A SEARCH FOR 6.7 GHz METHANOL MASERS IN M33
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Received 2007 February 27; accepted 2007 October 3

ABSTRACT

We report the negative results from a search for 6.7 GHz methanol masers in the nearby spiral galaxy M33. We observed 14 GMCs in the central 4 kpc of the Galaxy, and found 3σ upper limits to the flux density of ~4 mJy at a velocity resolution of 0.35 km s⁻¹. By velocity shifting and combining the spectra from the positions observed, we obtain an effective 3σ upper limit on the average emission of ~1 mJy in a 0.25 km s⁻¹ channel. These limits lie significantly below what we would expect based on our estimates of the methanol maser luminosity function in the Milky Way. One possible explanation for the absence of detectable methanol masers appears to be the metallicity of M33, which is somewhat less than that of the Milky Way.

Subject headings: galaxies: individual (M33) — ISM: individual (methanol) — ISM: molecules — masers

1. INTRODUCTION

The 6.7 GHz methanol masers are the second brightest maser transition ever observed and are typically much brighter than OH masers. The properties of methanol masers in the Magellanic clouds (Sinclair et al. 1992; Ellingsen et al. 1994; Beasley et al. 1996) are consistent with those of our Galaxy, given appropriate consideration for different galactic properties such as metallicity. The Small Megellanic Cloud (SMC) has an oxygen abundance log(O/H) = 7.96 (Vermeij & van der Hulst 2002), which is a factor ~6 smaller than that of giant molecular clouds (GMCs) in the Milky Way (Peimbert et al. 1993).

The 6.7 GHz methanol masers have not been discovered in galaxies beyond the Magellanic clouds. In particular, surveys have shown that there is no analog to OH megamasers at 6.7 GHz (Ellingsen et al. 1994; Phillips et al. 1998; Darling et al. 2003). It would be of interest to detect methanol masers in a Milky Way—like galaxy. If the number of sources detected were large, one could derive the methanol maser luminosity function, since all sources would be at the same distance. One could then look for correlations between methanol masers and giant molecular cloud masses and other types of masers, for example. The Arecibo radio telescope offers unequaled sensitivity for targeted surveys for methanol masers, and the nearest spiral galaxy that can be observed is M33 (Peimbert et al. 1993).

It is difficult to develop an optimal strategy to search for extragalactic methanol masers since the luminosity function of methanol masers in our Galaxy is not known. However, methanol masers in our Galaxy are associated with early phases of massive star formation (e.g., Ellingsen 2006), which occurs primarily in GMCs. Thus, we targeted 14 massive GMCs in M33 for our search and report our results here.

2. OBSERVATIONS

The search for methanol masers in M33 was carried out using the 305 m Arecibo telescope and the C-band high receiver (Pandian et al. 2006) between 2005 July 9 and 21. The positions in M33 observed were the 14 most massive clouds given in Table 1 of Engargiola et al. (2003; reproduced in Table 1). Each cloud was observed for a total of 30 minutes on source. The data were taken in standard Arecibo position-switched mode by combining a set of integrations in which the source is observed for 5 minutes, and then a reference position at the same azimuth and zenith angle range (to remove standing waves) is observed for an equal length of time. The spectrometer used was the interim correlator. Two boards recorded the two orthogonal linear polarization data at 0.069 km s⁻¹ resolution (3.125 MHz bandwidth with 2048 lags) while the two other boards recorded the same data at a higher velocity resolution of 0.034 km s⁻¹ (1.5625 MHz bandwidth with 2048 lags). All the boards were centered on the CO velocity as given by Engargiola et al. (2003).

System temperatures varied between 23 and 34 K, with approximately 20% difference between the two polarizations. The data were reduced using standard procedures. The signal was calibrated in terms of antenna temperature using noise diodes, and the antenna temperature was converted to flux density using the elevation-dependent gain curve for this frequency, with a typical conversion factor of 5 K Jy⁻¹ (Pandian et al. 2007). The resulting rms for the low-resolution data after averaging the two linear polarizations is 3 mJy, and for the high-resolution data is a factor of √2 higher. The full width at half-maximum (FWHM) beam width of the telescope at 6.7 GHz is 40 ″. This corresponds to a linear size of 160 pc at the distance of M33, which we adopt to be 840 kpc, averaging the results of Lee et al. (2002) and Freedman et al. (1991), which gives a result consistent with the distance determined by Kim et al. (2002).

