THE ASTROPHYSICAL JOURNAL, 494:L89–L92, 1998 February 10

SiO MASER FOREST AT THE GALACTIC CENTER

HIDEYUKI IZUMIURA
Okayama Astrophysical Observatory, National Astronomical Observatory, Kamogata, Asakuchi, Okayama 719-02, Japan; izumiura@oao.nao.ac.jp
SHUJI DEGUCHI
Nobeyama Radio Observatory, National Astronomical Observatory, Minamimaki, Minamisaku, Nagano 384-13, Japan; deguchi@nro.nao.ac.jp
AND
TAKAHIRO FUJII
Department of Astronomy, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan; fujii@astron.s.u-tokyo.ac.jp
Received 1997 July 9; accepted 1997 December 5; published 1998 January 20

ABSTRACT

A moderately deep survey of stellar maser sources toward the Galactic center has been made in the SiO $J = 1$–0, $v = 1$ and $v = 2$ transitions (~43 GHz) with the Nobeyama 45 m telescope with a beam size of about 40″. At the Galactic center (Sgr A*), seven (four new) SiO maser sources were detected in one beam. In order to investigate the spatial distribution of SiO maser sources, we have also observed the offset positions by ±40″ in Galactic longitude from the Galactic center. In total, seven (four new) SiO maser sources were detected at the offset positions. Taking into account the shorter integration time at the offset positions, we find that the surface number density of SiO maser sources is nearly constant at the Galactic center. The number density of SiO maser sources is found to be an order of magnitude higher than the density of OH 1612 MHz objects. A radial velocity gradient in Galactic longitude was not detected. These facts indicate that the SiO maser sources seen toward the Galactic center are mostly associated with the stellar population of a Galactic stellar nuclear disk of more than a few arcminute radius.

Subject headings: Galaxy: center — masers — radio lines: stars — circumstellar matter — stars: late-type

1. INTRODUCTION

It is known that a cluster of evolved stars surrounds the Galactic center (Blum, Sellgren, & DePoy 1996; Morris & Serabyn 1996).[1] These evolved stars very often exhibit molecular line masers (Winnberg 1996) and have been used for studying the structure of the Galactic center disk. OH 1612 MHz and SiO 43 GHz maser lines have been used to obtain radial velocities for sources in the Galactic center region (Lindqvist et al. 1991; Lindqvist, Habing, & Winnberg 1992a), for the Galactic bulge *IRAS* sources (Izumiura et al. 1995), and for sources toward the Sgr B2 molecular cloud (Shiki, Ohishi, & Deguchi 1997). Maser sources very close to the Galactic center are useful for establishing a concordance between radio and infrared position-reference frames (Menten et al. 1997), identifying the Sgr A* in the infrared (Eckart et al. 1993), and studying proper motions (Eckart & Genzel 1997). With the Very Large Array (VLA), sensitive surveys of maser sources near Sgr A* have been made in the OH 1612 MHz line (e.g., Sjouwerman et al. 1997). A VLA survey in SiO/H_2O lines (Menten et al. 1997) was made with velocity resolution of 2.7 km s^{-1} with 32 channels, resulting in two new SiO maser sources associated with known infrared objects very near Sgr A*. The detection limit of this VLA survey was at the level of ~0.05 Jy at 43 GHz.

In this Letter, we report an attempt to survey SiO maser sources near the Galactic center with the Nobeyama 45 m telescope. We have detected seven SiO sources at the Galactic center. In order to investigate the source density near the Galactic center, we have also observed the two offset positions by ±40″ in Galactic longitude, resulting in detections of a similar number of sources.

[1] We refer to the dynamical center of our Galaxy as the radio continuum source Sgr A* in this Letter.

2. OBSERVATIONS

Simultaneous observations in the SiO $J = 1$–0, $v = 1$ and $v = 2$ transitions at 43.122 and 42.821 GHz, respectively, were made with the 45 m radio telescope at Nobeyama on 1997 April 25 and May 10, 11, and 12. A cooled SIS receiver with a bandwidth of about 0.4 GHz was used, and the system temperature (including atmospheric noise) was 190–200 K. The aperture efficiency of the telescope was about 0.60 at 43 GHz. The half-power beam width (HPBW) was about 40″ at 43 GHz. A factor of 3.6 Jy K^{-1} was used to convert antenna temperature to flux density. An acousto-optical spectrometer array of a low resolution (AOS-W) was used. Each spectrometer has a 250 MHz bandwidth and 2048 frequency channels, giving the velocity coverage of about 1700 km s^{-1} and the spectral resolution of 1.7 km s^{-1} (per two binned channels). Observations were made in a position switching mode, and the off position was chosen 10′ away from the Galactic center in azimuth.

