The Astrophysical Journal, 727:99 (5pp), 2011 February 1 doi:10.1088/0004-637X/727/2/99

MULTIPLE HIGH-VELOCITY SiO MASER FEATURES FROM THE HIGH-MASS PROTOSTAR W51 NORTH

Se-Hyung Cho[1,2], Jaeheon Kim[1,3,4], and Do-Young Byun[1,4]
[1] Korean VLBI Network, Korea Astronomy and Space Science Institute, P. O. Box 88, Yonsei University, Seongsan-ro 262, Seodaemun, Seoul 120-749, Republic of Korea; cho@kasi.re.kr, jhkim@kasi.re.kr, bdy@kasi.re.kr
[2] Department of Astronomy, Yonsei University, Seongsan-ro 262, Seodaemun, Seoul 120-749, Republic of Korea
[3] Department of Astronomy and Space Science, Kyung Hee University, 1 Seocheon-dong, Giheung-gu, Yongin-si, Gyeonggi-do 446-701, Republic of Korea
[4] Yonsei University Observatory, Yonsei University, Seongsan-ro 262, Seodaemun, Seoul 120-749, Republic of Korea
Received 2010 September 7; accepted 2010 November 18; published 2011 January 10

ABSTRACT

We present the detection of multiple high-velocity silicon monoxide (SiO $v = 1$, 2, $J = 1$–0) maser features in the high-mass protostar W51 North which are distributed over an exceedingly large velocity range from 105 to 230 km s^{-1}. The SiO $v = 1$, $J = 1$–0 maser emission shows 3–5 narrow components which span a velocity range from 154 to 230 km s^{-1} according to observational epochs. The SiO $v = 2$, $J = 1$–0 maser also shows 3–5 narrow components that do not correspond to the SiO $v = 1$ maser and span a velocity range from 105 to 154 km s^{-1}. The multiple maser components show significant changes on very short timescales (<1 month) from epoch to epoch. We suggest that the high-velocity SiO masers may be emanated from massive star-forming activity of the W51 North protostar as SiO maser jets and will be a good probe of the earliest evolutionary stages of high-mass star formation via an accretion model. Further high angular resolution observations will be required for confirmation.

Key words: ISM: jets and outflows – masers – radio lines: stars – stars: formation – stars: individual (W51 North)

1. INTRODUCTION

One of the most interesting fundamental issues in astrophysics is how do high-mass stars (10 or more times that of the Sun) form. Concerning the formation of high-mass stars, two theories have been proposed: (1) the accretion model through dense disks with jets/outflows (Jijina & Adams 1996; McKee & Tan 2002; Krumholz et al. 2009) similar to the low-mass paradigm and (2) the merger model through the merging of smaller stars (Bonnell et al. 1998; Zinnecker & Bate 2002). In recent years, circumstellar disks around a high-mass protostar supporting the accretion model have been reported (Patel et al. 2005; Zapata et al. 2008, 2009a; Kraus et al. 2010). Kraus et al. (2010) reported near-infrared interferometric observations that show an AU-scale disk similar to the disks observed in low-mass star formation around the high-mass ($\sim 20\,M_\odot$) young stellar object IRAS 13481−6124. However, another key element is the highly collimated supersonic jets/outflows, which have been rarely observed for high-mass star-forming regions exceeding $10^5\,L_\odot$ (corresponding to $\sim 25\,M_\odot$) due to rapid evolution and large distance (Zinnecker & Yorke 2007).

The W51 North object in the W51 IRS2 cluster is at a young high-mass star forming stage of O5-type protostar in its center through molecular accretion (Zapata et al. 2008). In particular, this object is associated with strong OH and H_2O masers (Schneps et al. 1981; Gaume & Mutel 1987) at a distance of 6.1 ± 1.3 kpc (Imai et al. 2002). The SiO ($v = 1$, 2, $J = 1$–0) maser emission was also detected from this object (Hasegawa et al. 1986; Morita et al. 1992; Zapata et al. 2009b). Observations of H_2O masers (Imai et al. 2002; Eisner et al. 2002) and SiO ($v = 0$, $J = 5$–4) molecule (Zapata et al. 2009a) revealed the presence of a collimated outflow perpendicular to the dusty circumstellar disk and molecular ring. Using high angular resolution observations of H_2O and SiO ($v = 2$, $J = 1$–0) masers, Eisner et al. (2002) have linked the SiO maser source to a protostellar outflow associated with intense H_2O maser sites. However, all of these SiO and H_2O maser observations have been carried out at different epochs by using different radio telescope and receivers. In addition, high-velocity SiO maser emission associated with jets/outflows was so far not detected from any star-forming regions nor from asymptotic giant branch (AGB)/post-AGB stars. All of this motivates us to perform the simultaneous monitoring observations of H_2O and SiO masers with the Korean VLBI Network (KVN) Yonsei 21 m radio telescope in order to investigate a mutual temporal variation of H_2O and different SiO maser transitions connected with their bipolar outflows.