3. RESULTS

The observation of 14 massive GMCs in M33 yielded no methanol maser detections at a 3σ level of 9 mJy. Smoothing the data to a velocity resolution of 0.35 km s⁻¹ to match the typical observed linewidth of Galactic methanol masers (Pandian & Goldsmith 2007) gives individual 3σ detection limits of 4 mJy. Assuming that all the GMCs do exhibit methanol maser emission at a weak level, one can combine the data for all GMCs to get a better upper limit on the emission. This assumes that the emission occurs at the same velocity offset with respect to the velocity of the central channel in any given spectrum. To allow for different emission velocities in different GMCs, we adopt the
TABLE 1
GMCs in M33 Observed for Methanol Masers

| No.     | α(J2000.0) | δ(J2000.0) | V(CO)  | V(Hi)   | M(CO)   | M*(CO) |
|---------|------------|------------|--------|---------|---------|--------|
|         | (1)        | (2)        | (3)    | (4)     | (5)     | (6)    |
| 1.............. | 1 34 09.3 | 30 49 06.1 | -248.0 | -246.4  | 69.1    | 73.4   |
| 2.............. | 1 33 59.0 | 30 48 57.3 | -247.5 | -243.3  | 69.2    | 73.6   |
| 3.............. | 1 34 00.0 | 30 40 43.9 | -210.2 | -207.6  | 49.6    | 54.3   |
| 4.............. | 1 33 40.9 | 30 39 14.7 | -165.6 | -165.3  | 34.0    | 38.9   |
| 5.............. | 1 34 13.7 | 30 33 43.5 | -156.5 | -156.7  | 31.1    | 36.0   |
| 6.............. | 1 34 10.6 | 30 36 14.7 | -159.6 | -166.1  | 19.1    | 23.9   |
| 7.............. | 1 34 08.8 | 30 39 10.9 | -193.7 | -194.1  | 21.2    | 26.0   |
| 8.............. | 1 34 33.1 | 30 46 48.0 | -243.4 | -240.9  | 43.9    | 48.7   |
| 9.............. | 1 34 34.6 | 30 46 16.8 | -221.7 | -233.4  | 20.8    | 25.7   |
| 10.............| 1 34 06.6 | 30 47 51.3 | -256.8 | -250.9  | 33.6    | 38.5   |
| 11.............| 1 34 38.0 | 30 40 28.6 | -117.5 | -114.4  | 20.9    | 25.8   |
| 12.............| 1 33 46.9 | 30 32 41.0 | -117.5 | -114.4  | 20.9    | 25.8   |
| 13.............| 1 33 59.1 | 30 36 08.7 | -153.8 | -154.2  | 18.7    | 23.5   |
| 14.............| 1 33 23.6 | 30 25 39.3 | -112.9 | -111.1  | 23.4    | 28.2   |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Coordinates of GMCs and information from Engargiola et al. (2003). Col. (6) gives the cloud mass determined from the sum over spatial pixels of the CO emission; col. (7) gives the mass corrected for “missed” flux, which is a relatively small effect for the relatively massive clouds considered here.

Fig. 1.—Bottom: Result of adding the spectra of 14 GMCs that have been shifted in velocity to the velocity of peak cross-correlation with a Gaussian template. This spectrum is denoted spectrum A. The x-axis of the plot shows the velocity offset from that of the CO emission line. Top: Shifted individual GMC spectra, each of which is smoothed to a linewidth of 0.25 km s⁻¹. The side panel shows the velocity shift applied to each spectrum.
following procedure. We first select a section of the spectrum ($\pm 40$ km s$^{-1}$ wide) around the velocity of CO emission for each GMC including the largest offset that one would expect between the methanol maser and the molecular line emission (expected to be less than 15 km s$^{-1}$). Each subspectrum is then cross-correlated with a Gaussian whose width represents the expected linewidth of the maser emission ($\sim 0.30$ km s$^{-1}$). Each subspectrum is then shifted by the offset between the central channel and the channel of maximum cross-correlation amplitude. Following this procedure, the shifted data for all GMCs are added together. We denote the resulting spectrum as “A,” and it is shown at the bottom of Figure 1.

The above procedure will create a line feature resembling the correlation template (a Gaussian signal in this case) from the constructive alignment of purely random noise. Hence, the procedure is repeated for a different portion of the spectrum, where one does not expect to see any methanol maser emission, and the resulting spectrum is denoted “B” (Fig. 2). We then compare the A and B spectra. A weak emission feature would be manifest by the peak in spectrum A being higher than the peak in spectrum B by a statistically significant amount. Since this is not the case as can be seen by comparing Figures 1 and 2, we conclude that there is no detectable methanol maser emission in the data. The resultant 3 $\sigma$ upper limit on the average emission is $\sim 1$ mJy.