We observed three positions near the Galactic center: one at the position of Sgr A*, (R.A., decl., epoch) = ($17^h42^m29\overset{s}{.}314$, $-28°59′\,18\overset{″}{.}3$, 1950) [($l$, b) = ($359\overset{°}{.}944$, $-0\overset{°}{.}046$); Rogers et al. 1994], and the other two at the positions offset by one beam on either side of Sgr A* in the Galactic longitude, (Δl, Δb) = (±40″, 0″). We performed the observations on clear nights without wind. Telescope pointing was carefully checked before and after each observation using a nearby strong SiO maser source, OH 2.6−0.4. The average pointing accuracy was confirmed to be better than 5″. The total integration time was 6.8 hr for the center and 3.0 hr each for the offset positions. For the center, (Δl, Δb) = (0″, 0″), we combined the spectra taken on 1997 April 25 and May 10. For the offset positions, data were taken on May 11 and May 12. Weather conditions on May 12 were not perfect when the position (+40″, 0″) was observed; T_{sys} was about 220 K, and the wind speed was about 5 m s^{-1} (which might have caused the pointing error of about

5″). Thus, the noise level on the spectrum at (+40″, 0″) was slightly higher than that on spectra taken on the other days.

Obtained spectra toward Sgr A* exhibited a baseline offset of about 3.2 K from zero due to the continuum emission. This corresponds to a flux density of about 12 Jy at 43 GHz, which is consistent with the previous measurement of the Sgr A* (11.6 Jy) at 43 GHz with the 45 m system (Sofue et al. 1986). The spectra exhibited a baseline distortion (of about 0.3 K at the maximum) and weak ripples probably due to standing waves in the 45 m telescope system. The ripples in the velocity range of ±350 km s^{-1} of the SiO lines were relatively weak (of about 0.02 K on average). In order to remove complex ripple features from the spectra, we took running means of the spectra (average of 100 channels, or about the 80 km s^{-1} width), and averaged spectra were subtracted from originals. With this procedure, the baseline of the resulting spectra became quite flat. Because the SiO maser lines are quite narrow (the widths less than 10 km s^{-1}) and weak ($T_a < 0.2$ K), this method seems to work well. There are other molecular and atomic lines possibly contaminating the SiO $J = 1$–0, $v = 2$ line at 42.821 GHz: ^{29}SiO $J = 1$–0, $v = 0$ (42.879 GHz), H53α (42.891 GHz), SiC_4 $J = 14$–13 (42.945 GHz), and C_6H $J = 31/2$–29/2 (42.970 and 42.970 GHz). These lines might appear as broad features at the Galactic center and may overlap somewhat with the SiO $J = 1$–0, $v = 2$ line, causing a bad baseline.

With this baseline removal, broadline features of the above mentioned molecules, even if present, were eliminated. The spectra finally obtained are shown in Figure 1. The rms noise temperatures at the center, (Δl, Δb) = (0″, 0″), are 0.004 and 0.009 K at 42.821 GHz (SiO $J = 1$–0, $v = 2$) and 43.122 GHz (SiO $J = 1$–0, $v = 1$), respectively. The spectrometer used for the $v = 1$ line gave systematically higher rms value of noise. This is probably due to a calibration error of the photodiode levels in the spectrometer.

Detections of the SiO maser components were judged by the following criteria (both must be satisfied):

1. Line intensities in either transition must be greater than 5 times the rms noise level with line widths greater than three channels (2.5 km s−1).
2. Emission peaks are seen at the same velocity in both the $J = 1$–0, $v = 1$ and $v = 2$ transitions (within 2 km s−1), or, at least, a peak is seen in one transition and a positive deflection (not trough) is seen in the other transition.

These criteria worked nicely in our experiences, guarding against identification as signal of anomalous noises known in AOS data. For the case of a short integration, the second criterion has been quite useful, and follow-up integrations revealed the SiO lines very often.