2. OBSERVATIONS

From 2009 December 2 to 2010 June 22, monitoring observations of ^{28}SiO $v = 1$, 2, $J = 1$–0 (43.122080 GHz and 42.820587 GHz), ^{29}SiO $v = 0$, $J = 1$–0 (42.879916 GHz), and H_2O 6_{16}–5_{23} (22.235080 GHz) maser lines toward W51 North (R.A. = $19^{\mathrm{h}}23^{\mathrm{m}}40\overset{\mathrm{s}}{.}10$, decl. = $+14^\circ 31' 06\overset{''}{.}0$ (J2000)) were performed with the KVN Yonsei 21 m radio telescope at Yonsei University campus, Seoul. The KVN antenna optics were designed for simultaneous observations of four bands of the H_2O 22 GHz and SiO 43, 86, and 129 GHz bands (Han et al. 2008). The 22 GHz and 43 GHz beams were split by a low pass filter and received by both 22 GHz and 43 GHz band receivers installed on the same plate, simultaneously. The half-power beam widths and aperture efficiencies were 137″, 0.72 (at 22 GHz) and 70″, 0.69 (at 43 GHz), respectively. Cryogenic 22/43 GHz high electron mobility transistor (HEMT) receivers were used with a left circularly polarized feed during our observations. The system noise temperatures (SSB) ranged from 80 K to 230 K (at 22 GHz) and from 130 K to 300 K (at 43 GHz) depending on weather conditions and elevations. We used a digital spectrometer with total band widths of 64 MHz mode. These band widths cover the velocity widths of 870 km s^{-1} (at 22 GHz) and 450 km s^{-1} (at 43 GHz), respectively and the velocity resolutions correspond to 0.21 km s^{-1} (4096 channels at 22 GHz), 0.22 km s^{-1} (2048 channels at 43 GHz), respectively. The data were calibrated by the chopper wheel method, which corrected for atmospheric attenuation and antenna gain variations depending on elevation, to yield an antenna temperature T_A^*. Integration time was 30–50 minutes to achieve 0.04 K at the 3σ level. The conversion factor from the antenna temperature to the flux density is about 11.1 Jy K^{-1} at 22 GHz and 11.6 Jy K^{-1} at 43 GHz.

3. OBSERVATIONAL RESULTS AND DISCUSSION

Figure 1 shows a time series of H_2O and SiO spectra obtained during five epoch monitoring observations from W51 North. The spectra are plotted in terms of antenna temperature (T_A^*, in K) versus velocity with respect to the local standard of rest (v_{LSR}, in km s^{-1}). We find for the first time 3–5 narrow maser components of SiO $v = 1$, $J = 1$–0 lines ($\Delta V_{\mathrm{FWHM}} = 0.2 \sim 2.2$ km s^{-1}), which are extended from the peak velocity of $V_{\mathrm{LSR}} = -85.0$ to 164.1 km s^{-1} according to observation epochs (Table 1). The velocity range between the most extremely blueshifted and redshifted components at the 2010 May 13 epoch is 230.4 km s^{-1}. The outflow velocity implied by this velocity separation without considering the projection to the sky is about 115 km s^{-1}. The central main component of SiO $v = 1$, $J = 1$–0 maser which is detected by Zapata et al. (2009b) is always peaked in the range of $V_{\mathrm{LSR}} = 48$–49 km s^{-1} and shows relatively stable peak intensity from 0.1 to 0.15 K in comparison with the $v = 2$ maser. However, other newly detected blueshifted and redshifted components are highly variable on very short timescales (<1 month) in both peak velocity and intensity as shown in Figure 1 and Table 1. The velocity structure of the four narrow components in the SiO $v = 1$, $J = 1$–0 maser at epoch 2010 June 22 shows a relatively good symmetry with respect to the central main component ($V_{\mathrm{LSR}} = 49$ km s^{-1}), though they have some offsets.

