Cosmic Masers - from OH to H_0
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44 GHz Methanol Maser Surveys

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Abstract. Class I 44 GHz methanol masers are not as well-known, as common, or as bright as their more famous Class II cousins at 6.7 and 12.2 GHz. Nevertheless, the 44 GHz masers are commonly found in high-mass star forming regions. At times they appear to trace dynamically important phenomena; at other times they show no obvious link to the star formation process. Here, we summarize the major observational efforts to date, including both dedicated surveys and collateral observations. The principal results are presented, some that were expected, and others that were unexpected.

Keywords. masers, surveys, stars:formation

1. The Early Days

The first detection of maser emission in the 44 GHz methanol line was reported in the literature by Morimoto *et al.* (1985). Emission was found in four galactic sources, all of them regions hosting high-mass star formation. It wasn't immediately clear if the 44 GHz line (the $7_0 - 6_1$ A^+ transition) was a class I or class II maser. In fact, determining to which maser class it belonged was one of the chief motivations of the early surveys. The first survey, made by Haschick, Menten & Baan (1990) with the Haystack 37-m telescope, targeted 50 galactic star formation regions. Their 50% detection rate not only identified many new masers, but confirmed the 44 GHz transition as belonging to class I, along with the 25, 36, 84, and 95 GHz lines. Until it was largely taken over by the U.S. Air Force, the Haystack telescope continued to be productive for methanol maser surveys, most notably that of Pratap *et al.* (2008).

Additional northern hemisphere single-dish surveys were reported by Bachiller *et al.* (1990) and Kalenskii *et al.* (1992). Both of these surveys used the Yebes 14-m telescope. The former targeted 124 regions of known water maser emission and yielded a 13% detection rate; all of the maser detections were associated with compact HII regions. The latter targeted 137 cold IRAS sources and had a frigid detection rate of 2%, detecting only 3 masers.

A southern single-dish survey was reported by Slysh *et al.* (1994) who observed with the Parkes 64-m telescope. Their sample of 250 objects consisted mostly of HII regions and sources known to present maser emission in some other molecular species; they had a 22% detection rate, discovering 25 masers.

These early single-dish surveys produced a sample of about 110 known 44 GHz masers and clearly established this transition as being class I, and arising in massive star formation regions. All four of these surveys, and several later interferometric surveys, have been nicely cataloged by Val'tts & Larionov (2007).

2. Follow-up Interferometric and Single-Dish Surveys

The single-dish surveys laid the crucial groundwork for establishing the nature of 44 GHz masers, but of course they lacked the angular resolution needed for more detailed studies. Interferometric surveys became possible when the VLA was outfitted with 7 mm receivers in the mid-1990s.

Kogan & Slysh (1998) published positions for masers in eight well-known star formation regions that had been identified in the early single-dish surveys. They noted the appearance of 44 GHz masers in regions where class II methanol masers had been reported, suggesting that some of the more empirical aspects of the early class I/II definitions might need revision.

A similar conclusion was reached in a second VLA survey, reported by Kurtz, Hofner & Vargas (2004). They observed 44 galactic star formation regions with an 84% detection rate. The heterogeneous nature of their sample limits the significance of this detection rate; in particular, about one third of their targets were selected from the detections reported by Bachiller *et al.* (1990).

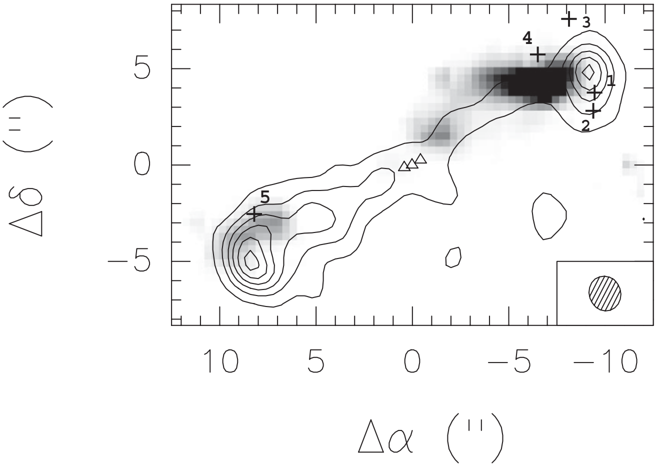

Figure 1. The IRAS 20126+4104 molecular outflow. The greyscale shows H_2 emission (Cesaroni *et al.* 1997) while the contours show SiO emission (Cesaroni *et al.* 1999). The 44 GHz methanol masers reported by Kurtz *et al.* (2004), shown as crosses, clearly coincide with the edges of the outflow lobes, where the molecular outflow interacts with the ambient medium, as was speculated by Plambeck & Menten (1990).

