., 1999, *ApJ*, 519, 236
 Sobolev A. M., Wallin B. K., Watson W. D., 1998, *ApJ*, 498, 763
 Stanke T., Williams J. P., 2007, *AJ*, 133, 1307
 Tafalla M., Myers P. C., Mardones D., Bachiller R., 1999, *A&A*, 348, 479
 Tafalla M., Myers P. C., Mardones D., Bachiller R., 2000, *A&A*, 359, 967
 Terebey S., Vogel S. N., Myers P. C., 1989, *ApJ*, 340, 472
 Williams J. P., Plambeck R. L., Heyer M. H., 2003, *ApJ*, 591, 1025
 Yun J. L., Clemens D. P., 1992, *ApJ*, 385, L21
 Yun J. L., Clemens D. P., 1994, *AJ*, 109, 742

APPENDIX A: LIST OF NON-DETECTIONS AT 44 AND 36 GHz

Table A1 presents the list of non-detections at 44 and 36 GHz. The fifth column presents the LSR velocities that correspond to the centre of the spectrometer bandwidth and the sixth column the upper limits of flux densities at 3σ level. Note 'hvb' means 'high-velocity bullet' and 'p', outflow with peculiar morphology; other notes are the same as in Table 2.

Table A1. Non-detections at 44 and 36 GHz.

Source	Line	RA (J2000)	Dec. (J2000)	V_{LSR} (km s^{-1})	S_{ν} (Jy)	Notes	Ref.
CB6	44	00:49:25.0	+50:44:45.1	-12.4	11.1	c	22,28
L1448IRS3	44	03:25:36.0	+30:45:20.0	-25.0	9.0	mo;c;b	4,17,18,25
L1448mm	44	03:25:38.8	+30:44:05.0	67.0	9.3	mo;c;r	4,17,18,23,25
L1448mm	44	03:25:38.8	+30:44:05.0	4.0	9.3	mo;c;r	4,17,18,23,25
L1448mm	36	03:25:38.8	+30:44:05.0	4.0	2.4	mo;c;r	4,17,23,25
L1448	44	03:25:40.9	+30:41:55.0	28.0	16.5	r	4,17,25
L1448	44	03:25:41.0	+30:42:50.0	55.0	13.5	r	4,17,25
L1448	36	03:25:41.0	+30:42:50.0	55.0	2.4	r	4,17,25
RNO15FIR	44	03:27:39.0	+30:13:03.4	5.0	5.1	c	13,14,18,23
RNO15FIR	44	03:27:43.0	+30:14:03.2	5.0	4.5	b	13,14,18
N1333I2A	44	03:28:48.0	+31:14:55.0	2.9	3.9	b	6,25,26
N1333I2A	44	03:28:55.4	+31:14:35.0	7.8	4.8	c	6,18,23,25,26
N1333I4A	44	03:29:06.5	+31:12:18.5	7.0	3.9	b	8,25,26
IRAS 03282	44	03:31:20.4	+30:45:24.7	1.2	3.9	c	3,5,18,25
IRAS 03282	44	03:31:30.3	+30:43:34.2	1.2	4.2	b	3,5,25
