WIDESPREAD METHANOL EMISSION FROM THE GALACTIC CENTER: THE ROLE OF COSMIC RAYS

F. YUSEF-ZADEH1, W. COTTON2, S. VITT3, M. WARDLE4, AND M. ROYSTER1

1 Department of Physics and Astronomy & Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA
2 National Radio Astronomy Observatory, Charlottesville, VA 22903, USA
3 Department of Physics and Astronomy, University College London, Gower St. London, WC1E 6BT, UK
4 Department of Physics & Astronomy, Macquarie University, Sydney NSW 2109, Australia

ABSTRACT

We report the discovery of a widespread population of collisionally excited methanol $J = 4_1$ to $3_0$ E sources at 36.2 GHz from the inner $66' \times 18'$ (160 $\times$ 43 pc) of the Galactic center. This spectral feature was imaged with a spectral resolution of 16.6 km s$^{-1}$ taken from 41 channels of a Very Large Array continuum survey of the Galactic center region. The revelation of 356 methanol sources, most of which are maser candidates, suggests a large abundance of methanol in the gas phase in the Galactic center region. There is also spatial and kinematic correlation between SiO (2–1) and CH$_3$OH emission from four Galactic center clouds: the +50 and +20 km s$^{-1}$ clouds and G0.13$-$0.13 and G0.25$+$0.01. The enhanced abundance of methanol is accounted for in terms of induced photodesorption by cosmic rays as they travel through a molecular core, collide, dissociate, ionize, and excite Lyman Werner transitions of H$_2$. A time-dependent chemical model in which cosmic rays drive the chemistry of the gas predicts CH$_3$OH abundance of $10^{-8}$ to $10^{-7}$ on a chemical timescale of $5 \times 10^4$ to $5 \times 10^5$ years. The average methanol abundance produced by the release of methanol from grain surfaces is consistent with the available data.

Key words: astrochemistry – cosmic rays – Galaxy: nucleus – ISM: molecules – masers – stars: early-type

Online-only material: color figure, machine-readable table

1. INTRODUCTION

Large-scale molecular line surveys of the inner few hundred pc of the Galaxy, also known as the central molecular zone (CMZ), have detected emission lines from a wide array of molecular species formed in gas phase (e.g., H$_2$, CO, CS, CH$_3$OH, and NH$_3$) chemistry (Martin-Pintado et al. 1997; Martin et al. 2004; Oka et al. 2005; Riquelme et al. 2010; Jones et al. 2012). What is interesting about these results is that the gas characteristics are similar to those of hot cores associated with protostars and yet the distribution of molecular gas is widespread over a few hundred parsecs with a few isolated pockets of star formation such as Sgr B2. The gas in the Galactic center has a higher temperature than the dust temperature $\leq$30 K (e.g., Figure 3 of Molinari et al. 2011). This characteristic of the warm gas is hard to explain if the hot cores are heated by high mass protostars throughout the population of Galactic center molecular clouds. To investigate the chemistry of the gas in the CMZ, we carried out a high-resolution survey of methanol emission from the inner $66' \times 18'$ of the Galactic center.

Here we report the discovery of a large population of collisionally excited methanol $J = 4_1$ to $3_0$ E emission at 36.2 GHz. Class I methanol masers are collisionally pumped and are generally correlated with outflows in star-forming sites (e.g., Voronkov et al. 2006). Given the pervasive distribution of detected maser candidates, we suggest instead that enhanced abundance of methanol is produced globally by the interaction between enhanced cosmic rays and molecular gas in the CMZ.