SiO maser components detected at the three positions are shown in Table 1. It is well known that the SiO maser velocity of a single source coincides with the stellar velocity, i.e., with the middle of the OH 1612 MHz double-peak velocities within a few km s^{-1} (Jewell et al. 1991; Jiang et al. 1995). Therefore, if the velocity of the detected SiO feature is close to the velocity of an already known OH 1612 MHz source at the Galactic center, it is highly probable that the SiO source is associated with the OH source. With this velocity coincidence, we have assigned probable associations with OH/IR sources in Table 1.

3. DISCUSSION

The radial velocity of SiO maser emission indicates the stellar velocity, i.e., the velocity of a central star. Velocity widths are known to be less than 10 km s^{-1} in most SiO maser sources. Especially for the case of a source at the Galactic center, we can detect only a narrow emission peak and not a weak broad pedestal. From these facts, we can safely assume that the detected SiO peaks, if separated more than 10 km s^{-1}, come from individual sources in the telescope beam. In the following discussion, we regard each SiO component listed in Table 1 as an individual source.

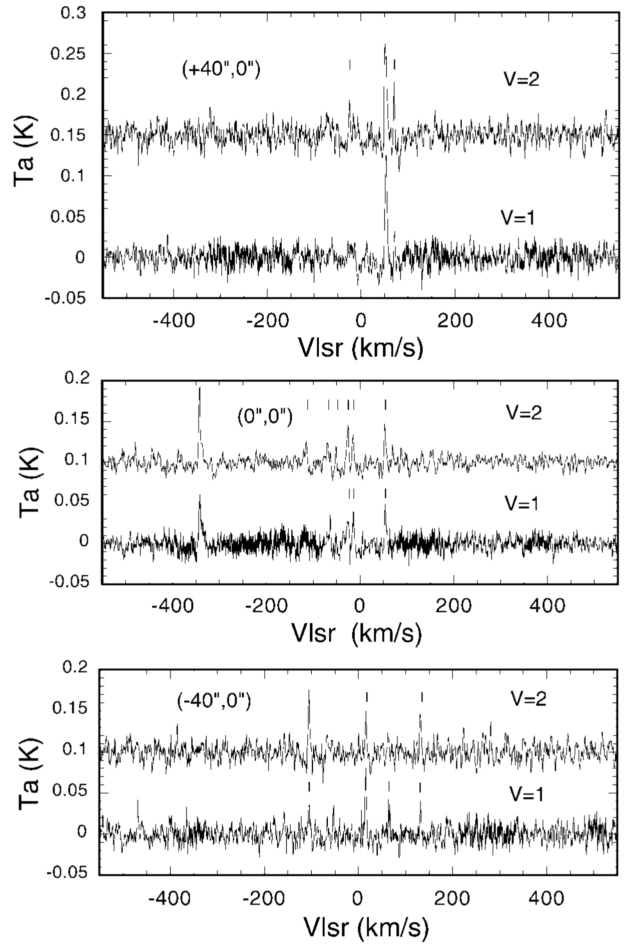

FIG. 1.—Spectra of the SiO $J = 1$–0, $v = 1$ and $v = 2$ transitions toward the Galactic center: *top*, at (Δl, Δb) = (+40″, 0″); *middle*, at (0″, 0″); and *bottom*, at (−40″, 0″). Detections except strongest ones are marked by ticks.

3.1. *Associations with Previously Known Objects at the Galactic Center*

Extensive surveys of the Galactic center region have been made before with the VLA in OH 1612 MHz (Lindqvist et al. 1992b; Sjouwerman & van Langevelde 1996) and in H_2O and SiO lines (Levine et al. 1995; Menten et al. 1997). Because sources detected in this Letter are within a 1′ radius from the Galactic center, four sources in the list of Lindqvist et al. (1992b) are considered to be candidates for associations: OH 359.939−0.052 ($V_{av} = 52.2$ km s^{-1}), OH 359.946−0.047 ($V_{av} = -27.2$ km s^{-1}), OH 359.952−0.036 ($V_{av} = 82.2$ km s^{-1}), and OH 359.954−0.041 ($V_{av} = 70.2$ km s^{-1}). In addition, we take into account five SiO/H_2O sources listed by Menten et al. (1997), one of which coincides with OH 359.946−0.047.