The SiO $v = 2$, $J = 1$–0 masers also reveal 3–5 components that are distributed over 105–154 km s^{-1} in our observations. However, they do not correspond to SiO $v = 1$, $J = 1$–0 maser components, which show a different peak velocity of each component except for the known central main component (peak velocity of $V_{\mathrm{LSR}} = 48.5$ km s^{-1}) detected on 2009 December 2 and 2010 May 13. The $v = 2$ masers were also highly variable. They were not detected on 2010 June 22 and showed only redshifted components on 2010 March 23 and 2010 May 13 with respect to the known central main component. The SiO $v = 1, 2$, $J = 1$–0 maser lines obtained during monitoring observations do not show any periodicities.

In comparison with that of SiO masers, the H_2O maser emission shows a considerably extended velocity range: 221–249 km s^{-1} compared with those of SiO masers. The peak velocities ($V_{\mathrm{LSR}} = 56$–66 km s^{-1}) of the strongest H_2O maser component are redshifted compared with those of SiO masers ($V_{\mathrm{LSR}} = 48 \sim 49$ km s^{-1}). They show gradually redshifted emission from $V_{\mathrm{LSR}} = 56$ (2009 December 2) to 66 km s^{-1} (2010 June 22). The strongest H_2O peak intensity of 2010 June 22 is 17 times that of 2010 March 23 like H_2O maser burst as shown in Table 1. But the SiO $v = 2$, $J = 1$–0 maser was not detected on 2010 June 22. We cannot find any direct correlation between the peak intensity of the H_2O maser and that of SiO maser.

Unlike the case of the H_2O maser, the high-velocity SiO maser emission distributed over a large velocity range was not detected toward any other celestial objects containing star-forming regions, post-AGB stars, and active galactic nuclei in all previous observations. In this paper, we report the detection of the high-velocity SiO maser emission in the range of 100–230 km s^{-1} toward a high-mass star-forming region W51 North for the first time.

We suggest that the multiple high-velocity SiO maser emission might be emanated from high-mass star-forming activities of the W51 North protostar as SiO maser jets. High angular resolution observations with the Very Large Array (VLA) and Very Long Baseline Array (VLBA; Eisner et al. 2002) have already shown that the masers of W51 North trace star-forming activities in the denser portions of a molecular core and the outflow traced on small scales by the SiO maser appears to be reflected on large scales by the H_2O maser outflow (outflow velocity of ~ 80 km s^{-1}). Eisner et al. (2002) also proposed that the SiO masers trace an accelerating bipolar protostellar outflow inclined less than 20° with respect to the plane of the sky. Observational data of Zapata et al. (2009a) revealed that the H_2O and SiO masers associated with the highly embedded protostar are tracing the innermost parts of SiO ($v = 0$, $J = 5$–4) thermal bipolar outflow. The outflow velocity (77–115 km s^{-1}) implied by the velocity separation of SiO $v = 1$, $J = 1$–0 masers is comparable to and higher than that of H_2O measured by Eisner et al. (2002) and Imai et al. (2002), respectively. In addition, blueshifted and redshifted components show a discontinuity and a symmetry at a particular epoch with respect to the central main component, which resemble the discrete knots and bullets in the case of jets of low-mass star-forming regions (Bachiller et al. 1991). The multiple high-velocity SiO maser emission reveals rapid time variations on very short timescales. These characteristics imply the presence of SiO maser jets, though the distribution and proper motion of maser spots must be checked by high angular resolution observations in the future.

SiO maser jets can be developed near the protostar W51 North at the earliest stages of accretion-based high-mass star formation prior to the formation of an ultracompact (UC) region and deeply surrounded by large-scale H_2O and SiO thermal outflows similar to the scenario suggested by Beuther (2004). Therefore, SiO maser jets may become a good candidate for studying the primary jet, which provides clues to constrain the launching mechanism of the outflows such as optical jets (de Gouveia Dal Pino 2005; Hirano et al. 2010). Moreover, Zapata et al. (2008) confirmed that the W51 North as a very young massive star-forming region is associated with high-mass accretion rates ($\sim 10^{-2}$–10^{-4} $M_\odot$ yr^{-1}), which are sufficient to quench the formation of an UC H II region. It will be worth investigating how the variations of the high mass accretion rates onto the forming star can result in the rapid time variations of the multiple high-velocity SiO maser emission, which are seen in the low-mass protostar jets/outflows (Arce et al. 2007).