In some cases the interferometric surveys simply confirmed what was already known from the earlier, single-dish surveys. For example, Kurtz *et al.* (2004) found evidence for thermal methanol emission in some sources, but such emission was already well-known from the Haschick *et al.* (1990) survey. Interferometric observations, however, did permit the location of this thermal emission with respect to other star formation tracers. For example, Araya *et al.* (2008) used thermal methanol emission to trace the hot molecular core in G31.41+0.31, which is spatially offset from both the ultracompact HII region and the masers. An additional example of affirming earlier results was the discovery of the close association of methanol masers with the outflow lobes of IRAS 20126+4104. Such an association was anticipated by Plambeck & Menten (1990) who originally proposed that class I masers arise in molecular gas shocked by outflows (see Fig. 1).

Kurtz *et al.* (2004) also found evidence for the maser–outflow association in DR21, locating two distinct lobes of maser emission, with a velocity separation of about

5 km s^{-1}. The intriguing aspect of this outflow is that the masers themselves seem to define the outflow lobes. Their finding was followed up by more sensitive maser and centimeter continuum observations reported by Araya *et al.* (2009), who found four maser arcs (two blue-shifted and two red-shifted) and speculated that there were two distinct outflow events, each one producing a pair of maser arcs (see Fig. 2).

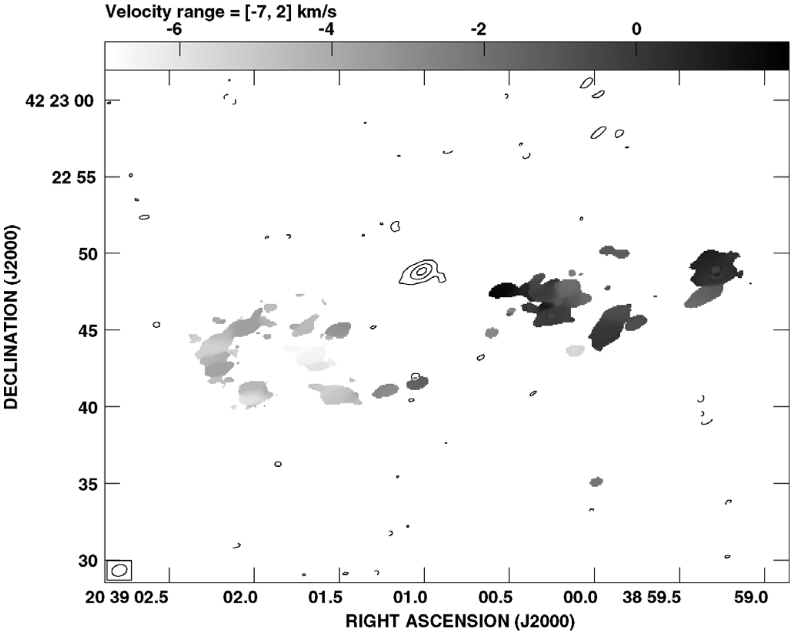

Figure 2. The DR21 region shows a bipolar outflow traced by 44 GHz methanol masers. The red lobe (toward the west) and the blue lobe (toward the east) have a velocity difference of about 5 km s^{-1}. The grey scale shows the first moment map while contours show the 7 mm continuum emission. The figure is adapted from Araya *et al.* (2009).

In other cases, the interferometric surveys produced unexpected results. For example, Kurtz *et al.* (2004) found a median projected separation of 0.2 pc between the 44 GHz masers and the compact HII regions in their sample (see Fig. 3). This was substantially closer than the nominal 1 pc typically quoted for class I masers.

3. Methanol Masers in Low-Mass Star Forming Regions

Until recently, methanol masers were thought to arise *only* in high-mass star formation regions — unlike the far more ubiquitous water masers, which occur in both low- and high-mass star forming regions (and indeed, in evolved objects as well). Although class II masers still appear to be unique to high-mass star formation regions, recent surveys by Kalenskii *et al.* (2006, 2010a) have identified several 44 GHz maser candidates. Their two single-dish surveys, made with the Onsala 20-m telescope, targeted nearby, chemically rich outflow regions. Although 39 regions had no emission at the 3–5 Jy level, four regions did show 44 GHz emission: NGC1333 I2, NGC1333 I4A, HH25 MMS, and L1157. So far only the L1157 region has been observed interferometrically (Kalenskii *et al.* 2010b); their VLA observations confirm the maser nature of the emission (see Fig. 4).