What do our results tell us about the methanol maser population of M33 compared to the Galactic sample? In our Galaxy, 6.7 GHz methanol masers appear to be associated exclusively with massive star formation. This is illustrated by a comprehensive search for methanol masers toward low-mass young stellar objects which did not result in any detections (Minier et al. 2003). Williams & McKee (1997) estimate the median mass of a molecular cloud having at least one O star to be $\sim 10^5 M_\odot$. Using the cumulative distribution of molecular clouds within the solar circle derived by Williams & McKee (1997) the number of clouds with mass greater than or equal to $10^5 M_\odot$ is $\sim 1120$. The number of methanol masers in the Galaxy was estimated to be around 1200 by van der Walt (2005) and further refined to be between 1290 and 1350 by Pandian & Goldsmith (2007) using the statistics of the blind Arecibo methanol maser Galactic plane survey. One can thus assume that essentially every GMC in the Galaxy that is forming massive stars also hosts one or more 6.7 GHz methanol masers. The larger number of methanol masers compared to GMCs forming massive stars can then be attributed to the formation of massive stars in clusters, resulting in the occurrence of multiple methanol masers in some GMCs.

If the environment of massive star formation in M33 is similar to that of the Galaxy, one can evaluate the expected distribution of flux density of methanol masers in M33. However, this is not trivial, since the luminosity function of Galactic methanol masers is not known. This is mostly due to the difficulties in determining distances to methanol masers in the Galaxy. Most distances are estimated from the kinematics of differential Galactic rotation and can have significant uncertainties due to streaming motions from spiral shocks, uncertainties in the rotation curve, distance
between the Sun and the Galactic center, etc. To compound these uncertainties, many distances in the first and fourth Galactic quadrant are double valued due to the kinematic distance ambiguity.

Hence, we have adopted the following approach. We selected sources from the general catalog (Pestalozzi et al. 2005), eliminating sources within $10^\circ$ of longitudes $0^\circ$ and $180^\circ$, since kinematic distances for these sources are unreliaible. For all sources that suffer from the distance ambiguity, we (1) assign the near distance to all sources and (2) assign the far distance to all sources, and then scale the flux density of the source to the distance of M33. Figure 3 shows the resulting histograms of “expected” methanol maser flux densities for the two cases above. If the methanol maser population of M33 is similar to that in our Galaxy, the real histogram of flux densities can be expected to be in between the two curves shown in the figure. Note that the methanol maser sample of 2005 (Pestalozzi et al. 2005) is derived from various targeted and unbiased surveys, and so the derived histograms in Figure 3 are likely to suffer from some biases.

From Figure 3, approximately 27% of the total number of masers in case (1) would be expected to have flux density greater than 1 mJy, with about 9% having flux density greater than 4 mJy, with the corresponding numbers for case (2) being 62% and 29%, respectively. Thus, the probability of having 14 nondetections at a level of 4 mJy is 0.29 and 0.009 for cases (1) and (2), respectively. In light of this discussion, it is surprising that we did not detect any methanol masers in our survey, and this suggests that there is some large-scale difference between the molecular clouds or massive young stars in M33 and those in the Milky Way.

4. DISCUSSION AND CONCLUSIONS

Explanations of the rarity of methanol masers in external galaxies have focused on (1) insufficient methanol density over the path where amplification could take place and (2) insufficient pumping to invert the methanol transition in question (Phillips et al. 1998). Both of these can result from low metallicity. A reduced abundance of oxygen, for example, will likely reduce both the abundance of methanol (CH$_3$OH) and that of dust, which is required to convert the short-wavelength radiation from massive young stars to the infrared wavelengths required for maser pumping. The rarity of masers in the Magellanic clouds has been discussed in similar terms by Beasley et al. (1996). The O/H ratio in the Magellanic clouds is dramatically lower than that of the Milky Way (see discussion in Beasley et al. [1996] and the more recent measurement by Vermeij & van der Hulst 2002). For M33, the O/H ratio is only slightly less than that of the Milky Way. Vilchez et al. (1988) determined that $12 + \log(O/H) = 9.0$ at the center of M33, falling to $\approx 8.5$ at distances between 2 and 5 kpc from the center of the galaxy. The study of Zaritsky et al. (1994) included M33 (NGC 598) and found $12 + \log(O/H) = 8.7$ at 3 kpc from the center of the galaxy, with a smaller gradient than found by Vilchez et al. (1988). The study of neon abundances in M33 by Willner & Nelson-Patel (2002) points out the difficulties of determining the oxygen abundance from optical lines and suggests that the very flat Ne abundance they find from IR lines is not consistent with the large gradients found in some previous studies. The best-fit line of Crockett et al. (2006) to their new data plus previous data has a very small slope of $-0.012$ dex kpc$^{-1}$ and $12 + \log(O/H) = 8.3$ at 5 kpc from the center of M33.