IRAS 03282	44	03:31:31.4	+30:44:09.1	7.0	10.2	b	3,5,25
HH211	44	03:43:55.0	+32:01:04.0	18.2	4.8	r	24,35
HH211	44	03:43:56.8	+32:00:50.0	9.2	4.8	c	24,35
HH211	36	03:43:56.8	+32:00:50.0	9.2	2.7	c	18,24,35
HH211	44	03:44:00.0	+32:00:36.0	2.2	2.7	b	24,35
CB17	44	04:04:33.7	+56:56:10.3	-4.7	4.2		28
L1489	36	04:04:43.0	+26:18:56.9	7.0	3.0	c	9,36
IRAM 04191	44	04:21:54.0	+15:28:40.0	6.6	8.4	b	29,30
IRAM 04191	44	04:21:57.0	+15:29:46.0	6.6	3.0	c	18,29,30
L1527	44	04:39:53.9	+26:03:10.4	6.0	5.4	c	36
L1527	36	04:39:53.9	+26:03:10.4	6.0	2.7		36
CB26	44	04:59:52.4	+52:04:45.1	5.8	3.3		28
IRAS 05155	44	05:18:17.3	+07:11:00.0	-1.6	10.5	c	29
OMC3	36	05:35:26.0	-05:01:38.0	7.5	4.8	mo	11,18,42
OMC3	36	05:35:22.0	-05:01:38.0	7.5	5.1	mo	11,42
OMC3	36	05:35:18.0	-05:01:38.0	7.5	4.2	mo	11,42
OMC3	36	05:35:13.7	-05:01:38.0	7.5	3.9	mo	11,42
OMC3	36	05:35:13.7	-05:00:28.0	7.5	5.1	mo	11,42
OMC3	36	05:35:19.3	-05:00:28.0	7.5	5.1	mo	11,42
OMC3	36	05:35:26.0	-05:00:28.0	7.5	5.1	mo	11,42
OMC3	36	05:35:32.7	-05:07:08.0	7.5	5.1	mo	11,42
OMC3	36	05:35:38.7	-05:07:08.0	7.5	25.8	mo	11,42
OMC3	36	05:35:28.7	-05:07:08.0	7.5	5.4	mo	11,42
OMC3	36	05:35:23.3	-05:07:08.0	7.5	5.1	mo	11,42
OMC3	36	05:35:16.7	-05:05:28.0	7.5	6.6	mo	11,42
OMC3	36	05:35:21.8	-05:05:28.0	7.5	6.6	mo	11,42
OMC3	36	05:35:26.0	-05:05:28.0	7.5	7.5	mo	11,42
OMC3	36	05:35:32.7	-05:05:28.0	7.5	7.5	mo	11,42
IRAS 05336	44	05:36:18.7	-06:22:10.0	7.2	11.7	c	18,23,38
NGC 2023	44	05:41:20.1	-02:16:02.9	30.0	4.2	r	37
NGC 2023	44	05:41:21.1	-02:17:48.0	30.0	4.2	r	37
NGC 2023	44	05:41:28.5	-02:19:18.6	-7.0	4.2	b	37
NGC 2023	44	05:41:24.8	-02:18:09.3	9.8	3.9	c	18,37
NGC 2024FIR6	44	05:41:45.1	-01:56:01.7	12.0	4.5	c	10,18
B35	36	05:44:29.8	+09:08:53.7	11.7	2.1	r;b	34,41
HH212	44	05:43:49.0	-01:04:10.0	-10.0	7.5	r	31
HH212	44	05:43:51.4	-01:02:53.0	1.7	5.1	c	18,31
HH212	44	05:43:54.0	-01:01:30.0	-10.0	6.9	b	31