Concerning the H_2O masers, their spike components are also highly variable on the short timescales (< 1 month) in both peak velocities and intensity as shown in Figure 1 and Table 1. Eisner et al. (2002) reported that the H_2O masers from W51 North trace the shocks that were formed when the ballistic outflow ran into the ambient material. Therefore, the short time variability of the H_2O maser spots might be due to the varying shock conditions associated with the outflow. This is because the shocks can increase H_2O column density and disturb the gas over a large distance. Short timescale monitoring observations (<1 month) of both H_2O and SiO masers are required toward W51 North.

We also obtained 23.1 GHz (Class II) and 44.1 GHz (Class I) CH_3OH spectra toward the same position of W51 North, as shown in Figure 2. KVN single dish beams at these frequencies contain the W51 IRS2 cluster. It was known by VLBA observations that 12.2 GHz CH_3OH masers emanate from a UC H II region W51 d2 (Minier et al. 2001). Therefore, 23.1 GHz and 44.1 GHz CH_3OH lines seem to emerge from the W51 d2 region. The 23.1 GHz CH_3OH line shows a typical maser feature with a spiky emission. The peak velocity of

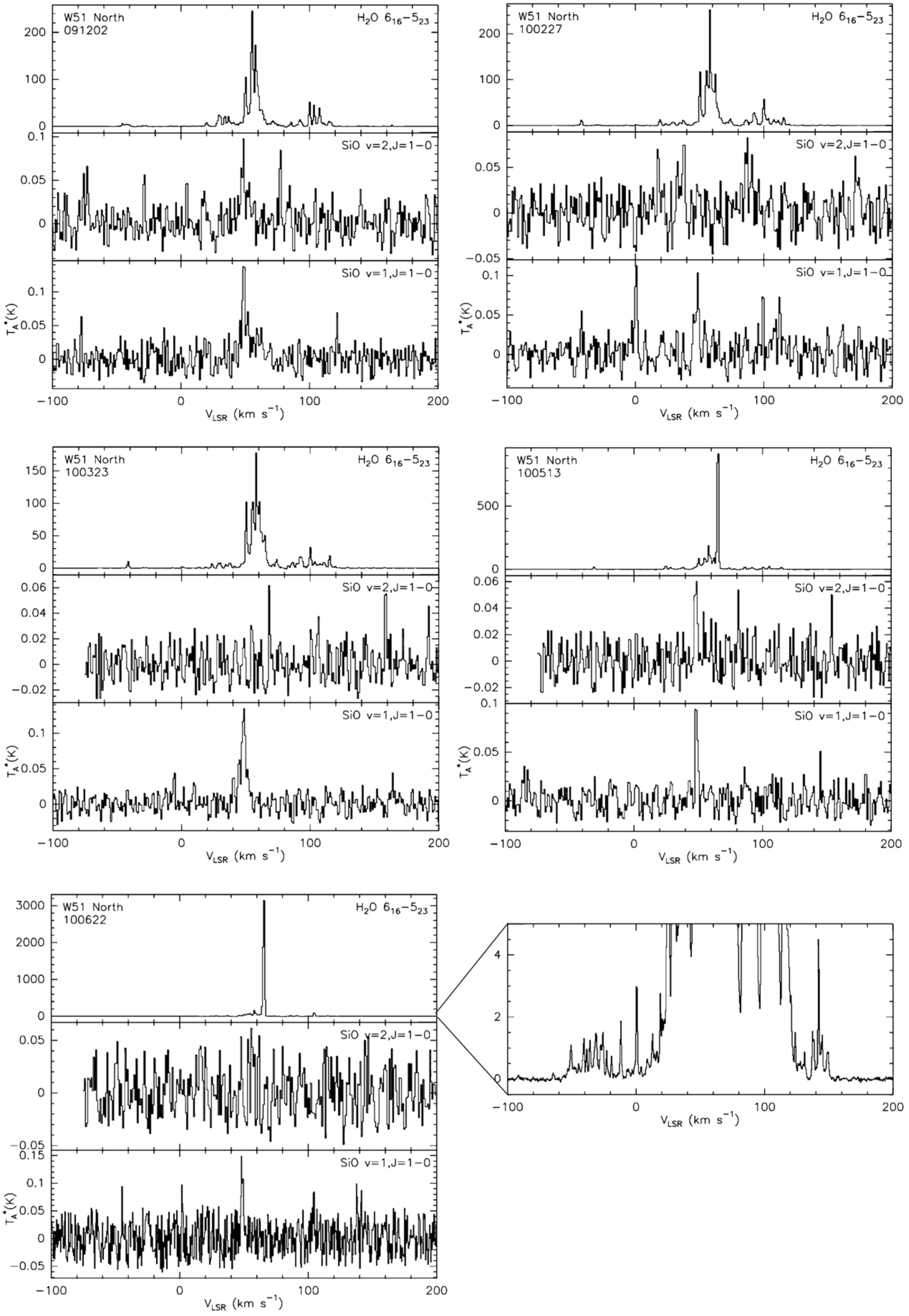

Figure 1. Spectra obtained by simultaneous time monitoring observations of H_2O, SiO $v = 1, 2, J = 1–0$ maser emission toward W51 North. The SiO $v = 1, J = 1–0$ spectrum of 2010 June 22 was not smoothed.

Table 1
Peak Antenna Temperatures and LSR Velocities of SiO and H_2O Masers from W51 North