Kalenskii *et al.* (2010b) developed a model in which the maser emission arises in a collapsing clump of molecular gas. Although the model qualitatively explains the L1157

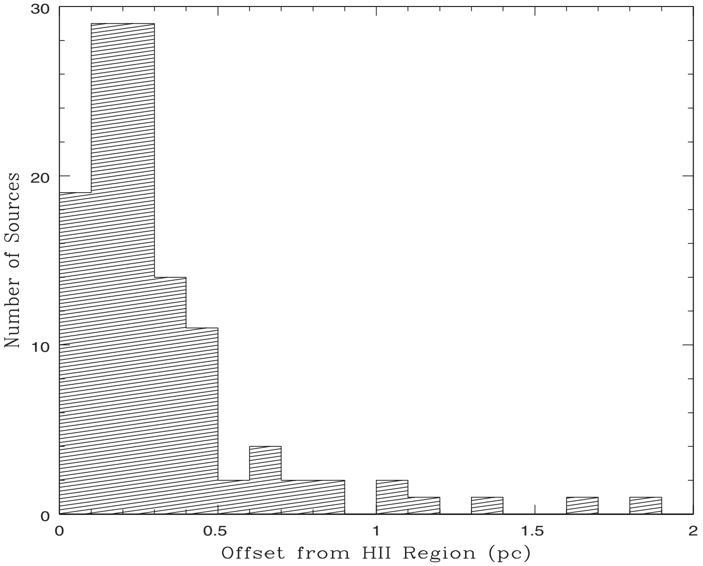

Figure 3. Histogram of the projected distance between the 44 GHz maser position and the geometric center of nearby ionized gas emission, from Kurtz *et al.* (2004). The median projected distance is 0.2 pc — substantially less than the nominal distance of 1 pc normally used in the class I maser definition.

maser, they are hesitant to suggest it as a general explanation for low-mass methanol masers because none of the other sources present a double-line, red-asymmetry profile (see Kalenskii *et al.* this volume). Based on their single-dish survey they argue that a minimum methanol column density of 10^{14} cm^{-2} is required for maser emission. One result of their work is to break the strangle-hold of high-mass star forming regions on class I masers. In a sense it is a loss to no longer have class I masers as a *unique* indicator of high-mass regions. Hopefully there will be some compensation by having nearby masers in less-complicated environments (compared to high-mass star forming regions) thus facilitating their study. In any case, the upper limit of a 10% detection rate implies that although class I masers my not be unique to high-mass star forming regions, they certainly are not a common phenomenon in low-mass star forming regions.

4. More Recent Single-Dish Surveys

Two recent single-dish surveys of the 44 GHz methanol maser line are particularly noteworthy. One of these, Bae *et al.* (2011), a simultaneous water plus methanol survey of 180 young stellar objects, made with a 22-meter dish of the Korean VLBI network, is described in detail elsewhere in this volume by K. T. Kim.

The other survey, Fontani *et al.* (2010), observed a sample of about 300 young stellar objects (YSOs) in the 6.7 GHz (class II) methanol line with the Effelsberg telescope, and a randomly selected sub-sample of 88 objects in the 44 and 95 GHz (class I) lines with the Nobeyama 45-m. A statistical comparison of their data for the different lines suggests that the 95 GHz maser is intrinsically fainter, and that the class I masers are spread over a larger sky area than the class II masers. More significantly, as we will discuss below, they find a higher 44 GHz maser detection rate in older objects (48% ±8%), and a lower detection rate in younger objects (17% ± 5%), suggesting that class I masers preferentially arise in *older* regions.