Table A1 – *continued*

Source	Line	RA (J2000)	Dec. (J2000)	V_{LSR} (km s^{-1})	S_{ν} (Jy)	Notes	Ref.
HH26M	44	05:46:03.0	−00:15:00.0	10.0	5.1	c	14,21
HH24MMS1	44	05:46:08.6	−00:10:00.0	10.0	5.7		14,21
HH24MMS	44	05:46:08.6	−00:10:41.0	10.0	4.2	c	14,18,21
CB34	44	05:47:05.3	+21:00:42.0	0.7	9.9	c	22,28,43,44
HH111B2	44	05:51:31.4	+02:48:58.0	−50.0	3.9	hvb	32
HH111B1	44	05:51:34.9	+02:48:51.0	−50.0	3.6	hvb	32
HH111O	44	05:51:41.2	+02:48:39.0	1.0	3.0	b	32
HH111MMS	44	05:51:46.2	+02:48:30.0	9.0	3.3	c	18,32
CB101	44	17:53:05.2	−08:33:41.0	6.7	3.8		22
L483	44	18:17:33.2	−04:39:44.1	9.0	3.9	r	1,25,40
L483	44	18:17:27.7	−04:39:34.5	1.0	7.2	b	1,18,25,40
S68FIRS1	44	18:29:49.8	+01:15:20.6	8.1	3.3	mo;c	18,20,23
SERP-SMM4	44	18:29:58.6	+01:12:16.2	8.1	5.7	mo;b	15,20
SERP-SMM4	44	18:29:52.6	+01:13:45.8	8.1	4.5	mo;b	15,20
SERP-SMM4	44	18:29:56.6	+01:13:16.1	8.1	5.4	mo;c	15,18,20
L723K	44	19:17:46.0	+19:13:15.0	10.0	3.3	p;r	25,29,2
L723SE	44	19:17:58.0	+19:11:40.0	10.0	3.9	p;b	29,2
L723S1	44	19:17:50.0	+19:11:30.0	10.0	3.3	p;r	29,2
CB199	44	19:37:10.2	+07:36:50.0	8.4	3.9	c	22
CB205	44	19:45:21.3	+27:50:40.0	8.0	3.0	c	12,43,44
L1157	44	20:39:04.0	+68:04:45.0	15.0	1.8	r	7
L1157	36	20:39:04.2	+68:03:30.0	15.0	1.5	r	7
L1157	44	20:39:04.2	+68:03:30.0	15.0	3.0	r	7
CB230	44	21:17:39.4	+68:17:31.9	2.7	2.4	c	18,28,43,44
CB232	44	21:37:11.3	+43:20:36.0	12.6	3.3	c	18,22,23,28,43,44
NGC 7129-FIRS1	44	21:43:20.0	+66:08:00.0	0.0	5.1	r	19
NGC 7129-FIRS2	44	21:43:01.7	+66:03:25.0	0.0	2.4	mo;c	18,19
L1031	36	21:47:20.8	+47:32:03.6	3.2	2.4	c	16,34,41
L1251A	36	22:35:24.3	+75:17:05.7	−5.0	2.4	c	23,33
L1211-MMS1	44	22:47:02.2	+62:01:31.0	14.0	3.3	c	39
L1211-MMS4	44	22:47:17.2	+62:02:34.0	−10.0	6.0	c	18,39
CepE	44	23:03:13.0	+61:42:59.0	−11.2	7.2	r	18,23,27
CepE	44	23:03:13.0	+61:41:56.0	−11.2	10.2	b	23,27
L1262A	36	23:25:46.5	+74:17:38.2	4.2	2.4	c	18,41

References: 1 – Anglada, Sepulveda & Gomez (1997); 2 – Avery, Hayashi & White (1990); 3 – Bachiller et al. (1994); 4 – Bachiller et al. (1995a); 5 – Bachiller et al. (1995b); 6 – Bachiller et al. (1998); 7 – Bachiller et al. (2001); 8 – Blake et al. (1995); 9 – Brinch et al. (2007); 10 – Chernin (1996); 11 – Chini et al. (1997); 12 – Clemens et al. (1996); 13 – Davis et al. (1997a); 14 – Davis et al. (1997b); 15 – Davis et al. (1999); 16 – Dobashi et al. (1992); 17 – Dutrey, Guilloiteau & Bachiller (1997); 18 – Froebrich (2005); 19 – Fuente et al. (2001); 20 – Garay et al. (2002); 21 – Gibb & Heaton (1993); 22 – Gómez et al. (2006); 23 – de Gregorio-Monsalvo et al. (2006); 24 – Hirano et al. (2006); 25 – Kalenskii et al. (2007); 26 – Knee & Sandell (2000); 27 – Ladd & Hodapp (1997); 28 – Launhardt & Henning (1997); 29 – Lee et al. (2002); 30 – Lee, Ho & White (2005); 31 – Lee et al. (2006); 32 – Lefloch et al. (2007); 33 – Meehan et al. (1998); 34 – Myers et al. (1988); 35 – O’Connell et al. (2005); 36 – Ohashi et al. (1996); 37 – Sandell et al. (1999); 38 – Stanke & Williams (2007); 39 – Tafalla et al. (1999); 40 – Tafalla et al. (2000); 41 – Terebey, Vogel & Myers (1989); 42 – Williams, Plambeck & Heyer (2003); 43 – Yun & Clemens (1992); 44 – Yun & Clemens (1994).

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.