Masers and Components		091202		100227		100323		100513		100622	
		T_A^* (K)	V_{LSR} (km s^{-1})	T_A^* (K)	V_{LSR} (km s^{-1})	T_A^* (K)	V_{LSR} (km s^{-1})	T_A^* (K)	V_{LSR} (km s^{-1})	T_A^* (K)	V_{LSR} (km s^{-1})
^{28}SiO	First	0.07	−77.3	0.05	−41.8	0.04	−5.5	[a]0.04	−85.0	0.09	−44.8
($v = 1$)	Second	†0.05	−13.1	0.11	0.7	0.14	48.5	0.10	48.0	0.10	1.9
	Third	0.14	48.8	0.10	48.6	0.05	164.1	[a]0.04	86.1	0.15	48.2
	Fourth	0.07	121.6	0.07	99.3	...	...	0.05	145.4	0.09	104.6
	Fifth	...	...	0.07	112.2	...	...	...	...	0.10	137.7
^{28}SiO	First	0.07	−72.7	0.07	17.4	0.06	68.2	0.06	48.5	< 0.06	...
($v = 2$)	Second	0.06	−28.3	0.08	37.7	0.04	106.3	0.05	81.4	...	...
	Third	†0.05	4.8	0.08	87.3	0.06	158.9	0.05	153.6	...	...
	Fourth	0.10	48.5	0.06	171.5	0.05	192.3	...	...	...	...
	Fifth	0.08	77.6	...	...	...	...	...	...	...	...
^{29}SiO ($v = 0$)	<0.06	...	< 0.05	...	< 0.04	...	< 0.04	...	< 0.05	...	
H_2O	EB	0.07	−82.0	0.10	−62.7	0.22	−62.7	0.11	−63.3	0.10	−91.7
	SP	251.50	55.6	258.46	57.9	181.43	58.2	921.77	65.6	3158.70	65.6
	ER	3.14	164.4	0.10	173.5	0.34	165.0	0.27	157.7	0.14	157.7

Notes. Multiple components above 3 rms level are indicated by an ordinal number from the left of LSR velocity. EB : extremely blueshifted component; SP : strongest peak component; ER : extremly redshifted component.

The systemic LSR radial velocity of the ambient molecular cloud is about 60 km s^{-1} (Zhang et al. 1998).

[a] Marginal detection as 3 rms level.

^{29}SiO maser shows only upper limits.

The numeral indicates the observation date; for example, 091202 means 2009 December 2.