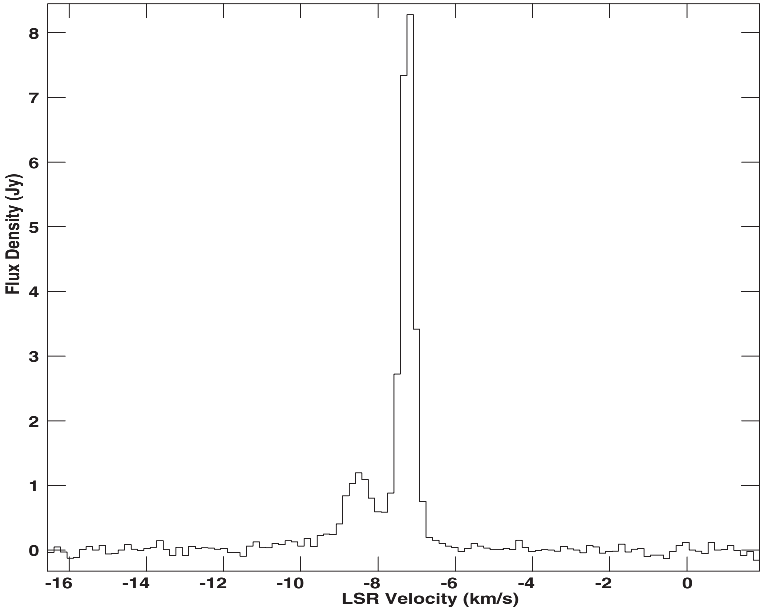

Figure 4. Spectrum of two of the 44 GHz masers in the low-mass star formation region L1157, reported by Kalenskii *et al.* (2010b). The stronger peak corresponds to source M1a while the weaker peak is M1b. Note that both the velocity and the brightness axes in their paper were incorrectly labeled. The correct units for the brightness scale are Jy beam^{-1}, giving brightness temperatures in excess of 2000 K for the brighter maser component.

5. Two New Interferometric Surveys

Two well-known and well-studied samples of high mass protostellar objects (HMPOs) and/or YSOs have emerged in the past 10 years: the samples of Molinari *et al.* (1996) and of Sridharan *et al.* (2002). The Molinari sample consists of 163 IRAS sources, half with colors of cold clouds, half with colors of ultracompact (UC) HII regions. The sample has been the subject of many additional studies, including a search for molecular outflows by Zhang *et al.* (2005) that identified 35 outflows in a sub-sample of 69 objects.

A second sample, also of 69 objects, was identified by Sridharan *et al.* (2002). Their selection criteria included colors indicative of UC HII regions but with 6 cm flux densities lower than 25 mJy, and the presence of molecular gas. Thus, like the Molinari sample, the Sridharan sample identifies young (possibly proto-) stellar objects.

We have completed a 44 GHz maser survey of the Molinari/Zhang sample and are mid-way through observations of the Sridharan sample. Both surveys are made with the VLA, with angular resolutions of about 2″ and 3σ detection limits of about 0.15 Jy. The Molinari/Zhang sample will soon be submitted (Gómez-Ruíz *et al.* in prep.) and here we mention several results from that survey.

As in the Kurtz *et al.* (2004) survey, some findings were no surprise. For example, Fig. 5 shows a histogram of the relative velocity between the masers and the systemic velocity of the region. The narrow velocity range found in this survey is consistent with earlier findings that class I masers usually occur at velocities very close to systemic.

An unexpected result of this survey is that the masers appear to be slightly closer to the ionized gas (when present) than they are to the IRAS positions. The trend is not particularly pronounced, but on average the masers appear to be about 0.1 pc closer to the ionized gas than to the embedded infrared sources. The IRAS positional uncertainty

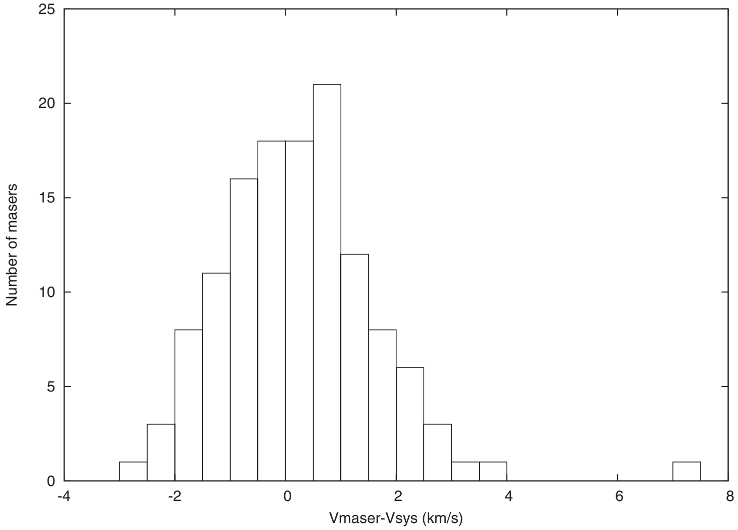

Figure 5. Histogram of the relative velocity between the maser component and the systemic velocity of the region. The latter is traced by ammonia velocities, as reported by Molinari *et al.* (1996). Apart from one outlier, the distribution is fairly narrow, and approximately centered on zero.

is of the same order as the statistical difference in the separations, so it isn't clear how robust the result is; a comparison with Spitzer images would definitely be worthwhile.