The judgment for association is based on the velocity coincidence. The position (±20″) and velocity (±3 km s^{-1}) co-

TABLE 1
LIST OF DETCTED SiO PEAKS (SOURCES)

SiO l, b (deg) (Δl, Δ b)	No.	$J = 1$–0, $v = 2$ V_{lsr} (km s^{-1})	$J = 1$–0, $v = 2$ I_{peak} (Jy)	$J = 1$–0, $v = 2$ F (Jy km s^{-1})	$J = 1$–0, $v = 1$ V_{lsr} (km s^{-1})	$J = 1$–0, $v = 1$ I_{peak} (Jy)	$J = 1$–0, $v = 1$ F (Jy km s^{-1})
SiO 359.933−0.046							
(−40″, 0″)	1	131.2	0.167	0.647	131.2	0.143	0.380
	2	...	...	...	63.7	0.152	0.227
	3[a]	15.9	0.179	0.497	15.9	0.289	0.942
	4	−105.1	0.273	0.921	−104.2	0.127	0.511
SiO359.944−0.046							
(0″, 0″)	1	53.1	0.169	0.712	54.4	0.177	0.738
	2[b]	−14.6	0.121	0.435	−13.8	0.153	0.440
	3[c]	−25.2	0.164	0.797	−25.2	0.099	0.560
	4	−51.2	0.072	0.143	...	...	...
	5	−69.6	0.087	0.575	...	...	...
	6[d]	−114.9	0.094	0.497	...	...	...
	7	−341.9	0.333	0.195	−341.9	0.216	1.395
SiO 359.955−0.046							
(+40″, 0″)	1[e]	70.0	0.234	0.494	...	...	...
	2[f]	50.6	0.403	2.377	52.6	0.450	2.173
	3	−24.7	0.158	0.474	...	...	...

[a] =OH 359.931−0.050, $V_{av} = 17$ km s^{-1}; Sjouwerman et al. 1997.
[b] =IRS 15NE = SiO(+1.2, +11.3), $V_{av} = -15$ km s^{-1}; Menten et al. 1997.
[c] =OH 359.946−0.047 = IRS 10EE, $V_{av} = -27$ km s^{-1}; Lindqvist et al. 1992b.
[d] =IRS 7 = SiO(0.0, +5.6), $V_{av} = -120$ km s^{-1}; Menten et al. 1997.
[e] =OH 359.954−0.041, $V_{av} = 70$ km s^{-1}; Lindqvist et al. 1992b.
[f] =OH 359.956−0.050, $V_{av} = 50$ km s^{-1}; Sjouwerman & van Langevelde 1996; Levine et al. 1995.

incidences are shown as footnotes in Table 1 for each SiO component. The radial velocities of source 3 (−25.2 km s^{-1}) at (0″, 0″) and source 3 ($V_{lsr} = -24.5$ and -28.3 km s^{-1}) at (+40″, 0″), are quite close. It is possible that they are the same source that is located at the middle of the two beams. However, source 3 at (0″, 0″) is probably associated with SiO(+7.7, +4.2) = IRS 10EE in Table 1 of Menten et al. (1997) and OH 359.946−0.047 in Lindqvist et al. (1992b). In this case, the intensity of this source at (+40″, 0″) should be 7% of the signal intensity at (0″, 0″), or at most 14% even if a pointing error of 5″ is taken into account, indicating that it is undetectable at (+40″, 0″). Therefore, we conclude that these two emissions at similar velocities come from different sources.

3.2. *Velocity Distribution*

It is interesting to examine how the average velocity of sources varies with Galactic longitude, because fast-rotating gas components of about 200–300 km s^{-1} have been found in the Galactic center spiral of an angular size of about 30″ (Lo & Claussen 1983; Lacy, Achtermann, & Serabyn 1991). We have made a linear regression analysis of V_{lsr} with l. Source positions were assumed to be exactly at beam centers, i.e., −40″, 0, and +40″ in longitude. The least-squares fit to the radial velocities of the detected sources gives $V_{lsr} = -25.5(\pm 32.2) - 0.098(\pm 1.14)(\Delta l/\text{arcsec})$ km s^{-1}, indicating a quite small velocity gradient.