2. OBSERVATIONS AND DATA REDUCTION

The maser observations were conducted with the K. Jansky Very Large Array of the National Radio Astronomy Observatory in its C configuration as part of a continuum survey in which one subband was centered on the rest frequency of the rotational class I methanol masers (36.169265 GHz). This subband had 64 $\times$ 2 MHz channels giving a velocity resolution of $\approx$16.6 km s$^{-1}$. Each of the $\geq$900 single snapshot pointings was imaged independently and the results combined in a linear mosaic. These observations were made in six sessions between 2012 February 21 and March 10 under project code 12-120A. J1744-3116 was used as the phase calibrator and 3C286 was used as the photometric and bandpass calibrator with an assumed flux of 1.70 Jy and an uncertainty of 5%. Using the Obit package, calibration, editing, and imaging were done on each session independently and consisted of determining first instrumental group delay offsets from observations of 3C286 and J1744–3116, and applying to all data. The methanol features were much narrower in frequency than a channel, so the stronger features gave significant Gibbs ringing in frequency due to the limited range of lags used by the correlator. The resolution is approximately $1.8' \times 0.7'$ with rms noise $\approx$2.5 mJy beam$^{-1}$. The image cubes for each pointing were collapsed to a single plane containing only “significant” pixels and all pixels within eight cells of significant pixels (see Figure 2(d)). These were the brightest points in each image plane which was in excess of six times the off-source rms and more than 0.15 times the brightest pixel in the channel image. Masers were selected from the combined, collapsed cubes, and elliptical Gaussians fitted. Note that this procedure will select continuum as well as maser candidates. Maser candidates were then tested using the spectrum extracted at the appropriate location from the combined

5 The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

6 http://www.cv.nrao.edu/~bcotton/Obit.html
spectral cube (see Figure 2(d)). Spectral features were accepted if the channel with the highest flux density was in excess of five times the rms of the other channels.

3. RESULTS

Figure 1(a) reveals a color-coded distribution of 356 methanol sources found in the region between Galactic longitude $-30' < l < 36'$ and latitude $-12' < b < 6'$. The size of each methanol source is proportional to the line flux of each source. The list of methanol sources of Table 1 in 10 columns gives the source number, Galactic coordinates, the spatially integrated line flux, the center velocity, the lower limit to the brightness temperature ($T_b$) estimated from the maximum value in the spectrum interpolated at the fitted centroid of the spot in the collapsed image, the fitted values of the angular size and references. Given the large channel width (16.6 km s$^{-1}$), we can only identify maser candidates by their high estimated $T_b$, without information on the linewidths. For unresolved point sources, the line flux ranges between 0.19 and 468.31 Jy km s$^{-1}$, corresponding to brightness temperatures ranging between $T_b = 8.5$ K and $2.1 \times 10^4$ K, respectively. Typical masers have linewidths that are one-to-two orders of magnitudes smaller than the channel width we used, thus these sources could be much brighter if measured with smaller channel widths. As for sources with low brightness temperature, it is possible that these weak sources trace thermal methanol gas. However, thermal emission is generally spatially extended and the present snapshot survey does not have the sensitivity to detect extended emission on a scale $\geq 22''$. To test that bright sources in Table 1 include previously detected masers, we compare our sources with those of Sjouwerman et al. (2010, hereafter SPF) who had spectroscopically identified 36.2 GHz masers in the 50 km s$^{-1}$ molecular cloud. SPF tabulates 10 methanol masers (number 10, 6, 7, 8, 9, and 4 in their Table 1) ranging in
brightness temperature $6.6 \times 10^4 < T_b < 2.3 \times 10^6 \text{ K}$. Six of the brightest sources coincide with sources that are detected in our survey (number 160, 164, 165, 167, 168, 169 in our Table 1) having similar LSR velocities. These spatial and spectral coincidences confirm maser candidate identification of bright sources in our survey.