It's reasonable to expect that the physical conditions might be different closer to the UCHII regions; for example, the dust is likely to be hotter, and the grain size distribution is likely modified. But changes in the dust would most likely affect the radiation field, and class I masers are thought to be collisionally — not radiatively — pumped.

One way to understand how the difference in distances might arise is shown in Fig. 6. If the masers arise close to an outflow interaction region, then their distance to ionized emission *or* the dust emission could be rather meaningless; whichever of these two components is closer to the outflow would show smaller offsets from the maser, but without implying any physical connection between them. As noted by Hoare *et al.* (2007), emission from ionized gas and from warm dust are generally not spatially correlated in massive star forming regions. Because the two components generally do not coincide, some difference in separation is expected.

A distinct surprise in the Gómez-Ruíz survey was the maser detection rate when the sample was divided by source type. In particular, the 40% *overall* detection rate of the survey changes when the sample is separated by those sources with UC HII regions (presumably older) and those without UC HII regions (presumably younger or HMPO). The detection rates are 59% for the former and 35% for the latter. The same trend is seen by Fontani *et al.* (2010) who, as mentioned above, report a 48% ± 8% detection rate for the "high" sources and 17% ± 5% for the "low" sources.

These trends are in sharp contrast to the phenomenally high 90% detection rate for 44 GHz masers in EGOs (Extended Green Objects) reported by Cyganowski *et al.* (2009). EGOs are thought to be in a fairly young evolutionary state. And indeed, deep centimeter continuum observations reported by Cyganowski *et al.* (2011) found compact/ultracompact HII regions in only 2 of 14 sources observed, The lack of free-free emission strongly indicates that EGOs are young objects, typically in a pre-UCHII

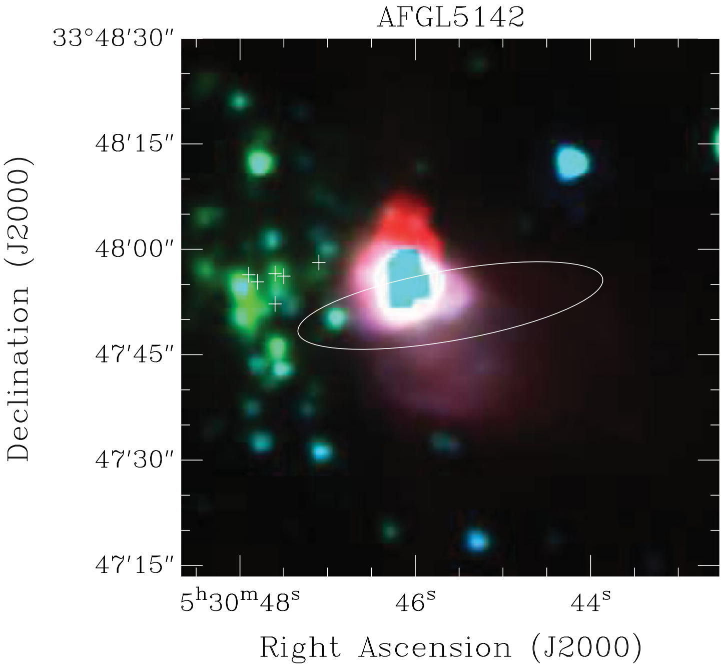

Figure 6. A Spitzer 3-color image (3.6, 4.5 and 8.0 μm) of M10 (AFGL 5142) with the IRAS error ellipse shown and the 44 GHz masers indicated with crosses. Image from Gómez-Ruíz (in prep.)

region phase. But the two surveys mentioned above find *lower* detection rates in younger objects — certainly nothing approaching 90%.

The strikingly high detection rate of 44 GHz masers in EGOs probably has more to do with EGOs being good tracers of outflows than with the overall evolutionary state of region. The association of Class I masers with outflows is fairly clear, but the relation of 44 GHz masers to the overall evolutionary state of the region is still rather murky. Moreover, as the Gómez-Ruíz survey shows, although the presence of an EGO is an exceedingly good predictor of the presence of a 44 GHz maser, the inverse relationship does not hold. To wit, the majority of regions where they detect 44 GHz masers are *not* regions that host EGOs.