These values can be compared to Galactic values of $12 + \log(O/H) = 8.51$ for Orion and 8.78 for M17 (Peimbert et al. 1993). The GMCs that we have observed are located between 0.5 and 4 kpc from the center of M33, with a mean distance of 1.9 kpc. We conclude that the relevant O/H ratio in M33 is between 0.1 and 0.4 dex below that of the Milky Way. This difference is much smaller than that between the SMC and the Milky Way, for which log (O/H) differs by $\pm 0.8$ dex. If the relatively small difference between the metallicity in the Milky Way and M33 is responsible for the lack of methanol masers in the latter, it suggests that the maser luminosity must be a very sensitive function of the galactic metallicity.

Henkel et al. (1987) have detected thermal methanol emission from two galaxies, IC 342 and NGC 253, finding that the fractional abundance of methanol is $\approx 10^{-7.5}$. This is similar to that found in GMCs in the Milky Way but is a factor of at least 100 lower than that required for high-brightness methanol maser luminosity as discussed by Sobolev et al. (1997). However, this difference is also found in comparing hot cores in the Milky Way, presumed to be the sites of methanol masers, with more extended molecular cloud regions. The methanol abundance is presumably greatly increased in regions near hot stars by desorption of molecules frozen onto grain surfaces. We have no direct evidence regarding the methanol abundance in M33, so it is possible that the lower O/H ratio does yield an insufficient methanol abundance to produce highly luminous masers.

The effect of metallicity on methanol maser luminosity is also difficult to quantify in the Milky Way. While the number of methanol masers does decrease in the outer Galaxy (where the metallicity is lower), so does the surface density of molecular gas (a comparison of the two is found in Fig. 2 of Pestalozzi et al. 2007). Hence, it is difficult to disentangle the effect of metallicity with regard to methanol abundance, and the reduced rate of massive star formation due to the lower molecular gas surface density. It is difficult to draw a clear conclusion on the effect of the slightly lower metallicity in M33 on its methanol maser population (if it exists) from the data in our Galaxy.

While M33 is not very active in terms of star formation activity, the star formation rate per unit mass, which is proportional...
to the inverse of the gas depletion time, is quite high compared to that of other galaxies (compare depletion times given by Heyer et al. [2004] with those given by Wong & Blitz [2002]). Thus, there would not appear to be an a priori lack of large-scale infrared radiation for pumping methanol masers. There are individual regions within M33, presumably powered by massive young stars (Hinz et al. 2004), which are strong far-infrared sources. The infrared flux is a critical requirement for maser pumping as elaborated in models of Cragg et al. (1992), Sobolev & Deguchi (1994), and Sobolev et al. (1997). The transition to the second torsional excited state occurs at a wavelength of $\lambda_{22} = 30\,\mu m$, so that dust temperatures of at least 150 K are required to achieve high maser brightness (Sobolev et al. 1997). Among our targets was No. 8 of Engargiola et al. (2003), which lies within 1500 of the optical nebula NGC 604. This source has an IRAS luminosity of $L_{\text{IR}} = 6.8 \times 10^5 L_\odot$ (Rice et al. 1990), and the associated GMC has a mass derived from CO of $4.4 \times 10^5 M_\odot$ (Engargiola et al. 2003). By Galactic standards this region would seem likely to harbor a high-luminosity methanol maser, but no such emission was detected.

Fix & Mutel (1985) were unsuccessful in a search for highly luminous OH masers in M33. Their limit of $\approx 25$ mJy (5 $\sigma$) was sufficient to eliminate the presence of any type I maser as luminous as the brightest type I masers in the Milky Way. The present work thus reemphasizes the mystery of the lack of luminous masers in M33.