Figure 1(b) shows the distribution of all detected methanol sources with their peak velocities superimposed on a grayscale continuum image of the Galactic center at 5 GHz. The peak velocities are accurate to within 10 km s$^{-1}$ and cannot identify multiple velocity components. Prominent radio continuum sources Sgr A, the nonthermal vertical, and thermal
arched filaments of the radio Arc, Sgr B1, and Sgr AC (the region between Sgr A and Sgr C) are labeled. The largest concentration of maser candidates lies in Sgr AC near $l \sim 40\degree$ and the radio Arc near $l \sim 0.1\degree$–0.2. We note a total of 200 and 150 sources distributed between $-0.5 < l < 0\degree$ and $0\degree < l < 0.5$, respectively, suggesting an asymmetry with respect to Galactic longitude. We divide the source list into strong or weak maser candidate sources with line fluxes greater than or less than 10 Jy km s$^{-1}$ ($T_b \sim 446$ K for unresolved sources), respectively. This threshold is selected because the gas temperature in the CMZ is much less than 446 K. Figure 1(c) shows the distribution of all methanol maser candidates superimposed on a gray-scale 24 μm image showing similar asymmetry in terms of the number of young stellar object candidates (Yusef-Zadeh et al. 2009). This implies that star formation processes may be contributing to the origin of this asymmetry.

To examine the relationship between CH$_3$OH (36.2 GHz) maser candidates and dust emission, Figures 2(a) and (b) show the distribution of weak and strong methanol emission superimposed on the distribution of dust clouds at 850 μm, respectively (Pierce-Price et al. 2000). Methanol sources generally follow the “bow-tie” dust layer which runs parallel to the Galactic plane. The brightest methanol sources in Figure 2(b) show a good correlation of maser candidates and dust emission from the CMZ. To examine the central region of the CMZ in more detail, Figure 2(c) views the distribution of weak maser candidates superimposed on a gray-scale image of SiO (2–1) line emission map (Tsiboi et al. 2011). Figure 2(d) shows the spectrum of a representative maser candidate and a collapsed image showing the distribution of bright sources in G0.13–0.13. A correlation between methanol maser candidates and SiO line emission suggests that the chemistry in producing enhanced methanol and SiO line emission is similar. This is interesting because the abundance of SiO produced in the ambient gas is too low, thus grain-surface chemistry is needed to enhance the abundance of both SiO and CH$_3$OH throughout the Galactic center. In the following, we briefly discuss the distribution of methanol sources toward four Galactic center molecular clouds.

The 50 km s$^{-1}$ cloud. The 50 km s$^{-1}$ M–0.02–0.07 is physically interacting with an expanding shell of the Sgr A East SNR G0.0+0.0 (e.g., Tsiboi et al. 2011). The presence of OH (1720 MHz) masers at the site of the interaction suggests that the abundance of OH is enhanced behind a supernova shock driving into the molecular cloud (Yusef-Zadeh et al. 1999; Wardle 1999). Figure 3(a) shows contours of SiO (2–1) line emission superimposed on a 5 GHz continuum image. The crosses represent the positions of 18 CH$_3$OH (36.2 GHz) maser candidates detected toward this cloud. The peak velocities, which are drawn next to the position of individual maser candidates, range between 20 and 50 km s$^{-1}$ with the exception of one source showing a peak velocity of $-133$ km s$^{-1}$. The largest concentration of maser candidates coincides with a region where SiO (2–1) emission is strong but is offset by $\sim 30\prime\prime$ (1.2 pc) from the compact H ii regions. The circumnuclear ring orbiting Sgr A* lies to the west of the 50 km s$^{-1}$ cloud in Figure 3(a) and shows a lack of CH$_3$OH (36.2 GHz) maser candidates (see also SPF). This result is consistent with CH$_3$OH (96 GHz) observations of the inner 10° of the Galactic center by Stanković et al. (2007), who suggest that strong UV radiation from young stellar clusters at the Galactic center is responsible for the destruction of methanol in the circumnuclear ring.