Table 2
Peak Antenna Temperatures and LSR Velocities of CH_3OH Masers from W51 North

Molecule and Transition	T_A^* (K)	V_{LSR} (km s^{-1})	rms (K)	Date (yymmdd)
CH_3OH 7(0,7)–6(1,6)A^+	0.49	60.9	0.018	10 05 13
CH_3OH 9(2,7)–10(1,10)A^+	0.06	60.9	0.016	10 05 13

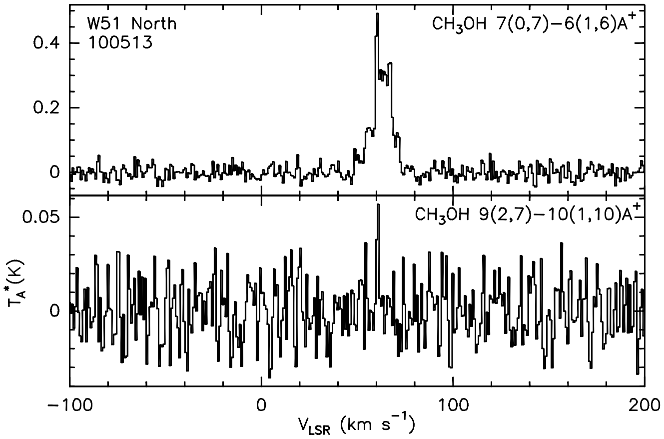

Figure 2. Simultaneously obtained spectra of 23.1 GHz CH_3OH 9(2, 7)–10(1, 10)A^+ and 44.1 GHz CH_3OH 7(0, 7)–6(1, 6)A^+ lines toward the same position of W51 North on 2010 May 13. KVN single dish beams at 23.1 GHz and 44.1GHz contain W51 d2 which are offset in the west about 3″from W51 North.

23.1 GHz CH_3OH is well consistent with that of 44.1 GHz CH_3OH, $V_{LSR} = 61$ km s^{-1} (Table 2) which is close to the systematic LSR radial velocity (∼60 km s^{-1}) of the ambient molecular cloud. Together with the multiple high-velocity SiO maser emission (SiO maser jets), we confirm that W51 North is currently in an extremely young massive star-forming stage, which is earlier than W51 d2 according to the age sequence of interstellar masers (Reid 2007). However, we cannot exclude the possibility that 23.1 GHz and 44.1 GHz CH_3OH masers are associated with W51 North, as W51 North also has a systematic velocity of about 60 km s^{-1}.

In addition, SiO maser emission can trace the region close to the massive protostar because of its excitation requirements ($v = 2$, $J = 1$–0: $n_{H2} \sim 10^{10}$ cm s^{-3}, $T_{ex} \sim 3500$ K; Elitzur 1992), and it will be a good probe for investigating the launching place of jets/outflows and their collimation mechanism. The multiple SiO ($v = 1, 2, J = 1$–0) high-velocity masers show a different feature in different epochs and ^{29}SiO $v = 0$ line is not detected during our observations. Except for the central main component of the SiO $v = 1$ maser, the multiple SiO $v = 1$ and $v = 2$ maser components show different radial velocities in every epoch and those features observed at the same time in the $v = 1$ and $v = 2$ maser emission do not show any correlations. These properties suggest that the ejection phenomenon of SiO maser spots in W51 North is intrinsically episodic as in young molecular outflows from low-mass protostars (Arce et al. 2007). These rapid variations of radial velocities and features would be especially well reflected in SiO maser emission due to the exponential phenomenon of masering close to the protostar. From a radiative transfer analysis, Goddi et al. (2009) suggested that the $v = 2$, $J = 1$–0 transition is optimized at higher temperatures, and it is more strongly inverted in a strong, hot radiation field than the $v = 1$ transition in Orion KL source I. Therefore, these different characteristics between SiO $v = 1$ and $v = 2$ masers from W51 North would not be strange. These characteristics allow us to study the different physical conditions near the protostar according to different SiO transitions.

Finally, we could not exclude the possibility that the multiple high-velocity SiO maser emission emanated from the material expelled from a rotational disk around protostar W51 North similar to Orion SiO around protostar source I, as suggested by Greenhill et al. (2004) and Reid et al. (2007). Therefore, time-monitoring VLBI observations of SiO ($v = 1, 2, J = 1$–0) masers are required in the future for confirming the origin of the multiple high-velocity SiO maser emission.

This work was supported by Basic Research Program (2009–2010) and also partially supported by "KASI–Yonsei Joint Research Program (2010) for the Frontiers of Astronomy and Space Science" funded by the Korea Astronomy and Space Science Institute. We thank Dr. David C. Y. Hui (Department of Astronomy & Space Science, Chungnam National University) for English language assistance.