6. Conclusions

Numerous surveys have been made of the 44 GHz methanol maser, using both single-dish telescopes and interferometers. The more recent (and extensive) surveys have confirmed a number of behaviors that were seen in the early (and generally less extensive) surveys. Examples include the low number of velocity components in the 44 GHz class I spectra, the close agreement between maser velocities and ambient gas systemic velocities, and the fact that the maser positions generally do not coincide with infrared and centimeter continuum emission.

Nevertheless, the newer surveys have also produced some surprises, One of these is that the 44 GHz class I maser *can* appear in low-mass star formation regions. Additionally, the closer (but still offset) maser positions with respect to infrared/centimeter sources was an unexpected contribution of the interferometric surveys. Perhaps most significant is the finding of the phenomenally high detection rate of these masers toward EGOs.

The latter point is still somewhat mysterious, because of the finding in several surveys that detection rates increase with the apparently increasing age of host star formation region. Reconciling these detection rates with the evolutionary picture of methanol masers in star forming regions will require further study.

References

Araya, E., Hofner, P., Kurtz, S., Olmi, L., & Linz, H. 2008, *ApJ* 675, 420

Araya, E., Kurtz, S., Hofner, P., & Linz, H. 2009, *ApJ* 698, 1321

Bachiller, R., Gómez-González, J, Barcia, A., & Menten, K. M. 1990, *A&A* 240, 116

Bae, J.-H., Kim, K.-T., Youn, S.-Y., Kim, W.-J., Byun, D.-Y., Kang, H., & Oh, C. S. 2011, *ApJS* 196, 21

Cesaroni, R., Felli, M., Testi, L., Walmsley, C. M., & Olmi, L. 1997, *A&A*, 325, 725

Cesaroni, R., Felli, M., Jenness, T., Neri, R., Olmi, L., Robberto, M., Testi, L., & Walmsley, C. M. 1999, *A&A* 345, 949

Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2009, *ApJ* 702, 1615

Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2011, *ApJ* 743, 56

Fontani, F., Cesaroni, R., & Furuya, R. S. 2010, *A&A* 517, 56

Haschick, A. D., Menten, K. M., & Baan, W. A. 1990, *ApJ* 354, 556

Hoare, M. G., Kurtz., S. E., Lizano, S., Keto, E., & Hofner, P. 2007, in: B. Reipurth, D. Jewitt, & K. Keil (eds.), *Protostars and Planets V*, (Tucson: University of Arizona Press), p. 181

Kalenskii, S. V., Bachiller, R., Berulis, I. I., Val'tts, I. E., Gómez-González, J., Martin-Pintado, J., Rodríguez-Franco, A., & Slysh, V. I. 1992, *SvA* 36, 517

Kalenskii, S. V., Promyslov, V. G., Slysh, V. I., Bergman, P., & Winnberg, A. 2006, *Astron. Rep.*, 50, 289

Kalenskii, S. V., Johansson, L. E. B., Bergman, P., Kurtz, S., Hofner, P., Walmsley, C. M., & Slysh, V. I. 2010a, *MNRAS*, 405, 613

Kalenskii, S. V., Kurtz, S., Slysh, V. I., Hofner, P., Walmsley, C. M., Johansson, L. E. B., & Bergman, P. 2010b, *Astron. Rep.*, 54, 932

Kogan, L. & Slysh, V. 1998, *ApJ* 497, 800

Kurtz, S., Hofner, P., & Vargas-Álvarez, C. 2004, *ApJS* 155, 149

Molinari, S., Brand, J., Cesaroni, R., & Palla, F. 1996 *A&A* 308, 573

Morimoto, M., Kanzawa, T., & Ohishi, M. 1985 *ApJ* (Letters) 288, L11

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

Sridharan, T. K., Beuther, H., & Schilke, P. 2002, *ApJ* 566, 931

Slysh, V. I., Kalenskii, S. V., Val'tts, I. E., & Otrupcek, R. 1994, *Mon. Not. Royal Astron. Soc.* 268, 464

Val'tts, I. E. & Larionov, G. M. 2007 *Astron. Rep.* 51, 519

Zhang, Q., Hunter, T. R., Brand, J., Sridharan, T. K., Cesaroni, R., Molinari, S., Wang, J., & Kramer, M. 2005, *ApJ* 625, 864