We are grateful to Phil Perillat for many discussions regarding the performance of the Arecibo telescope, and for supplying routines for data reduction. We thank German Cortes-Medellin and Lynn Baker for their contributions to the receiver system development, Kurt Kabelac and David Overbaugh for machining most of the dewar components, and Rajagopalan Ganesan and Lisa Locke for calibrating the C-band high receiver used in this work. We are also grateful to numerous other members of the staff at the Arecibo Observatory who helped us in the receiver installation and calibration and in setting up our observations. We thank the referee for a number of helpful comments and suggestions that improved the paper significantly. This work was supported in part by the Jet Propulsion Laboratory, California Institute of Technology. This research has made use of NASA's Astrophysics Data System.

REFERENCES

Beasley, A. J., Ellingsen, S. P., Claussen, M. J., & Wilcots, E. 1996, ApJ, 459, 600
Cragg, D. M., Johns, K. P., Godfrey, P. D., & Brown, R. D. 1992, MNRAS, 259, 203
Crockett, N. R., Garnett, D. R., Massey, P., & Jacoby, G. 2006, ApJ, 637, 741
Darling, J., Goldsmith, P. F., Li, D., & Giovanelli, R. 2003, AJ, 125, 1177
Ellingsen, S. P. 2006, ApJ, 638, 241
Ellingsen, S. P., Norris, R. P., Whiteoak, J. B., Vaile, R. A., McCulloch, P. M., & Price, M. G. 1994, MNRAS, 267, 510
Ellingsen, S. P., Whiteoak, J. B., Norris, R. P., Caswell, J. L., & Vaile, R. A. 1994, MNRAS, 269, 1019
Engargiola, G., Plambeck, R. L., Rosolowsky, E., & Blitz, L. 2003, ApJS, 149, 343
Fix, J. D., & Mutel, R. L. 1985, AJ, 90, 736
Freedman, W. L., Wilson, C. D., & Madore, B. F. 1991, ApJ, 372, 455
Henkel, C., Jacq, T., Mauersberger, R., Menten, K. M., & Steppe, H. 1987, A&A, 188, L1
Heyer, M. H., Corbelli, E., Schneider, S. E., & Young, J. S. 2004, ApJ, 602, 723
Hinz, J. L., et al. 2004, ApJS, 154, 259
Kim, M., Kim, E., Lee, M. G., Sarajedini, A., & Geisler, D. 2002, AJ, 123, 244
Lee, M. G., Kim, M., Sarajedini, A., Geisler, D., & Geisler, D. 2002, ApJ, 565, 959
Minier, V., Ellingsen, S. P., Norris, R. P., & Booth, R. S. 2003, A&A, 403, 1095
Pandian, J. D., & Goldsmith, P. F. 2007, ApJ, 669, 435
Pandian, J. D., Goldsmith, P. F., & Deshpande, A. A. 2007, ApJ, 656, 255
Pandian, J. D., et al. 2006, IEEE Microwave Magazine, 7, 74
Peimbert, M., Storey, P. J., & Torres-Peimbert, S. 1993, ApJ, 414, 626
Pestalozzi, M. R., Chrysostomou, A., Collet, J. L., Minier, V., Conway, J., & Booth, R. S. 2007, A&A, 463, 1009
Pestalozzi, M. R., Minier, V., & Booth, R. S. 2005, A&A, 432, 737
Phillips, C. J., Ellingsen, S. P., Rayner, D. P., & Norris, R. P. 1998, MNRAS, 294, 265
Rice, W., Boulanger, F., Viallefond, F., Soifer, B. T., & Freedman, W. L. 1990, ApJ, 358, 418
Sinclair, M. W., Carrad, G. J., Caswell, J. L., Norris, R. P., & Whiteoak, J. B. 1992, MNRAS, 256, 33P
Soibolov, A. M., Cragg, D. M., & Godfrey, P. D. 1997, A&A, 324, 211
Soibolov, A. M., & Deguchi, S. 1994, A&A, 291, 569
van der Walt, J. 2005, MNRAS, 360, 153
Vermeij, R., & van der Hulst, J. M. 2002, A&A, 391, 1081
Vilchez, J. M., Pagel, B. E. J., Diaz, A. I., Terlevich, E., & Edmunds, M. G. 1988, MNRAS, 235, 633
Williams, J. P., & McKee, C. F. 1997, ApJ, 476, 166
Willner, S. P., & Nelson-Patel, K. 2002, ApJ, 568, 679
Wong, T., & Blitz, L. 2002, ApJ, 569, 157
Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. 1994, ApJ, 420, 87