The 20 km s$^{-1}$ cloud. Another prominent Galactic center molecular cloud within 4 arcmin of Sgr A* is the 20 km s$^{-1}$ molecular cloud M-0.13–0.08. Figure 3(b) shows contours of SiO (2–1) line emission from this cloud superimposed on a gray-scale 5 GHz continuum emission. Maser candidates are mainly concentrated in the region where SiO (2–1) line emission peaks having velocities $\sim 20$ and $\sim 0$ km s$^{-1}$ to the north and south of the cloud, respectively. The distribution of SiO (2–1), CH$_3$OH (36.2 GHz), and CH$_3$OH (96 GHz; Stanković et al. 2007) is remarkably similar to each other suggesting that the abundance of SiO and CH$_3$OH in the gas phase is enhanced. A circular-shaped compact H ii region Sgr A–G lies to the north and two extended nonthermal filaments Sgr A–E (G359.88–0.08) and Sgr A–F (G359.90–0.06) lie to the south. Both nonthermal filaments have X-ray counterparts showing a nonthermal spectrum (Sakano et al. 2003; Yusef-Zadeh et al. 2005), perhaps due to upscattering of far-infrared photons from dust emission of the 20 km s$^{-1}$ cloud by the relativistic electrons in the radio filaments.

G0.13–0.13. This cloud lies along the nonthermal filaments of the radio Arc near $l \sim 0\degree$–2, the most prominent network of magnetized filaments in the Galactic center. The kinematics of CS line emission from G0.13–0.13 suggests an expansion of molecular gas into the nonthermal filaments (Tsiboi et al. 1997). Figure 3(c) shows the distribution of CH$_3$OH (36.2 GHz) emission from this cloud. Like the 50 and 20 km s$^{-1}$ molecular clouds, 45 maser candidates with velocities that range between 0 and 50 km s$^{-1}$ appear to trace the distribution of SiO (2–1) line emission with similar velocity. We also find three high velocity maser candidates at the eastern and western boundaries of the cloud. This cloud has recently been studied in detail showing

---

**Table 1**

| Source | G. Long (°) | G. Lat (°) | Flux (Jy km s$^{-1}$) | Vel (km s$^{-1}$) | $T_b$ ($K \times 10^2$) | Fit Major (°) | Fit Minor (°) | PA (°) | Ref. |
|--------|------------|------------|-----------------------|-----------------|---------------------|-------------|-------------|-------|-----|
| 1      | 0.57307    | 0.04923    | 7.32                  | -33.2           | 63.14 ± 12.60       | 6.00        | 0.66        | 3.7   |     |
| 2      | 0.56038    | 0.02935    | 3.74                  | 49.7            | 24.77 ± 4.38        | 6.00        | 0.86        | 2.9   |     |
| 3      | 0.55883    | -0.09493   | 2.00                  | -16.6           | 23.00 ± 4.17        | 2.27        | 1.31        | 3.8   |     |
| 4      | 0.55429    | -0.11371   | 2.63                  | -16.6           | 29.65 ± 4.94        | 2.24        | 1.35        | 5.2   |     |
| 5      | 0.54816    | 0.04345    | 6.57                  | 49.7            | 44.01 ± 6.30        | 6.00        | 0.85        | 4.7   |     |
| 6      | 0.53183    | -0.02997   | 11.49                 | 49.7            | 51.91 ± 6.19        | 6.00        | 1.26        | 3.3   |     |
| 7      | 0.53134    | -0.02220   | 5.67                  | 33.2            | 51.40 ± 7.58        | 3.73        | 1.01        | 0.2   |     |
| 8      | 0.49866    | -0.04223   | 2.68                  | 99.5            | 33.00 ± 5.07        | 2.62        | 1.06        | 4.3   |     |
| 9      | 0.46208    | -0.07243   | 5.55                  | 82.9            | 63.26 ± 5.93        | 2.63        | 1.14        | -0.4  |     |
| 10     | 0.43104    | 0.03018    | 6.49                  | 0.0             | 52.39 ± 6.99        | 4.92        | 0.86        | 2.7   |     |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 3. (a) Top left: CH$_3$OH (36.2 GHz) maser candidates (crosses) and LSR velocities on the shell-type SNR G0.0–0.0 image and its four compact H$_2$ regions. Contours of SiO (2–1) line emission integrated between 0 and 50 km s$^{-1}$ on the gray-scale 5 GHz image. (b) Top right: similar to (a) except the 20 km s$^{-1}$ molecular cloud. (c) Bottom left: contours of CS (1–0) line emission integrated between 0 and 50 km s$^{-1}$ from G0.13–0.13 with a resolution of 45$''$ (Tsuboi et al. 1997) on a 1.4 GHz image (gray-scale range $-9.4$ to 128). Contour levels are 2, 4, 6, 8, and 10 km s$^{-1}$ K ($T_A^*\)$. (d) Bottom right: CH$_3$OH (36.2 GHz) maser candidates and contours of SiO (2–1) line emission on a 24 $\mu$m map of G0.25+0.01 (gray-scale range 0.11–1.5).