It can be considered that the high-velocity source 7 at (0″, 0″) may influence the results. Because the SiO intensity of this source is quite strong, this high-velocity source may be located closer to the Sun than the other sources on the same line of sight. We have also made the linear fit excluding this source and obtained $V_{lsr} = -0.9(\pm 21.6) - 0.010(\pm 0.734)(\Delta l/\text{arcsec})$ km s^{-1}. The result does not differ significantly from the previous one.

The velocity dispersion (deviation from the regression line) is 111.4 km s^{-1} for the set of all sources and 71.2 km s^{-1} for the set excluding the high-velocity source 7. This value is comparable with the velocity dispersion of ∼125 km s^{-1} of infrared stars within 20″ from the center (McGinn et al. 1989). However, it seems significantly smaller than 154 (±19) km s^{-1} for the helium-rich blue supergiants/Wolf-Rayet stars with distances of 1″–12″ from the Galactic center (Krabbe et al. 1995).

Lindqvist et al. (1992a) found that the linear regression of the (l-v) diagram for their 134 OH/IR sources is about $V_{lsr} = -7 + 180(\Delta l/\text{deg})$ km s^{-1}, or if expressed in the above unit, $V_{lsr} = -7 + 0.05(\Delta l/\text{arcsec})$ km s^{-1}. The gradient is as small as the value obtained in this Letter. Lindqvist et al. (1992a) mentioned that the smaller number of samples within 10 pc (about 4′) from the Galactic center gave the larger velocity gradient. From their Figure 9, we can estimate this gradient for the smaller sample as 0.83 km s^{-1} arcsec^{-1}. McGinn et al. (1989) also gave the velocity gradient of ∼1.0 km s^{-1} arcsec^{-1} from infrared stars within 100″ from the center (estimated from Fig. 4 in their paper). These values are consistent with the present nondetection of rotational motion within the errors. Genzel et al. (1996) found that late-type stars within 5″ from the center exhibit a gradient of about 5 km s^{-1} arcsec^{-1}, which is somewhat larger than the present result.

If SiO sources near the Galactic center have the same kinematic properties as the stars detected by McGinn et al. (1989) and Lindqvist et al. (1992b), i.e., they belong to the nuclear disk of a size of more than a few arcminutes, the nondetection of the rotational motion in the present Letter seems reasonable. The velocity dispersion obtained is also consistent with the previous measurements for the stellar disk.

3.3. *Source Number Density*

We detected four, seven, and three sources at the three positions (−40″, 0″), (0″, 0″), and (+40″, 0″), respectively. The apparent decrease in the number of sources at the off-center positions is probably due to the larger noise level (less integration time) at these positions. In fact, if we correct the source counts for the noise levels, assuming that we try to detect the (0″, 0″) sources 1–7 with higher noise levels, the expected detections above 5 σ are three and one with the noise levels at ($-40''$, $0''$) and ($+40''$, $0''$), respectively. Taking into account statistical uncertainties, we conclude that the source surface number density is not peaked at the Galactic center on a scale of about $40''$.

It is interesting to compare the SiO source surface density with the density of OH/IR sources. Lindqvist et al. (1992a) gave the OH 1612 MHz source density of 1700 $\deg^{-2}$, which corresponds to about 0.47 sources arcmin^{-2}. Apparently, the number of SiO sources at ($0''$, $0''$) (=seven per $40''$ beam) is about 40 times that expected from the OH/IR survey. The number density of SiO maser sources found in the present survey is an order of magnitude larger than the density of OH 1612 MHz maser sources that were detectable with the VLA. Hence we would like to call the cluster of SiO maser lines at the Galactic center a "SiO maser forest."

OH/IR stars with OH 1612 MHz emission are highly obscured red supergiants, while SiO maser stars are very often less massive semiregular or Mira variables that have weak or no OH 1612 MHz emission. For example, W Hya, a semiregular variable at the distance of 95 pc (Reid & Menten 1997), exhibits strong SiO maser emission of about 700 Jy in the $J = 1$–0, $v = 1$ and $v = 2$ transitions but shows no OH 1612 MHz line. If it is placed at the Galactic center (at the distance of 8 kpc), the flux density of the same line would be 0.1 Jy, which is comparable to the flux densities observed in the present survey. Therefore, many of the SiO sources we have detected at the Galactic center might be Mira and semiregular variables. While the statistics of a sample of 172 bulge OH/SiO sources (observed by both OH and SiO lines; Jiang et al. 1995) show that the number of SiO sources without OH is comparable with the number of OH sources with and without SiO, if the same statistics apply to the Galactic center sources, we should detect more OH 1612 MHz sources. Therefore, some violent mechanism might strip the outer (OH emitting) envelope of AGB stars near the Galactic center, causing the underdensity of OH 1612 MHz sources at the Galactic center.