REFERENCES

Arce, H. G., Shepherd, D., Gueth, F., Lee, C. -F., Bachiller, R., Rosen, A., & Beuther, H. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 245

Bachiller, R., Martín-Pintado, J., & Fuente, A. 1991, A&A, 243, L21

Beuther, H. 2004, in X-ray and Radio Connections, ed. L. O. Sjouwerman & K. K. Dyer (Santa Fe, NM: NRAO), 8 (http://www.aoc.nrao.edu/events/xraydio)

Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93

de Gouveia dal Pino, E. M. 2005, Adv. Space Res., 35, 908

Eisner, J. A., Greenhill, L. J., Herrnstein, J. R., Moran, J. M., & Menten, K. M. 2002, ApJ, 569, 334

Elitzur, M. 1992, Astronomical Masers (Dordrecht: Kluwer)

Gaume, R. A., & Mutel, R. L. 1987, ApJS, 65, 193

Goddi, C., Greenhill, L. J., Chandler, C. J., Humphreys, E. M. L., Matthews, L. D., & Gray, M. D. 2009, ApJ, 698, 1165

Greenhill, L. J., Reid, M. J., Chandler, C. J., Diamond, P. J., & Elitzur, M. 2004, in Proc. IAU Symp. 221, Star Formation at High Angular Resolution, ed. M. G. Burton, R. Jayawardhana, & T. L. Bourke (Cambridge: Cambridge Univ. Press), 155

Han, S.-T., Lee, J.-W., Kang, J., Je, D.-H., Chung, M.-H., Wi, S.-O., Sasao, T., & Wylde, R. 2008, Int. J. Infrared Millim. Waves, 29, 69

Hasegawa, T., Morita, K., Okumura, S., Kaifu, N., Suzuki, H., Ohishi, M., Hayashi, M., & Ukita, N. 1986, in Proc. of Haystack Observatory, Masers, Molecules and Mass Outflows in Star Forming Regions, ed. A. D. Haschick (Westford, MA: Haystack Observatory), 275

Hirano, N., Ho, P. T. P., Liu, S.-Y., Shang, H., Lee, C.-F., & Bourke, T. L. 2010, ApJ, 717, 58

Imai, H., Watanabe, T., Omodaka, T., Nishio, M., Kameya, O., Miyaji, T., & Nakajima, J. 2002, PASJ, 54, 741

Jijina, J., & Adams, F. C. 1996, ApJ, 462, 874

Kraus, S., et al. 2010, Nature, 466, 339

Krumholz, M. R., Klein, R. I., McKee, C. F., Offner, S. S. R., & Cunningham, A. J. 2009, Science, 323, 754

McKee, C. F., & Tan, J. C. 2002, Nature, 416, 59

Minier, V., Conway, J. E., & Booth, R. S. 2001, A&A, 369, 278

Morita, K.-I., Hasegawa, T., Ukita, N., Okumura, S. K., & Ishiguro, M. 1992, PASJ, 44, 373

Patel, N. A., et al. 2005, Nature, 437, 109

Reid, M. J. 2007, in Proc. IAU Symp. 242, Astrophysical Masers and their Environments, ed. J. M. Chapman & W. A. Baan (Cambridge: Cambridge Univ. Press), 522

Reid, M. J., Menten, K. M., Greenhill, L. J., & Chandler, C. J. 2007, ApJ, 664, 950

Schneps, M. H., Lane, A. P., Downes, D., Moran, J. M., Genzel, R., & Reid, M. J. 1981, ApJ, 249, 124

Zapata, L. A., Ho, P. T. P., Schilke, P., Rodríguez, L. F., Menten, K., Palau, A., & Garrod, R. T. 2009a, ApJ, 698, 1422

Zapata, L. A., Menten, K., Reid, M., & Beuther, H. 2009b, ApJ, 691, 332

Zapata, L. A., Palau, A., Ho, P. T. P., Schilke, P., Garrod, R. T., Rodríguez, L. F., & Menten, K. 2008, A&A, 479, L25

Zhang, Q., Ho, P. T. P., & Ohashi, N. 1998, ApJ, 494, 636

Zinnecker, H., & Bate, M. R. 2002, in ASP Conf. Ser. 267, Hot Star Workshop. III. The Earliest Stages of Massive Star Birth, ed. P. A. Crowther (San Francisco, CA: ASP), 209

Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481