compelling evidence for the interaction of molecular gas with nonthermal electrons (Yusef-Zadeh et al. 2013a).

G0.25+0.01. G0.25+0.01 is a quiescent giant molecular cloud that coincides with the darkest cloud at mid-IR wavelengths in the so-called Dust Ridge (Lis & Carlstrom 1994). This cloud has a mass of $1.4 \times 10^5$ M$_\odot$ and exhibits little star formation (Lis & Carlstrom 1994; Immer et al. 2012). Figure 3(d) shows the spatial distribution of CH$_3$OH (36.2 GHz) maser candidates and is represented as crosses with corresponding velocities superimposed on a 24 $\mu$m image. Contours of SiO (2–1) line emission are also superimposed on Figure 3(c). Like the above-mentioned clouds, maser candidates in G0.25+0.01 follow the distribution of SiO (2–1) and dust emission. There are no signatures of high mass star formation in this cloud,
such as compact H\textsc{ii} regions excited by OB stars, CH$_3$OH (6.6 GHz) masers, or shocked molecular outflows associated with protostars.

### 4. DISCUSSION

The distribution of methanol emission throughout the Galactic center raises an important question: what is the mechanism by which methanol molecules are released off dust grains to enhance its abundance in the gas phase over such a widespread region. The tight correlation between SiO and CH$_3$OH emission suggests that grain-surface chemistry is responsible for their production. Methanol is formed by hydrogenation of CO on interstellar grains at temperatures of 10–20 K (Watanabe & Kouchi 2002) and is released into the gas phase by heating provided by UV radiation, by shocks due to cloud–cloud collisions, and by protostellar outflows. These processes are known to be important in star-forming regions where hot molecular cores are formed and in cloud–cloud collisions where shocks drive into clouds. UV radiation can be important to release methanol but it is not possible to produce widespread methanol emission from dense, self-shielded Galactic center molecular clouds. The difficulty with large-scale shocks produced by cloud–cloud collisions is that methanol maser candidates are seen deep within dense giant molecular clouds and these shocks are most effective at the surface of clouds where the interaction takes place. Shocks can be generated locally in star-forming sites.

However, with the exception of Sgr B2, there is no evidence for widespread ongoing star formation throughout the CMZ. The four giant molecular clouds that were discussed previously are examples in which ongoing massive star formation has low efficiency (e.g., Immer et al. 2012). A more detailed discussion of additional issues related to enhanced SiO abundance in the Galactic center is discussed elsewhere (Yusef-Zadeh et al. 2013b).

Instead, enhanced cosmic rays in the Galactic center interacting with molecular clouds provide a mechanism for globally enhancing the abundance of methanol. Recent large-scale studies indicate that the cosmic ray ionization rate over the inner few hundred pc is $10^{-15}$ to $10^{-14}$ s$^{-1}$, which is about one-to-two orders of magnitude larger than in the Galactic disk (Yusef-Zadeh et al. 2013a; Ao et al. 2012). Cosmic rays traverse a molecular cloud and collide with, dissociate, ionize and excite Lyman and Werner transitions of H$_2$ and include photodesorption of methanol from dust grains (Prasad & Tarafdar 1983; Roberts et al. 2007). The FUV emission resulting from these interactions can heat dust grains and evaporate methanol. There are other mechanisms that can evaporate methanol but total desorption of icy mantles, in a shielded environment, could only be explained by high rates of cosmic ray ionization (Roberts et al. 2007).