4. CONCLUSIONS

We have detected 14 SiO maser sources at the Galactic center and at the $40''$ off-center positions; six of these sources are associated with already known OH 1612 MHz or SiO sources, and eight are new detections.[2] We find that the radial velocity gradient with respect to Galactic longitude is small. The SiO source number density is an order of magnitude higher than the density of previously found OH 1612 MHz objects toward the Galactic center. The flat distribution of the source number density around the center and the velocity dispersion indicate that these SiO sources are associated with the Galactic nuclear stellar disk. The small radial velocity gradient of the sources also does not conflict with this interpretation.

We thank David Morris for reading the manuscript. We also thank Drs. N. Ukita, Y. Nakada, O. Kameya, S. Matsumoto, and H. Imai for discussions and encouragements. This research was partly supported by Scientific Research Grant 08640337 from the Ministry of Education, Science, Sports, and Culture, Japan.

[2] Menten & Reid (1997) recently reported the detections of several more SiO sources [two of them are associated with sources 5 and 7 at ($0''$, $0''$) in Table 1].

REFERENCES

Blum, R. D., Sellgren, K., & DePoy, D. L. 1996, ApJ, 470, 864
Eckart, A., & Genzel, R. 1997, MNRAS, 284, 576
Eckart, A., Genzel, R., Hofman, R., Sams, B. J., & Tacconi-Garman, L. E. 1993, ApJ, 407, L77
Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E. 1996, ApJ, 473, 153
Izumiura, H., Deguchi, S., Hashimoto, O., Nakada, Y., Onaka, T., Ono, T., Ukita, N., & Yamamura, I. 1995, ApJ, 453, 837
Jewell, P. R., Snyder, L. E., Walmsley, C. M., Wilson, T. L., & Gensheimer, P. D. 1991, A&A, 242, 211
Jiang, B. W., Deguchi, S., Izumiura, Y., Nakada, Y., & Yamamura, I. 1995, PASJ, 47, 815
Krabbe, A., et al. 1995, ApJ, 447, L95
Lacy, J. H., Achtermann, J. M., & Serabyn, E. 1991, ApJ, 380, L71
Levine, D., Figer, D. F., Morris, M., & Mclean, I. S. 1995, ApJ, 447, L101
Lindqvist, M., Habing, H. J., & Winnberg, A. 1992a, A&A, 259, 118
Lindqvist, M., Winnberg, A., Habing, H. J., & Matthews, H. E. 1992b, A&AS, 92, 43
Lindqvist, M., Winnberg, A., Johansson, L. E. B., & Ukita, N. 1991, A&A, 250, 431
Lo, K. Y., & Claussen, M. J. 1983, Nature, 306, 647
McGinn, M. T., Sellgren, K., Becklin, E. E., & Hall, D. N. B. 1989, ApJ, 338, 824
Menten, K., & Reid, M. 1997, a poster paper presented in IAU Symp. 184, The Central Region of the Galaxy and Galaxies, Kyoto, 1997 August 18–21
Menten, K., Reid, M., Eckart, A., & Genzel, R. 1997, ApJ, 475, L111
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Reid, M. J., & Menten, K. M. 1997, ApJ, 476, 327
Rogers, A. E. E., et al. 1994, ApJ, 434, L59
Shiki, S., Ohishi, M., & Deguchi, S. 1997, ApJ, 478, 206
Sjouwerman, L. O., & van Langevelde, H. J. 1996, ApJ, 461, L41
Sjouwerman, L. O., van Langevelde, H. J., Winnberg, A., & Habing, H. J. 1997, A&A, in press
Sofue, Y., Inoue, M., Handa, T., Tsuboi, M., Hirabayashi, H., Morimoto, M., & Akabane, K. 1986, PASJ, 38, 475
Winnberg, A. 1996, in ASP Conf. Ser. 102, The Galactic Center, ed. K. Gredel et al. (San Francisco: ASP), 294