Large Velocity Gradient (LVG) modeling of CH$_3$OH emission from the inner 30 pc of the Galactic center at 96 and 242 GHz requires a two-component model (Stanković et al. 2004).
The H₂ density and temperature are $n = 10^5 \text{ cm}^{-3}$ and $T \sim 90 \text{ K}$ in the warm phase with column density $N_{\text{CH}_3\text{OH}} \sim 2.6 \times 10^{15} \text{ cm}^{-2}$, whereas in the cold phase, $N_{\text{CH}_3\text{OH}} \sim 8 \times 10^{15} \text{ cm}^{-2}$ is estimated for $n = 5.5 \times 10^6 \text{ cm}^{-3}$, $T = 15 \text{ K}$ (Stanković et al. 2007). Typical column densities of H₂ toward Galactic center clouds are $10^{23}$ to $10^{24} \text{ cm}^{-2}$, thus the abundance of methanol ranges roughly between $10^{-7}$ and $10^{-6}$ in these two phases. To explore the effect of high cosmic-ray ionization rates on the chemistry of the gas, we use a gas-grain time-dependent chemical model, UCL_CHEM, to investigate the abundance of different species and compare them with observed values (Viti et al. 2004). This model initially follows the collapse of a prestellar core, and subsequently the warming and evaporation of grain mantles due to either the increase of temperature and/or an enhanced cosmic-ray ionization rate. Given that $T_{\text{dust}} \lesssim 30 \text{ K}$, thermal evaporation is insignificant in this model. Figure 4 shows the abundance of CH₃OH, SiO, OH, and NH₃, as a function of time, for a grid of models. These species are either produced on the surface of the grains (CH₃OH, NH₃), or undergo an enhancement due to the release of the parent species from the grain mantles (SiO, OH). In these models, we varied the density from $10^4 \text{ cm}^{-3}$ to $10^6 \text{ cm}^{-3}$ and the cosmic-ray ionization rate from $5 \times 10^{-16}$ to $5 \times 10^{-14} \text{ s}^{-1}$. The models presented in Figure 4 give suitable CH₃OH abundances before they are destroyed. It turns out that the very process that is responsible for enhancing the abundance of methanol in gas phase also destroys it on a timescale of $10^4$--$10^5$ years. Figure 4 shows that methanol for low cosmic-ray ionization rates lasts longest for both high and low density gas. In other words, as the cosmic-ray ionization rate decreases, the chemical timescale for destruction of methanol increases. Methanol is highly volatile at high cosmic-ray ionization rates, thus has a short destruction timescale. This is somewhat puzzling given that methanol emission is detected throughout the CMZ, which consists of several giant molecular clouds distributed within several hundred pc. One possibility to account for this behavior is that methanol is constantly being replenished, thus increasing the destruction timescale. The reformulation of methanol on the surface of dust grains can occur by the cold and dense component of the gas observed in the CMZ (Hüttemeister et al. 1998) during which methanol is being ejected from grain surfaces by cosmic rays. Other hydrogenated species are not destroyed as fast as methanol in this picture. The other possibility is that we may be seeing a relatively short-lived phase of the gas. This is because the medium is clumpy with several cores at different ages. Both of these possibilities will be investigated theoretically in more detail elsewhere.

In summary, we carried out a survey of the Galactic center which resulted in the discovery of a large number of probable methanol masers at 36.2 GHz. These maser candidates were detected as part of continuum observations at 35 GHz. We found a strong correlation of maser candidates and molecular gas distribution in the CMZ. The identification of methanol emission as maser lines needs to be further investigated because of the poor spectral resolution employed in the continuum settings. While maser features are much narrower in frequency than our single channel width, we can put a lower limit on the brightness temperature of our maser candidates. It is possible that detected maser candidates have broad linewidths because they arise in molecular clouds with large linewidths or are contaminated by cluster of masers with different velocities. Future spectral line measurements will be able to distinguish thermal and maser emission. We explained the origin of enhanced abundance of methanol in terms of the interaction of cosmic rays and molecular gas in the CMZ. This interaction picture also accounts for high temperature molecular gas, enhanced FeI Kα line emission as well as diffuse GeV emission from the CMZ.

We thank the referee for useful comments. This research is supported in part by grant AST-0807400 from the NSF the National Science Foundation.

REFERENCES

Ao, Y., Henkel, C., Menten, K. M., et al. 2012, A&A, in press (arXiv:1211.7142)
Hüttemeister, S., Dahmen, G., Mauersberger, R., et al. 1998, A&A, 334, 646
Immer, K., Menten, K. M., Schuller, F., & Lis, D. C. 2012, A&A, 548, 120
Jones, P. A., Burton, M. G., Cunningham, M. R., et al. 2012, MNRAS, 419, 2961
Lis, D. C., & Carlstrom, J. E. 1994, ApJ, 424, 189
Martin, C. L., Walsh, W., Xiao, K., et al. 2004, ApJS, 153, 395
Martin-Pintado, J., de Vicente, P., Fuente, A., & Planesas, P. 1997, ApJL, 482, L45
Molinari, S., Bally, J., Noriega-Crespo, A., et al. 2011, ApJL, 735, L33
Oka, T., Geballe, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882
Pierce-Price, D., Richer, J. S., Greaves, J. S., et al. 2000, ApJ, 545, 121
Prasad, S. S., & Tarafdar, S. P. 1983, ApJ, 481, 263
Riquelme, D., Bronfman, L., Mauersberger, R., et al. 2010, A&A, 523, A45
Roberts, E., Rawlings, J. M. C., Viti, S., & Williams, D. A. 2007, MNRAS, 382, 733
Sakano, M., Warwick, R. S., Decourchelle, A., & Predhel, P. 2003, MNRAS, 340, 747
Sjouwerman, L. O., Pihlström, Y. M., & Fish, V. L. 2010, ApJL, 710, L111
Stanković, M., Sequist, E. R., Muhle, S., Leurini, S., & Menten, K. M. 2007, in Molecules in Space and Laboratory, ed. J. L. Lemaire & F. Combes (Paris: Obs. Paris), 15
Tsuboi, M., Tadaki, K., Miyazaki, A., & Handa, T. 2011, PASJ, 63, 763
Tsuboi, M. M., Ukita, N., & Handa, T. 1997, ApJL, 481, 263
Viti, S., Collings, M. P., Dever, J. W., et al. 2004, MNRAS, 354, 1141
Voronkov, M. A., Brooks, K. J., Sobolev, A. M., et al. 2006, MNRAS, 373, 411
Wardle, M. 1999, ApJL, 525, L101
Watanahe, N., & Kouchi, A. 2002, ApJL, 571, L173
Yusef-Zadeh, F., Goss, W. M., Roberts, D. A., et al. 1999, ApJ, 527, 172
Yusef-Zadeh, F., Hewitt, J. W., Arendt, R. G., et al. 2009, ApJ, 702, 178
Yusef-Zadeh, F., Hewitt, J., Wardle, M., et al. 2013a, ApJL, 762, 33
Yusef-Zadeh, F., Wardle, M., Lis, D., & Viti, S. 2013b, JPhCh, submitted
Yusef-Zadeh, F., Wardle, M., Muno, M., Law, C., & Pound, M. 2005, AdSpR, 35, 1074